A Structural Design Methodology to Reduce Structural Complexity to Improve Coating Application and Performance in Water Ballast Tanks

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Abstract

The introduction of the IMO Performance Standard for Protective Coatings (PSPC) for dedicated water ballast tanks (WBT) has increased the importance of the coatings applied in these tanks. Typical structural configurations within Water Ballast Tanks (WBTs) have a high degree of complexity; these spaces contain a large extent of edges, corner details and welds, which are commonly cited as areas most likely to suffer coating failure. However there is no quantitative measure of complexity as an indicator of how difficult a structure is to coat reliably.

The concept of ‘structural complexity’ is considered with the intention of improving the in-service performance of applied coatings by proposing ships structures that include the coating process as a design consideration. As a means to try and provide a quantitative measure indicative of how easy a structure is to coat, the idea of ‘structural complexity’ is developed based on fundamental structural features. This measure is then used to understand the influence that different stiffener profiles and stiffener spacing may have on the coating process if structural configurations are sought that have reduced complexity.

Investigation of the principal developments of the coating process indicates that any improvement is unlikely to be driven by coating technology or process alone. If improvements are to be made the suggestion here is that they should be driven by improving the design of the structure to be coated. The intention is to promote a ‘design for the coating process’ methodology to achieve this.

The global ship and structural design process have been reviewed, where the classical approach looked at the relationship between weight and strength. This work concurrently considers the implications of different structural configures on not only weight and strength but also ease of coating.

The relationship between the topology of the structure and the physical task of applying paint to it has formed the foundation of a ‘design for coating’ methodology, where the influence of structural complexity on all aspects of performance is considered with equal merit. A coating cost estimator has been developed in order to demonstrate the potential savings that could be realised by considering the coating process during the design phase.

A simple optimisation routine has been used to seek solutions for minimum, complexity, weight, steelwork and coating costs. This allowed the balance to be explored between the completing aspects of the steelwork and coating processes. These alternative design solutions have been assessed using mathematical computational methods to ensure that the designs provide adequate structural performance.

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Nomenclature

A = Cross sectional area of plate stiffener combination;

Ab_{cons} = Abrasive blasting material usage (kg/m^2);

Ab_{cost} = cost of abrasive blasting materials;

A_{fp} = Area of unstiffened plate;

A_{min} = Total surface area without adequate standoff;

$A_{min'}$ = Non dimensional total surface area without adequate standoff;

A_T = Total surface area;

A_p = Surface area of plate;

A_{Ratio}' = Non-dimensional area ratio;

A_{sl} = Surface area of longitudinal stiffeners;

A_{st} = Surface area of transverse stiffeners;

A_l = Lost surface area;

b = Stiffener spacing;

$\mathrm{b_{eff}}$ = Effective stiffener spacing;

B_{plate} = Breadth of plate;

C_A = Area complexity;

C_{AM} = Minimum area complexity;

C_{FE} = Free edge complexity;

CI = Complexity Index;

C_V = Volume complexity;

C_{WL} = Weld length complexity;

DFT = required dry film thickness (DFT) in microns;

E = Modulus of Elasticity;

e_{cost} = cost of edge grinding (€/m);

e_t = cost of stripe coating (€/m);

$f\,e$ = Component free edge length;

FC = Global cost function (in Euros);

F_{cons} = Cost of consumables for manufacturing process;

F_{lab} = Cost of building labour.

F_{mat} = Cost of materials;

f_t = Flange thickness;

f_w = Flange width;

l_{eff} = Length of ‘column’;
l_{FE}' = Non-dimensional free edge length;
l_{plate} = Length of plate;
L_{prep} = surface preparation labour costs (€/day);
L_{paint} = protective coating application labour costs (€/day);
l_{sl} = Length of longitudinal stiffeners;
l_{st} = Length of transverse stiffeners;
l_{WL}' = Non-dimensional weld length;
l_W = Component weld length;
L = paint loss factor;
I = Second moment of area of plate stiffener combination;
M_{prep} = Surface preparation material costs;
M_{paint} = Protective coating material costs;
N_c = number of applied coats;
n_i = Number of intersections.
nS_l = Number of longitudinal stiffeners;
nS_t = Number of transverse stiffeners;
P_{mat} = Coating process material costs;
P_{lab} = Coating process labour costs;
PL_{costs} = surface preparation labour cost (€/day);
Pt_{cost} = cost of protective coating (€/litre);
P_c = Paint application cost (€/m^2)
S = Actual paint spread rate;
SP_{prod} = surface preparation production rate (m^3/h);
s_w = average width of stripe coat;
t = Thickness of plate;
σ_y = Yield stress of steel;
V_{Ratio}' = Area volume ratio;
V_t = Volume of space;
VS = volume solids of the paint;
w_t = Web thickness;
w_h = Web height.
Z = Section modulus

1 INTRODUCTION

1.1 Introduction

The work presented within this thesis seeks to address some of the issues associated with ship Water Ballast Tanks (WBT) with particular attention being focused on the protective coatings that are applied to them. The International Maritime Organisation (IMO) Maritime Safety Committee (MSC) identified that coating performance within ships Water Ballast tanks (WBT) was of global concern for the safety and integrity of ships. Following a long period of technical discussion, the PSPC for WBTs was approved on the 5th December 2006 and adopted in July 2008. Resolution MSC.215(82) is now mandatory for dedicated seawater ballast tanks on all ship types of more than 500 gross tonnes and double skin spaces in bulk carriers of greater than 150m in length. The overarching aim of the PSPC is to improve the standards of WBT coatings during the application at new builds, to achieve a 15 year target life for those coatings.

The introduction of the Performance Standard for Protective Coatings (PSPC) has led to a greater need to focus on identifying suitable coating products and consideration of whether current structural designs are actually capable of being coated efficiently and reliably. The PSPC highlights this issue in section 3.3.2 it states that:

> *"the coating performance can be improved by adopting measures at the ship design stage such as reducing scallops, using rolled profiles, avoiding complex geometric configurations and ensuring that the structural configuration permits easy access for tools and to facilitate cleaning, drainage and drying of the spaces to be coated"*.

Thus for the first time the new regulations establish a formal link between the design and corrosion of ballast tanks on board ships. This thesis includes an examination of the development ship design methodologies and implementation of technology. Industrial research has highlighted the major factors that have caused the disparity between the steelwork and coatings processes in terms of their advancement. The purpose of the research is to improve the safety of ships by looking at new ways in which structural design can be improved to gain the optimum benefit from modern coating materials, surface preparation and application technology.

The work of this thesis focuses on the influence of simple design changes and will investigate, areas such as the use of different stiffener sections and provision of better access to the surface within the tanks. Better integration will seek to identify the benefits of a more holistic approach to design.

Rochefoucauld (1613-1680) is quoted as stating that “the only constant in life is change”, this is especially true within any industry that produces or manufactures a product. Operating cost will always increase, due to increasing material and labour costs, thus to maintain the overall cost of a product or process, improvement must be continually sought and implemented. Isambard Kingdom Brunel also observed, “the most useful and valuable experience is that derived from failure and not from success” (***Caldwell 1980***). Caldwell went on to say that when this philosophy is applied to engineering “future development is based upon past failures, not its success that merely act to limit engineering knowledge”. As such successful designs may well be over engineered, resulting in them being grossly overweight and less than optimum. The process of improving design is to examine the areas whereby a failure to deliver can be identified. When considering structural design, it is relativity easy to determine when a design has ‘failed’, however it is far more difficult to define when a design has failed to provide the working conditions necessary to construct and protect the structure.

A recent editorial comment (***OMT 2012***) describes how current design philosophies are driving designers to minimise the extent of non-revenue generating spaces within a ship. This has led to a situation where by these spaces are being squeezed into smaller spaces. As there is an inherent amount of steelwork structure that must be present to provide the necessary strength, as these spaces become smaller, the result is that the complexity of these spaces is increasing.

1.2 Collaboration with Industrial Partners

This project will be undertaken within the framework of a Knowledge Transfer Partnership (KTP) programme over a period of 3 years, with the funding being provided by AEA PLC acting on behalf of the Technology Strategy Board.

The involvement of industrial partners has allowed the author to explore what could be achieved by altering the approach to structural design and how much it can be optimised for coating activities, without having to compromise either shipbuilding or operational requirements. This research was carried out in collaboration with, American Bureau of Shipping (ABS), a world leading classification society, IHC Merwede Offshore & Marine, an innovative and specialist shipbuilder in the Netherlands, Jotun Paints of Norway, one of the marine paint majors and Muehlhan International of Germany, one of the world's best known marine painting contractors, and Safinah a leading Marine Coating Consultancy. This formed the research project known as Design to Improve Structural PROtection (DISPRO) which was lead by the author sought to explore what can be achieved by altering the approach to structural design and how much it can be optimised for coating activities, without having to compromise either shipbuilding or operational requirements.

IHC Merwede Offshore & Marine (IHC) provided the author with first hand access to the complete design and build process of what could be classed as small highly complex ships. This involved discussing the design process with the design team, observing the construction process and the blasting and painting process, subsequently referred to as the coating process. This allowed the author to document the problems created for the coating process during design and construction. IHC have a committed policy of exploring new designs in order to reduce the build costs of a vessel. This is especially important due to the fact that a significant percentage of the vessel that they deliver are one off designs thus meaning that they are unable to gain the production advantages that are typical when building a series of vessels.

Interaction with Muehlhan provided insight into the problems that design creates for the operators of the coating process. Muehlhan also provided the methodology that they use to determine the cost of preparing and coating a space, based upon the geometry and lay out of the space. This formed the basis for the development of the complexity index described within this project. Muehlhan's involvement in the project is also driven by a need to better determine work content for a given tank. Fixed price contracts are a primary factor behind this, as unexpected work or rework will have a large impact on the profitability of a contract.

Jotun Paints provided access to the development process of past, present and future marine coatings. This involved observing the initial development and testing of coatings, including access to the testing facilities where the current WBT coatings testing protocols where developed. Jotun also provided input on the limitations on the capabilities of paints during the application process, which aided the development of the Complexity Index. Jotun's involvement stems from the fact that they are confident that the protective coatings that they have developed for WBTs are capable of exceeding the 15 year target life specified by the PSPC. However they are continually seeing coating failures, thus they want to better understand the factors that affect the in service lifetime of coatings. They are also looking beyond the PSPC requirements and they see this project as a way of building knowledge to feed back into the coatings development process for the future

The American Bureau of Shipping (ABS) is currently the only Classification Society which is actively involved in research and development with regard to coatings. They developed the CPS (coating Performance Standard), this Guide, specifies the criteria that must be met to achieve the class notation CPS. The guide has been developed with the objective of promoting the effective use of protective coatings on ABS-classed vessels. Even so Mr Edward Jansen the principal engineer in the shared technology centre, who has been the driving force behind ABS's involvement in coatings based research stated during an early project meeting that "Class are not interested in paint, only the steelwork below it". As a whole ABS have provided invaluable support in providing feedback on the design methodology that has been developed within this thesis.

1.3 Aims and Objectives

The work presented within this thesis examines the coating process within the shipbuilding industry and presents a number of factors that would improve the performance of applied protective coatings. The main focus of the work has been to develop a methodology to calculate the complexity of a given structure, on the basis that if it is possible to measure something it is possible to reduce it, and thus deliver quantifiable savings for both the steelwork and coating processes. The hypothesis of this work is that structural complexity has an influence on the physical tasks of the coating process. To quantify that effect a cost estimation model for the coating process has been developed which includes the complexity of a given structure.

A design space has been defined using well defined structural measures and an optimisation model has been developed to allow alternative solutions to be explored. An optimisation model has been developed to compare the solutions returned by five different objective functions which seek to minimise: complexity; weight; steelwork costs; coating costs and total costs. The resultant stiffener dimensions from the optimisation models have been used to construct a number of mathematical models to assess the structural performance of the design solutions.

The overall aim of the project was to reduce the complexity of WBT design to improve the safety of vessels at sea, whilst trying to provide benefits to the coating process. These benefits included reduced man-hours; improved productivity in shipyards; reduced repair hours; potentially improve turnaround in dry-dock; increased coating life; reduced operational and maintenance cost to the owner. The wider shipping industry views on the coating process have been gathered by means of a questionnaire, this supplement the key industrial partners who provided input on addressing the problems created for the coating process by structural design of WBTs..

1.4 Major Contributions of the Thesis

There is often a great deal of discussion on the complexity of one tank or area of a ship compared to another, for example the factors used for in the Jotun Coating Manual (***Jotun 2001***). This thesis has sought to provide a means of identifying and quantifying the influence of the elements that contribute to the complexity of a structure. On the basis that once it is possible to quantify something then you can explore ways of reducing it. Input from the industrial partners was used to aid in determining which factors had the greatest effect on the cost of overall production of a water ballast tank.

This knowledge was then used to examine a range of stiffener types and topologies to determine what improvements can be realised through altering the dimensions of a given stiffener and also by the use of alternative stiffener profiles. The lead to the development of the Complexity Index, this uses the stiffener topology to determine the total surface area, the none visible area when viewed normal to the plate, the arc length which is driven by the relationship between the web height and flange width, as well as the amount of free edge and weld length. By combining these factors the tool determines the level of difficulty an operator would expect to encounter when undertaking the physical activities of the coating process.

This work has focused on identifying structural solutions for the primary structure that provide practical improvements for the shipbuilding industry. This work has sought to find a method to quantify the complexity of given element of structure, alternative solutions have then been proposed that provide improvements to the working environment and thus cost savings. This is based on the assumption that if a task is ‘easier’ to do then there is a greater probability that it will be performed to a high standard more often.

Solutions have been sought where the objective function has been to minimise complexity, weight, steelwork costs, coating costs and ultimately total cost. This enables the development of alternative structural solutions which are capable of fulfilling the necessary structural requirements. A total cost estimate to produce a ship section has been proposed including the coating cost calculator which has built on ***Rigo’s*** (***2010***) method of calculating the steelwork costs. This method essentially breaks costs down in to those associated with the materials needed, e.g. steel or coatings, and to the labour costs associated to carry out the task, i.e weld or apply paint.

To ensure that the proposed alternative design solutions provide adequate structural performance, a number of constraints have been used to ensure that all of the alternative solutions are practical. These constraints include limiting the ratios between; web height and flange thickness, the height and thickness of the web, and thickness and width of the flange. In this study, the section modulus has been maintained for all of the alternative solutions as equal to that of the benchmark structure, as this provides a suitable indication of structural performance.

The work in this thesis developed from examining: a range of individual stiffeners and their associated plating; a stiffened double bottom panel; and a full midship section from a typical oil tanker. It should be noted that although class rules have been examined they have not been used as a constraint as this thesis seeks to explore the potential benefits that could be realised if the structures within WBTs were significantly easier to prepare and paint.

1.5 Outline of Thesis Chapters

The work in this thesis covers a number of areas, namely how WBTs have become integral to the safe operation of today’s merchant ships. The development of shipbuilding technology has been examined and highlights the gulf that has grown between the steelwork focused activities and the coating process. It is this relative lack of development that is believed to be one of the principal causes of many the paint failures witnessed. The ultimate goal of any applied paint system is to protect the steel substrate, thus the corrosion process is discussed briefly along with a range of typical paint failure modes.

This work is seeking alternative structural design solutions that provide improvements to the coating process. Chapter three provides an overview of the wider design process and more specifically the ship structural design process. The rationale behind the choice of structural design constraints is also discussed along with the numerical methods that will be used to assess the performance of panels and compartments.

Chapter four examines the ship production process in more detail, and looks at previous design and production methodologies. There have been a number of studies that have examined the coating process within shipbuilding, however none of these have considered the impact that design has both during the initial application but also subsequent maintenance and repair of applied coatings. Due to the industrial focus of this work, insight was sought from a range of people who are involved in the marine coatings industry.

Chapter five provides presents an approach to defining structural complexity and its relationship with the production work content. The factors that contribute to structural complexity are defined and methods for their calculation described. The proposed approach to quantifying structural complexity is set out and a method of calculating each of the elements of the complexity is described. A number of potential benefits that could be realised through the reduction of structural complexity are discussed, such as less direct cost savings and ship operational benefits.

Chapter six further investigates the relationship between structural arrangement and complexity, and how operators interact with the structure when they are preparing the surface and applying protective coatings. This begins with a single stiffener plate combination, cause and effect study and is subsequently developed to consider a full plate from the double bottom of an oil tanker. The knowledge gained was used to progress to a number of optimisation routines with objective functions for minimum complexity, weight, steelwork cost and coating costs.

Chapter seven examines the influence of the structural design constraints of the costs of constructing and painting a given panel and the trade-off between the production costs and weight. The developed approach has then been applied to a double bottom compartment; the balance between structural performance and costs is then discussed. Finally the entire midship section has been optimised and the potential savings presented for a number of different stiffener spacing limits based upon the Common Structural Rules.

Chapter eight presents the conclusions of this work and sets out future work both in terms of work to develop the direct findings of this work as well as recommendations to the wider shipbuilding and coatings industry.

2 THE BACKGROUND TO THE COATING OF WATER BALLAST TANKS

2.1 Introduction

This chapter charts the development of ballast requirements from simple fixed weights added to wooden sailing vessels to the large complex Water Ballast Tanks (WBTs) structures we see today. The recent introduction of the International Maritime Organisations Performance Standard for Protective Coatings (IMO PSPC) has led to much greater importance being attached to the activities of applying paint to WBTs; this was developed and adopted due to the large number of ship losses through structural failures as a result of corrosion in WBTs that occurred in the 1990’s. The development of the standard from an industry guideline to mandatory requirement is shown, and the implications for the coating process are discussed. The overall development of shipyard technology is presented and the lack of integration of the coating process with other shipyard activities, such as steelwork and outfitting, has been discussed. This is supported by the conclusions drawn from a number of studies that have been conducted to assess the state of the coating process.

2.2 The Inception of Water Ballast Tanks

Prior to the 1850’s ocean going ships were constructed from wood but by the late 1870’s more and more vessels were being constructed from iron and later steel, including composite steel framed structures, (***White, 1877***). As a result it became much easier to subdivide the hull structure into separate watertight spaces for the carriage of both cargo and ballast. The loss of a number of vessels, namely S.S. London and U.S. Monitor Weehawken, (***White, 1877***), highlighted the need to sub-divide the internal space to improve the watertight integrity of vessels and hence enhance their safety. With the introduction of steam power came the possibility of transferring seawater into and out of fully enclosed spaces much faster and cheaply than loading traditional ballast of rubble, (***White, 1877***). Thus WBTs where created in double bottom and wing tanks and have since remained a central design requirement of most ship types.

As iron and steel replaced wood, so corrosion replaced rot and worm attack as major causes of concern; ***White*** (***1877***) noted that guarding against rusting was *"by no means insignificant"*. With the introduction of the mild steel ship the problem of corrosion became still more significant and has been a constant battle for ship owners ever since. Corrosion in Water Ballast Tanks, and other double bottom spaces, was noted as a particular problem as early as 1906, when heavy grease paints were applied to new buildings under construction in the North East of England. These grease paints were a very labour intensive activity as they were applied by hand during final outfitting; however they proved to be highly successful at preventing corrosion in void spaces and WBTs. Such coatings became well known for their longevity as evidenced by their good condition when the vessels were scrapped, (***Towers, 2007***).

As with many industries, the Second World War accelerated major changes in the shipbuilding process. Riveting was replaced by welding as the method of connecting pieces of steel in the hull structure as it was far quicker and required less labour. The major influence of the introduction of welding was that it enabled ships to be pre-fabricated in blocks; this in turn allowed fabrication of blocks off-site and greatly reduced assembly time of the ship on the building berth, which was the traditional shipyard bottleneck, (***Bruce, 1999***). This allowed shipbuilding technology to become easily transferrable; as shown in the post war period where Germany, Sweden and Japan all took particular advantage in the implementation of these developments.

As the size of ships increased, so shipbuilders increased the size of block fabrications. The introduction of airless spray painting machines enabled shipbuilders to apply the coatings more quickly to match the increased surface areas of these larger ships. As the blocks size increased it became most cost efficient for shipbuilders to paint greater amounts of the ship at the block stage, (***NSRP, 2006*****)**. With the increase in the size of the vessel there was an associated increase in the requirement for water ballast; this drove up the size and capacity of the WBTs required and accordingly increased the amount of internal surfaces to be coated.

Prior to the early 1990's the coating of ballast tanks was a voluntary practice, the motivation to paint these areas was driven by cost consideration; by painting the steel substrate owners could reduce the costly practice of future steel work renewals. Coal tar epoxy coatings became the industry standard for WBT application. They are essentially a mix of coal tar and epoxy resins.

This type of coating was at its peak of popularity in the 1960's and regularly applied until the late 1980's, (***Towers, 2007***). They were phased out as a result of health concerns over long term exposure and direct contact with the 'tar'.

However as many of those vessels that had been supplied without WBT coatings began to age, an increasing number suffered structural failures that in some cases were severe enough to cause loss of the ship. From 1990 to mid-May 1997 a total of 99 bulk carriers sank with the loss of 654 lives. It was widely accepted that many of those ships that were lost during this time disappeared unexpectedly due to severe structural failure originating in the WBT spaces, in some cases ships had simply broken apart without warning, (***IMO, 1999***). As a result of this the IMO adopted a series of measures to improve bulk carrier safety, culminating in November 1997 when an IMO conference adopted important new regulations designed to prevent bulk carrier losses, (***IMO, 1998***). They entered into force on 1st July 1999 and are now a mandatory requirement for new builds. The development of this regulation will be discussed in detail later.

Following investigations, the International Association of Classification Societies (IACS) introduced a new enhanced survey regime that covered hull design changes, types of coatings applied, more intensive inspection standards and shorter survey intervals. This was successful in achieving the principal goal of minimising losses; another important consequence was that it opened a wider debate on how to raise the global standards of protection of the steel work within Water Ballast Tanks.

The lack of mandatory provisions relating to coatings for cargo holds and WBTs was further highlighted by the European Maritime Safety Agency, (***EMSA, 2005***). They reaffirmed the relationship between the breakdown of a protective coating and the subsequent rapid corrosion of unprotected steel that will occur. Additionally, the subsequent repair of the failed coating was found not to be to the same standard as that achieved at the first application during the new-build process. In the EMSA study a comparison was made between the condition of the WBT coatings of two ships of the same age and it was concluded that the significance of using the correct application procedures was of the upmost importance to ensure coating reliability.

2.3 The Function of Water Ballast Tanks

For vessels such as tankers or dry bulk carriers vessels, water ballast is required to enable an unladen ship to achieve a suitable draft to ensure propeller immersion and acceptable trim and stability; in the cases of tankers the minimum draft in the ballast condition is achieved to ensure adequate propeller immersion. The MARPOL regulations place a limit on cargo tank size and thus subdivides the ship's hull both longitudinally and transversely and thus defines the maximum individual size of the associated WBTs (***MARPOL, 2007***). In contrast, an offshore supply vessel has a very low total ballast capacity; it being principally used for trimming and heeling the vessel during operation. This ballast capacity is broken up in to a number of small WBTs to achieve this function. The size of the vessel then introduces the problem of access in ballast tanks as, due to their ranges of sizes some require multiple staging to gain access to the entire tank whilst others are very small and confined.

For capacity carriers, such as passenger, container and offshore vessels ballast is only used to control operational trim and heel conditions necessary to maintain adequate stability. Due to the wide range of vessel type and tank locations, it is not possible to consider a typical WBT as one does not exist upon which to base any investigations

The requirements for a double hull in all tankers operating in US waters as result of the Exxon Valdes accident, (***OPA 90, 1990***) has had the effect of hugely increasing the internal surface area of WBTs (***OCIMF, 1997***). This was later applied to all new-build tankers, known as Regulation F 'Prevention of oil pollution in the event of collision or stranding', which entered into force in July 1993. As a result, WBT have become more difficult to physically access to effectively conduct the activities of the coating process, as set out in the IMO Performance Standard for Protective Coatings (IMO PSPC), (***IMO, 2009***). Ways of minimising coating maintenance in such spaces will become increasingly important because of cost and manpower issues; this issue has been identified by ***Hyun- Kug*** (***2007***) as a result of the PSPC.

Deadweight carrier vessels require a large amount of ballast water, this means that WBTs have become the largest single area of structure that will be coated with the same paint system. Table 2-1 shows for different vessels types with increasing deadweight (Dwt) how the corresponding underwater area and WBT compare to each other. This demonstrates that WBT area can be as much as 10 times the underwater (U/W) area. Due to the large volumes of paint required in WBT's, the motivation for exploring all ways of minimising the initial cost of applying coatings and any subsequent coating maintenance and repair is obvious.

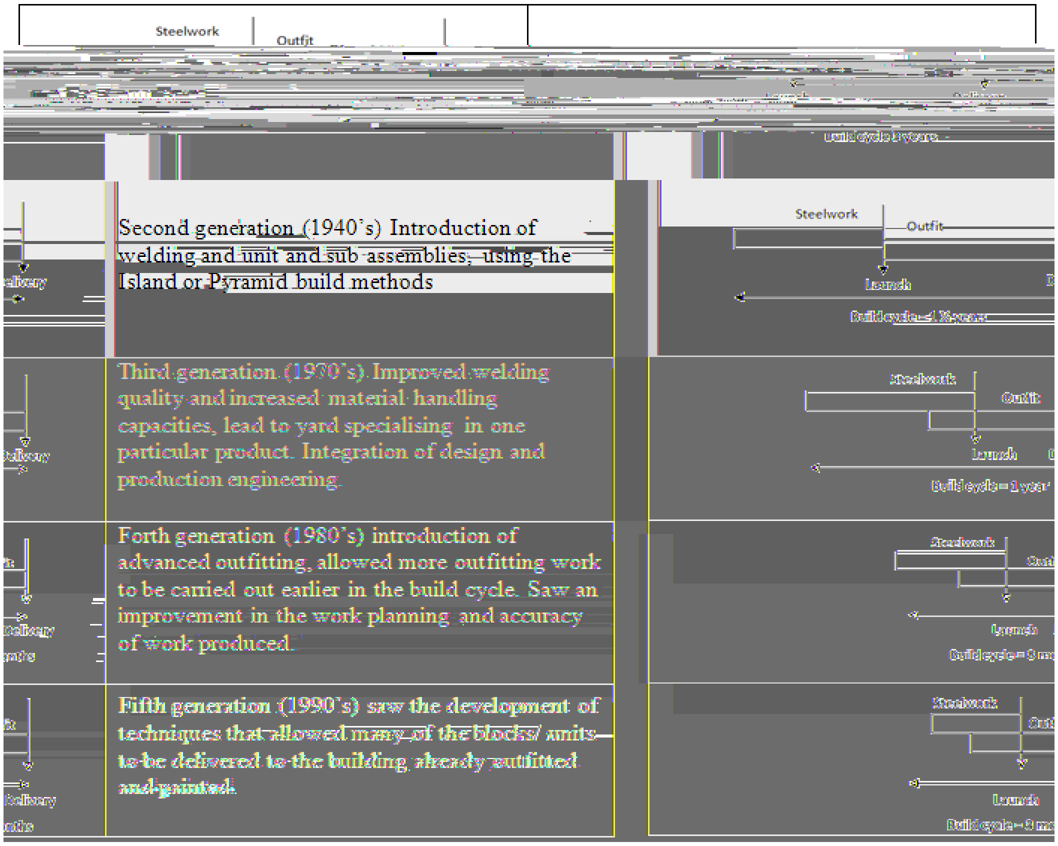
Table 2-1 Typical area values for different vessel types

Type of ship	Dwt	U/W area m2	WBT area m2	Area Ratio U/W : WBT
Dry cargo	15,000	3,400	11,000	1:03
Bulk carrier	30,000	6,000	42,000	1:07
Bulk carrier	60,000	10,800	65,000	1:06
Product tanker	80,000	12,000	125,000	1:10
VLCC D/hull	300,000	40,000	280,000	1:07

2.4 The Historical Perspective of the Coating Process Within Shipbuilding

To understand why many of the problems exist with the process of coating ships, it is important to examine the development of shipbuilding and shipyards since the Second World War. If the coating process is classed as all those activities involved in taking bare steel through to a painted item ready for service. It is possible to separate it into distinct activity groups; surface preparation, both primary and secondary, paint application, repair and touch up and inspection and edge preparation (where appropriate). The requirements for all of these activities are very similar in terms of the need for access and ventilation. Comparing the coating process to the steelwork and outfit activities it is clear that the technology used in the coating process is considerably less developed. As evidence of this, the first abrasive blasting process was patented by Benjamin Chew Tilghman in 1870, (***Plaster, 1993***). The first 'airless spray' paint unit was introduced by the Gray Company in 1958 (***Graco, 2010***). In terms of automation in shipyards within the coating process, the first centrifugal driven blasting machine (often referred to by the brand name ‘wheelabrator’) entered service at the Burmister and Wain yard in 1960 (***Baldwin, 1995***). From this it is apparent that it is at least 50 years since the last major technological development in the coating process. Whereas the investment in enhancing steel work and outfit activities has driven the development of shipyards (***Bruce, 1999***).Table 2-2 demonstrates how the build cycle time has reduced as shipbuilding technology has advanced, and shows the integration between the steel work and outfitting activities.

Table 2-2 Shipyard development *(Bruce 1990)*



Second generation (1940's) Introduction of welding and unit and sub assemblies, using the Island or Pyramid build methods

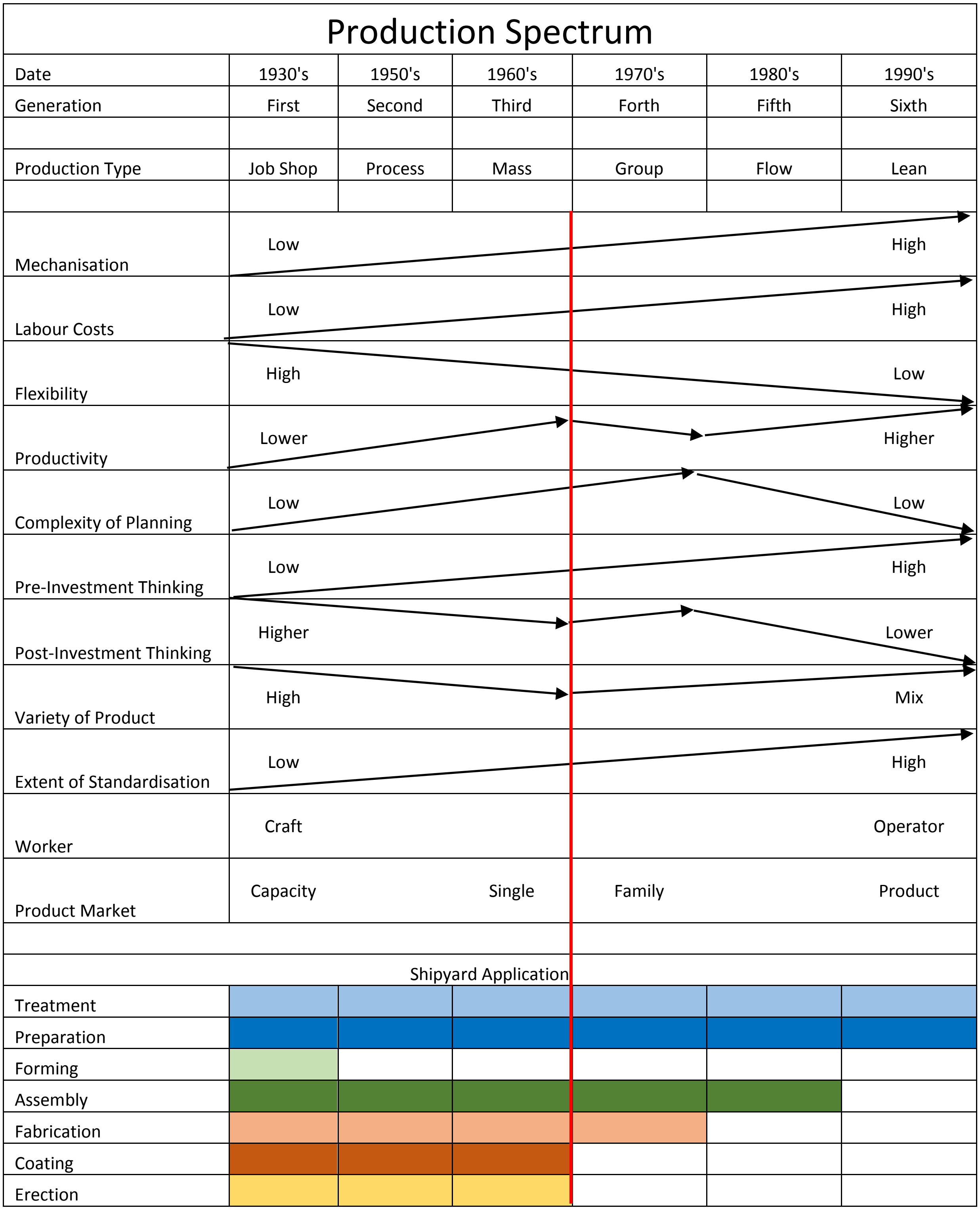
Third generation (1970's) Improved welding quality and increased material handling capacities, lead to yard specialising in one particular product. Integration of design and production engineering.

Forth generation (1980's) introduction of advanced outfitting, allowed more outfitting work to be carried out earlier in the build cycle. Saw an improvement in the work planning and accuracy of work produced.

Fifth generation (1990's) saw the development of techniques that allowed many of the blocks/ units to be delivered to the building already outfitted and painted.

To achieve the reductions in build times, shown in Table 2-2, shipyards invested heavily in automation of the steelwork facilities, and vessels were designed to suit the facilities of a particular shipyard. Against the background of the reduction in overall build time, the drying time of the coatings and the production rates of other coating activities has not drastically reduced/improved. This has resulted in increased time pressures on the coating process. The predictability of performance of the steelwork process has increased but this has not reflected in the coating processes to the same degree, if at all.

In order to identify areas that are in need of improvement within the coating process it was deemed prudent to chart the progress against that of other aspects of the ship building industry. Figure 2-1 (***Kattan unpublished***) shows the development of the shipbuilding industry from the 1930's through the generations up until the mid-1990's. It identifies how the relative importance of the factors affecting shipbuilding has altered during this time. This also serves to reinforce the lack of development of the coating progress since the late 1950's, around the time of the introduction of the 'wheelabrator'.



Production Spectrum

Date	1930's	1950's	1960's	1970's	1980's	1990's
Generation	First	Second	Third	Forth	Fifth	Sixth
Production Type	Job Shop	Process	Mass	Group	Flow	Lean
Mechanisation	Low					High
Labour Costs	Low					High
Flexibility	High					Low
Productivity	Lower					Higher
Complexity of Planning	Low					Low
Pre-Investment Thinking	Low					High
Post-Investment Thinking	Higher					Lower
Variety of Product	High					Mix
Extent of Standardisation	Low					High
Worker	Craft					Operator
Product Market	Capacity		Single	Family		Product

Shipyard Application

Treatment	🟦	🟦	🟦	🟦	🟦	🟦
Preparation	🟦	🟦	🟦	🟦	🟦	🟦
Forming	🟩					
Assembly	🟩	🟩	🟩	🟩	🟩	
Fabrication	🟧	🟧	🟧	🟧		
Coating	🟧	🟧	🟧			
Erection	🟨	🟨	🟨			

Figure 2-1 Development of Shipbuilding Technology

Figure 2-1 further reinforces that the coating process has lagged behind the steelwork activities creating an imbalance in production. The capacity of the steel work and outfit departments has increased whilst the coating throughout remains the same, resulting in a bottleneck at the coating stage of production.

If the breakdown of the cost of a typical 80,000 dwt bulk carrier new-build vessel is considered, it is apparent from Figure 2-2 that, the paint acquisition cost represents a very small amount of the total new-build price of a vessel. This further compounds the perception of coatings and their application as being a 'low value' process. This compounds the lack of development has taken place in the last 50 years to improve practices and the technologies of the coating process. During this period generally coating chemistry technologies have advanced however as will be discussed later there has been little development of heavy duty protective coating chemistry. It is the steelwork activities that have continued to drive forward shipyard technological advances. This is further compounded by the lack of development in the management systems used within the coating process as a whole. Thus the coating process has become unstable and unpredictable without suitable controls (***Kattan, 2007***).

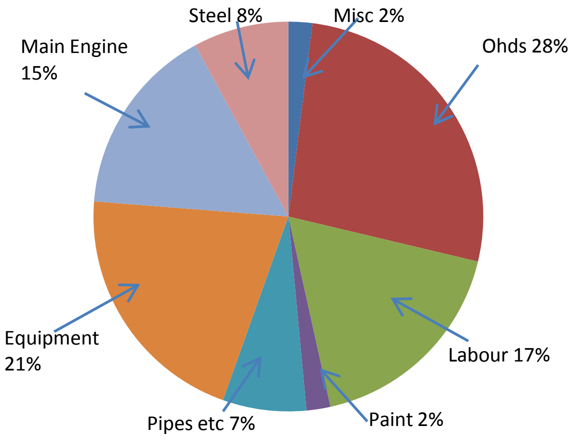


Figure 2-2 Typical New Build Cost Breakdown, *Safinah (2005)*

A number of papers have examined the production cycle within various shipyards (***Kattan et al, 1994; Baldwin, 1995; Easton, 1996; Baldwin & Kattan, 1997; Kattan & Baldwin, 1996; Kattan et al, 2003; Kattan, 2007***) and identified how the lack of pre-production planning and integration of the coating process has led to the creation of a bottleneck in the painting of finished steelwork blocks. The scheduling of painting activities are often determined by the planning of steelwork to maximise steel throughput, rather than prioritising the coating activities themselves. Similarly the coating process is often used as a buffer to compensate for steelwork and other production delays (***Kattan et al. 2003***). The problems associated with the reliability of coating application cannot be addressed in isolation; in order to achieve consistent high quality finishes emphasis also needs to be placed on the 'value adding' aspect of the coating process activities.

2.5 Types of Corrosion in Ballast Tanks

Corrosion occurs with the formation of hydrated ferric oxide, commonly termed as rust, from the electrolytic reaction between iron metal, oxygen and water. The corrosion process releases the energy that was added in order to convert iron ore to useable steel products. The reaction mechanism is generally accepted to involve anodic and cathodic processes. The surface of the iron or steel in contact with water develops localised anodes and cathodes at which these corrosion processes take place. The electrolytic process at the anode and cathode that leads to the formation of ferrous hydroxide, that in the presence of excess oxygen is further oxidised to form hydrated ferric oxide is shown schematically in Figure 2-3:

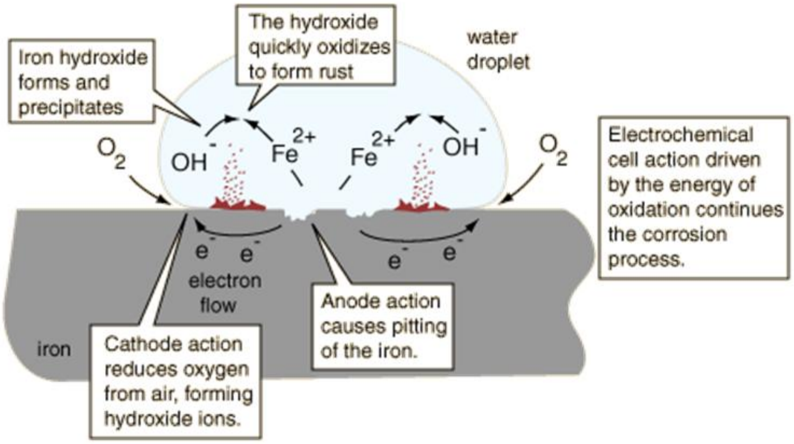


Figure 2-3 Typical corrosion cell

At anode:

$$4\ Fe \rightarrow 4\ Fe^{++} + 8\ e \qquad \text{2-1}$$

At cathode:

$$4\ H2O + 2\ O2 + 8e \rightarrow 8\ OH^{-} \qquad \text{2-2}$$

Product of oxidisation:

$$4\ Fe^{++} + 8\ OH^{-} \rightarrow 4\ Fe\ (OH)\ 2 \qquad \text{2-3}$$

There are a number of accepted different general types of corrosion, which will be discussed in the following sections.

2.5.1 Uniform Corrosion

Uniform or general corrosion is was is typically referred to as rusting of steel. The life of components is currently estimated based on relatively simple immersion test results. Allowance for general corrosion is relatively simple and commonly employed when designing a component for a known environment. Uniform or general corrosion usually occurs in stagnant or low flow seawater at a rate of approximately 5 – 10 microns per year on mild and low-alloy steels as shown in Figure 2-4. Uniform corrosion on these types of steels is the most common form of corrosive attack on ships.

Figure 2-4 Example of uniform corrosion

2.5.2 Crevice Corrosion

Crevice corrosion is a localised form of corrosive attack. Crevice corrosion occurs at narrow openings or spaces between two metal surfaces or between metals and non-metal surfaces as shown in Figure 2-5. A concentration cell forms with the crevice being depleted of oxygen. This differential aeration between the crevice, microenvironment, and the external surface the bulk environment, gives the crevice an anodic character. This can contribute to a highly corrosive condition in the crevice. This type of rapid failure is dangerous since it may jeopardise the integrity of the ship structure. Crevice corrosion has a tendency to occur in components where fasteners and lap joints are presented such as non-continuous welds, brackets and side frames

Figure 2-5 Example of crevice corrosion

2.5.3 Pitting Corrosion

Pitting corrosion is a form of extremely localised corrosion that leads to the creation of small holes in the substrate. The principal mechanism for pitting corrosion is similar to that of crevice corrosion in that there is a lack of oxygen in a small area. This area becomes anodic while the area with excess of oxygen becomes cathodic; leading to very localised galvanic corrosion. The corrosion area tends to bury into the mass of the metal, with limited diffusion of ions, further pronouncing the localised lack of oxygen. This kind of corrosion is extremely insidious as it causes only a small effect on its surface, but it significantly damages through thickness of the metal, it is particularly prevalent on the bottom surfaces of Cargo Oil Tanks (COTs). The pits on the surface are often obscured by corrosion products making this form of corrosion more difficult to detect as shown in Figure 2-6.

Figure 2-6 Examples of pitting corrosion

Pitting can be initiated by a small surface defect, such as a scratch or a local change in composition, or damage to protective coating. It is a major concern with pressure vessels, such as boiler drums, and compressed air receivers. In ballast tanks pitting corrosion mainly occurs due to irregularities in coatings due to improper surface preparation and coating practices. Though pitting may or may not result in the formation of holes in the substrate, it causes major damage to the structural integrity of the tank that can result in catastrophic failure.

Alloys most susceptible to pitting corrosion are usually the ones where corrosion resistance is caused by a fascination layer; stainless steels, nickel alloys, aluminium alloys. Metals that are susceptible to uniform corrosion in turn do not tend to suffer from pitting corrosion, for example regular carbon steel will corrode uniformly in sea water, while stainless steel will suffer pitting.

2.5.4 Galvanic Corrosion

This occurs when two dissimilar metals are connected in an electrolyte, thus causing the more anodic metal to dissolve and be deposited on the cathodic metal. The advantage of this phenomenon can be used for example where zinc anodes are used to protect the steel within a

WBT in the event of small coating break down. However the anodes are only able to protect the steelwork when the ballast tanks are full, thereby completing the electrical circuit. One common problem that can occur is when dissimilar metals are used for the internal pipework.

2.6 Corrosion Rate Modelling

A great deal of work in the field of predicting accurate rates of corrosion in the marine environment has been undertaken (***Melchers 1995***, ***2003a&b***, ***2006***, ***2007***, ***Gardiner and Melchers***, ***2003***, ***Melchers and Jeffery 2007***, ***Gudze and Melchers 2008***). This work had focused on developing probabilistic models for steel corrosion on marine infrastructure and determining the influence of the different factors on corrosion rates. The models have been based on work that has been carried out in the field and from data gathered from ships in service rather than laboratory based testing.

Gardiner and Melchers (***2003***) considered the physical processes of corrosion in a number of different areas within bulk carriers. The three different environments that are present within a vessel are: immersion in sea water; exposure to an enclosed environment; and exposure to porous media. In combination with the fundamental variables which influence corrosion in each environment, corrosion rate databases where proposed which are representative of actual in-service conditions for each area. Of most interest to this work is the reported average corrosion rates for sideshell frame, web and flange plating. It was noted that the topside tanks displayed smaller areas of coating breakdown and rust that in the double bottom tanks. This was attributed to the lack of damage from cargo operations in the topside tanks.

Melchers (2003a) reported on the lack of results for corrosion on structures in-service in maritime environments. In order to ensure that a structure is capable of performing its role during its expected life time the current practice is to add a corrosion allowance to the scantlings. The amount of additional material required is based upon empirical formula, which is based upon tests carried out under laboratory conditions. It is dangerous to assume that if additional material is added uniformly that a structure will perform throughout its expected life time. The presence of pitting corrosion is an example of this as it is possible to have deep localised corrosion that may penetrate through a steel plate comprising the integrity of the structure.

Melchers (***2006***) proposed a model (Figure 2-7) that provided a description of the progression of corrosion loss that is different from the conventional description based only on oxidation. It questioned the widely used corrosion laws that had been developed from short term experimentation and then extrapolated for long term predictions.

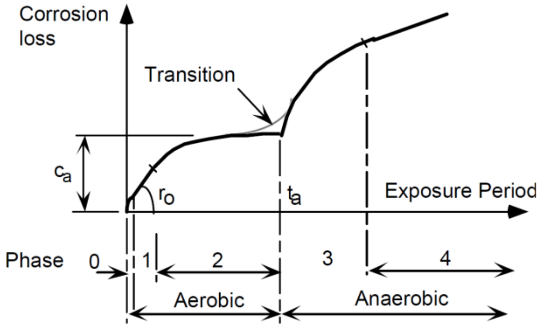


Figure 2-7 Melchers probabilistic corrosion model

Table 2-3 Summary Description of the phases of Melchers corrosion model

Phase	Corrosion Identification	Rate Controlling Process
0	On immersion steel surface is colonised by bacteria and marine organisms and subject to a complex mix of influences	Various local chemistry reactions largely unhindered by external diffusion or transportation limitations
1	Oxidation – controlled by rate of oxygen at the metal surface. Rust layers still very thin. The resulting corrosion loss may be modelled, closely, as a linear function	Maximum rate of oxygen diffusion from waters adjacent to corroding surfaces (‘oxygen corrosion control’)
2	Build-up of corrosion products (rust) tends to reduce the rate of oxygen supply to the corroding surface. Solution of governing diffusion equations provides theoretical solution (Melchers 2013)	Rate of corrosion depends on rate of bacterial metabolism. This depends on rate of supply of nutrients, including those stored in the rust layer.
3	Increasing thickness of the rust layer reduces the capability for oxygen to reach the corroding surface, thereby allowing localised anaerobic conditions to develop. SRB can flourish under the appropriate nutrient supply conditions (Melchers and Wells 2005)	Rate of corrosion depends on the rate of bacterial metabolism. This depends on the rate of supply of nutrient, including those stored in the rust layers.
4	Metabolism of SRB dependent on rate of appropriate supply of nutrients. Typically this	Rate of supply of nutrients and rate of loss of rust layer.

	in near-steady state. Also slow loss of rush layer through erosion and wear.	

Points of note to be taken from Melchers work shown in Table 2-3, the composition of steels with relatively low alloy contents there is essentially no difference between phases 0-2. This is as a result of the corrosion rate being controlled by the rate of oxygen diffusion to the corroding surface. Phase one is controlled by the rate of oxygen diffusion of the water and is the permeability if the rust layers that is the controlling factor in phase 2. The situation does not change as the alloy content is increased, apart from the oxygen diffusion through the rust layers tends to be become more difficult. It is for this reason that the corrosion loss tends to decrease with various alloys (***Melchers 2004***), but their effect depends on how much they can influence the permeability of the rust layers.

In phases 3 and 4 the corrosion rate is controlled by the anaerobic bacterial activity which is in turn dependent on rate of nutrient supply and the resistance of the steel to the metabolic products of the bacterial activity. It is generally accepted that the principal metabolite is H_2S, therefore the ability of added alloys to resist H_2S, which will determine the corrosion resistance of any given steel.

De Baere et al*. (*2011*)** studied the in-service condition of a large number of ballast tanks, a visual assessment based upon the IACS scale was used (IACS 2006***), from with the IMO PSPC, ‘GOOD’, ‘FAIR’ and ‘POOR’ representations have been developed. The approach adopted was to further subdivide the scale using a corrosion index (CI) on a one to ten scale (***Verstraelen et al*. *2009***). The CI was obtained by weighting the percentage of local and scattered corrosion on flat surfaces, the percentage of corrosion on edges and welds and the percentage of rust scale. This allows any given tank to be represented by one figure.

It is well known that over time that over time an applied coating film’s ability to provide an effective barrier between the steel substrate and the corrosive environment will reduce to the point at which widespread corrosion will occur. It is noted that there will be localised break downs on welds, edges and as a result of damage. However the point at which this occurs is still a relative unknown. Analysis of results of the condition surveys indicated that after 4.5 years corrosion became visible. If no maintenance work was undertaken then the tank condition would deteriorate from good to fair after 10.4 years, and to a poor state after 22.1 years (***Verstraelen et al**. **2009***). Figure 2-8, shows the weighted corrosion (CI) as percentage against the age of the coating. The colour bands, clear, yellow and red represent worsening condition of the coating in terms of coating breakdown.

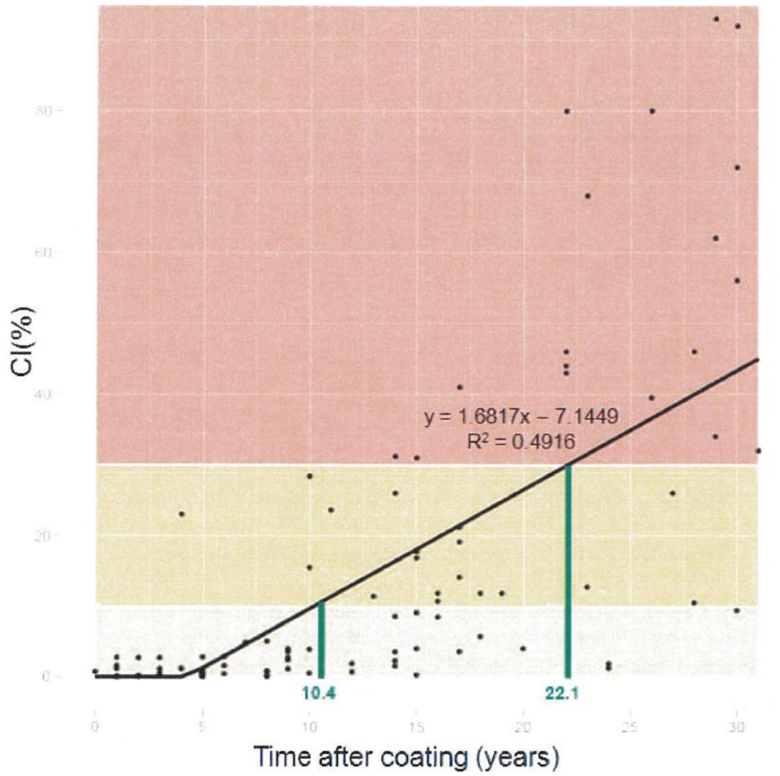


Figure 2-8 General corrosion model (Verstraelen et al**.** 2009)

The three different coloured areas represent the good, fair, and poor descriptions as per the IMO PSPC. This follows the corrosion model presented by Paik in his book ‘Ultimate limit state design of steel plated structures’ (***Paik 2003***), as shown in Figure 2-9. The time at which corrosion is likely to begin, is driven by the expected coating life t_c. Little work has been undertaken to predict this time period and thus identify the point at which the coating performance drops to a level below that which affords the steel adequate corrosion protection.

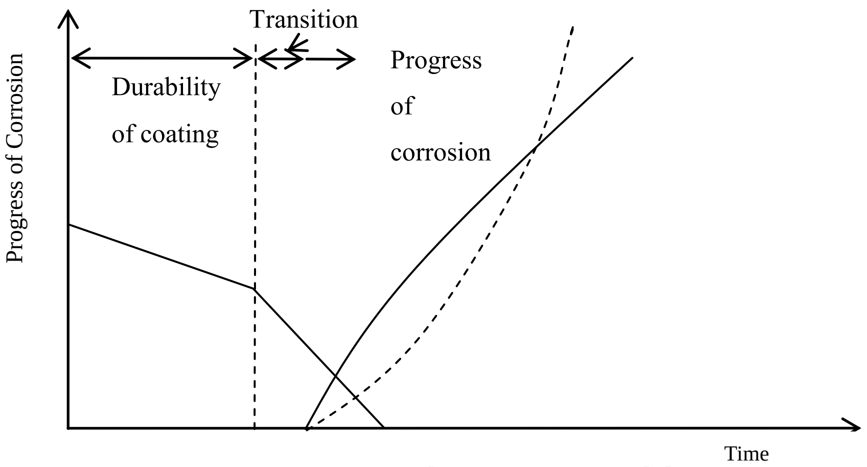


Figure 2-9 Paiks corrosion model

It would seem that the performance of an applied coating film is measured by its level of failure rather than an actual measure of its ability to provide an effective barrier. The work presented within this thesis is seeking methods to increase the length of time before the coating film breaks down thus leading to corrosion.

2.7 Methods of Corrosion Prevention

The cost of corrosion is estimated to be $2.2trillion worldwide however; it tends to be those areas deemed to be high risk to be given any real attention (***Hays 2010***). The problem remains how to prevent or at least minimise corrosion on a structure.

There are three main reasons why marine structures have protective coatings applied to them; corrosion protection; aesthetic appearance; and performance improvement. Corrosion prevention is obvious to maintain the integrity of a structure. In terms of the aesthetic appearance would be that of the automotive industry or the mega yacht sector, with antifouling paints applied to the underwater hulls of ships representing the performance improvement aspect of applied coatings.

The coatings applied to WBTs fall into the provision of corrosion protection to the steel structure. ***Qin and Cui,*** (***2003***) stated that 90% of all ships structural failures can be attributed to corrosion, and a principle Lloyds surveyor has been quoted as saying "*effective corrosion control in segregated water ballast spaces is probably the single most important feature, next to the* *integrity of the initial design, in determining the ships effective life span and structural reliability*".

To achieve the necessary lifespan of a structure the shipbuilding industry has adopted the approach whereby structures are protected by the application of a suitable protective coating and the use of sacrificial anodes. The coating film provides protection by forming an isolating layer between the steel substrate and the surrounding environment. The sacrificial anodes provide cathodic protection to areas where there is a break in the protective coating. The zinc or aluminium anodes are more anodic than the steel and therefore will deplete in preference to the steel as a result of them being far less noble. The presence of the zinc anodes prevents accelerated corrosion occurring at small localised breakdowns of the coating. However this is only effective when the galvanic cell is complete, i.e. when the tank is full of seawater. There may also be cases when the WBT is full of seawater but air pockets exist in the upper regions preventing full protection.

2.7.1 Materials

There are other options by which to reduce corrosion of the primary material of a structure. The use of alternative materials which possess corrosion inhibiting properties is one such method, there is the possibility of using materials such as:

- Weathering steel;
- Stainless steel;
- Aluminium.

2.7.1.1 Weathering steel

NSGP steel which is manufactured by Nippon Steel has successfully been used in the bottom plates of a number of cargo oil tanks on board the vessel AKAMINE (Built by Mitsubishi Heavy Industry). Laboratory studies predicated a pitting corrosion rate of less than 3mm per 2.5years, which has been confirmed by field testing on board a number of VLCCs (***Shiomi et al 2007***). This could result in a vessel not requiring steelwork repair or replacement during its expected lifetime, however this is highly dependent on adequate cleaning of the steel surface during dry dock (***Kawasaki 2009***). One of the major benefits this product has over carbon steel, is that the corrosion protection performance is not dependent of the workmanship on the working conditions during the coating process as there is no need for protective coatings.

The 3 year study conducted by Panel SR242 of the Shipbuilding Research Association of Japan, commented on the physical properties of the material and its workability experienced during the construction process being very similar to that of conventional hull steels (***Shiomi et al 2007***). NSGP has been identified as a candidate for an alternative corrosion protection system specified under the draft SOLAS amendment on protection of COT of tankers (***Kawasaki 2009***).

2.7.1.2 Stainless Steel

Stainless Steel forms a protective layer on its surface to prevent corrosion due to the chromium content of the material. To maintain this, the surface it must be kept clean so that it has access to atmospheric oxygen. Stainless steel with such an oxide layer are known as ‘passive’; i.e. the chromium oxide confers ‘passivity’ to the stainless steel. It should be noted that if the chromium oxide layer is removed constantly over a longer period of time through reaction with the environment, the material will corrode. Other metals that exhibit passivity in a similar way include aluminium, titanium, magnesium and copper.

Stainless steel can be used as a tank lining on chemical tanks where the cargos are high value. In order to realise the benefits of the product for the areas identified within a WBT, stainless steel would have to be used as the primary building material. There are a number of differences in the material properties between stainless steel and ordinary carbon steel. The most important differences between the two are cost and the stress-strain relationship.

It is possible to use stainless steel as a primary building material and thus remove the need to apply protective coatings, providing problems with dissimilar metals are avoided. The greatest factor preventing this is the significantly higher material costs, and to a lesser extent the joining technology required. The high cost of Stainless Steel does prohibit its wider use and often when used on other areas inferior grades of stainless steel are specified to save costs and hence often do not achieve the required corrosion protection. Figure 2-10 compares the cost per tonne in US$, of stainless steel, 304 and 316, and carbon steel over the period September ’09 to April ’10. This demonstrates the higher cost of using stainless steel (SS), as the cost can be as much as 8 times that of ordinary carbon steel (CS).

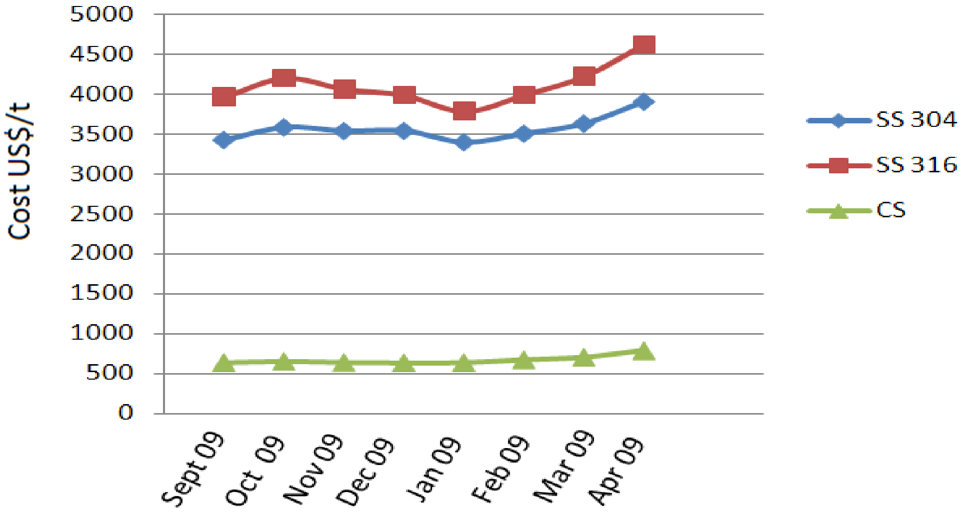
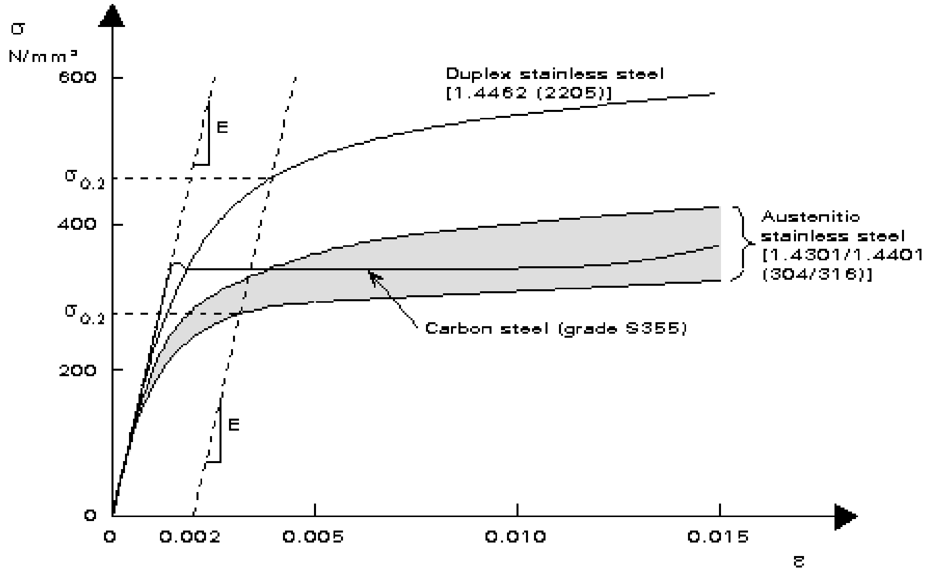


Figure 2-10 World Steel Prices (*MEPS 2010*)

Mild or carbon steel normally demonstrates linear elastic behaviour up to the yield stress with a plateau before strain hardening. However, stainless steel begins to exhibit a non-linear response at a much lower value of stress than carbon steel and thus displays more rounded response without a well-defined yield stress as demonstrated in Figure 2-11.



Typical stress-strain curves for stainless steel and carbon steel

($\sigma_{0.2}$ is the 0.2% proof strength, E is Young's modulus)

Note: These values are typical experimental values and should not be used in design. For grades 1.4301 (304) and 1.4401 (316) steels, the two curves shown indicate the extreme values from a series of tests and thus they represent a scatter band.

Figure 2-11 Stainless Steel Stress Strain Curve (*BSSA, 2010*)

The different strength characteristics of stainless steel would require a structural redesign involving the generation of complex finite element models of each of the sections to ensure the integrity of the structure is maintained. Finally unless stainless steel is used throughout the entire structure the potential for galvanic corrosion between stainless and mild steel, such as with pipes, must be considered.

2.7.1.3 Aluminium

Aluminium has been used for the construction of sections of the superstructure on board large cruise ships. It has also found favour as a construction material in the fast ferry market due to its reduced weight for equal strength capabilities. An aluminium hull structure, built to the same standards**,** weighs as much as 45% less than the same hull in steel (***Kasten 2009***) but can create a more complex structure. The most suitable grade of aluminium for marine use is the 5xxx series.

It is important to note that unlike steel, aluminium does not possess a fatigue limit. That is to say that it will fail at any stress if subjected to enough load cycles. This means that the fatigue life and strength for aluminium is lower than that for carbon steel. There are then implications for ships designed in aluminium, as a result of the dynamic loading nature of a ship in a seaway.

Similar to stainless steel, the corrosion resistance of aluminium is dependent upon a protective oxide film. However this is only true in certain operating conditions, as the oxide film is stable in aqueous media when the pH is between about 4.0 and 8.5. The oxide film will naturally self-renew rapidly following accidental abrasion or other mechanical damage of the surface film.

One of the major factors that has precluded the wide spread use of aluminium in shipbuilding is the joining technology. While aluminium can be joined to most other metals relatively easily by adhesive bonding or mechanical fastening, special techniques are required if it is to be arc welded to other metals such as steel. Very brittle inter-metallic compounds are formed when metals such as steel, copper, magnesium or titanium are directly arc welded to aluminium. To avoid these brittle compounds, some special techniques have been developed to isolate the other metal from the molten aluminium during the arc welding process. The two most common methods of facilitating arc welding of aluminium to steel are bimetallic transition inserts and/or coating the dissimilar material prior to welding.

As with Stainless steel the cost of aluminium is considerably higher than carbon steel, which can be as much as 4 times greater as shown in Figure 2-12. However as previously mentioned a well-designed aluminium structure can be considerable lighter than a corresponding steel configuration. It is possible to provide an aluminium structure that exhibits similar strength capabilities to steel at a comparative price, and be considerably lighter without the need of protective coatings. In many cases it is recommended that coatings are only applied in areas where crevice corrosion is likely.

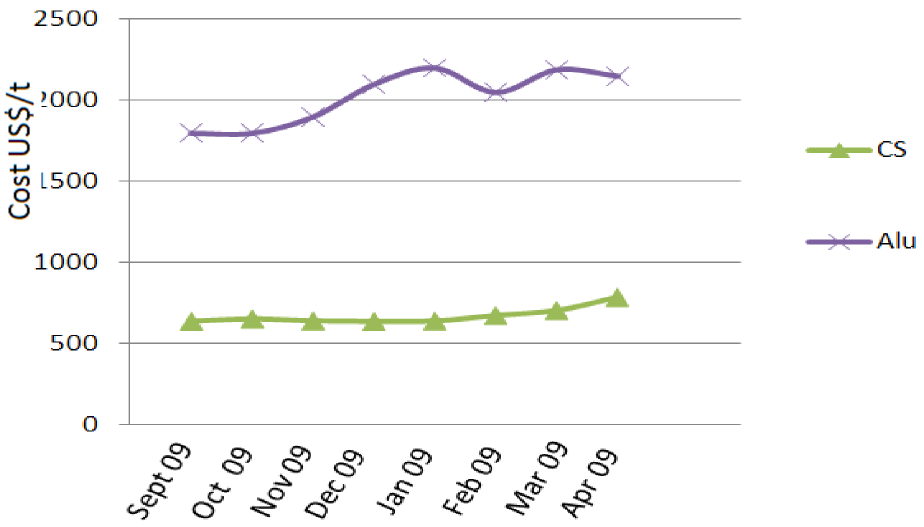


Figure 2-12 Steel and Aluminium Prices (Medgalv 2010)

2.7.2 Assessment of Alternative Material Usage

To summarise; there are benefits for the use of corrosion resistant steel, stainless steel and aluminium in place of ordinary carbon steel. However these are offset and in many cases out weighted by their cost or production issues. It is possible to select grades of either material that will provide corrosion protection, without the need for the application of protective coatings. The benefits for this approach are:

- Reduction in total paint consumption thus reduction of emissions of Volatile Organic Compounds (VOC's) and used paint tins;
- Reduction in surface preparation in way of blast media used and waste produced;
- Reduced energy requirements:
    - Paint transport costs
    - Paint application

Aluminium has the further benefit that an equivalent structure will weigh less; in shipping terms, this will reduce the lightship mass of the vessel, allowing more cargo to be carried for the same deadweight. This provides the ship designer with the opportunity to improve performance of the vessel per tonne of cargo carried. The advantage of this is that for a given vessel at a given speed less fuel would be consumed; therefore fewer emissions will be produced for the same cargo carrying capacity.

There are however a number of factors that continue to preclude the wider use of these materials in shipbuilding. Primarily it will come down to cost, in terms of both material and production costs, as it has been shown that structures can be designed with comparable structural performance. For example corrosion resistant steels have shown favourable performance characteristics when used in the deck plates and tank tops within cargo holds of Oil Tankers, however more research is needed to assess its suitability for use as a primary building material for WBTs. Stainless steel will continue to be limited to high revenue generating areas of a vessel, i.e. cargo tanks on chemical tankers due to the high purchase price of the material. Whereas aluminium will continue to be used in smaller high speed vessels where higher build costs can be justified on the basis of lighter weight hull structures.

The conclusion that can be reached for the corrosion resistant materials is that there are clear advantages in their use however, currently they do not offer a ‘near-market’ solution for more widespread use areas of high complexity such as WBTs where applying a protective coating to a high standard is currently very difficult.

2.7.3 Protective Coatings

Currently the application of protective coatings to a mild steel substrate provides the most cost effective method of protecting the steel from corrosion. The paint film prevents the electrolytic cell being formed by isolating the steel from the seawater electrolyte, whilst the paint film remains intact with zinc anodes used for additional protection.

The industry standard for spray paint application has been dominated for some four decades by use of the single feed, cold, airless spray. Airless pump pressure ratios have become higher but the technology of the application has not changed. The author has been told that a few years ago, Korean shipbuilders did make a change to plural component pumps for block stage application work, but it is understood that these yards have now mostly reverted back to using the simpler and cheaper single feed, cold, airless machine.

However the limitations of the single feed, cold, airless spray pump must be understood. The standard for viscosity measurement within the paint industry is poise with conversion between stokes and poise being 1:1. The maximum viscosity for successful application of a paint applied by single feed, cold, airless spray is around 6 poise at 25ºC. When developing a new paint product manufactures design their products to meet this constraint; to put this into context the majority of ballast tank protective coatings have been developed with a viscosity of around 3-4poise at 25ºC. Typically a shipyard would not monitor the actual viscosity of the paint during application, it is more common to observe the atomisation of the paint leaving the nozzle to give a good indication of the viscosity of the products.

Solvent free epoxies and some new technology coatings have viscosities as high as 25poise; so to achieve good atomisation these products have been developed by the manufactures to be used with heated application equipment. Coatings with viscosities above 15poise are best applied by hot single feed pumps which can cope with short pot life at elevated temperatures. For coatings with higher viscosities, around 25poise, hot twin feed machines must be used. These kinds of hot spray and plural component pumps are considerably more expensive to buy and take a higher level of skill to operate properly. Such types of product are often used as abrasion resistant epoxy coatings with a volume solids of around 95%, and are used for underwater areas of ice class vessels and is an example of a coating which must be applied using a hot twin feed.

There is then an upper limit on viscosity which limits a marine paint chemist’s choice of available options. Despite this application equipment for spraying coatings of higher viscosity and lower VOCs, are available in the market, as are the coatings. The current preference of major shipbuilders in the Far East continue to use single feed, cold, airless equipment, will remain a major factor resisting the introduction and use of new technology coating products.

Another factor acting against change in application methods used in shipyards, is that the current regulations limiting VOC emissions in the three major shipbuilding countries, Japan, Korea and China, are either too weak, or effectively non-existent or poorly policed. Regulations tend to drive change, and if these are not in place, then the shipbuilders will continue to see little reason or advantage in their adopting new and different application methodologies at the present time.

2.7.3.1 Research into New Paint Technologies and Products

Epoxies were invented in the 1930s (***Shell 1992***). Subsequent development led to the now well-known and almost universally used Bisphenol A based epoxy resins. Cross-linked with amine based curing agents; these have been used extensively in heavy duty protective coatings since the 1950s.

Significant advances have been made in epoxy technology for use in areas such as composite applications or powder coatings. By contrast, there has been little significant development in resins for heavy duty ambient cured liquid paints. Most of the development work has gone into process improvements, not changing the base molecules. This may simply be due to the global success of Bisphenol A based technology, which has limited the time and energy devoted to basic new development.

One of the driving factors behind this is that the development of new molecules, either epoxy or amine, does not generally lie within the capabilities of the paint company but is more the speciality of the raw material supplier. There has however been more progress in the area of amine curing agents, and a number of newer amines have become available over the past 20 years. The most successful of these is probably MXDA and its derivatives, which are finding more use in low temperature curing formulations (***Guy 2010***).

As a consequence of the legislation to reduce the solvent emissions from paints, development of heavy duty protective coatings has become more focussed around raising volume solids and lowering the VOCs of epoxy and polyurethane based products. In general, epoxy paints with volume solids of around 60% contain solid resins (solid epoxy resins, solid amine curing agents and occasionally solid extending resins) as this provides the fastest drying times. It is also worth noting that with regard to low or solvent free paints and winter curing products, that high volume solid paints have been around since the early 1970’s (IP’s THA 150), and that low temperature curing products have also been widely available since the 1970’s.

Higher volume solids paints would generally be classed as having a 70 to 80% solid content. In general this dictates the use of liquid epoxy resins in order to achieve an acceptable application viscosity of around 6 poise. If a liquid epoxy resin is cross linked with lightly modified amine curing agent, then liquid diluents are not needed to achieve this viscosity.

However, if the volume solids are increased to 80 to 100%, then in order to achieve application viscosity the only option is use liquid epoxy resins, in combination with diluents. This is true for the current application practice of single or hot twin feed airless spray. It should be noted that in general as the liquid epoxy resin content is raised, the paint film becomes more brittle ***(Guy 2010)***.

In order to maintain the desired application viscosity it is, therefore necessary to alter the physical nature and molecular weight of paint components, as the percentage of solids increases. The components that can be altered include the epoxy resin, the amine curing agent, pigment, accelerator, solvent, diluents, pigmentation, PVC, and the ratio of epoxy to amine, i.e. the stoichiometry. This interaction is very complex and beyond the scope of this work. It is the author’s belief that high solids paints have become more widespread as a result of environmental regulations rather than them being introduced as they offer improvements to the coating process.

Formulators of heavy duty paints have access to a range of materials – epoxy resins, amine curing agents, diluents (reactive and non-reactive) - from which to choose. There is a fundamental requirement for a heavy duty paint to be capable of being applied using the currently available equipment, and in shipbuilding, as stated earlier, this is still predominantly the single feed cold airless spray. This application requirement places an upper limit on the viscosity of the paint, and this viscosity limitation is the same no matter whether the paint is of low volume solids (60%) or solvent free (say 95% volume solids). Figure 2-13 shows graphically how the relative composition of the different elements of the wet paint can change as the volume solids increases and solvent content decreases.

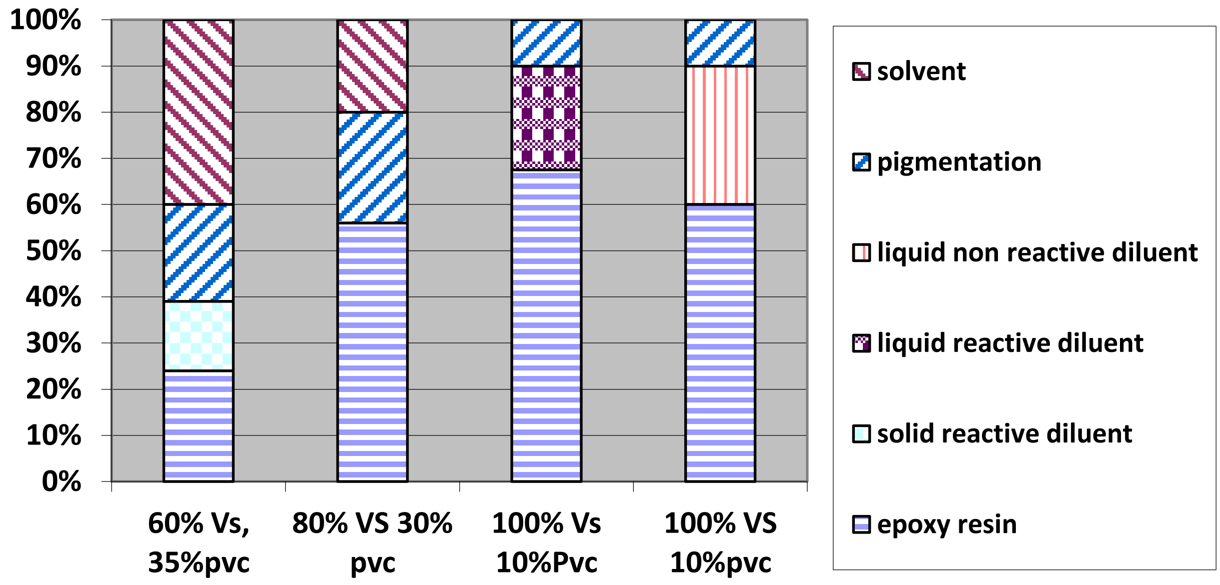


Figure 2-13 Composition of wet paint

It should be noted that altering the paint composition in order to achieve the required viscosity cannot be done in isolation. By changing the relative proportions of the paint components, the chemical nature of the paint will be altered for example the molecular weights, polarity, degree of modification and glass transition temperature (*Tg*).

The chart also shows that a volume solids of 80-85% is about the limit to which an epoxy can be formulated without diluents. For solvent based coatings, this may therefore be the optimum volume solids level, which can be reached. The problems for the paint formulator are therefore a complex one of, not only having to balance the proportionate actions of chemical components, but also to take into account both the general application practice that has been adopted in shipyards, and feedback received about product performance from ships in service.

With the knowledge of all these varied and complex constraints, the formulator will generally follow specific routes. The skill is to balance a number of variables to arrive at an optimised formulation for both product purpose and application. Generally trade-offs are necessary. One example would be when trying to achieve shorter drying times at higher a volume solid, which is commonly requested by shipbuilders, will inevitably result in a shorter pot life. However, the requirement for a suitable application viscosity cannot be compromised, unless there is a wholesale change in the application equipment.

Epoxies are the most common product used for corrosion protection due to their superior anti corrosion properties, there is often confusion of the different types of Epoxy, it is possible to classify them into four different types.

- can be defined as an epoxy paint where a proportion of the non-reactive components of the formulation have an initial boiling point equal to or less than 250^{o}C at an atmospheric pressure of 101.3kPa.
- can be defined as an epoxy paint wherein all of the components in the base (epoxy side) are epoxy functional and will react with the amine curing agent to produce a cross-linked network. Pure epoxies do not contain non-reactive diluents that may subsequently remain in the film after curing.
- can be defined as an epoxy paint that contains low volatility materials – co-resins such as coal tar or hydrocarbon resins - that do not react with either epoxy or amine functionality. These therefore remain un-reacted in the film after curing. The co-resins (or modifying resins) can be either liquid or solid materials at room temperature.
- can be defined as an epoxy paint where all of the non-reactive components of the formulation have an initial boiling point greater than 250°C at an atmospheric pressure of 101.3kPa.

Finally, it should also be stated, that whilst there are some exotic chemistries available and more will emerge, there will always be some reluctance to adopt them if they do not fit in with the current shipyard application practice. However, shipbuilding is constantly looking for products and processes that will improve their efficiency. This may in time enable a move away from the current single feed cold airless spray, but detailed cost benefit analysis would be required before any such major steps are taken.

2.8 Typical Paint Failure Modes

A protective paint film can be said to have failed when it is no longer protecting the substrate from the surrounding environment. Due to the scale of the application of paint within the marine industry there is a graduated scale to ascertain the degree of paint film failure. A number of studies have been carried out to determine the cause of paint failures. Figure 2-14 shows the results of a study undertaken at Safinah Ltd which tallies with similar results published by ***Muhlberg*** (***2010***). The majority of coating failures are generally attributed to the process stage namely surface preparation and paint application. It should be noted that the chart does not take into account the cost or value of the failure.

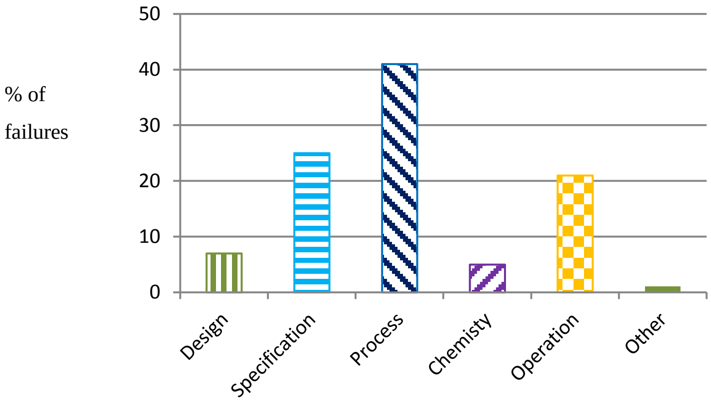


Figure 2-14 Major Causes of Coating Failures

What is interesting to note is that ***Muhlberg*** (***2010***) compares results of similar studies which were conducted before and after introduction of the ISO 9000 which is a standard that covers the requirements for a quality management system. The conclusion is that although the quality assurance systems have been improved, the distribution of the causes of failure has moved from poor process to incorrect specification. What is most relevant to this body of work is that very few failures are attributed to poor design. The question must be asked what was the under lying cause of the process failures? The work within this thesis proposes that the root cause in large number of the failure that are labelled as process failures is the design of the structure. In that the structure did not allow adequate access to the substrate to enable appropriate preparation, cleaning and/or coating application. This is supported by evidence from inspections undertaken by the author. One point that is worth noting is that above finding don't attribute a cost to the failures, as such is the design does not allow adequate access leading to a coating failure, this will not only occur the first time the structure is coating, it will apply to all subsequent applications, thus having a significant influence on the coats.

It is important to note that all coating systems will fail over time. There are a large number of different ways in which a paint coating can fail, however these are the symptoms not the cause. The factors that cause paint failures can be split into five main categories, premature failures as a result of any of these factors will lead to an increase in maintenance costs and possibly availably of the vessel.

- Incorrect Specification;
- Poor manufacture;
- Poor surface preparation;
- Poor application;
- In service operations.

2.8.1 Incorrect Paint Specification

The use of a functional paint specification and subsequent product selection is important as it will set out the needs and attributes of each individual area that is to be painted. The characteristics of a range of suitable paint products are then compared against these and given a score; the product selected should be the one that meets the new building and the through-life needs required. As an example the best fouling prevention system is the one that best fulfils the demands of both, the application requirements of the shipbuilder; and provides a consistent predictable level of performance for the region the vessel is expected to trade in. To highlight this, the current range of silicon based Foul Release Coatings (FRC) coatings are well suited to vessels which have high activity rates and operate at relatively high service speeds such as container vessel. However if they were applied to a product tanker there is a high likelihood of fouling, due to a high proportion of inactivity and differences between the head haul and back haul as there will not be the flow of water over the hull to 'clean' away fouling.

2.8.2 Poor Paint Manufacture

The occasions where paint fails in service due to bad formulation are extremely rare, due to the intense testing protocols used by paint companies. There are however cases of a ‘bad batch’ or contamination of the paint during the manufacture of the paint.

2.8.3 Poor Surface Preparation

2.8.3.1 Blistering

The blisters indicate a local loss of adhesion from the substrate. The cause is often a result of contamination by grease, oil, salt, rust, trapped moisture and retained solvent. In WBTs salt contamination of the surface can result in osmotic blistering.

2.8.3.2 Adhesion Failure

This is shown by often large areas of paint detaching from either the substrate or the underlying paint layer. The most probable cause of this is contamination of the surface or the formation of condensation. Inter-coat adhesion failure often results due to exceeding the maximum overcoating interval.

2.8.4 Poor Coating Application

2.8.4.1 Runs or Sags

This failure is caused by an excessive amount of paint being applied, often as a result of holding the spray gun too close to the surface, and or the surface is too smooth for the paint to adhere to properly.

2.8.4.2 Cratering

Craters are small indentations in the surface of the paint film which are caused by air being trapped during spraying. The indentations can trap moisture and salt whereas trapped air can cause blisters. It is often cause by the paint film not having enough time to flow into a uniform film, commonly known as wetting out.

2.8.4.3 Fish eyes

This is a separation or pulling apart of the coating. Fish eyes often can be seen immediately after the coating has been applied. They are the result of either poor surface preparation or contamination of the liquid paint. The presence of oil or dirt on the substrate surface or silicone in the paint is a common cause of this failure.

2.8.4.4 Wrinkling

Characterised by a rough crinkled surface skin which is caused by application over an uncured previous paint film or when applied at excessive ambient temperatures. Again the uneven surface will trap moisture and solids leading to premature coating failure.

2.8.4.5 Pinholing

Pinholing is evident by minute holes in the wet paint film during application or drying due to air or solvent bubbles. The small holes fail to coalesce before the film dries. This problem is common when coating a porous surface such a zinc filled primers. Pinholes can also be caused by incorrect spray application or incorrect solvent blend.

2.8.4.6 Alligatoring

The formation of vary large checking of cracking with resembles the skin of an alligator of crocodile. In some cases the cracks can penetrate down to the substrate surface. This is a result of the internal stresses in the coating, where the surface shrinks faster than the main body of the paint. It can often by caused by excessive applied film thicknesses and limited paint flexibility, an example would be hard topcoats applied over a soft undercoat.

2.8.5 In-Service Failures

2.8.5.1 Bloom

This is characterised by a hazy deposit on the surface which results in a loss of gloss and dulling of colour. The cause of this is exposing the paint film to condensation or moisture during curing; this is very common with amine cured epoxies. It can also be attributed to the incorrect use of solvent bland. It can be cause of intercoat adhesion failure if it occurs on an underlying coat in a paint scheme.

2.8.5.2 Chalking

Evidence of this will be a change or fading of colour with a friable, powdery layer on the surface. The amount of chalking varies with pigment concentration and the choice of binder. The epoxy paints used in ballast tanks are known to suffer from chalking, as the paint binder disintegrates when exposed to UV light.

2.8.5.3 Water spotting

Water marks on the surface are caused by rain or condensation forming on the surface of the paint before it has sufficiently hardened.

2.9 Influence of Recent Regulations

2.9.1 IMO Performance Standard for Protective Coatings for Dedicated Water Ballast Tanks (PSPC)

The principal reason behind the adoption of the PSPC was the prevention of loss of life at sea resulting from unacceptable high levels of vessel failures which were directly attributable to corrosion as discussed previously. The IMO Maritime Safety Committee (MSC) identified that coating performance was of global concern for the safety and integrity of ships. Following a long period of technical discussion, the IMO Performance Standard for Protective Coatings (PSPC) for WBTs was approved on the 5th December 2006 and adopted in July 2008. Resolution MSC.215(82) is now mandatory for dedicated seawater ballast tanks on all ship types of more than 500 gross tones and double skin spaces in bulk carriers of greater than 150m in length. The overarching aim of the PSPC is to improve the standards of WBT coatings during the application at new builds, to achieve a 15 year target life for those coatings.

By the inclusion of the IMO PSPC into the International Convention for the Safety Of Life At Sea (SOLAS), Regulation II-1/3-2, the importance of WBT coating has been raised to a similar level of importance mandatory safety equipment such as ships lifeboats. The SOLAS

Convention in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. It was first adopted in 1914 in response to the loss of the RMS Titanic. This was followed by the second Convention in 1929, the third in 1948, and the fourth in 1960 (***SOLAS 2004***).

The implication for 'new-builds' is that a vessels WBT coating must be applied in accordance with the IMO PSPC regulations. As a ship cannot sail without meeting SOLAS requirements, it is now mandatory that a vessel's WBT coatings are deemed to comply with SOLAS before it can put to sea; this has obvious implication for the availability of the ship. In the case of Bulk carriers the IMO PSPC it was incorporated into the IACS Common Structural Rules (CSR). Subsequent discussions between IACS have lead to the removal of the PSPC requirement from the CSR, thus is now remains solely under SOLAS regulations.

The precedent for a standard for protective coatings was set by the Tanker Structure Cooperative Forum (TSCF). This group, which was formed in 1982, had the brief of sharing experiences and holding technical dialogues on structural aspects of tankers (***Weber, 2007*)**. In 1998 the group produced a Guidance manual (***TSCF, 1998***) this guidance manual was based on collective experience of the members of the forum in inspecting, assessing and repairing tanker structures. In 2002 the group addressed the increased regulatory oversight of the protective coatings for WBTs (***TSCF, 2002***). The publication was in response to the general dissatisfaction with the performance of coating applications (***Weber, 2007***). If the contents of this guide are examined it is clear that they formed the basis of the PSPC.

It is worth noting that the TSCF developed coating schemes with expected in-service life spans of 10, 15 and 25 years. The principal difference between these is in the number of stripe coats applied to the edges and welds and number of full spray coats applied and the overall final Dry Film Thickness (DFT). For a 10 year scheme the TSCF calls for one stripe coat followed by two full spray coats to achieve a 250μm final DFT. The 15 year scheme requires two stripe coats and two full spray coats and total DFT of 300μm, whereas the 25 years scheme has three stripe coats and three full spray coats to achieve a DFT of 350μm.

At the 47th session of the IMO's subcommittee on design and equipment (DE) a working group on bulk carrier safety finalised the draft SOLAS chapter XII (additional safety measures for bulk carriers). The report was sent to the MSC in time for its 78th session in May 2005. At the 79th session in December 2004 adopted a new text for SOLAS Chapter XII, incorporating revisions to some of the regulations and new requirements relating to double-skin bulk carriers.

In addition to the statement that structural designs should consider the coating process by reducing complexity as noted in the introduction, the IMO PSPC sets out quite a specific framework with regard to the selection of coatings for ballast tanks and their application. In broad terms the PSPC defines:

- Basic coating requirements;
- Type approval testing for coatings;
- The need for a tri-partite agreement between owners, builders and coating producers;
- Surface preparation procedures;
- Application procedures;
- Data collection and reporting in a coating technical file (CTF);
- Inspection needs and procedures.

In order to provide an introduction and insight to the PSPC regulations, a summary of these key requirements and considerations governing the selection and application of coatings is now provided.

The PSPC states that when selecting a coating system, the parties involved must consider the service conditions and planned maintenance routines, relevant to different vessel types. Aspects that need consideration include location of the space relative to heated surfaces such as fuel oil or cargo tanks. In addition to the ballasting cycles, the inclusion of supplementary cathodic protection systems must also be borne in mind when selecting a coating system as well as the impact of Ballast Water Management Systems.

To gain type approval a coating must pass the test procedures as defined in Annex 1 of the PSPC. Epoxy based systems that were tested prior to the entry into force of the regulation can be approved if there is evidence of field exposure showing that the coatings have remained in ‘GOOD’ condition for not less than 5 years.

The PSPC also sets out the standards for both primary and secondary surface preparation. Primary surface preparation is based on the Swedish standard ‘Sa 2 ½’ (***ISO, 8501***). This standard requires a very thorough blast cleaned surface that when viewed without magnification is to be free of oil, grease, dirt and poorly adhered mill scale, rust, paint coating or any other foreign matter. This standard of blasting should provide surface profiles of between 30-75 μm.

Secondary surface preparation should also be to a ‘Sa 2 ½’ standard on areas of damaged shop primer and in way of weld seams. Shop primer that has not passed pre-compatibility testing requires ‘Sa 2’ surface preparation, with removal of at least 70% of any such primer. Surface blasting or coating application cannot be carried out when the relative humidity is greater than 85% or the surface temperature of the substrate is less than 3˚C above the dew point. The water soluble salt limit, equivalent to NaCl, is set at $50mg/m^2$ and the shop primer should be a zinc based product containing inhibitor free zinc silicate or equivalent. The compatibility of the shop primer with the main coating system is to be confirmed by the coating manufacturer.

The job specification defines that there are to be a minimum of two stripe coats on edges and welded seams plus a multi coat system for the rest of the structure. It does note that the second stripe coat may be reduced in way of welded seams to prevent unnecessary over-thickness. The total nominal dry film thickness (NDFT) is set as 320μm and the layers are to be appropriately cured before application of the next coat. The measured dry film thickness should meet the ‘90-10’ rule, namely 90% of measurements are to be greater or equal to 320 μm within the remaining 10% greater than 288 μm.

To comply with the regulations the shipbuilder must prepare and deliver a CTF with respect to the whole WBT coating process. Coating manufactures are required to provide technical assistance and documentation of the satisfactory performance of their products, and offer adequate technical support. The ship owners are to supply the number and location of the WBTs. The shipbuilder will provide information on the surface preparation standards and paint application process along with repair and touch procedures and an inspection program. All of this information is agreed then collated and submitted to Class for approval. The CFT document is required for each new ship to act as an 'as-built record'. The inspection records are also to be included within this document and are used to manage the on-going maintenance of the WBT coatings.

A set of guidelines have recently been published by the IMO (***IMO, 2009***) to aid the relevant parties with the maintenance and repairing process of protective coatings. The areas and extent of the survey process of a ships WBTs is further defined. The guidelines also give further definition on the three terms used to define the quality of a coating, namely 'Good', 'Fair' and 'Poor'. They also draw a distinction between coating maintenance, which can be undertaken by ships staff and repair which would be carried out during a scheduled repair period. Thus the PSPC is very clear as to how the steel substrate is to be prepared, cleaned, painted and inspected. In order to comply with the regulations there is a great demand placed on information recording as part of the inspection process. Coupled with this a suitable information management system is required in order to compile the CTF.

2.9.2 The VOC Solvent Directive

This EU directive, 1999/13/EC, is the main policy instrument for the reduction of industrial emissions of volatile organic compounds (VOC's) in the European Union. It covers the use of solvents across a wide range of activities, for example printing, surface cleaning and vehicle coating. The regulation requires installations that produce VOC's to either comply with the emission limit values set out in the Directive or with the requirements of the so-called reduction scheme. Emission limits of VOC's in waste gases and maximum levels for fugitive emissions (expressed as percentage of solvent input) or total emission limit values are set out in the Directive. The rationale behind the scheme is supporting operators in their use of methods to reduce their VOC emissions. Typically this may be achieved by the substitution of products with high solvent content for those with low-solvent or even solvent-free compositions. New installations have to comply with the requirements of the VOC Solvents Emissions Directive at the time they are starting the activity. The final implementation date for existing installations was 31 October 2007, (***EC Europa, 2010***).

In addition, some of the industrial sites covered by the VOC Solvents Emissions Directive are also covered by the Integrated Pollution Prevention and Control (IPPC) Directive. In these cases, the VOC Solvents Emissions Directive only sets minimum obligations which are not necessarily sufficient to comply with the IPPC Directive. Such compliance may involve more stringent emission limit values, emission limit values for other substances, other media, and other appropriate conditions. Details of emissions from installations falling under both VOC Solvents Emissions Directive and IPPC Directive can available via the European Release and Transfer Register (E-PRTR).

The EU Commission's proposal for a Directive on Industrial Emissions considers the interaction of the VOC Solvents Emissions Directive and IPPC Directives. This proposal aims to recast the VOC Solvents Emissions Directive and six other existing Directives related to industrial emissions into a single clear and coherent legislative instrument (***EC Europa, 2010***)

2.9.3 The Clean Air Act

Within the United States the Clean Air Act is the law that defines the Environmental Protection Agency (EPA) responsibilities for protecting and improving the nation's air quality and the stratospheric ozone layer. The last major change to, the Clean Air Act, were the amendments enacted by Congress in 1990. The act seeks to improve the air quality within the US by encouraging and assisting the development and operation of regional air pollution prevention and control programs. It seeks to achieve this by initiating and championing a national research and development program to achieve the prevention and control of air pollution. The latest version of this document was published in 2004, (***Clean air, 2004***).

This is perhaps most prevalent for the surface preparation and cleaning elements of the process, as these activities can release large amounts of dust and particles into the atmosphere. It is clear that the current regulations are more likely to become more stringent, which has implications of the current practices used in shipbuilding becoming increasingly regulated or banned.

2.10 Conclusions

This chapter considered the development of WBTs from the initial fixed weights used in wooden sailing vessels to the highly complex spaces seen in modern ship designs. The previous studies reviewed identified a wealth of knowledge on what could be considered as good practice. However due to the lack of importance afforded to the coating process, much of this information is rarely applied in practice so the potential benefits are never realised, as coating it is not seen as a value adding process.

There has been little investment of both time and money into the coating process and the equipment in use since the 1950's. Due to the relatively small size of the marine market there is unlikely to be any major injection of funding in to the design of new coatings application equipment as there is little opportunity to recoup any investment. As shipyards continue to strive to reduce their costs and with a greater focus placed on the reducing environmental impact, the importance of the coating process has begun to be recognised.

The recent adoption of the IMO PSPC has highlighted the issue of reduction of structural complexity, however until now the extent of the influence that this has over the coating process has not been investigated. The regulations have also has forced shipbuilders to reconsider their approach to the coating process within WBT's however current industry research is being focused on identification of new processes and products. The major paint companies continually strive to develop new improved products however the design space is tightly constrained, and the time required to develop a new paint product precludes any major innovations in the next 5 years. However before any benefits of these products or processes can be realised an improvement in the management systems employed for coatings must be enhanced to bring the process under control.

2.11 Summary

This chapter has examined the development and function of water ballast tanks, and their influence on improving the safety of merchant ships through the provision of adequate coating protection. The corrosion mechanisms typically found in WBTs have been identified. The background to providing adequate structural protection through coatings and their application in the shipbuilding process has been considered. The new IMO PSPC requirements have been reviewed and previous coatings studies have been scrutinised to identify best practice for potential improvements to the coating process.

Having examined the development of the shipbuilding industry the coating process and coating technology, the next element to discuss is the design process. Beginning with a review of general engineering design, and moving to examine the ship design process most specifically the design of ships WBTs

3 OVERVIEW OF THE SHIP STRUCTURAL DESIGN PROCESS

3.1 Introduction

This chapter discusses the development of the design process within the shipbuilding industry over the last 30 years. It describes how the views of the wider shipbuilding industry have been captured through the design and distribution of a questionnaire focused on the complexity of ships structures. This provided insight as to how the different disciplines involved in process of designing and building a ship view the tasks of the coating process. A range of obvious and more subtle benefits that could be realised following the adoption of an alternative design methodology are also discussed. The aim and objectives of The Design to Improve Structural PROtection (DISPRO) project are introduced. The DISPRO project brings together key partners to address the problems of design.

3.2 Background to Engineering Design

'The only constant in life is change', ***Rochefoucauld*** (***1613-1680***), this is especially true with technology, to ensure that any engineering business remains current innovation is almost mandatory. Innovative activity may take a number of different forms such as introducing new products or processes, or developing improved services, restructuring, or providing staff with training courses on new skills or techniques. If the innovation process leads to the development of new products or adapting of new ones, then the design process will be required to a greater or lesser extent.

Birmingham et al. (***1997***) describes engineering design as 'a process for satisfying perceived needs through the creation of technical solutions to problems'. It demonstrates that the technological change cycle can also create new needs and requirements. The innovation process can be used to facilitate a firm gaining a competitive advantage in the production process employed to manufacture the product. The DISPRO project, which will be described in detail in a subsequent section, has been set up to utilise this ethos.

Gobeli and Brown (***1987***) developed a matrix of the view points of the manufacturer and the customer of an innovation. They devised a matrix with four different types of innovation technology: incremental, technical, application and radical, as shown in Figure 3-1.

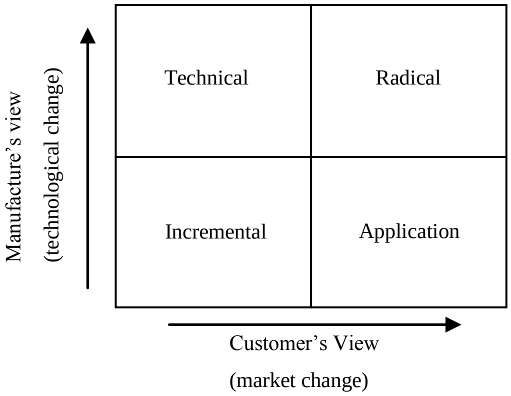


Figure 3-1 Product innovation matrix and the four types of innovation activity

In this model, radical and incremental represent the extremes of innovation activity. Typical incremental activity would be low or moderate advances in technology, focusing on existing markets. At the other end of the spectrum radical innovation involves not only significant technical developments but also entry into new markets. Technical innovation is best described as introducing new technologies to an existing market; application innovation is the introduction of an existing product to a new market.

Following this approach ***Pahl and Beitz*** (***1984***) defined three distinct types of design activity:

- Original design – this involves taking an existing solution and developing it further to improve its performance;
- Adaptive design – this involves taking a known solution and applying it to another task, following the same principals;
- Variant design – this involves altering the size and or arrangement of particular aspects of a system, while the function and solution method remain the same.

These different design approaches are ordered in terms of the respective effort that they require, with original design being the most onerous. One example, could be the design effort required for the transportation and location of a satellite in orbit around the earth. If the need for the vehicle to be reusable is added to the requirements then it is clear why the space shuttle took many years to move from the identification of the need to the development of a solution.

In contrast the effort required for adaptive and variant design; the change from the typewriter to the PC keyboard. The solution principal for the keyboard could easily be developed from the typewriter to meet the requirements of the computer. In shipbuilding terms, container vessels present a good case of variant design, in that all designs must meet the need to carry unitised cargo. The first container vessels entered service in the mid 1960's and all subsequent vessels are parametric versions of these vessels (***Birmingham et al. 1987***).

The process of innovation comes with inherent risk, the greater the level of innovation the greater the risk, with risk comes reward. The relationship between product and process innovation and risk has been represented by ***Birmingham et al.*** (***1987***).

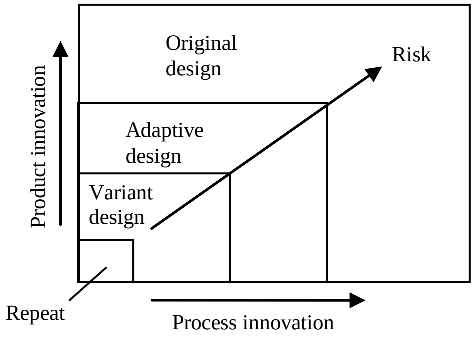


Figure 3-2 Product-process innovation, and the relationship with risk

The definition of innovation is very much dependent on its perspective, a useful and simple definition, that has a very board approach, is 'the successful exploitation of new ideas' (***HMSO, 1994***). This very simple definition articulates three important aspects of innovation.

Firstly the concept of new ideas; these can take many different forms, such as technical or non-technical which may require different levels of change

The three different elements of design are not mutually exclusive, as a result innovation in one area may then present demands on other sectors. For example even the simplest technical alteration to a product will have some impact on the production process. Therefore all of the elements of the production process should be considered during the design process, and it is important that the designer is available throughout the production process to assist with any problems that are likely to arise. Good communication is essential between the design and production teams to ensure a smooth and efficient transfer from design drawings to the final finished product (***Birmingham et al. 1987***). It will be shown in this work that this element is not fully utilised when considering the coating process within shipbuilding.

The decision making process associated with design has a hierarchy; this is especially true in ship building due to the diverse nature of vessel systems. Thus the problem of identifying a suitable ship design for a given problem is broken down into more manageable pieces. This then requires team work to deconstruct the problem into smaller sub-problems. These sub problems often have further division, with a highly demanding element of the design team being establishing the factors that affect other elements of the problem and producing a suitable design solution.

Newell (***1969***) proposed that design problems could be defined as well-structured or ill-structured in nature, ***Simon*** (***1984***) went on to identify the attributes of these design problems. He recognised that well-structured problems have clear goals and often have a single correct or optimal answer. It is possible to deconstruct these problems in branches of sub-problems and sub-sub-problems, with there being very little interaction between the individual elements of the problem. It is clear that this cannot be said for the majority of design problems as they fall into the ill-structured category, as there are one or more interdependencies between different elements. This often creates the situation whereby a solution to one element creates irreconcilable conflicts within other elements.

Simon (***1984***) argued that many ill-structured problems could through thorough analysis and problem definition could be formulated as well-structured problems. Particularly many sub or sub-sub-problems could be well structured, even if the overall problem was ill-structured. This echo’s the belief of Chirilo who is quoted as saying “A plate is a plate is a plate”.

This situation is common within the shipbuilding industry and has led to the development of iterative design processes, or design spirals. The first design diagram was presented by ***Evans*** (***1959***). It has since become known as the 'Ship design spiral'. The major characteristic of this design approach is the sequential and iterative nature rather than it being concurrent. ***Buxton*** (***1972***) introduced economic issues into the spiral and ***Andrews*** (***1981***) introduced time as the third dimension. ***Mistree et al.*** (***1990***) recognise the importance of the design spiral, and note the complementary nature of converging and diverging models of Evans and Buxton. Evan's model shows how the spiral converges towards a final product, while Buxton's model diverges to demonstrate the increasing levels of information and detail of definition. The design spirals represent a descriptive model that portrays how design is undertaken; it represents both state-of-art and state-of-industry. The techniques and tools available at the time required a sequential and iterative design methodology. Computers where used to increase the speed at which a designer could move around the spiral (***Mistree et al. 1990***).

The cyclic nature of the ship building industry, results in both times of prosperity and austerity. The major problem with the spiral approach is it does not encourage the identification of superior design solutions. During the periods of high demand for vessels, there is little need to examine improved solutions as the majority of design effort is rewarded with a building contract. It is relatively easy to implement small incremental improvements across a large run of vessels, and a large amount of information is available of similar ships. However when there is a reduction in the demand for new ships, often with a resultant over capacity in the building market, the spiral approach being rather protracted can be seen to be uneconomical for radically new design solutions (***Lyon and Mistree 1985***).

The shortcoming of the design spiral method is that it is limited to a single objective function, which is unlikely in the real world. Thus ***Mistree et al.*** (***1990***) proposed a change from a sequential spiral to a concurrent scheme. This shift is visualised as the frustum of a cone in Figure 3-3 and Figure 3-4.

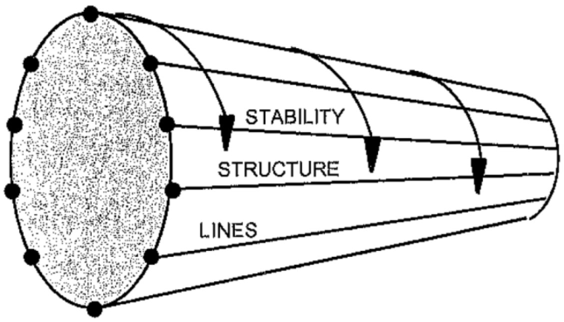


Figure 3-3 Frustum of a cone (***Mistree et al.*** (***1990***))

The design process represented by this model can be view from both the inside and outside. Figure 3-3 shows the outside following the same notion proposed by ***Andrews*** (***1981***), where the design interactions between design considerations only pass on information in a sequence of forward-chained steps, this then requires a large amount of iteration to satisfy all of the constraints. The view of the design process from the inside of the cone and shown in Figure 3-4, does not strictly define the ordering of the calculations. This allows the idea of concurrence to be accommodated within the design process.

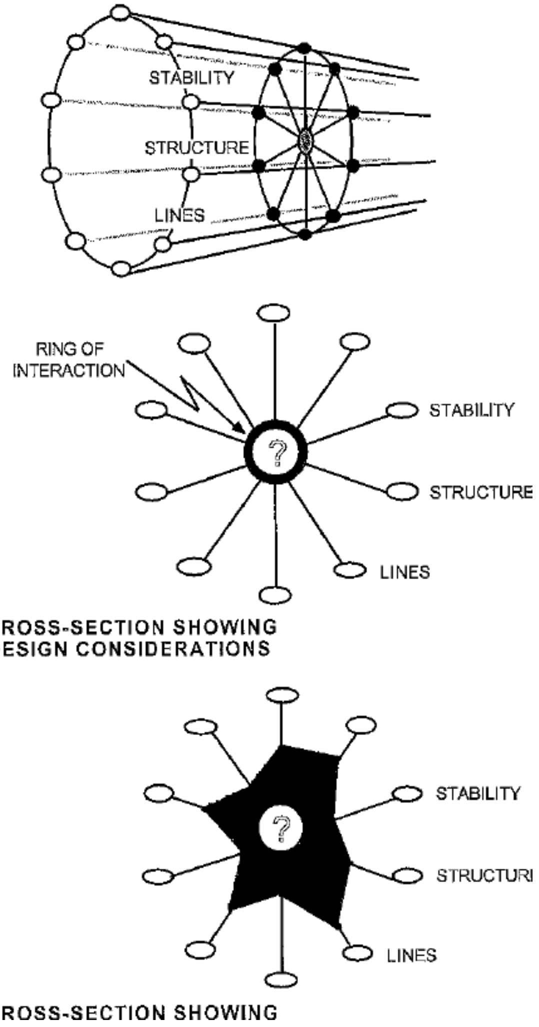


Figure 3-4 Design on the inside: state-of-research (***Mistree et al.*** (***1990***))

Winner et al. (***1988***) provided a formal definition of concurrent engineering:

"Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements".

One of the mainstays of concurrent engineering is that by improving the process there will be a resultant increase in quality, and improving the design, production and support processes is a continuous activity ***Winner et al.*** (***1988***). The differences between sequential engineering, as used by in the design spiral, and concurrent engineering where presented by ***Mistree et al.*** (***1990***) as shown in Figure 3-5. This model was adapted from the work of ***Winner et al.*** (***1988***).

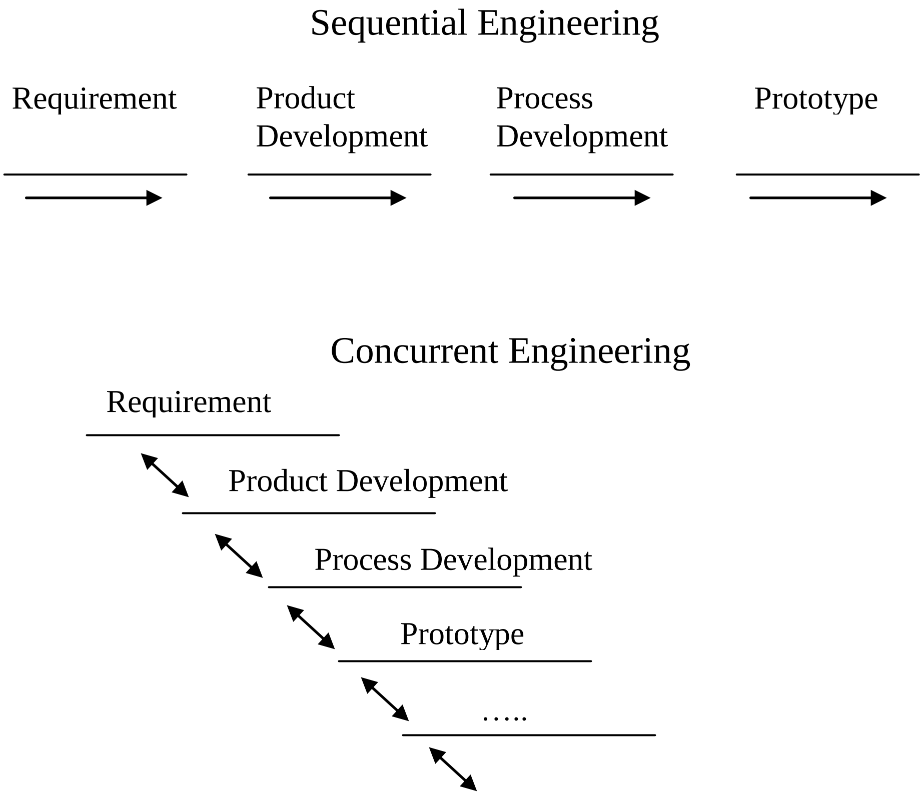


Figure 3-5 A comparison of sequential and concurrent engineering

Winner et al. (***1988***) reported the results of six leading American firms: McDonald Douglas; Boeing Ballistic System Division; AT&T; Deere & Company; HP instrument Division and IBM. The reported benefits where:

- A reduction of around 50% in engineering changes in early production as a result of an improvement in the quality of the designs;
- A reduction of 40-60% in product development cycle times;
- A reduction of 30-40% in manufacturing costs when multifunctional teams integrated product and process designs;

- A reduction of rework and the costs of scrap of 75% through product and process design optimisation.

There are three generic elements that concurrent engineering realises on; multifunctional teams that integrate the different elements of the product, the widespread use of computer aided design methods, and use of a variety of analytical methods to optimise the design, manufacturing and support processes. The major difference between traditional engineering design and concurrent design is what plays the central role in the process, synthesis of the product plays the central role in traditional engineering whereas it is synthesis of the process, including design, manufacturing, and support, that dominant feature of concurrent engineering.

Concurrent design has seen a recent resurgence for example the European Space Agency (esa) have adopted this approach as it allows design work to be collaborative, co-operative, collective an simultaneous (***esa 2014***). The marine field is well suited to this design approach as designers are faced with ever increasing amounts of numbers of considerations and data from a greater number of specialist fields within the overall design process.

3.3 An Overview of Ship Structural Design

The first known calculations for vertical bending where undertaken by I. K. Brunel during the design process of the Great Eastern. It was Brunel's belief in the economies of scale that convinced him to build a ship that was almost eight times larger than any vessel afloat at that time (***Caldwell 1980***). Figure 3-6 shows Brunel's concern that such a large vessel must contain sufficient longitudinal bending strength. The calculations show the ship in an extreme hypothetical bending condition, and how Brunel was trying to adjust the deck and bottom plating thicknesses to withstand the resultant bending moment. Subsequently Brunel revised these calculations and added a safety margin to guard against hull bending failure and provide adequate shear strength in the ship side shell.

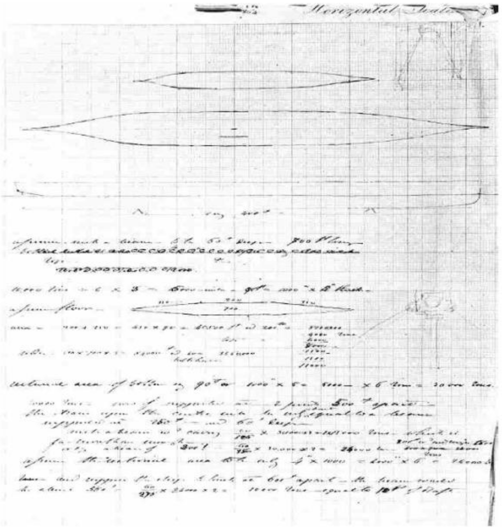


Figure 3-6 Brunel's calculations (*Rutherford* and *Caldwell 1990*)

What is perhaps most interesting is that the foundations of what is now referred to as ‘traditional’ longitudinal strength analysis were not laid until twenty years after the Great Eastern (***Caldwell 1980***; ***Rutherford*** and ***Caldwell 1990***; ***Rawson and Tupper 1994***).

3.4 Methods of Load Prediction

With any structural design the greatest difficult lies with determining the magnitude and direction of the loads that the structure is likely to be subjected too. The publication by the Ship Structures committee ‘Probability Based Ship Design; Loads and Load Combinations (***SSC 1994***) discusses a range of methods that can be used to determine the expected loads on a ship’s hull girder. It separates expected loading into four categories:

- Hull Global loads;
- Local pressure loads;
- Fatigue loads;
- Special load.

3.4.1 Hull Girder

The loads that the hull girder will experience arise from the following sources:

- Still water loading condition;
- Low frequency, steady state motion related wave excitation;
- High frequency steady state wave excitation aka springing;
- High frequency transient wave impact from slamming.

The publication notes how the calculation of the still water moments and forces are relatively simple to calculate, but that the wave induced shear forces, bending and torsional moments have a greater degree of uncertainty. The traditional approach to calculating these forces is the use of linear strip theory based on ship motion analysis

3.4.2 Local Pressure

Local pressure loading can be separated into the following categories:

- Still water, external static loads;
- Low frequency wave loads;
- High frequency slamming loads;
- Internal cargo inertia acceleration loads;
- Liquid sloshing loads.

The still water loads are static. The low frequency wave loads are steady state dynamic; as are the cargo inertial loads. Both are typically treated in a quasi-static manner for purposes of obtaining the load effects. The high frequency slamming loads and the liquid sloshing loads are transient and dynamic. Their effect on the structure must typically involve dynamic structural analysis. All the local loads noted above are pressures. The publication notes how often the reason given for the lesser uncertainty in global loads is that the ‘integration’ process involved in obtaining the global loads from the local ones leads to the averaging of some of the errors involved.

3.4.3 Fatigue Loads

As ship structures have become increasingly efficient, fatigue has emerging as a hugely important failure mode that needs explicit consideration in design. This is based upon structures becoming lighter through optimisation leading to design improvements. An example of this would be the use of higher strength steels, which have been used in areas of ships that experience high loading in order to reduce the overall mass of the structure. The problem with these steels is that although they possess higher ultimate strengths and associated maximum allowable strengths, there fatigue lives are no different to that of ordinal mild steel, as such there are susceptible to fatigue failure.

Fatigue loads in the long term arise primarily from the following sources:

- Loads due to overall (primary) hull girder bending
- Loads due to water pressure oscillation (local).

To calculate potential fatigue damage it is necessary to establish a stress range and expected number of cycles histogram for the structural detail of interest. This process is also likely to suffer problems due to the uncertainly of determining expected loads. In addition to this a level of uncertainty also arises from the establishment of the number of cycles associated with a given stress range, due to inaccuracies in Miner's rule (***Munse*** et al. ***1982***), which is used to accumulate damage from the stress fluctuations of various magnitudes and due to mean stress effects. The contribution of the stress range has a far greater impact on the likelihood of fatigue damage than the number of cycles. This is a result of fatigue damage being a function of the stress range raised to a power of three or greater.

In the primary hull envelope, the fatigue damage at the deck and bottom is mostly a function of the hull girder loads, at least in the midship region of the vessel. On the side shell, however, local pressure fluctuations are important. While there are currently no studies in the public domain relating to local pressure related fatigue effects in the fore and aft regions of the vessel, it is likely that local pressures are a significant factor in the fore body regions in addition to slam effects. In the aft body, it is important to consider loads due to propeller and machinery vibration.

3.4.4 Special Loads

These loads include ice loads, thermal loads, and also vibration loads due to the propeller and machinery. For certain types of vessels (e.g., ice breakers), for certain parts of some vessel types (e.g., the containment structure in LNG vessels), or for reasons other than structural integrity and strength (e.g., crew comfort), it may become necessary to explicitly consider special loads and their related effects.

3.5 Structural Failure Modes and Criteria

A perfect structure with material that follows an ideal elastic-plastic stress- strain curve will exhibit the following successive modes of collapse:

- Buckling of plating between stiffeners;
- Buckling of longitudinal stiffeners and plating between transverse stiffeners;
- Overall buckling of the grillage between stiff frame supports.

The difficulty with these assumptions is that in practice no structure is perfectly flat at a zero stress state prior to any load being applied to it. Plates will distort as a result of the heat input during the welding process, the amount of residual stress can be increased if the plates require straightening to remove/reduce the amount of distortion.

Buckling of the plating between stiffeners will not necessarily result in the ultimate failure of a well-designed structure. When the plate has buckled, there will still be a region of the plate, namely along its edges which is still carrying load and continuing to assist the longitudinal stiffener to resist buckling.

Buckling of the longitudinal stiffeners occurs when a particular panel collapses when the local reserve strength has been fully utilised, this results in load shedding to adjacent panels. If these panels have sufficient reserve strength to absorb the extra load then overall the structure may remain intact. Design with large differences in load bearing capacity, such that the adjacent grillages would be capable of picking up significant amounts of additional load are not common. Thus there is an assumption that ultimate collapse will occur once one grillage has collapsed.

Critical areas for this type of collapse are the upper deck and double bottom structures which are designed with fairly uniform grillages and scantlings, thus they provide very little reserve strength upon stiffener failure.

It is typical that the bending moment loads will drive the design of a hull girder structure, but it is important not to forget to account for the shear loads. These loads are normally calculated by determining the load that will be applied to the area. In most cases it is sufficient to ensure that the applied stress is less than half the shear yield stress, which normally taken as half the tensile yield stress.

3.5.1 Basic Concepts of Longitudinal Strength

The plaudits for the foundations of the calculation of longitudinal strength go to W.G. John who published ‘The Strength of Iron Ships’ in 1874. His approach used classical linear-elastic beam bending theory, in which longitudinal stress was calculated by placing the ship on a standard wave form. This established the preferred method of calculations for Naval Architects for many generations whereby the still water loading was combined with a quasi-static representation of the ‘dynamic’ wave loading. Subsequently the method has been refined and modified in order to account for the effects of such things as superstructure, hatch openings, torsional bending and to account for the effects of shear stress and shear lag. Techniques have also developed to account for the full effects of the complex dynamic motions and loading that are to be expected during the operational life of a vessel.

In a rough seaway the ship’s structure will be subjected to a wide range of continually changing forces. This is due to the effects of not only the external water acting against the hull but also the inertial response of the vessel and its contents. A ship’s hull is often considered as a hollow box girder, as it does not behave like a simple beam for a number of reasons. Most notably being that at higher stress levels, local yielding will redistribute the load-bearing capabilities of each component of structure and its contribution to the load-bearing capability of the overall cross section.

3.5.1.1 Moment Curvature Relationships

The expected vertical bending moment curvature capability relationship for a ship’s hull would be of the form shown in Figure 3-7. As pure bending is applied to the structure the resultant curvature and internal moment of resistance increase in a linear elastic manner. A point will be reached whereby parts of the hull girder stop reacting in an elastic manner as a result of plate buckling for example. The point at which the change in moment over change in curvature becomes zero or changes sign represents the Ultimate Longitudinal Bending Strength of the hull.

In normal practice the values of *M* for hogging and sagging will be different as a result of hull girders not being symmetrical about the horizontal neutral axis, (***Rutherford*** and ***Caldwell 1900***).

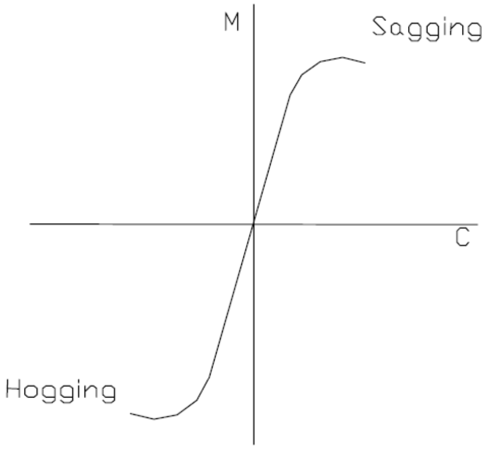


Figure 3-7 Illustration of a Typical Moment - Curvature Relationship

3.5.2 Progressive Collapse Analysis

Caldwell (***1965***) took a stiffened cross section and idealised it into one of equivalent thickness with no stiffening in order to generate the effective plastic modulus of the whole section. As the compressive strength cannot reach the material yield stress if local buckling occurs on the compressive side of the overall bending, all material cannot be effective to the yield strength. In order to accommodate this factor ***Caldwell*** (***1965***) introduced a stress reduction factor which determined the ultimate strength as the bending moment capability produced by this reduced stress.

It is clear that not all structural elements in the hull girder will reach their individual ultimate strength at the same point due to the differing radii throughout a large hull girder, as inferred by the Caldwell approach. ***Yao*** (***1999***) discussed how the reduction in capacity of the structural members beyond their ultimate strength was not considered in the Caldwell method. The implication of this that once the ultimate strength has been reached the hull girder is maintained in a rigid plastic manner as further loading is applied.

Further work has been carried out by a number of researchers to improve upon Caldwell's method to improve the derivation of stress reduction factors, the phase lag of structural components in collapse and the reduction in the capacity of structural members beyond their individual ultimate strength.

Maestro and ***Marino*** (***1989***) modified Caldwell's method in order to estimate the influence of grounding or collision damage of the ultimate hull girder strength. ***Yao*** (***1999***) discussed the modification work carried out by researchers in this field. However none of the improved methods account for the explicit stress reduction in structural components at strain levels beyond their ultimate strength.

As discussed calculation of the ultimate strength of a ship hull girder does not include the reduction in strength of the individual elements once they have reached their ultimate strength (***Yao 1999***; ***Yao*** et al. ***2000***). As a result this does not actually reflect the behaviour of the structural components within a ship hull girder, this leads to errors in the calculation of the ultimate strength of the midship section. The use of Finite Element Method (FEM) allows calculation of the strength reduction of the individual components to provide accurate predictions during simulation of the collapse performance of the hull girder. FEM allows large deflection behaviour, geometric and material non-linearity to be incorporated in to design. The process used for finite element analysis is discussed in more detail in section 3.7

3.5.3 Limit State Design

Limit State Design (LSD) is in essence a system whereby a given design is provided with a safety margin between the demands placed upon the structure throughout its life and the expected loads that are applied to it. These loads can range from the routine to extreme or accidental. The role of the safety factor is to account for the large range of uncertainties and inaccuracies that exist in estimating the magnitude of loads and the resulting effects such as stress and deformation it also accounts for variations from the design and build processes.

Paik and ***Thayamballi*** (***2003***) provide the following definition of safety factor based design

$$\boldsymbol{safety\ measure} = \frac{\boldsymbol{C_d}}{\boldsymbol{D_d}} > 1 \qquad 3\text{-}1$$

Where:

C_d = is the design capacity;

D_d = is the design demand.

Further definition is of the terms:

$$\boldsymbol{D_d = \gamma_0 \sum_i D_{ki}\left(F_{ki}\gamma_{fi}\right)} \qquad 3\text{-}2$$

$$\boldsymbol{C_d = \frac{C_k}{\gamma_M}} \qquad 3\text{-}3$$

Where $D_{ki}(F_{ki}, \gamma_{fi})$ is the characteristic measure of demand for load type i, this is determined from the characteristics of the load(s) F_k, and magnified by the partial safety factor, γ_f, which accounts of the uncertainties related to the loads. γ_0 is the partial safety factor that accounts for the seriousness of the limit state in question with regard to factors such as safety and economical related to failure.

C_k is the characteristic measure of capacity, $\gamma_M = \gamma_m \gamma_c$ is the capacity related safety factor, where γ_m accounts for uncertainties related to material properties, and γ_c is the partial safety factor accounting for the uncertainties of the capacity of the structure, such as quality of construction or corrosion which forms an integral part of the work in this thesis.

Traditional allowable stress design methods aim to maintain the stress that results from the design loads below a given level. This is normally based upon a successful previous experience, within the shipping industry this experience is provided by classification societies. The major difference between this approach and that of limit state design is the explicit consideration of the variation conditions whereby the structure is unable to meet the operation requirements it was designed for.

A limit state is defined by describing the condition which a particular structure or an individual member associated with the structure fails to operate in the manner is was design to do so. Four types of limit state design have been defined for steel structures:

- Serviceability limit state (SLS);
- Ultimate limit state (ULS);
- Fatigue limit state (FLS);
- Accidental limit (ALS).

The work within this thesis is principally concerned with the serviceability limit state, as corrosion can be considered as a form of local damage which reduces the effectiveness of the elements within the structure to meet the requirements for which they were designed. Corrosion can cause both very localized and more general loss of material, thus increasing the stress for a given load. This can lead to an ultimate strength limit state as the entire structure collapses due to a loss of stiffness and strength.

3.6 The Role of Class

The purpose of a Classification Society is to provide classification and statutory services and assistance to the maritime industry and regulatory bodies as regards maritime safety and pollution prevention, based on the accumulation of maritime knowledge and technology. Numerous agencies such as hull and machinery underwriters, protection and indemnity insurers, charterers and Flag states rely on the classification society certification regime to give assurance that vessels are built and maintained to a certain standard.

The inception of classification societies can be traced back to the 18th century. Where a group of marine insurers, who based themselves at Lloyd's coffee house in London, and developed a system whereby they could assess the ships that were presented to them for insurance cover. Following this a Committee was formed 1790 with this as their primary focus, the earliest existing result of their initiative being *Lloyd's Register Book* for the years 1764-65-66. (***ICAS 2011***).

This group to annually 'classify' the condition of each ship, with the hull being classified A, E, I, O or U, according to the quality of its construction and the opinion of the surveyor as to the continuing soundness. Equipment was G, M, or B: simply, good, middling or bad. In time, G, M and B were replaced by 1, 2 or 3, which is the origin of the well-known expression 'A1', meaning 'first or highest class' (***ICAS 2011***).

With regard to the structural design of ships the classification societies aim is still very much the same as it was in late 1760's, they continue to aim to verify the structural strength and integrity of essential parts of the ship's hull.

The development of Classification Society Rules has relied on empirical experience gained from classing a wide variety of ship types over many years. This has been coupled with continued research that contributes towards the continual development of relevant, advanced technical requirements. It is worth noting however that, IACS are clear in stating that Classification Rules are not intended as a design code and in fact cannot be used as such.

The implementation of the published rules the role of Class of is defined by ***IACS*** (***2011***) as:

- A technical review of the design plans and related documents for a new vessel to verify compliance with the applicable Rules;
- Attendance at the construction of the vessel in the shipyard by a Classification Society surveyor(s) to verify that the vessel is constructed in accordance with the approved design plans and classification Rules;
- Attendance by a Classification Society surveyor(s) at the relevant production facilities that provide key components such as the steel, engine, generators and castings to verify that the component conforms to the applicable Rule requirements;
- Attendance by a Classification Society surveyor(s) at the sea trials and other trials relating to the vessel and its equipment prior to delivery to verify conformance with the applicable Rule requirements;
- Upon satisfactory completion of the above, the builder's/shipowner's request for the issuance of a class certificate will be considered by the relevant Classification Society and, if deemed satisfactory, the assignment of class may be approved and a certificate of classification issued;

- Once in service, the owner must submit the vessel to a clearly specified programme of periodical class surveys, carried out onboard the vessel, to verify that the ship continues to meet the relevant Rule requirements for continuation of class.

On 14 December 2005, the Common Structural Rules for Tankers and Bulk Carriers (CSR) were unanimously adopted by the IACS Council for implementation on 1 April 2006. The CSR were developed by IACS to harmonise minimum standards of construction for bulk carriers and tankers between the various member societies. Common Rules are IACS Unified Requirements and they cover a broad area of classification requirements which, once adopted by IACS Council, shall be applied by all Members without the possibility of reservations. The CSR are a comprehensive set of minimum requirements for the classification of the hull structures of bulk carriers and double-hull oil tankers. A new set of harmonised CSR are due to enter force in 2015, these rules have been updated with more focus on ultimate strength regulations.

The current set of rules are under continual refinement and development as more information is gathered through ship operation and research projects, such as this one. IACS is quick to point out that it is the marine community, through representation at governmental level within the IMO, determines the level of risk associated with the conduct of marine transport. There are two approaches to the setting of standards; they may be prescriptive or goal based. To achieve the former it is common for class to develop unified interpretations which explain the intent and application of the international standards. In the case of goal-based standards, the IMO will establish general requirements, allowing class to develop the details of the rules and ensure that industry complies.

Hoppe (***2006***) noted that with prescriptive regulations, that parties are only required to carry out the mandated actions to discharge their legal responsibilities. If the actions taken are subsequently not sufficient to prevent failure or accident then it is the regulators who are seen to be deficient. In addition prescriptive regulations tend to be a distillation of past experience, which can creates a situation whereby the gained knowledge becomes less relevant which could lead to unnecessary dangers.

An example of the shift of the IMO away from complex largely prescriptive statutory regulations towards a transparent goal-based regulatory framework would be the revision of Chapter II-2 on Construction – Fire Protection, fire detection and fire extinction (***Hoppe 2006***).

The overall aim is to move the regulatory framework from a culture of compliance that is governed by prescriptive rules to a culture of benchmarking that is backed by functional risk-based requirements. This approach encourages alternative designs that still provide the required level of safety whilst using new or alternative technology and innovation.

3.7 Assessment Criteria for Stiffened Panels

3.7.1 Empirical Indices

The previous discussions have centred on how Class considers the overall hull girder. The distance between of the spacing of the longitudinal stiffeners, spacing between transverse frames, and the thickness of the shell plating and the profile of the stiffeners are the factors normally used to describe the geometry of hull girder structure. Within this there are a number of ratios and indices that are regularly used in ship structural design to assess the performance, suitability and efficiency of a structure. As these variables also characterise the topology of the structure they provide the opportunity to use them both as a measure of complexity and structural efficiency. These can then be used to define a feasible region in which less complex more easily coated alternative structures can be identified. These structural variables include:

- Stiffener plate area ratio based on cross sectional area of both components;
- Stiffener thickness plate span ratio;
- Plate slenderness ratio.

Figure 3-8 shows a typical orthogonal panel and identifies all of the different parameters within the panel.

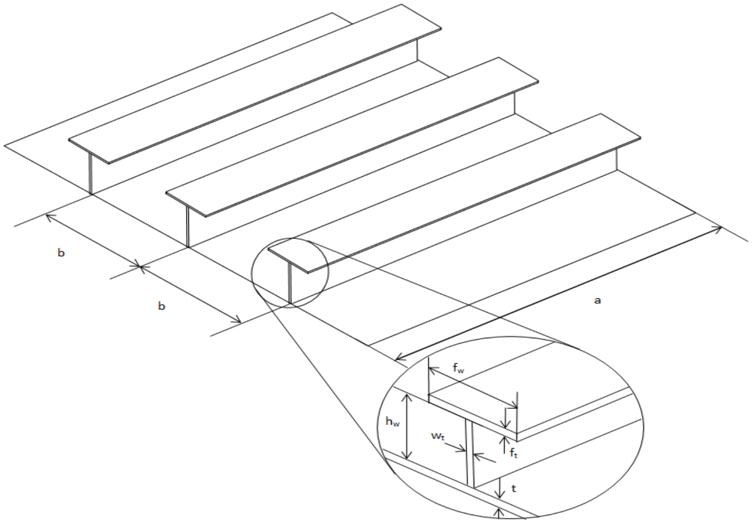


Figure 3-8 Typical orthogonally stiffened panel

The area ratio is the measure of stiffener area and the area of the associated plate-stiffener combination, good practice and experience suggests values between 0.1 and 0.2 (***Dow 2010***). Too high or low values indicate inefficient stiffener-plate combinations. If the resultant value is less than 0.1 the plate is at risk of elastic buckling, and if it is greater than 0.2, the structure will have an inefficient weight balance. Common practice for merchant vessels is to have values closer to 0.2, whereas naval vessels are closer to 0.1, which implies a lighter but more complex structure.

$$\boldsymbol{A_r = \frac{Area_{Stiffener}}{Area_{Plate\ \&\ stiffener}}} \tag{3-4}$$

Another useful check with respect to buckling resistance is the slenderness ratios of the plates; this is measure of the breadth of a plate to its thickness. The values of β for normally associated with good ship structural design practice are in the region of 1 to 2.5.

$$\boldsymbol{\beta = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}}} \tag{3-5}$$

Beta is used to describe the slenderness of a plate, a slender plate is termed as one with $\beta > 2.5$, these plates exhibit elastic buckling stress significantly below that of the material yield stress. Such plates exhibit stable post buckling behaviour as the plate does not collapse when the elastic buckling load is reached. This is a result of the boundary conditions preventing the unloaded edges of the plate. Intermediate plates, those with 1< β >2.4, exhibit a theoretical elastic buckling stress of a similar magnitude to that of the yield stress. The initial imperfections have a significant influence on the buckling and collapse responses on the plate. These imperfection are magnified as the applied load increases, this causes a loss of stiffness and some local yielding, which in turn causes non-uniform stress redistribution. This can cause the stress in the central regions of the plate to reach the yield stress meaning no further load can be supported. As for slender plates, the outer portions of the plate support the load. Collapse will occur when the average equivalent stress along the sides of the plate reaches yield stress.

Work undertaken in the 1930's investigated the load carrying ability of steel plates, ***Schuman and Back*** (***1930***) noted how a buckled plate was behaving as if only part of the width of the plate is effective in carrying load. ***Karman*** *et al*. (***1932***) applied this concept to produce an expression for effective plate width, which was shown to be equivalent to:

$$\frac{b_e}{b} = \sqrt{\frac{\sigma_{cr}}{\sigma_Y}} \qquad 3\text{-}6$$

Where:

b_e is the effective width;

b is the full plate width;

σ_{cr} = plate buckling stress;

σ_Y = material yield stress.

The method proposes that the ultimate collapse load is taken by two yielding strips either side of the stiffener web, or the plate edge. The collapse strength can be calculated using the width of these strips in conjunction with the plate thickness. The effective width is equal to the actual width for stocky plates, β < 1, with the effective ratio reducing as the slenderness increases, thus:

$$\frac{b_e}{b} = 1.0 \qquad for\ \beta < 1 \qquad 3\text{-}7$$

$$\frac{\boldsymbol{b_e}}{\boldsymbol{b}} = \frac{\boldsymbol{2}}{\boldsymbol{\beta}} - \frac{\boldsymbol{1}}{\boldsymbol{\beta^2}} \qquad \boldsymbol{for\ \beta} > 1 \tag{3-8}$$

3.7.1.1 Faulkner formula

Faulkner (***1975***) proposed an empirical formula to estimate the strength of simply supported steel plates under longitudinal compression. The formula defines the ultimate plate strength $\phi_{xu,}$ as a function of the slenderness ratio:

$$\frac{\boldsymbol{\sigma_u}}{\boldsymbol{\sigma_0}} = \boldsymbol{1.0} \qquad \boldsymbol{for\ \beta} < 1 \tag{3-9}$$

$$\frac{\boldsymbol{\sigma_e}}{\boldsymbol{\sigma_0}} = \frac{\boldsymbol{2}}{\boldsymbol{\beta}} - \frac{\boldsymbol{1}}{\boldsymbol{\beta^2}} \qquad \boldsymbol{for\ \beta} > 1 \tag{3-10}$$

The two terms within this formula accounts for both the effective width and critical elastic buckling stress approaches; by approximating the effective width formula at high slenderness ratios and increasing the influence of the $1/\beta^2$ term at lower slenderness ratios to account to reduce the overall collapse load significantly.

3.7.1.2 Steel panel design charts

Once knowledge of the effective width of the plate is available it is possible to estimate the collapse strength of the longitudinal stiffeners using column buckling theory. This was traditionally was done using Euler column formula to the point of yield, with the structure assumed to have pinned ends. However this method does not account for the residual stress as a result of any deformation. The slenderness of a plate gives a useful initial estimate of the elasto-plastic buckling strength of the structure. A measure of this is the Johnson parabola based on the 'column' slenderness ratio, λ, which is useful for ship type structures, ***Chalmers*** (***1993***). This is defined in a similar manner to β but is a function of the ratio of the length of the plate to the radius of gyration, based on the second moment of area of the section; again a lower value implies higher complexity:

$$\lambda = \frac{l_{eff}}{\pi k}\sqrt{\frac{\sigma_y}{E}} \tag{3-11}$$

Where *k* is the radius of gyration:

$$\boldsymbol{k} = \sqrt{\frac{\boldsymbol{I}}{\boldsymbol{A_T}}} \qquad \text{3-12}$$

And I is the second moment of area of the plate-stiffener cross section for the full with of the panel not the effective width, this has been used throughout the rest of this work:

With this method residual stress can be accounted for by modifying the effective width of the plate. This method does not explicitly account for deformation, as opposed to the empirical methods, residual stress is based on experimental data, both of these phenomena are implicitly included.

Chalmers published a series of steel panel collapse curves (***Chalmers 1993***) which are based upon a numerical analysis ***(Smith*** et al. ***1991***) and experimental data (***Little 1982***), (***Dorman*** and ***White 1973***). The numerical method used finite element analysis to model a stiffener element in the beam-column, the attached plating is represented implicitly with a plate load shortening curve. These curves provide a very close match to the peak strength formula defined by Faulkner.

The curves were developed using admiralty long stork tee bar sections, with area ratios from 0.1 to 0.4. Figure 3-9 shows an example set of curves for average imperfections. The curves are presented in two forms: as a function of plate slenderness and column slenderness.

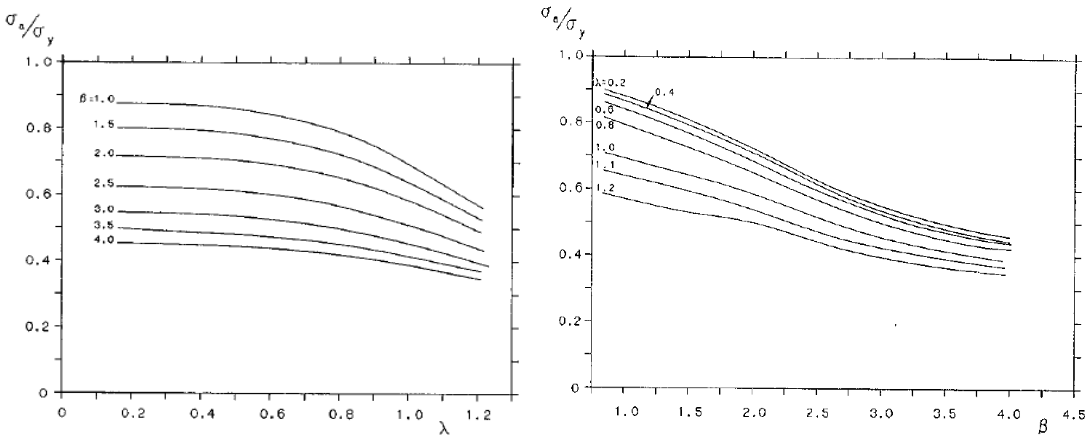


Figure 3-9 Chalmers Design Chart Column Collapse Curve - Average Imperfections

This thesis has not provided an exhaustive list and review of the methods that are currently available to assess the structural performance of a stiffened panel. The basis of this work is not to propose alternative or novel methods for structural response; it is to explore the financial benefits that could be achieved by considering the coating process during the design phase, using the most suitable measures to identify a region of suitable structural performance. Within this design space the influence of different structural configurations will be investigated. This will allow the structure to be optimised in terms of structural performance and its suitability for the coating process.

In order to ensure that any new configurations provide adequate structural performance the values of the structural indices must be maintained. The sensitivity of the structures ‘coatability’ to these indices must be understood. To achieve this, this simplified structure will be optimised both with the values fixed and with acceptable limits set to allow a degree of variance.

Table 3-1: Recommended values of structural constraints (***Smith*** et al. ***1991***)

Plate slenderness, β	1 ~ 2.5
Column slenderness, λ	0 ~ 0.45
Area ratio, A_r	0.1 ~ 0.2
b/t	35 ~ 60
a/k	40 ~ 70

The interaction of these indices will be discussed further in chapter 5 and part of the detailed analysis of the midship sections.

3.7.2 Applicability of Rules and Regulation for this Study

In this study a double hull tanker has been used as a benchmark from which to explore the potential benefits of different structural design methodologies relating to the coating process. The topography and dimensions of the structure have been used as the basis against which any improvements can be assessed against.

One of the considerations for the midship section of a vessel is the moment of inertia provided by the structural configuration. This study seeks to explore the potential benefits of alternative structural designs in particular the reduction of the number of longitudinal stiffeners. This vessel had been certified according to the classification rules in place at the time of construction, as such the moment of inertia of the benchmark vessel has been set as one of the constraints for the design problem.

3.7.3 Introduction to Finite Element Analysis

The indices discussed previously consider individual plates and columns, to assess the impact of alternative design solutions Finite Element Method (FEM) will be used to model panels and ultimately the midship section from a contemporary oil tanker. Finite Element Method or Analysis (FEA) allows a complicated problem to be replaced by a simpler one, as a result the solution that is derived will be an approximate one rather than exact. In many cases it is possible to improve or refine the approximate solution by expending more computational effort. When applying the FEM to a complex structure such as the midship section of a ship, the section is considered to be built up of many small interconnected sub-regions called finite elements. A convenient approximate solution is assumed and the conditions of overall equilibrium of the structure are derived. Satisfying all of the conditions will yield an approximate solution for the displacements and stresses.

Rao, (***2005***) provides a concise review of the history and development of the FEM, he notes that the name of finite element was coined by ***Clough***, (***1960***). ***Turner*** et al. (***1956***) used pin-joined bar and triangular plate with in-plane loads to represent an aircraft structure to undertake a finite element analysis of an aircraft; this is cited as one of the key contributions in the development of the method. ***Zienkiewicz*** and ***Cheung***, (***1967***) presented work on the suitably of FEM to any general field problem. Their interpretation of FEM led to the FE equations being derived using a weighted residual method such as the Galerkin method or the least squares approach. Following this, mathematicians began using FEM to solve linear and nonlinear differential equations.

3.7.4 General Description of the Finite Element Method

When undertaking a Finite Element Analysis on structure, the actual structure is represented by a series of smaller sections known as finite elements. These elements are connected by nodes or nodal points. In the majority of cases these nodes lie on the boundary of an element adjacent to the neighbouring connected element boundary. In the case of structural analysis the field variable is typically the displacement or stress inside the element is not known. To allow the analysis to be undertaken the variation inside the finite element is approximated by number of simple functions. These approximation functions, also known as interpolation models, are defined in terms of the values of the field variables at the nodes. When the equilibrium or field equations are written for the entire structure composed of all of the individual finite elements, the new unknowns will be the nodal values of the field variable. These field equations are typically written as matrixes, and when solved provide nodal values of the field variable.

The step-by-step process to undertake a finite element analysis was set out by ***Rao***, (***2005***) as follows:

3.7.4.1 Step 1: Discretization of the structure

This process involves separating the entire structure into individual elements, the number size type and arrangement of the elements must be decided with care as they can have a significant effect on the processing of the model.

3.7.4.2 Step 2: Selection of a proper interpolation displacement model

As previously mentioned the displacement solution of a complex structure such as a midship section under a specific loading condition, cannot be predicted exactly. Therefore a suitable solution within an element that will approximate the unknown solution is selected. It is important that this assumed solution is simple to ease the computational requirements however it needs to satisfy the convergence requirements. In general a polynomial is used for the solution or interpolation model.

3.7.4.3 Step 3: Derivation of element stiffness matrices and load vectors

Using the assumed displacement model, the stiffness matrix $\left[K^{(e)}\right]$ and the load vector $\overrightarrow{P^{(e)}}$ of the element *e* are derived using the equilibrium conditions or a suitable variation principle.

3.7.4.4 Step 4: Assemblage of element equations to obtain the overall equilibrium equations

FE divides the structure in a number of individual elements, these element stiffness matrices and load vectors are assembled in a suitable manner and thus the overall equilibrium equations have to be formulated as;

$$[\boldsymbol{K}]\vec{\boldsymbol{\Phi}} = \vec{\boldsymbol{P}} \qquad 3\text{-}13$$

Where $[K]$ is the assembled stiffness matrix;

$\vec{\Phi}$ is the vector of nodal displacements

$\vec{P}$ is the vector of nodal forces for the complete structure.

3.7.4.5 Step 5: Solution for the unknown nodal displacements

The boundary equations of the problem require the overall equations to be modified. Once the boundary conditions have been incorporated the equilibrium equations can then be expressed as:

$$[\boldsymbol{K}]\vec{\boldsymbol{\Phi}} = \vec{\boldsymbol{P}} \qquad 3\text{-}14$$

If the problem is of a linear nature then the nodal displacement vector can be solved quite easily. However for non-linear problems the solution is obtained by modifying the stiffness and /or the load vector in a series of steps.

3.7.4.6 Step 6: Computation of element strain and stresses

From the known nodal displacements, it is possible to use the necessary equations of solid or structural mechanics to calculate the element strains and stresses.

The preceding six steps outline the process of undertaking a finite element analysis of a structure, by altering the terminology used the method can be applied to a range of other fields such as heat flow, hydrodynamics or geomechanics.

3.8 Conclusions

This chapter has indentified the assessment criteria will be used to identify a suitable design space within which alternative designs that provide improved solutions for the needs of the coating process can be investigated.

It is interesting to note that current structural design methods do not consider the effect of applied protective coatings, assumptions are made as to the length of time that applied coatings provide protection. If the application of coatings was made of a much higher importance then it is possible that the levels of uncertainly as to their lifespan and therefore rates of corrosion could be significantly reduced. Ultimately this would result in safer more predictable ships structures.

3.9 Summary

This chapter has examined the development of the ship design process and again how it has focused on steelwork. The methods used for load prediction and the modes of failure which are likely to occur have been discussed. A set of suitable assessment criteria for use on single and multiple stiffener plate combinations has been identified and there relevance discussed. In addition to this the Finite Element Method has been described. Suitable methods that will be used to determine the structural performance and structural design methodologies have been discussed. The next section will examine the coating process within shipbuilding.

4 THE COATING PROCESS WITHIN SHIP PRODUCTION

4.1 Introduction

Having discussed the ship design process previously, this chapter investigates the effects that the design process has on the physical activities needed to build a ship. The developments of the different design procedures such as design for production and for minimum weight are discussed.

The results of a number of studies that have previously been undertaken to assess the coating process have been used in conjunction with an industry questionnaire, that was developed as part of this work, to draw conclusions as to the current state of the coating process both within the shipbuilding industry as well as the wider heavy duty and marine construction industries.

This chapter highlights the in-balance between the design efforts that have been afforded to the different aspects of shipbuilding and how it is very much focused toward steelwork and outfitting. By re-addressing this balance a number of potential benefits that may be realised are discussed.

4.2 Design for Production

Kuo et al. (***1983***) discusses the development of structural design philosophy and presented the following definition:

> *'Design to reduce production costs to a minimum compatible with the requirements of the structure to fulfil its operational functions with acceptable reliability and efficiency'*

Design for Production (DFP) refers to methods that evaluate manufacturing system performance. For example:

- Does the production line have enough capacity to achieve the desired production rate?
- How long will it take the factory to complete customer orders?

- How much inventory will be required to maintain superior customer service in an international supply chain?

Answering such questions requires information about product design, manufacturing requirements, and production quantities along with information about the manufacturing system that will create the product.

Pahl and ***Beitz***, (***1996***) highlights the differences between mass and one-off or small batch production, shipbuilding typically falls in the second category. In order to minimise risk the design of one-off structures requires careful consideration of the physical processes and design details. In these cases it is common that functionality and reliability have greater importance than economic optimisation. Conversely when considering mass production there is far greater opportunity to realise process improvements to reduce costs.

A Design for Production Manual (***DPM***) ***1979*** which was produced by British Shipbuilders defines the concept of design for production as ‘in satisfying the statement of requirements, the ship design should also give attention to ease of production’ and suggests, two aspects of the overall design, namely:

- Design for performance;
- Design for production.

Two principals which were developed in the Design for Production Manual are; all design features must be compatible with the facilities available in the shipyard; all design features should be based on the concept of simplicity thereby reducing the inherent complexity. This idea will allow reduction of the inherent work content to be significantly reduced.

DPM also cover the acceptable environmental working conditions, and describes how design layouts should be avoided that may create environmental difficulties as a result of confined spaces. The example given is that of the minimum Classification double bottom height of a small vessel may be too small to undertake the production activities required; therefore the design should be altered to aid with the production process.

DPM notes that reducing the assembly and welding work content is important to reducing costs, but notes that any design changes must be checked as they may involve space and weight penalties. One means of achieving this is the use of large long plates and widely spaced and fewer stiffeners. It does however suggest intermittent welding must be avoided due to the problems with crevice corrosion. There is also reference to obtaining a balance with the design that is based upon manpower and material costs. The manual also discusses the importance of access to the weld joints and how where ever possible the surrounding structure should be designed to allow access or if staging needs to be erected then base areas and supports must be considered.

Thus it is clear that during the 1970's and into the 1980's shipyards were considering how designs impacted upon the physical processes needed to construct a ship. What is also apparent is that the research and subsequent design effort was very much focused upon the steelwork and outfit processes which echo's the finding of Chapter 2. To truly minimise the cost of building a ship all of the processes need to be taken into consideration, it is this that forms one of the cornerstones of the work in this thesis.

Recent work that has been undertaken at Michigan State University by ***Rigterink et al.,*** (***2012***) has examined the production process and has looked solutions that balance the needs of the production process and the cost of the panel. A structural complexity metric for a number of panels has been developed using seven 'producibility' drivers where each element receives a score of between 0 ~ 1, there are combined using common utility methods to give a single producibility score. The authors report that a 10% gain producibility would result in a less than 1% gain in cost. At the time of writing the work of the researchers at Michigan has been limited to smaller more complex panels such as those likely to be found in Naval Combatants.

4.2.1 Design for Weight

The idea of designing a structure to minimise it weight is a simple one, within the context of marine vehicles, minimising weight offers the following benefits:

- It allows a greater payload for a given size or weight of vessel;

- It can allow higher speeds to be achieved for the same installed power;
- It can reduce fuel consumption and environmental emissions for a given payload and distance travelled;
- It can reduce the material cost of building a vessel;
- In the cruise ship market it is possible to improve the stability of a vessel, by lowering the centre of gravity.

The as discussed in Chapter 2 the use of lightweight materials such as aluminium has been pursued by the fast ferry market, in such applications it is possible to extrude panels with the necessary stiffeners in place to reduce the production work content.

Within traditional shipbuilding i.e. steel built ships, weight is used as one of the global measures of merit (***Hills and Buxton 1989***), whereby studies examining the effect of design changes on production costs used weight as a basis. However they did highlight that work carried out by others on the estimation of work content as being a better measure of cost, although this work content was principally driven by the steelwork process. One reason for this was suggested by ***Hills et al.*** (***1990***), was that steelwork may not be the most important item of the total cost of a ship, but as it is the factor that is most under control of the ship building it tends to be their main area of focus.

One factor that highlights the focus on minimising steel weight is the introduction of the common structural rules as these harmonised the traditional prescriptive rules that had been used by individual classification societies for more than a century. Advances in technology allowed designers to optimise ship structural designs in very imaginative ways whilst still remaining within class rules. There was concern within the shipping industry that this was resulting in the construction of less robust ships (***Bureau Veritas 2006***). The adoption of one common set of structural rules still allows design innovation providing that the rules are met. The rules also ensured that the different classification societies were competing for business based on their service provision and expertise, rather than working to which ever set of rules allowed the 'most optimisation'. ***Card et al***. (***2004***) published a paper detailing the work that had been undertaken by ABS, DNV and LR following a central theme that classification societies should not compete on standards. The paper reported that the project was far bigger and more involved that had been perceived at the outset, for example initially the project aim was only to consider the main scantlings, but it became apparent that the scope had to be expanded to cover the entire vessel.

The CSR use a net scantling approach which was part of many of the larger classification society approaches prior to the introduction of the rules. Essentially this method ensures that the material required for the strength of the ship, or the net scantling, is supplemented by any additional specified thickness to account for corrosion as the vessel is operated and any owners addition thickness if they require. The approach adopted in the current rules is based on calculating the minimum allowable thickness that satisfies the requirement for strength, $t_{net\ required}$, and then adding a corrosion addition, t_{corr}, to obtain the minimum allowable gross thickness, $t_{gr\ required}$. The proposed thickness, $t_{gr\ offered}$, of any element of structure must therefore be greater than $t_{gr\ required}$.

4.2.2 Design for Coatings

The structural design of ships has conventionally sought to seek an appropriate balance of requirements with respect to strength, weight, operation, ease of construction and cost whilst still complying with Classification Society rules concerned with the safety of the vessel. Naval Architects have long been accustomed to designing vessels to meet these requirements.

The task of structural designers across all fields is to seek methods to minimise corrosion, thus ensuring the structure remains fit for purpose, for its entire operational life. The importance of good design as a means of preventing corrosion is not a new concept, as in 1972 the BSRA published ‘Recommended Practice for the Protection and Painting of Ships’. The book discusses a number of methods of good practice that a designer should incorporate into any ship design to minimise corrosion. Attention is brought to avoiding:

- Details that entrap corrosive agents, thus accelerating the corrosion process;
- ‘Back-to-back’ angles which prevent the application of an adequate paint film;
- Use of flat bar or offset bulb plate in place of angle bar stiffeners to improve the inspection and maintenance process;

- Consider the painting process at both the new build and the maintenance stages during the structural design process.

However the concept of design to improve the performance of coatings is a novel approach, in fact there is often a tendency not to take heed of this advice, and to create corrosion problems as a by-product of designing to meet other requirements, for example:

- Complex geometries that are difficult to prepare and coat adequately;
- Tight spaces that are difficult to access, ventilate and de-humidify;
- Tight spaces that cannot easily be coated using an airless spray gun and so require build up coats to be applied by brush and roller;
- Spaces that are subsequently difficult to repair and maintain;
- Flat surfaces with no camber or rise of floor to assist with drainage;
- Use of dissimilar metals;
- Poor placement of outfit items resulting in corrosion traps;
- Poor design details to assist with drainage.

There are a number of bodies of work that provide guidance and very useful insight on these issues as to what can be considered good practice for the design of structures. The UK based Marine Painting Forum (MPF) (***MPF 2009***) has produced a guide that is primarily aimed at naval vessels and the prevention of corrosion to secondary steel items such as bulwarks and stanchions. It does however make note of how a great deal of the in-service ship husbandry and the associated through-life cost of a vessel, can be reduced at the design and build stage, by closer attention to detailed design. The guidelines observe that careful consideration must be given to provide maximum access to any compartment that requires painting. So that coating work may be carried out throughout the ships life.

The Tanker Structures Cooperative Forum (TSCF) has produced a number of documents as discussed earlier; of most interest in this context are the ‘Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures’ ***TSCF (1995***) which highlights that any space should be designed to allow access for inspection and for ventilation to ensure adequate curing of the coatings. However no mention is made of provision of access to allow the physical tasks of the coating process to be undertaken. The topic of access will be discussed in the following chapter.

Furthermore there are number of International Standards Organisation (ISO) standards that do not cover design but are related to the process of the preparation of steel substrates namely ISO 8501, 8502, 8503 and 8504.

The ***ISO 12944*** standard deals with ‘Paints and varnishes – Corrosion protection of steel structure by protective paint systems’. It is made up of eight sections, should be noted that although these standards are not applicable to the wider shipbuilding industry or to WBTs specifically the following sections are of interest in the context of structural design:

- Part 3 – Design considerations;
- Part 4 – Types of surface preparation;
- Part 5 – Protective paint systems.

ISO 12944-3 notes how the design of a structure should be carried out in such a way as to facilitate surface preparation, painting inspection and maintenance. It also considers how the shape of a structure can influence its susceptibility to corrode, and recommends that the complexity of a structure should be kept to minimum. The standard also shows examples of good working practice in terms of rounding edges, spacing between stiffeners and use of corrosion resistant materials or the use of a corrosion allowance. A set of minimum required distances are presented which will allow adequate accessibility for the tools required for corrosion protection work.

ISO 12944-4 gives guidance on the range of surface preparation methods that are available to ensure that the surface provided permits satisfactory adhesion of the paint to the steel substrate. It notes that ISO 8503 specifies the requirements of surface profile required.

ISO 12944-5 defines the terms used within the paint industry and the different types of paint that are available. The standard sets out the classification of environments and provides guidance for the selection of different types of protective paint systems.

What seems to be very apparent it that little heed has been taken of all of the good work that has been undertaken. For example the TSCF manual was first published in 1995, and there are still ships under construction where this advice has been ignored. What is clear however is that together with the ISO Standards other than detail design guidance for issues such as edge preparation and the use of scallops, little consideration has been given to the global design of a structure to aid the actual physical tasks required in the coating process.

In merchant vessel structural design there is an emphasis on seeking designs with reduced complexity and inherent work content to facilitate ease of production and further exploit the increased utilisation of automation techniques and advanced modular outfitting. These first cost related objectives have been conventionally balanced against structural weight to identify ‘optimal’ weight-cost solutions. The issues of ease of coating and in service performance of coatings have not normally been considered as part of this trade-off but there is now a need to re-evaluate the design rational.

It is accepted wisdom that costs associated with maintaining the condition of a vessel’s coatings will increase as the vessel ages. Figure 4-1 gives an indication of how these costs increase for three typical areas of a vessel as it ages. The major cause of this rise as a vessel ages is as a result of the increase in the amount of surface preparation required to return older more corroded steel to a suitable standard for coating application. There will be a significant rise in the cost associated with WBTs which will be as a result the problems of gaining access to the spaces. It is also true that Figure 4-1 is purely representative as there will be a diverse range of costs attributable to different ship types.

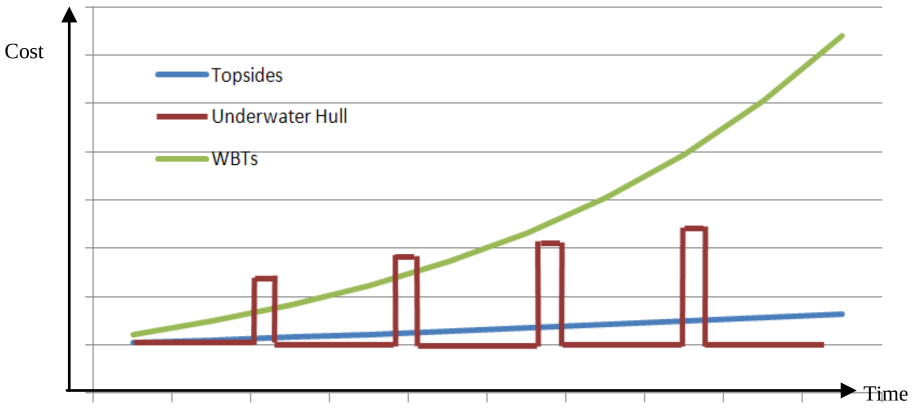
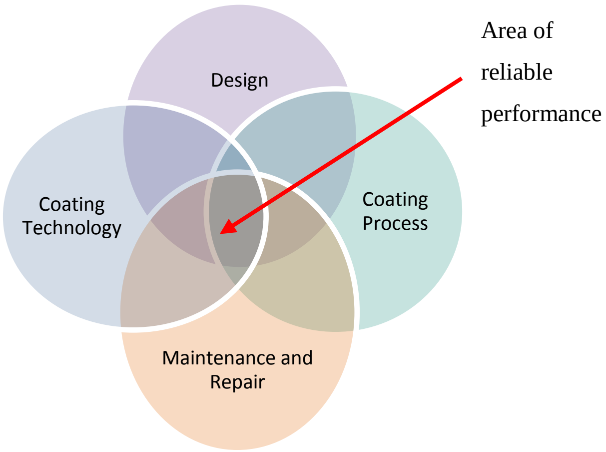


Figure 4-1 Representative Cost of Maintaining Coatings through a Vessels Life

It is possible to conclude from the information presented to date that the design stage has perhaps the greatest influence on a vessel in terms of cost and corrosion prevention throughout its working life. The PSPC seeks to reduce the failure rate of WBT coatings by imposing greater controls on the processes and the products applied to steel substrates.

Figure 4-2 can be used to highlight how the in-service performance of a coating system is not only dependent on the processes involved in preparing and painting a surface and the paint applied to it, but is also a function of the design of the structure itself.

It also shows that if any of the elements are not present then there is a high likelihood that a coating failure will occur. It has demonstrated that it is unlikely that there will be any major changes or improvements to either the coatings used of the methods used to apply them. Therefore if the ‘area of reliable performance’ is to be increased there is a requirement for improved designs and maintenance and repair procedures. It may be that through improvements in these areas that, opportunities may become apparent to improve processes and technology.



Reliable performance = Coating technology ∩ Design ∩ Coating process ∩ Maintenance and Repair

Figure 4-2 The main elements of a reliable coating system**.**

In the past the maintenance of coatings in water ballast tanks was often deferred, and passed on to the next owner or simply not done as ballast water is not a revenue earning aspect of running a ship. However in an effort to combat this, a set of guidelines have been published ***IMO*** (***2009***) to aid the relevant parties with the maintenance and repairing process of protective coatings. Within these guidelines the areas and extent of the survey process of a vessels WBTs is further defined. It should also be noted that since the publication of this document that more thought is being paid to the through-life performance of applied coatings.

Munger (***1999***) noted that the cost of maintaining a structure is directly related to its design, and that structures that have a minimum number of edges and corners will be much easier to maintain therefore will have a much longer life when exposed to corrosion atmospheric conditions

4.3 Ship Production Technology

As previously discussed there has been a great deal of research effort into improving the efficiency and cost effectiveness of the ship production process. The majority of this work has focused upon the steel work process, in particular the cutting and welding processes.

4.3.1 Welding

Weld length has traditionally been used as a measure of the work content of a structure. There are a range of different standards that are used to determine the quality of the welds and acceptable levels of imperfections such as ISO 5817:2003. *'Shipbuilding and repair Quality Standard for Hull Structures during Construction'* (***ABS 2007***) provides guidance on shipbuilding quality standards for hull structures. It also details the required qualification required for those involved in the welding process and subsequent inspections. There are a number differences between the standards of the welding and coating processes. Both processes require suitably qualified and experienced inspectors however there is major disparity between the qualifications of operators undertaking then processes. There are strict criteria for 'coded' welders whereas there are currently no formal qualification requirements for painters in shipbuilding. In addition to this, problems can be created by the differences in acceptable standard between the surface finish provided by the welding process (***ISO 5817:2003***) and those required by the PSPC.

Modern automatic welds that are used to join plates and stiffeners on a panel line are normally smooth, continuous and free from undercuts. However even high quality manual welding produces a rougher surface which increases the difficulty of applying a suitable protective coating this in turn means that the weld is more vulnerable to corrosion (***Munger 1999***).

4.3.2 Details and brackets

Work carried out by the Ship Structures Committee lead to the publication of SSC-331 'Design Guide for Structural Details' (***SSC 1990***). This work primarily focused upon the failure prevention due to the selection of design details, for example design considerations to prevent 'hard spots' where stiffeners connected to a bulkhead.

Of the greatest of interest within this publication, are the man hour rates that have been determined for different bracket types, shapes and connection techniques. It shows that it is possible to reduce the work content by lining up the brackets in such a way that all of the edges coincide with each other. As discussed in the previous chapter the welds within a WBT must be stripe coated, it is therefore possible to reduce both the steelwork and coating process work content by altering the method of bracket attachment. The guide also suggested that these methods would improve the in-service structural performance as the likelihood of cracks forming is reduced. Overall this would decrease the likelihood of corrosion due to the reduction of the total amount of edge length.

The guide provides information on the performance and the likelihood of cracks forming for a number of different intersection details. The importance of this in relation to the coating process is that the recommendation is to minimise the size of the cut outs as larger holes result in relatively large bending stresses in the lug near to the stiffeners. The problem that this creates is that of the application of a suitable amount of paint the edges within the cut-outs as a result of reduced access.

4.3.3 Edge Preparation

The PSPC requires all free edges to be rounded to improve the adhesion of the applied paints to edges on the structure. The reason behind this is that coatings exhibit considerable surface tension when they have cured and thus are likely to retreat from a sharp edge as the film shrinks away as it dries resulting low film thicknesses and a higher probability of corrosion (***Munger 1999***). The higher propensity of corrosion on edges and welds is accounted for in the PSPC as the ‘GOOD’ classification allows for up to 20% corrosion in these areas whereas on flat plates only 3% is allowable.

Work has been published on the effect of the radius of the plate on the thickness of the applied coating for a number of different edge profiles, (***Seo 2007***). This study concluded that secondary abrasive blasting plus a single pass with a grinding disc and a pass with a paper disc provided adequate results for the DFT on the edges of their test samples, and that excessive edge preparation can lead to high DFTs which are commonly cited as a cause of paint cracking. The difficulty with this conclusion is that not all shipyards use abrasive blasting for secondary surface preparation and it is very difficult to practically measure DFTs of edges.

4.4 Previous Coating Process Studies

The imbalance in the development of the shipyard processes has been discussed. There are a number of previous studies that have examined the coating process within the shipbuilding industry that are in the public domain; ***Baldwin*** (***1995***)***, Kattan*** (***2003***)***, Easton*** (***1996***)***, BESST*** (***2010***), broadly speaking these papers presented the results of studies which followed the progress of painted sections of steel in both shipbuilding and offshore construction industries from the shop primer line through to the building stage and identified the areas of damage and the processes that caused damage to the coatings on these panels.

Easton, (***1996***) concentrated on the offshore industry and identified the 'black box' and 'pancake' methods of building. He discussed their relative advantages and disadvantages on the build process including surface preparation and painting activities. The black box method involves the construction of the units or blocks from untreated steel; this allowed the formation of a ready-made blast and paint cells allowing the structure to painted in situ post erection and pre-outfitting. On completion of the coating activities the units are then outfitted, the study highlighted how late arrival, poor planning or damage would result in extensive coating rework. An advantage of this method is that no remedial coating work is required at section joints as coating work was carried out post erection. These joints are critical as the coating process often included a complex fire-proofing system that creates considerable problems for repair and touch up if subsequently damaged. This would result in significantly increased costs, time delays and inspection burdens.

The pancake method builds the sections in the same way as the black box, it differs in that the sections are blasted and painted prior to being transported to the erection area. By building in this way the final coating film is damaged less as large equipment is not moved within the painting area, and the sections are easier to pre-outfit. It does however require better planning of work and remedial work to the section joints.

The study also identified that a build method must be selected to suit the facilities at a given place. It was confirmed that, if a build process minimises the damage to an applied coating, then the overall cost can be reduced by minimisation of re-work.

Baldwin (***1995***) studied the building methodology concentrating on the surface coating from initial shop primer application at the plate treatment line through to the final paint system application at the outfit quay. The condition and treatment of the surface coating was assessed. Areas and processes were identified that caused damage to the shop primer. Damage was defined as areas which required additional surface preparation prior to later coating application. An example would be damage to the main anti corrosive/antifouling coats resulting in the need for repair. An initial flow chart was developed from work carried out by ***Yokata,*** (***1963***) to identify coating failures. From this further sub-flow charts were produced expanding the detail for each stage of the major shipbuilding processes:

- Plate treatment;
- Plate cutting;
- Panel production
- Preassembly production;
- Sub-section assembly and painting;
- Block assembly and painting;
- Block erection and painting;
- Outfit quay and painting.

During the analysis of these areas, several common causes of failure were identified as presented in Table 4-1.

Table 4-1 Table detailing causes of failure and damage *Baldwin* (*1995*)

Cause of Failure	**Description of Damage**	**Description of Re-work Requirements**
Mechanical abrasion	Removal of paint system by abrasion as a result of material handling, fairing, staging and access erection and steelwork and outfit activities	Shop primer removal by abrasion will result in the increase of surface preparation man hours and blast media consumption at future coating stages due to increased corrosion. Damage to anti-corrosive coating by abrasion will result in the need for repair and will therefore result in an increase in man-hour consumption though re-work.

Cut edge condition	Poor quality cut edge condition	Poor edge condition after cutting, e.g. sharp ragged edges will result in potential areas of coating breakdown.
Hotwork	Paint system damage due to heat input during welding, cutting and heat line fairing resulting in burn back of the coating.	Shop primer removal by heat damage will result in the increase of surface preparation man-hours and blast media consumption at future coating stages due to increased corrosion. Damage to anti-corrosive coating by abrasion will result in the need for repair and will therefore result in an increase in man-hour consumption though re-work.
Surface condition after preparation	Failure to achieve required surface profile and standard as per specification. Failure to remove blast debris prior to paint application.	Failure to remove all blast debris after blast cleaning will result in future paint system breakdown as the dust flakes away from the substrate. Failure to comply to specification for surface profile, i.e. surface profile to deep, will result in increased corrosion. Shop primer film thickness requirements for protection during steelwork construction will not be met. Failure to achieve surface standard will result in poor adhesion of the shop primer and increased surface preparation man-hour consumption at future paint coating stages.
Overspray	Inadequate control of coating quality, resulting in over application of paint, resulting in runs drips and sags.	Overspray of shop primer on the plate treatment line results in over thickness of primer, which may cause problems with welding, i.e. porosity problems Overspray of anti-corrosive coating will result in sags and drips which are potential areas of coating breakdown.
Underspray	Inadequate control of quality resulting in over application of paint, resulting in paint holidays.	Underspray of shop primer on the plate treatment line will result in increased corrosion prior to further coating stages, as the protection life will not be achieved, therefore increasing man-hour and blast media consumption. Underspray of anti-corrosive coating results in failure to attain the specification and the paint life span cannot be assured.

Paint curing time	Inadequate control of paint curing time prior to overcoating.	Inadequate curing time of a paint film prior to overcoating will result in unsatisfactory adhesion between the two coats.
Support stool positioning	Positioning of support stools in the paint cell, outside areas and building dock/berth resulting in paint free areas.	Support stools used at the paint cell, outside coating areas and the building dock/berth will result in areas uncoated. These areas will require overcoating at future coating stages. This will result in increased surface preparation and coating application man-hours as work is undertaken at less efficient locations.

Baldwin went on to consider the wider effects of coatings re-work, as he not only considered the costs associated not only with labour and materials, but also those related to the cost of space and the required resources such as heating and electrical power.

Kattan, (***2003***) commented that the activities of the coating process were in the past viewed as an 'unwanted necessity'. As they require all other work to stop for practical and health and safety reasons, and were perceived to be far less important than those of the steel and outfit work. The study presented a table of damage to the paint system during the build cycle. These damages very much agree with and build on those presented by ***Baldwin,*** (***1995***) it also included methods of surface preparation and paint application at the various stages of the build process. This paper highlighted the amount of money that is in effect wasted due to avoidable re-work and identified the penalties of lost production. These time penalties can often make the difference in terms of economic survival. As the more vessels that a yard can be build allows the fixed overheads to be shared over a greater number of products i.e. ships. This then increases the profitability per unit output of the yard.

The ***BESST*** (***2010***) survey identified that a great deal of damage is still done to the applied paint films during the build process. These results show remarkable similarities to the conclusions of the Baldwin study. Much of the damage caused can be attributed to a simple lack of care, mainly due to the low priority often afforded the coating process as a whole. These common types of damage can be divided in a number of different categories:

- Poor material handling;
- Poor protection;
- Poor coating scheme thickness control;
- Burn damage from cutting and welding/poor scheduling;
- Abrasion damage;
- Poor repair technologies/strategies;
- Design/engineering changes.

Additionally, comparison of the two studies has also highlighted some of the problems that occur when conducting the physical tasks associated with the coating process:

- Access;
- Masking;
- Work scheduling;
- Thickness control;
- QA/QC;
- Waste management.

4.5 Conclusions from Previous Coating Studies

The results of these coating studies provides evidence that although attitudes are changing within the shipbuilding industry towards the activities and management of the coatings process little has changed in the last 15 years. Applied paint films and the coating process are still not widely regarded as a value adding activity of equal worth to other production processes. It is also clear is that there are no ‘wonder’ technologies on the horizon that will provide major improvements to the coating process. The automotive and domestic application markets constitute the majority of the market for manufactures of paint spraying equipment. As the marketing brochures indicate that heavy industry only makes up a small proportion with the shipbuilding industry not mentioned at all. From this it is possible to conclude that the shipbuilding industry is a very small percentage of the market for spray equipment manufactures. The effect of this is a situation where there is little chance of any of these manufactures entering in to any significant research and development programs that will address the needs of the shipbuilding industry more directly, as it is unlikely that they will re-coop their investment.

Examinations of the studies that have investigated the coating process have indicated that there are two areas where with further research it may be possible to provide improvements the coating process. These can be grouped into process and product improvements, and are discussed in the following sections.

4.5.1 Process Improvement

It is possible that the application of alternative surface preparation methods may lead to improvements in productivity within a yard and improvement of the in-service performance of the applied coatings. This is evidenced by the use of Hydro blasting in conjunction with specifically designed Euronavy EN 301 coating. It has been reported in a number of sources that the combined system provides a range of benefits to the shipbuilding notably:

- The absence of dew-point restrictions and the surface preparation tolerance makes it possible to achieve good performance in the marine environment;
- Coating immediately after hydroblasting, without the need for drying, assures the lowest possible salt level.
- The process provides a more environmentally friendly process as no blast media is needed;
- It is claimed that it can provide lower cost solutions in many situations.

This has demonstrated an improvement the overall productivity of the process ***Azevedo*** (***2003***). It may be a happy coincidence but examining the first water ballast tank that the system was used upon, the structure appears to be of a much simplified design. This may have been to accommodate the hydro-blasting hose and nozzle needed which as a result has led to a reduction in the complexity, thus improving the working conditions for the applicators, which overall will no doubt have had a positive effect of the performance of the coating.

Surface preparation methods such as hydro blasting and slurry blasting drastically reduce, if not totally remove, the levels of dust that workers are exposed to. As a result of this, these types of systems are becoming more widely accepted especially in the repair market, it should however be noted that hydro blasting is unable to product a new surface profile. As discussed in the previous chapter, it is also fair to expect the allowable worker exposure limits to be reduced over time, thus any other solutions must seek to at least match current exposure levels if not reduce them.

4.5.2 Planning and Work Scheduling

What was very apparent from all of the studies and the author's visits to a number of different shipyards is that currently there is little control over the coating process. In many cases the process is unpredictable and information is not retained. As a result it is difficult to quantify the benefits of any improvements that are introduced. This serves to further undermine the coating department as a engineering discipline. Therefore before any systems or processes can be introduced the coating process as a whole must be brought under control. Control is defined by ***Juran,*** (***1964***) as adhering to a standard. That is to say changes must be made to ensure that requirements of the coating specification are met and the coating process is predictable and repeatable. ***Juran,*** (***1964***) also presented the idea that break through and control are part of the same cycle, which consists of alternating plateaus and gains in performance as demonstrated by Figure 4-3. Once a process is under control it is possible to introduce a change or break through, this will then lead to a period of instability as the change becomes accepted and initial teething problems are identified and rectified. Following this period the desired improvements should be realised leading to the coating process operating at a new higher standard.

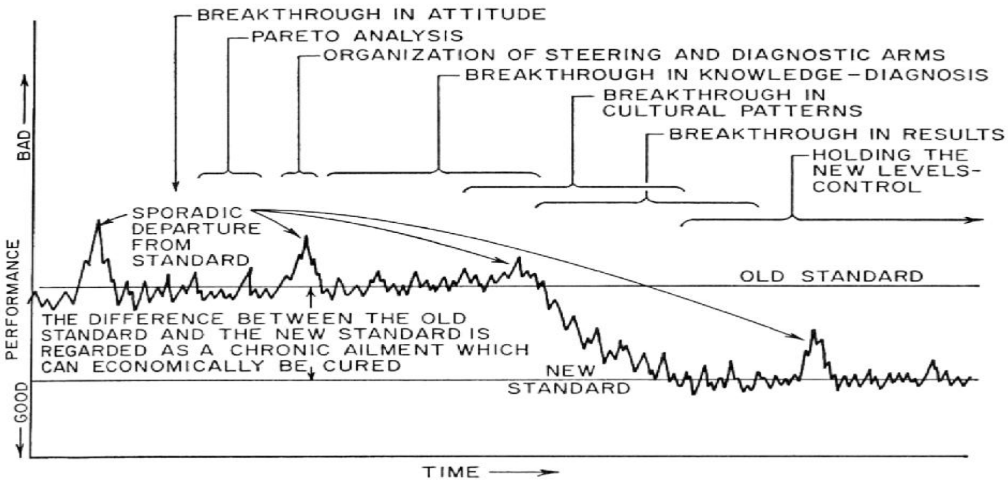


Figure 4-3 The basic performance time chart *(Juran 1964).*

Kattan, (2007), identified planning and scheduling as an area for improvement within the managements systems in shipbuilding. In its simplest form the most appropriate means of assessing the success of any planning activities is to implement a simple management tool, as shown in Figure 4-4:

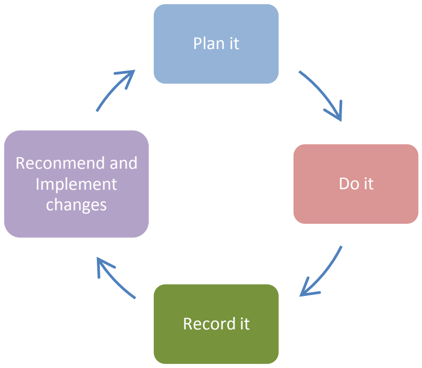


Figure 4-4 Simple planning feedback system

One of the major factors that has hindered the development of the management systems of the coating process within shipbuilding is the recording stage, through the use of sub-contracted often working to fixed price contracts. The coating technical file introduced as part of the IMO PSPC defines the required recording process within WBT's. However it is primary function is to act as an as-built record of the coating process, and not to be used as a tool for improvement.

Work carried out by Kattan and Baldwin, laid the foundations for a coating activity review currently employed at Safinah. This document contains a section on planning within which it is possible to quantify the level of development and importance attached to the planning of coating activities. The scale used is 1 ~ 4, with four being the highest.

- Level 1: The planning of coating activities is informally undertaken by supervisor/foreman as and when work arrives. No man-hour usage is collected and recorded, often leading to incomplete coated units/blocks arriving at the dock/berth. There is no monitoring or recording of re-work. The combination of these factors means that there is no real confidence in the feedback provided, nor is anything done with the feedback.
- Level 2: There is strategic planning for the coating requirement of each work stage. The units/blocks are timetabled specific weeks but the planning is still carried out by the foreman/supervisor. The majority of the work is completed pre erection but rework is still not monitored. Feedback is available but tends to be on a very informal basis.
- Level 3: Work is broken down into work packages and scheduled to match the available resources. The supervisor carries out detailed planning and monitors the re-work, which is monitored through specific work packages. On occasions units/blocks arrive at the berth/dock in an incomplete state, however formal feedback is recorded to allow improvements in planning for the next vessel.
- Level 4: A computer based system is used that breaks down the work of surface preparation and painting activities into work packages. These work packages are then scheduled according to the availability of resources. No units/blocks arrive in complete, and any re-work is logged as a separate work package(s). A good feedback loop is evident, showing any actions taken to prevent recurrence of problems and a continual improvement in the overall process.

Using this approach it is possible to ascertain the level of development of the management system used to control the coating process within a given yard. It is also possible to use this as a development plan as part of the strategic planning for a yard.

Another factor that greatly affects the performance of the coating process within a given yard is the development of coating work schedule. In the majority of cases a paint scheme comprises of a number of coats. So one aspect that must be considered during scheduling is at what stage of the build process each coat is applied.

The stage at which surfaces are coated within the build cycle presents a number of different challenges. If simple 2D or 3D sub-assemblies are painted early in the build cycle then there should be very few access problems for the application of coatings. However the applied paint will then be subjected to the rigours of the rest of the build cycle as these assemblies are combined into bigger units/blocks. There will be uncoated areas in way of subsequent welded unit/block joints as well as, damage to the coated surfaces as a consequence of lack of care in handling during subsequent outfit work. Often this results in the need to apply a finish or touch up coat prior to delivery, in addition to the specified scheme.

In simple terms the ideal would be to apply the whole scheme at the shop primer stage, as it is an automatic process with high productivity and low labour requirements resulting in reduced overall costs. The applied coatings would then need to be able to survive the rest of the build process. This could be achieved by the development of an impact, heat and abrasive resistant paint or by employing a means of protection film similar to that applied to automotive car body work. However we are a long way from achieving either of these.

If a ‘break’ is scheduled into the painting process and the final cosmetic coat(s) are applied just before delivery after all major units have been combined, there is then a reduced risk of damage occurring to the final coating. However there are then issues with overcoating intervals and ease of access and masking off. The maximum overcoating period is a function of the paint chemistry employed and can vary from a couple of weeks to many months. As a result of the size of many of the spaces created within a vessel, for example, the engine room on a typical bulk carrier, represents a large space that will require staging to reach all of the surfaces and masking to prevent overspray affecting previously installed equipment. This will have a very significant cost implication and reduced productivity attached to it.

The problems that are associated with work scheduling have been well documented by ***Kattan et al.*** (***2003***). The greatest challenge is considered to be changing attitudes towards coatings and to see them as a value adding process. Some shipyards do assign coating rework costs to the department that causes the damage. This is an attempt to focus the operations and planning of the other departments within the yard to minimise rework to coatings. This is particularly important as a repaired coating will never perform as well as the continuous coating film initially applied. Thus in order to maximise the in service performance of any coating applied to a vessel, it is important to preserve as much of the initial coating application as possible (***EMSA 2005***).

4.5.3 Product Improvement

The BESST survey also considered what improvements could be made to the coatings themselves to improve the integration within a shipyard. The conclusions were that the product investigation can be divided into two sections; primers and finish coats. The common improvements sought are:

- Improved corrosion resistance;
- Increase in resistance to chemical and oil degradation;
- Reduction in curing time;
- Wider range of substrate temperature application;
- Reduction in the amount of secondary surface preparation.

A universal primer specifically must possess the above plus be:

- Compatible with typical shipyard welding and cutting processes;
- Compatible with coating schemes applied to it.

Whilst there is a requirement for finish coats to exhibit:

- A smoother surface finish, particularly for external steelwork;
- Provide better impact and abrasion resistance.

Areas that have been highlighted for focus are the reduction of curing time and improving impact and abrasion resistance of the coating. As reducing the cure time will decrease the dwell times associated with the coating process. Thus improving the productivity of paint cells, and reducing the occurrence of handling damage during transit due to insufficiently cured paint. Whilst improved impact and abrasion resistance will reduce the amount of touch up required to coatings applied early in the build cycle. By addressing these areas it may be possible to gain more control over the coating process through the reduction of rework.

The BESST program tested a number of different coating systems for four different areas of a cruise ship namely:

- Interior crew spaces;
- Exterior passenger areas;
- Machinery spaces;
- Areas behind insulation.

Principally the program looked at the addition of commercially available products to improve the corrosion resistance, surface smoothness, to improve cleaning, chemical resistance and heat resistance. The results of the small scale testing program demonstrated that it may be possible to improve the performance of applied coatings by the addition of certain products. At the time of writing a longer term larger testing program was underway from which it should be possible to draw meaningful conclusions.

4.6 Seeking Stakeholders Opinion and Insight

Although the DISPRO partners gave the project a good grounding with the requirements of the shipbuilding industry wider industry involvement was required to ensure that the factors that contribute to the complexity with a WBT where captured.

4.6.1 Ship Surveys Undertaken

The beginning of the project the author spent a significant amount of time visiting a number of shipyard throughout Europe to observe the ship production and coating processes. Through the kind participation of the shipyards the author was able to inspect a range of tanks such as:

- Fore peak tanks
- After peak tanks

- Double bottom tanks
- Wing tanks
- Fresh (potable) water tanks
- Fuel tanks

The type of vessels built in Europe is such that these tanks were ideal to witness first-hand what has generally been referred to as complicated tanks. The vessels visited include, large cruise ships, large and small dredging vessels and offshore support vessels. Through the involvement of Safinah in the project the author was also able to visit a number of bulk carriers throughout the duration of the project and undertake inspections of the WBTs. This provided the antithesis of the small often cramped tanks seen on cruise and offshore vessels.

4.6.2 Development of a Suitable Questionnaire

Discussions with Muehlhan and IHC Marine identified free edges and weld length as primary factors constituting the complexity of a structure. This supports the findings of the PSPC which notes that these areas are receive two stripe coats in addition to the two spray coats.

In order to capture the current views of all of those involved in the process of protecting WBT from corrosion a survey was needed. The function of this would be to gain an insight into the problems faced and considerations made by:

- The designers designing the tanks;
- The production team constructing the structure;
- The paint chemists when formulating the paints;
- The applicators preparing the surface and applying the paint;
- The inspectors monitoring and reporting on the coating process.

To achieve this, a suitable questionnaire was prepares and circulated to a range of people involved in the shipbuilding industry. The course published on line by Drs Christine Thomas and Rachel Slater (***Thomas*** and ***Slater 2009***), was used as a guide when developing the questionnaire. When designing a questionnaire it is very important to clearly define the objectives. It is also important to maintain a logical flow, to maintain the responds interest. When deciding on the questions to ask it is important to achieve the correct balance between open, closed and open response option questions.

Open questions are those that ask for unprompted opinions, as there are no predetermined responses, such a question with multiple choice answers. This allows the participant to answer freely however he/she chooses. Open format questions are good for soliciting subjective data or when the range of responses is not tightly defined. The advantage of open questions is that the variety of responses should be wider and be more representative of the opinions of the respondents. They increase the likelihood of receiving unexpected or insightful comments or suggestions, as it is impossible to predict the full range of opinion.

There are however a number of disadvantages of open format questions. From an analysis view point their very nature requires them to be read individually, as there is no way to automatically tabulate or perform any statistical analysis on them. As a result of this open format questionnaires are not well suited to lower budget or time sensitive situations. There is also the issue of interpretation, as two readers many draw different conclusions from the answers given. With open format questions there is also the risk that due to time pressures the respondent may not have to opportunity to fully consider their answers or that they will not answer at all.

Closed format questions usually take the form of multiple choice questions. There doesn’t appear to be any clear consensus as to the number of answer options that should be given. The difficulty comes in providing enough choices to fully cover the expected range of answers, without providing too many that the distinction between them becomes unclear. This types of question ‘prompt’ the respondent, so there is less reliance on memory when answering the question.

One factor that must be considered is the choice between an even or odd number of options, when asking for a rating of a particular item. Odd numbers allow for a neutral or no opinion response whereas an even number forces the respondent to get off the fence. This may add some inaccuracies as the respondent may actually not have an opinion. There is also the argument that the neutral answer is over utilised, especially by bored respondents.

Closed format questions offer many advantages in terms of the analysis perspective, by restricting the answer set it is easy to calculate percentages and other hard statistical data over the whole group or any sub group of the participants. It is imperative that questions posed in this manner are not leading. For example in the case of this project the author has an idea of what factors influence the complexity of a structure, however it is important to get the views of the operators undertaking the coating process rather than present the question in such a way as they have little choice but to agree with that hypothesis.

Open response option questions combine elements of open and closed questions, providing a number of responses and opportunity for further explanation or discussion. A successful questionnaire will achieve the correct balance between open and closed format questions, as there will be a mix of data that is relatively easy to analyse and the possibility of insight of those close to the problem for which a solution is being sort.

One consideration was that of differing levels of education, as there is known to be a vast range, from completion of high school through to PhD doctors (***Oppenheim 1992***). Thus the questions must be constructed so as not to exclude anyone, a copy of the questionnaire can be found in Appendix A.

4.6.3 Questionnaire Responses

The returned questionnaires came from those involved in all aspects of the shipbuilding and paint industries these included:

- Ship structural designers;
- Ship builders;
- Paint chemists;
- Coating inspectors;
- Paint company technical service representative;
- Paint managers;
- Coatings consultants;
- Ship owners representative;

- Classification Society testing advisor.

The results from the questionnaire showed that WBTs and engine rooms where commonly cited as being areas that present difficulties to the physical tasks of the coating process. The reasons cited for both the surface preparation and paint application processes, was almost universally due to limited access and the arrangement of the steelwork.

Although free edge and weld length where highlighted by the project partners less than half of the returned questionnaires highlighted these. It is possible to conclude that free edge and weld length gives an indication of the number of individual items and therefore its complexity. However, the free edge and weld length themselves contribute more to the work content, thus ship builders and subcontractors would like to see these reduced to reduce the cost of coating process.

When asked for suggestions as to what changes would make their particular role easier the improvements in the design featured regularly. When asked to comment on what would make the application of paint easier the responses included:

- Qualifications for paint applicators;
- Improvements in equipment and processes;
- Better planning to paint more during pre-outfitting stage;
- Use of voids to avoid WBT regulations;
- Better work scheduling to prevent unnecessary re-work due to damage;
- Improved lighting and ventilation during application process

Within the questionnaire the respondents were asked to comment on five pictures as shown in Figure 4-5 and how difficult there though it would be to paint the different sections of typical ships structures. The pictures where to be awarded a mark between 1 ~ 5 with 1 being virtually impossible to achieve uniform dry film thickness (DFT) and 5 being very easy to achieve consistent DFT.

Picture 1

Picture 2

Picture 3

Picture 4

Picture 5

Figure 4-5 Pictures used in Questionnaire

Table 4-2 Results of picture responses in the questionnaire

	Picture 1	Picture 2	Picture 3	Picture 4	Picture 5
Mean	2.4	3.266	3.13	3.46	2.466
Median	2	3	3	3	2
Mode	2	2	2	3	4

The results in Table 4-2 reflect what would been expected, in that pictures 1 and 5 represent difficult or awkward sections of structure whereas 2, 3 and 4 are more typical examples. What is interesting to note is how the mode increases for pictures 4 and 5. Picture 4 shows a very typical bracket arrangement which is found in large numbers within a wide range of internal tank structures. Although the mean and median would indicate that the structure is regarded as relatively easy to paint there is clearly some disagreement to this.

Picture 5 shows a quite intricate pipework configuration which is reflected by the mean and median values returned in the questionnaires. Again however there does seem to be quite a wide spread of opinion as to the level of difficulty as shown by the value of the mode.

4.7 Perceived Trade-off of Coating Friendly Designs

Section 3.2 discussed a number of structural design methodologies that are currently in use, and how any design will involve the balancing of a number of often conflicting requirements. It is clear that to date the needs of the coating process have not been adequately taken into consideration during the design process.

As noted in the introduction the PSPC has led to a greater need to focus on identifying suitable coating products and consideration of whether current structural designs are actually capable of being coated efficiently and reliably. The PSPC highlights this issue in section 3.3.2 it states that:

> *"the coating performance can be improved by adopting measures at the ship design stage such as reducing scallops, using rolled profiles, avoiding complex geometric configurations and ensuring that the structural configuration permits easy access for tools and to facilitate cleaning, drainage and drying of the spaces to be coated"*.

Thus for the first time the new regulations establish a formal link between the design and corrosion of ballast tanks on board ships. If the requirements of the coating process are considered in isolation then the ideal solution would be completely flat internal surfaces with no additional stiffeners or other secondary material. However to provide such an idealised monocoque structure with the structural performance required to meet its operational loading would result in a heavy structure of thick plate that would disadvantage the performance of the vessel. From a structural perspective this is not a particularly elegant or efficient solution that would be subject to a significant weight disadvantage that may also prove impractical from a production view point. To provide more efficient distribution of structural material and reduce the weight of the structure, the conventional approach is to combine the plate with stiffeners. Although this leads to more efficient structural it has a detrimental effect on the physical activities of the coating process with the result that there may be areas of either inadequate or excessive coating film thickness.

Figure 4-6 is intended to diagrammatically illustrate this perceived trade-off between the influence of structural complexity on coating performance and structural efficiency as there is no data to formally define this relationship. A simple definition of structural efficiency in this context is defined as the ability to take the same design load but for a reduced structural weight through the more efficient distribution of material. There is also a trade-off between structural efficiency and inherent work content which should also be considered to ensure an appropriate balance between weight and production cost. The additional consideration of structural weight and production cost also influences this trade off. In general lighter weight configurations tend to have reduced plate thickness and more stiffeners whereas for less weight sensitive designs the plate thickness tends to be increased with fewer stiffeners. Due to the additional work content associated with lighter weight configurations they have a higher production cost and it is normal to find a compromise between weight and cost appropriate to the type of ship. The interaction between these factors is highlighted in

Figure 4-6, the green larger dashed line represents coating performance and the blue smaller dashed line represents structural efficiency.

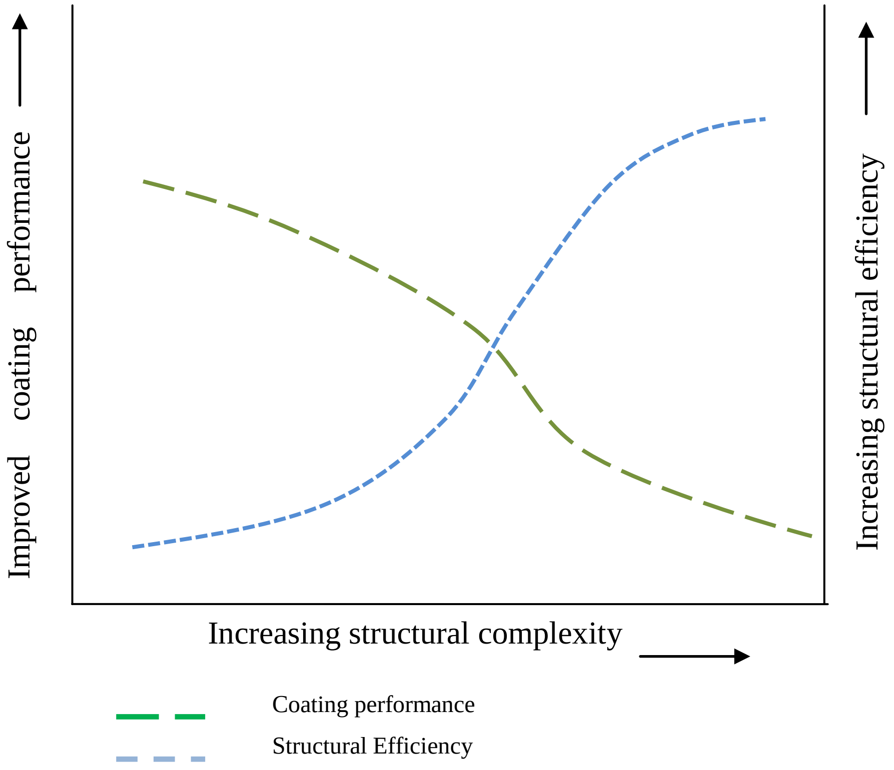


Figure 4-6 Coating performance and structural efficiency against complexity

The aim of this work is to include the influence of structural complexity on the coatings process in this accepted weight-cost trade off. This should then allow a re-evaluation of the relationship between strength, weight and cost including coating to identify a point at which the complexity of the structure begins to have a significant negative effect on the coating process. The approach suggested here is that now the performance of the coating is also included in identifying an appropriate solution in combination with weight and cost as a function of structural complexity.

It is very difficult to determine the level of in-service performance of an applied coating. The PSPC uses a number of measures to define good, fair and poor condition. This is based on the amount of coating breakdown, i.e. rusting, rather than the actual performance of the coating. The assumption here is that providing the best possible initial conditions for coating application will allow the applied film to realise the full potential of the coatings technology and therefore delay the onset of coating breakdown. The proposal is that the complexity of the geometry has a relationship with the in-service performance of the coating.

There is evidence that in the past shipbuilders, shipowners and/or operators were willing to accept a small increase overall steel weight if there is a clear savings in terms of work content, as highlighted by ***Hargroves et al.*** (***1975***). The authors note that the initial cost associated with capital outlay for technological advancement is easily calculated, whereas the savings as result of the investment are far more difficult to predict. If it is possible to demonstrate such savings ship owners may be willing to accept a marginally heavier vessel, which may mean a reduction in payload, for one which has a lower initial cost, and reduced through life maintenance costs.

In order to incorporate the influence of structural complexity on the coating process in WBTs, the approach that has been adopted is to first define a number of ‘typical’ WBT structures and then propose a measure of their structural complexity. This measure will then provide a means of seeking solutions balanced against weight, strength and overall production and through life cost including coatings.

4.8 Conclusions

The conclusion to be drawn from this chapter is that the coating process has traditionally not been considered during the design phase of shipbuilding. As design changes and improvements have been driven by steelwork production. There is however, a sizeable amount of information in the public domain that highlights the problems that can be created for the coating process by poor design, but to date very little if any of that has found its way into the ship design process.

Studies have been undertaken which have highlighted the problems that continue to exist with respect to the perception of protective coatings within shipbuilding. It is clear from analysis of the coating surveys that attitudes and practices have not improved by any significant degree over the least the last 15 years. This work through insight gathered for the industry at large has highlighted the varying perception of what is and isn’t difficult to paint. Most notably the difference of opinion of those designing and those applying paint to ships structures.

4.9 Summary

The coating process within the shipbuilding industry has been examined, with analysis of previous coating studies having been conducted. Opinion of a wide cross section of those within the shipbuilding and coatings industries has been sought to provide insight on the factors that constitute the complexity of a structure.

Well established alternative design methodologies such as for production and weight have been discussed. Literature such as the ISO standards, which are not directly applicable the design and subsequent painting of ships water ballast tanks has been reviewed.

Reviews of the most recent surveys have highlighted that new and novel coating technologies and paint products have and continue to be trialled in many shipyards. The major hurdle which continues to preclude there more widespread use is that of their suitability for use in the shipbuilding environment and demonstrating a definitive cost benefit over the existing, systems and products.

This chapter has identified some of the factors that contribute to the complexity of a structure the next chapter introduces a means by which a numerical value can be calculated, thus allowing the comparison of different structural configurations, ultimately leading to the development of a complexity index.

5 A METHODOLOGY TO QUANTIFY STRUCTURAL COMPLEXITY

5.1 Introduction

This chapter will build upon the findings from the questionnaire that was circulated and the finding of the author during the visits to shipyards. Principally this will investigate the influence of factors that contribute to the complexity of a structure.

In addition to this the design element introduced in the previous section will be expanded upon. This chapter investigates the detailed design process for WBTs within shipbuilding. The progress of work content estimation of ship designs has been examined.

The chapter explores what is meant by the term ‘complexity’ and provides a number of accepted different definitions. A method of understanding the elements that contribute to the complexity of a WBT are introduced and explained. The work content of a structure is compared from a steelwork and a coating perspective, and how an operator will interact with a structure whilst undertaken the tasks of the coating process is examined. A method of calculating the complexity of a given structure is developed and how it is then applied to a section of a typical WBT

5.2 Defining Complexity

The Oxford English Dictionary defines complex as, “consisting of many different and connected parts, not easy to analyse or understand; complicated or intricate”

Despite a great deal of research having been conducted in this area to find formal a definition of a complex system or the complexity of a system, certainly the application to the engineering domain remains difficult. Efforts have been scattered over many scientific and engineering disciplines such as software engineering, social sciences, economy, physics, chemistry, and biotechnology. ***Frei*** and ***Serugendo*** (***2010***) highlighted three different areas that received attention in order to define complexity:

- Understanding complexity as an emerging phenomenon in natural or engineered systems;
- Complexity as an engineering problem to be tackled, mostly by reducing the environmental complexity, or by augmenting the system's capabilities of coping with complexity.
- Complexity engineering using complexity for engineering - not fighting against it, but using it to the engineer's favour.

The importance of quantifying complexity in engineering and the associated management problems has been recognised by many researchers ***Chryssolouris***, (***1994***): ***Little et al***., (***1997***) and ***Calinescu*** et al., (***2000***). There is however still a great deal of difficulty in defining what constitutes a complex system, in this work the ships structure is the system, as such ***Simon*** (***1996***) proposed the following:

- Most complex systems contain a lot of redundancy;
- Complex systems contain many parts;
- There are many relationships/interactions between the parts;
- Complex systems can often be described with a hierarchy:
- Redundant components can be grouped together and considered as integrated units.

The paint manufacturer ***Jotun*** (***2001***), describe complexity for surface preparation and paint application as low, medium, high and very high. For example the flats of the ship's hull are classed as low, the cargo holds of a Bulk Carrier are given a medium rating, and WBTs are very high. This is classification is largely based on experience with no scientific method of accurately quantifying the different levels of classification.

5.3 Understanding Structural Complexity

The shipbuilding industry predominately uses an orthogonally stiffened panel structures, consisting of plating, relatively small longitudinal stiffeners and large transverse stiffeners. When considering any individual plate it will be subjected to both local and global loads as discussed in the previous chapter. As well as the local requirements placed upon the attached stiffeners, they provide an essential contribution to the global bending capacity of the hull girder. It is therefore important that geometry of the plate stiffener combinations are selected to provide adequate strength to resist the compressive in-plane forces that result from hull girder bending. This is achieved by spacing the longitudinals such that the slenderness ratio is not excessive.

The transverse framing provides intermediate support for the longitudinal structure by reducing the column length and thus increasing the buckling strength of the structure. The transverse structure also provides a significant contribution to the lateral strength of the hull.

The shipbuilding industry uses a number of 'standard' sections for secondary stiffening purposes. These are tee bar, angle bar, flat bar and offset bulb plate as shown in Figure 5-1:

Figure 5-1 Tee bar Angle bar, Flat bar Offset Bulb plate respectively

These stiffeners can be extruded or fabricated from flat plate. The sections are formed by pressing heated malleable steel billets through a shaped die, thus can be used to make a wide variety of shapes and sizes. Each of the stiffener profiles has a range of advantages and disadvantages, from a structural design perspective these stiffeners can be described as:

Tee bars advantages:

- Provide relatively large amounts of second moment;
- Have predicable structural response due to symmetry;
- Can be used to provide a lightweight solution;
- It is possible to fabricate to any size.

Tee bars disadvantages:

- Difficult to obtain formed T's as steel mills tend to produce 'I' beams
- High fabrication costs unless 'I' beams are cut in half;

Angle bar advantages:

- Typically used for brackets

Angle bar disadvantages:

- Typically formed, i.e. flat plate bent to shape of fabricated;
- Do not provide predictable solution due their asymmetry.

Flat bar advantages:

- Easy to produce;
- Have predicable structural response due to symmetry;

Flat bar disadvantages:

- Provide a heavy solution;
- Limited use for large stiffeners due to problems with tripping.

Offset bulb plate advantages:

- Full range of sizes produced;
- Simple elegant solution.

Offset bulb plate disadvantages:

- Do not provide predictable solution due their asymmetry;
- Can produce over engineered solution due to discrete size options.

Before any attempt can be made to reduce complexity, a simple and effective method must be developed to attribute a numerical value to a given structure. The first evidence of consideration of structural complexity is the work carried out by the British Shipbuilding Industry as part of the Group Technology. This work focused on the estimation of work content. The aim of this has always been to maximise the productivity of the production process by accurate prediction of the work flows at each station within the building process. Once again the steelwork and outfitting departments have led the way in this area. The third generation of shipyards that emerged during the 1970's saw an improvement in the quality of welding and material handling due in part to more accurate work content estimation. This period also saw the exploration of the Group technology principal by ***Gallagher et al.*** (***1974***) ***Banerjee*** (***1979***) ***Southern et al,*** (***1979***).

This principle seeks to identify and bring together related or similar components in a production process in order to take advantage of their similarities by making use of for example, the inherent economies of flow production methods. The extent to which it can be applied in a manufacturing organisation will depend on the quality and variety of the individual components being made and the manufacturing processes required by them. The aim is to substantially reduce work in progress and improve delivery performance by reducing throughput times. This is achieved by organising what may appear to be large number of very diverse components into families which require similar manufacturing processes and providing the most suitable manufacturing facilities for the groups of families ***Gallagher and Knight*** (***1973***). ***Vaughan*** (***1976***) highlighted the problems of trying to apply Group Technology to shipbuilding. Due to the number of units typically produced per year, it is difficult to class shipbuilding even as a small batch industry. It is noted that some of the larger shipyards in the Far East which have focused on one ship type could be considered to be ship factories. Also as shipbuilding is essentially an assembly flow industry, where items are joined together to form larger units, and the production flow is unidirectional. Vaughan argued that rather than expending effort to apply Group Technology to ship production, energy should be invested in improving the understanding of ship building process to a level comparable with Group Technology, leading to a Ship Production System Technology.

Standardisation is one method used to accurately predict work flow and work content and hence reduce product complexity, as feedback is used to update the initial estimates after each iteration loop. In general engineering productivity can be increased through reduced variety and continual feedback and improvement when large numbers of the same product are produced. However as a result of the small amount of units produced in shipbuilding it is often difficult to apply this practice directly. When considering the coating process in ship production, the use of subcontractors often results in a situation whereby accurate records are not taken and/or kept for the work content of a given structural design, thus feedback is not given to the designs to allow any improvements.

Group technology was also driving towards standardisation of parts and designs, thus yards would specialise in the production of one type of vessel, thereby reducing the complexity of product mix. There are a number of examples of the problems that are caused by too much standardisation within shipbuilding, most notably the collapse of the Swedish shipbuilding industry in the early 1970's. The industry was set up to build oil tankers and was at the time highly competitive and productive in building oil tankers. The problems of such a small product mix were brought to light by the first oil crisis in 1973, when the global demand for oil and its transportation massively reduced.

A great deal of the effort into the suitability of Group Technology for shipbuilding centred on the development of a code that would identify the dimensions and work required for each individual piece part. This code would indicate the amount of cut edge weld length and any required forming (***Banerjee 1979***). ***Southern,*** (***1979***) identified that the cut edge, or free edge and the weld length indicate the level of complexity of a structure, as would seem to be the general case this 'complexity' is in terms of the steelwork and no mention is made of coatings.

As the coating process lags the other shipbuilding processes there has been little research, since the work involved in Group technology in the 1970's, into what factors influence the complexity of a structure with respect to the coating process. It is clear that edge length and weld length are very important within a WBT as they are widely accepted as areas more likely to corrode, and as a result they impact on the work content due to the requirement for three pass grinding of free edges and stripe coating of both as discussed in Chapter 2.

Most recently work by ***Caprace*** and ***Rigo*** (***2010***) noted that the greater the complexity of a design the more fragile it becomes, which will lead to longer development schedules, and sub optimal trade-offs between competing goals. Their work has focused on the assessment and quantification of ship complexity at the initial design phase. They identify the need to objectively measure the complexity of design in order to systematically reduce the inessential details, which would allow a designer to be guided to create a product with the most effective balance of manufacturing and assembly difficulty.

Complexity implies time, quality, cost performance the factors that influence a products complexity are:

- Number of components;
- Number of interactions/connections;
- Number of assembly operations;
- Number of sub-assemblies;
- Number of branches in the hierarchy;
- Type of materials and connections;
- Properties of interactions and connections;
- Types of components:
    - Geometry;
    - Shape;
    - Materials;
    - Production process.

Caprace and ***Rigo*** (***2010***) noted that despite many years of research they have been unable to identify a formal definition of a ‘complex system’, as complexity is more often a term used to descried a characteristic. Much of the work of Rigo and Caprace has focused on the macro scale as such their efforts have centred on the initial phase of the design process. They did look at using the development of Compensated Gross Tonnage (CGT) as a measure and compare the productively of different shipyards in different locations building a range of vessel types. This measure can be used to identify vessel which will have a high inherent complexity such as passenger vessels and Liquefied Natural Gas carriers (LNG). It is these types of vessel that the complexity measurement has focused upon.

In shipbuilding terms ***Caprace*** and ***Rigo***, (***2010***), proposed three factors that contribute to complexity:

- Shape, manufacturing complexity:
    - Number of parts/compactness, volume/surface area.
- Assembly sequence complexity: amount of interconnectedness;
- Material complexity:
    - Number of different thicknesses/materials;
    - Number of different stiffener profiles.

Shape complexity will allow the fore and aft sections to be accounted for in the turn of bilge and define limits for different areas. Shape for 3D solids relates to the enclosing surface area of the volume, while 2D relates to the perimeter of the surface area.

Assembly complexity relates to the level of diversity and interconnectedness of the parts, thus the greater the variability in the design parameters the higher the complexity of the design. In Rigo's research a quantitative measure of the assembly complexity is based on the definition of the complexity of hierarchical systems provided by ***Ceccatto*** (***1988***). Material complexity for a stiffened panel ship structure, relates to the number of different combinations between plate thickness and material type. For stiffeners it is the number of combinations between profile type profile scantling and material types.

There is evidence that those within the ship building community have been aware of the problems for applied paint systems in complex areas in terms of the application and subsequent performance as highlighted by an extract from a paint guarantee offer by one of the major paint manufactures *"Coatings on surface areas which, because of their physical shape, characteristics or configuration, present special difficulties in effecting specified preparation and coating such as, but not limited to, ladders, platforms, heating coils, rivets, contact surfaces between profiles and all small area equipment and attachments having a surface area of less than 10 square metres per item"*

As a structure moves through the fabrication process and more elements are added to it access within the space becomes more difficult. The greater the extent of fabrication the higher the likelihood that access will be restricted. As discussed, ships are designed to carry cargos and its structure to provide strength, not necessarily to be painted. The topology of a typical bulk carrier merchant ship results in either vast empty spaces such as the midship ballast tanks or tight cramped confined tanks such as the after peak tank, neither of which is conducive to an effective working environment. In both cases the physical task of removing the necessary equipment, such as staging in large tanks, often causes a great deal of damage. There are a number of issues with regard to access, the two key factors relevant to this work are: being able to reach a surface and having enough space to work on that surface. For example a ballast tank of a large crane ship can be as much as ten metres high thus staging is required to reach the upper sections of the tank. On the other hand the forepeak and after-peak tanks of the same vessel are incredibly cramped and confined.

What must be stressed is that a space may not have limited access for all the tasks that are to be performed within it. For example the access requirements for surface preparation/cleaning and paint application are very different from those of inspection and ventilation. In order to ensure a high quality of surface finish it is important that the design of the structure allows all of these tasks to be properly undertaken.

A definition of limited access could be expressed as how much an operator has to physically move around within a space to gain access to all of the surfaces within a tank. This has been termed shadowing, i.e. the number of surface that cannot be seen or touched clearly from any specified vantage point. As such this has implications in terms of surface cleaning/preparation and inspection, depending on the type/ level of inspection required. If for example it is necessary to carry out none destructive testing (NDT) such as film thickness measurements then the access requirements are similar for all activities, as all surfaces must be within touching distance.

If however a simple visual inspection is needed then the access requirements are considerably different. There is also a requirement to have enough space to undertake the coating process, ISO 8503 defines minimum distance to allow surface preparation and coating application.

Work presented by ***Beitelman*** (***2007***) examined the problem of access with respect to the coating process. He defines access in three different levels:

- Access;

- Limited access:
- Inaccessible.

Access can be described as where there is no restrictions placed on the worker by the surfaces within a space or the tools that are being used within that space.

Limited access can be considered where the physical characteristics of a structure or surface restrict a worker from performing a task in the usual manner. Also a condition where the configuration of a structure or surface or characteristics of a tool restrict the use or performance of that tool at that location

Inaccessible would be an area having physical or chemically hazardous characteristics that restrict a worker from entering without special equipment or procedures.

What ***Beitelman*** (***2007***) identified was that limited access does not necessarily mean that a surface cannot be cleaned or painted, but it will require a greater level of skill to achieve the correct surface cleanliness, profile, or DFT. This will inevitably lead to an increase in costs due to the need for more highly skilled workers and longer time periods to complete the tasks.

What is clear is that the level of importance of not only of the paint systems, but also provision of access to all of the surfaces of steel structures has been known for many years. In his book, *La Tour de 300 Mètres* (*The 300 Meter Tower*), ***Eiffel*** (***1900***) noted that the first consideration for construction was that every single part be accessible so that each time the tower is inspected for rust, it can be treated. He considered the fight against the onset of corrosion to be of the utmost importance, and all sheet iron used for the tower's construction was conserved in enclosed hangars during the fabrication stage and rigorously sanded when needed. All exterior parts were laminated, even those that would no longer be exposed after assembly. That way, the iron was not exposed to rain until after assembly. He was quoted as saying *"We will most likely never realise the full importance of painting the Tower that it is the essential element in the conservation of metal works and the more meticulous the paint job, the longer the Tower shall endure".* Thus it is clear that during the design and build phase, Eiffel was very forward thinking in terms of maintaining the integrity of the coating during the towers life.

5.4 Proposed Approaches to Reduce Structural Complexity

In order to improve the in-service performance of an applied coating, the industrial and academic research identified four distinct barriers to be overcome to improve the in-service performance of applied coatings namely:

- Simple design changes to primary structure;
- Improved integration of secondary structure;
- Novel, coating friendly design solutions;
- Improved planning and work scheduling.

Finding successful practical solutions to these problems will improve the overall performance of coatings. As the structural configuration of WBTs can vary significantly within the same vessel depending on their position it is not possible to generalise about their complexity. Four different areas have been identified to allow more direct comparison of their inherent structural properties:

- Fore peak tanks;
- Aft peak tanks;
- Double bottom tanks;
- Wing tanks.

This follows the same line of thinking as that set out by ***Baere et al.*** (***2009***) in the development of the corrosion Index in their paper the “In situ study of the parameters quantifying the corrosion in ballast tanks and an evaluation of improving alternatives”

Examination these structures highlights the similarity of the topology of fore and aft peak tanks and wing and double bottom structures. The double bottom and wing tank structures will be used to base the initial investigations upon, as these areas tend not to have any curvature, apart for the turn of bilge. Figure 5-2 introduces the four step process and demonstrates the increasing levels of difficult and effort required to achieve of the steps.

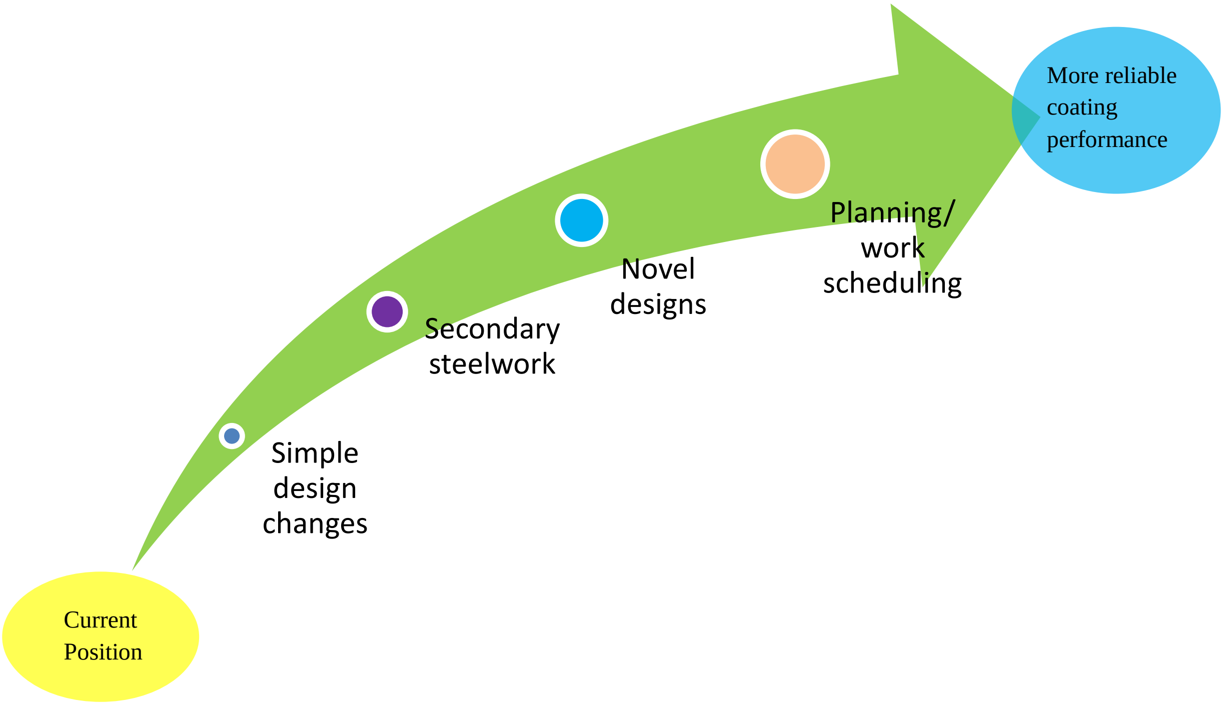


Figure 5-2 The Four Step DISPRO approach

This four step approach provides, in the first instance, a pragmatic near market approach that is nevertheless innovative as for the first time coating issues are being explicitly considered; however thought will also be given to more innovative concepts that may have current practical or technological limitations but may provide routes to further improvement in the future.

The next section will give details as to methods that will be employed for each of the four different areas that have been identified by the author's shipyard visits, the industrial partners input and the results of the distributed questionnaire.

5.4.1 Simple Structural Design Changes

The PSPC requires all of the free edges must be rounded to remove sharp edges and then two stripe coats applied to them, as these are regarded as areas likely to be the site of a coating breakdown. This represents a large amount of work content both from a steelwork production and a coating process point of view. Therefore methods should be sought to reduce the amount of free edge. Steel mills produce offset bulb stiffeners that have rounded profiles thus reducing the need for grinding however the stripe coating requirement still remains. Unfortunately offset bulb plate stiffeners are not always suitable due limitations on size.

Inspection of a number of WBT's and vessels throughout the construction phases has highlighted the use of the brackets that are used to attach the horizontal and vertical stiffeners. The process commonly used in merchant vessel construction is to overlap the brackets as shown in **Figure 5-3**.

Figure 5-3 Example of overlapped brackets

This allows for a greater degree of inaccuracy during the building process, the driving factor behind this is cost, as higher accuracy has a higher associated building cost. Common practice in the construction of naval vessels is to align the brackets and stiffeners as the structure is then symmetrical and will provide more predictable responses under loading (***Dow 2010***).

Weld beads are also given special treatment under the PSPC, in that they too require the application of two stripe coats as they are regarded as likely areas for corrosion due to the alterations that occur in the metal composition during the welding process. The reduction of the amount of weld length can only be achieved by the use of formed stiffener sections and or the use of less secondary stiffeners.

One aspect that became apparent during the WBT inspections was that once constructed all access in and out of a tank and much of the movement within a tank is via standard 1400 by 1000 mm manholes. If the physical activities of the coating process are considered then not only do the work force have to move through these small access holes, but all of the equipment including scaffolding and ventilation must also pass through these holes. The author witnessed the damage that is caused by the removal of the coating equipment from a tank on numerous occasions.

5.4.2 Improving Secondary Steelwork Integration

There appears to be very little integration and optimisation of the secondary items into the overall structure of a WBT. For example the ideal solution for water ballast piping is that of a minimum number of valves and bends. This results in the pipes being positioned such that they are close to the bulkheads within a space as shown in Figure 5-4. In many cases this results in a situation where both the back of the pipe and the bulkhead behind it cannot be accessed for paint application. This situation has become worse with the development of advanced outfitting schemes.

Figure 5-4 Example of problem created by secondary steelwork

By better integrating cable trays, pipework hangers and permanent means of access (PMA's) into the design of the WBT structure there may be opportunity to provide an overall improvement in the performance of the coatings applied in WBT's. This improvement would be provided by reducing the amount of edges, shadowing and overall surface area, as a result of integration of all of the steelwork items in a holistic manner.

5.4.3 Novel Designs Solutions

If the approach to the design of a WBT was altered, such that the requirements of the coating process were given the highest priority, then the likely design solution would be a completely flat structure with no additional stiffeners or other secondary material. To provide such an idealised monocoque structure with the structural performance required to meet its operational loading would almost certainly result in a heavy structure of thick plate that would disadvantage the performance of the vessel in terms of through its entire life cycle. This however could form the basis of an alternative design strategy. Rather than trying to design a structure that meets operational needs and then try and reduce its complexity. Why not design a structure that meets the needs of the coating process then adapt it to satisfy the operational requirements?

With the introduction of a number of novel steel composite structures there is certainly merit in considering these types of structures an example of which is shown in Figure 5-5

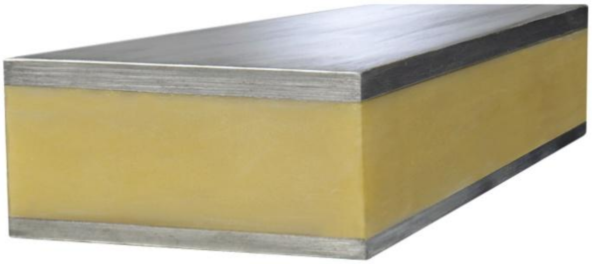


Figure 5-5 Example of a steel sandwich panel

. The three most likely solutions are the steel sandwich panel from intelligent engineering, the corrugated panels used by IHC to build a funnel deck house, and the composite sandwich panels being used by Meyer Werft for passenger balconies. Although these systems have been given class approval for use in certain areas, for example the SPS panel has successfully been used in RO-RO ferries for car decks. Although this indicates that the panels are capable of being designed to withstand the local loadings there are design implications in terms of transferring of global loading, between similar panels and to ‘conventional’ steel.

5.4.4 Improving Planning, Work Scheduling and Training

The issues surrounding scheduling have been previously discussed in Chapter 3. It is accepted that carrying out the painting process at a later stage in the build process, after all major units/blocks have been combined and outfitted, there is then a reduced risk of damage occurring to the final coating but the issues of ease of access and masking off become very significant and will increase cost and reduce productivity. This is a result of the size of many of the spaces created. For example, the engine room on a typical bulk carrier, when complete, represents a large space that will require staging to reach all of the surfaces and masking to prevent overspray affecting previously installed equipment.

The problems that are associated with work scheduling have been well documented by ***Kattan et al.*** (***2003***). The greatest challenge is considered to be changing attitudes towards coatings and to see them as a value adding process. Some shipyards do assign coating rework costs to the department that causes the damage. This is an attempt to focus the operations and planning of the other departments within the yard to minimise rework to coatings. This is particularly important as a repaired coating will never perform as well as the continuous coating film initially applied (***EMSA 2005***). Thus in order to maximise the in service performance of any coating applied to a vessel, it is important to preserve as much of the initial coating application as possible.

One factor that became clearly apparent, is the disconnect between the required qualifications of different trades within shipbuilding. Currently there is no requirement for any formal training of the operators that undertake either the preparation of the surfaces or the application of paint within the marine industry. This is not the case in other industries for example all painters and blasters bust have appropriate levels of training and qualification when working on UK infrastructure projects, or in other areas of the shipbuilding industry. For example all welders must have the appropriate ‘coding’ qualifications which are renewed on regular basis. Therefore to pick up on one of the responses from the industry questionnaire, it is highly likely that the quality in terms of consistency will improve with training and certification.

5.4.5 The Scope of the Current DISPRO Study

The work of this thesis focuses on the first element of the approach namely the influence of simple design changes. Efforts will investigate, areas such as the use of different stiffener sections and provision of better access to the surface within the tanks. Better integration will seek to identify the benefits of a more holistic approach to design, it is hoped that this approach could then be applied to secondary steelwork items such as pipework and walkways.

5.5 The Relationship Between Coating Complexity and Production Work Content

As discussed in Chapter 3 there has been significant effort invested into production technology and the reduction of work content primarily focused on steelwork and outfitting. Following this theme it is therefore interesting to examine the relationship between production, in this case steelwork, and coating work content. If it were possible to produce designs that not only provided benefits for the coating process but reduced the steelwork work content then there is a greater likelihood that the shipbuilding industry would be more receptive to change.

If two different 'T' stiffeners are all viewed normal to the plate surface that there are attached to then it is clear that the amount of none visible area is directly linked to their geometry. Under the assumption that these stiffeners are equivalent, in terms of section modulus, second moment of area and stiffness then the relationship between the geometry and the arc of shadow can be seen in Figure 5-6. From a production point of view if both of these were fabricated 'tees' then there would be no difference in terms of work content as there both contain four welded edges and four free edges that will require grinding, represented by green and yellow areas respectively.

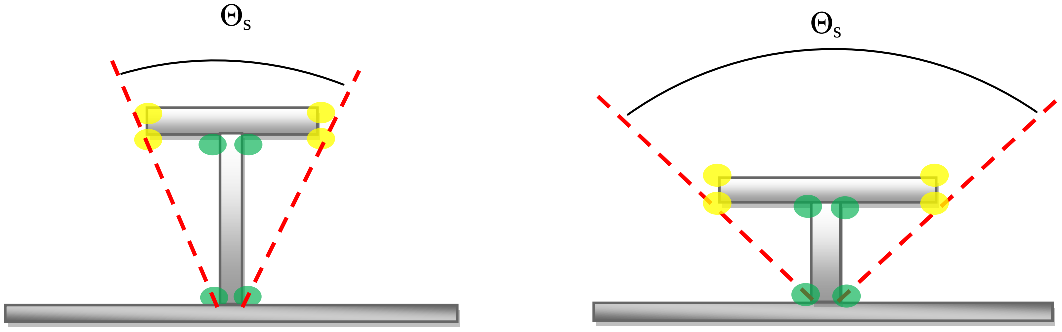


Figure 5-6 Comparison of equivalent 'T' sections

The result of this, with respect to both preparation and coating application is that from any individual view point portions of the structure are masked such that they are in ‘shadow’ or are competently inaccessible which makes it more difficult to apply the coatings to a sufficiently high standard of surface finish.

If different profiles such as flat bar and angle bar stiffener are examined then from a production work content and from a coating process stand point, the more flat bar stiffening that is used the lower the production work content and simpler the activities of the coating process as demonstrated by Figure 5-7.

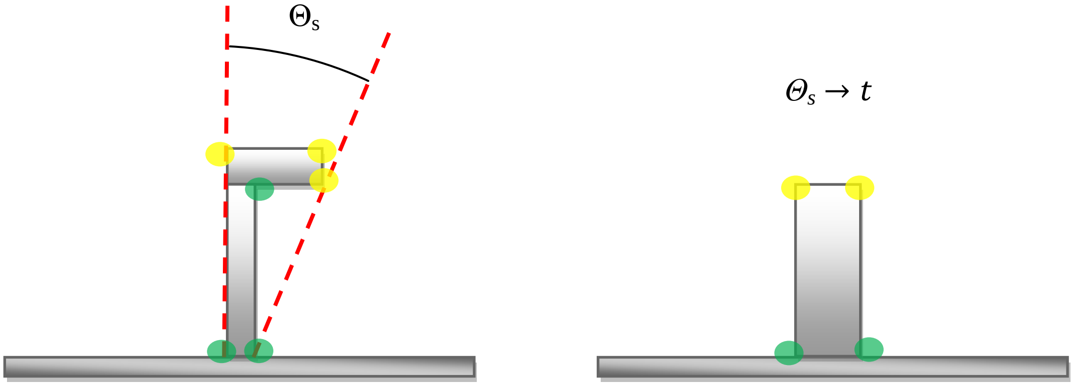


Figure 5-7 Comparison of angle bar and flat bar stiffeners

In order to understand the relationship between structural efficiency, coating performance and structural complexity there is a need to define appropriate measures of these quantities if such the link is to be understood.

5.5.1 Interaction with Surrounding Structure

The first factor that was considered was the surface area of the stiffener plate combination that is not visible when viewed orthogonal to the surface as shown in Figure 5-8.

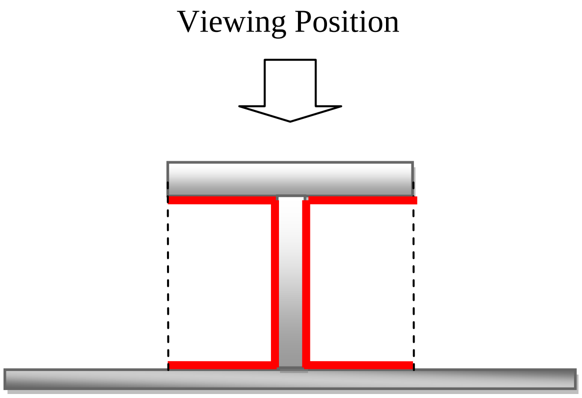


Figure 5-8 Non-visible area

This would give an indication of how much an operator would have to move around with a given space to gain access to the entire surface area within that space. Consider the shadow arc presented in Figure 5-6, if the stand-over height as prescribed by ISO 12944 is added to the stiffener height then it is possible to derive an effective working arc θ_w around any given stiffener profile as presented in Figure 5-9. It should be noted that although ISO 12944 was developed for airless spray application, it has not been applied to ships tank structures. It is the authors opinion that it is due to the design effort that would be required, particularly in the ends of the vessel where there is large amounts of double curvature. It has been used here to provide an indication of sensible working height.

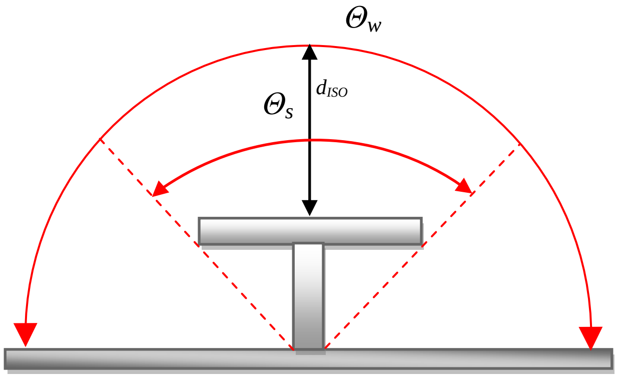


Figure 5-9 Working arc

Rather than just considering one stiffener in isolation, the interaction between adjacent stiffeners also needs to be taken in to account, so that the presence of multiple stiffeners can be incorporated in to this approach. There is an additional reduction in accessibility due to the presence of neighbouring stiffeners. This is indicated by the additional shadow sectors in Figure 5-10. The greater the proportion of the effective working arc, θ_w, that is lost due to the aggregated combination of shadow arcs, θ_s, then the greater the difficulty of coating the overall stiffened panel. It is proposed that the difference between the working arc and shadow arc can be considered as a measure of the overall ease of coating in terms of the visibility of internal vertices and accompanying surfaces of the plate stiffener combination. This has been termed the 'visible sector', θ_v, as shown in Figure 5-10.

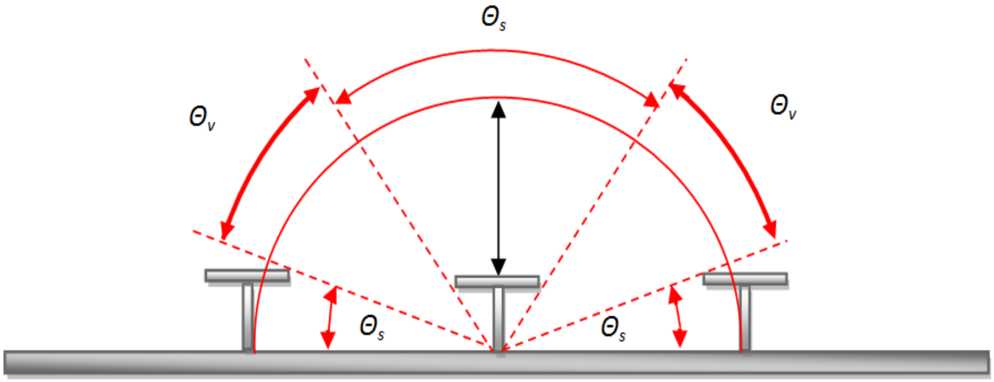


Figure 5-10 Influence of surrounding structure

There are two routes to improvement that are readily identifiable that would increase the visible arc length:

- Development of preparation and application tools that reduce the effective distance needed from a surface thereby reducing the radius of the working arc, θ_w, and hence increasing the proportion of θ_v;
- Alter the structural configuration to allow better access to the surfaces and so reducing θ_s and increasing, θ_v.

The ***BESST*** (***2010***) program examined the preparation and application tools that are used across a range of different industries in an attempt to identify processes and equipment that could be utilised in the marine industry. The project also examined the reasons for the lack of development of the tools used and concluded that the marine sector makes up such a small percentage of the sales for a painting equipment manufactures. As a result there is little opportunity for them to recoup any investment if they developed tools specifically for shipbuilding. It was concluded that there are unlikely to be any revolutionary new painting tools entering the market in the foreseeable future to facilitate the first of the two suggested routes to improvement.

The second suggested route to improve the visible proportion of a structure would be to suggest alternative, more beneficial structural configurations. The structural configuration could be altered in a number of ways, such as maintaining the stiffener profile and altering the spacing or maintaining the spacing and altering the stiffener profile. Figure 5-11 and Figure 5-12 demonstrate the benefits of altering the spacing and stiffener profile respectively in terms of increasing the amount of structure that is visible, i.e. increasing the visible angle or reducing the shadow angle. However this decision cannot be taken in isolation as the transverse and longitudinal stiffener spacing as well as stiffener profiles used in a vessel are critical to ensure structurally efficient and safe plate stiffener combinations. Thus a thorough analysis of any new proposal for stiffened panels is required to ensure that any new designs meet appropriate strength requirements.

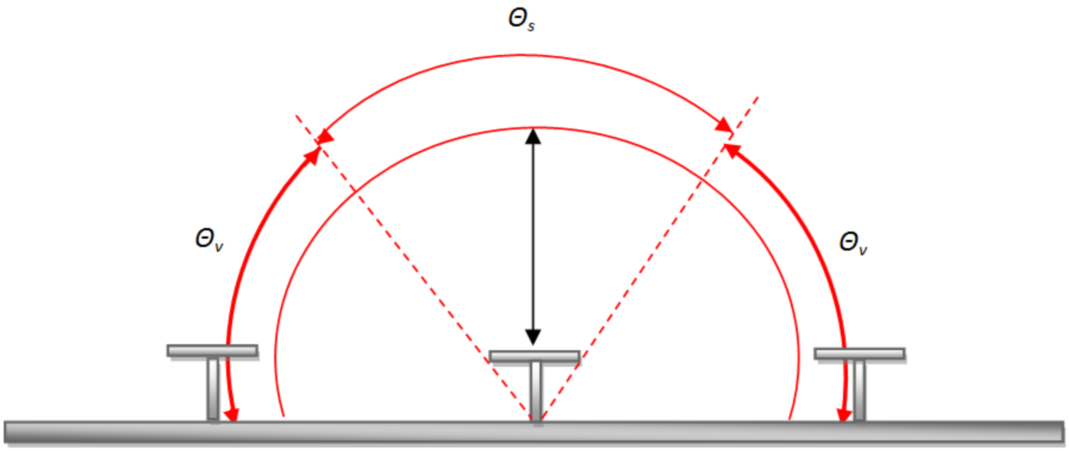


Figure 5-11 Comparison of alternative stiffener profiles and spacing’s

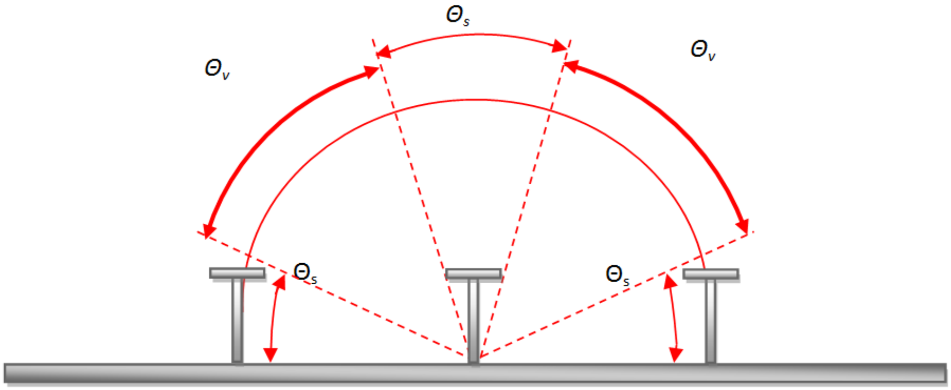


Figure 5-12 Comparison of alternative stiffener profiles and spacing's

These two figures simply demonstrate how the visible arc, θ_v, can be increased by increasing the stiffener spacing whilst the stiffener profile remain relatively unchanged, and increasing the stiffener web height and reducing the flange width whilst maintaining the stiffener spacing. It should be noted that this is a gross simplification of the problem of ensuring the panel provides adequate strength and stiffness and buckling resistance. However it does allow an initial representation of the problem to aid in further investigation.

5.5.2 Interference of Surrounding Structure

To expand on the minimum working distances presented by ISO12944, if an item of surrounding structure falls within the defined working arc then the coating process is going to be negatively affected. To consider the effect of adjacent stiffeners, regardless of the profile, if the stiffener spacing is less than that of the minimum standoff distance, then problems will occur during painting. This will be further compounded when the overall stiffener profile is considered. Figure 5-13 shows how the effective working arc for the centre stiffener becomes the total arc minus both the shadow angle and twice the angle produced by the adjacent stiffeners θ_A. θ_s and θ_A are functions of the geometry and stiffener spacing of the structure, by reducing these the effective arc will increase, which in turn reduced the difficulty involved in the coating process.

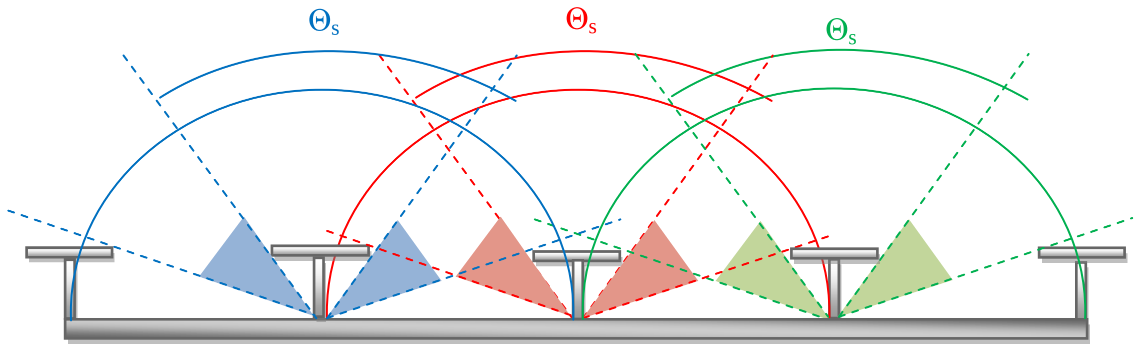


Figure 5-13 Influence of surrounding structure

A review of work carried out on the cost implications of increasing the stiffener spacings appears to have divided opinion. ***Kuo et al***. (***1983***) gives a review of the development of the structural design process and how the coating procedures have evolved to be able to represent and quantify a range of production factors and link them in a rational manner with design variables. It notes that many of the costs are relative and it is only these that are of importance when considering different design solutions. ***Kuo et al***. (***1983***) concluded that for a double bottom unit that the total cost will increase with the stiffener spacing. However in the written comments to the paper Winkle disagrees that the steelwork labour rates will rise as the stiffener spacing increases. This is supported by ***Winkle*** and ***Baird*** (***1985***) which presents the results of a study undertaken on stiffened panels which shows that a panel having what could be seen as good painting characteristics has a low weight and labour content. To further support this view in the written response Prof Faulkner notes that there is optimum stiffener spacing of around 1000mm rather than the then current 600mm optimum. Caldwell also presented results which demonstrate that the lightest weight structure for a given load will require the smallest frame spacing; however this will require a far greater work content thus driving up the total cost of the panel.

5.6 Application of the Complexity Index to a Typical WBT

Having introduced the elements that contribute to the complexity of a structure a method is needed to determine a numerical value. As discussed it is typical when considering the coating process that ships structures are simply classed has low, medium or high complexity dependent on the location in the vessel and the structural configuration in such areas. There are no formal measures of structural complexity that include detailed features of an actual structure such as stiffener profiles, cut-outs etc. and it was highlighted in the returned questionnaires that these areas contribute significantly to the complexity of a space. There is therefore a need for a more refined measure of complexity to assess, in this context, the differing complexity of WBTs in different locations within a vessel or across a range of vessel types.

The influence of each of the factors both individually and collectively must also be determined, as there is unlikely to be single optimum design solution. This element was discussed in Chapter 3, whereby it is typical that a design study returns a number of feasible solutions and it is down to the skills of the design team to select the most suitable solution. Thus it would be possible to provide a designer with the appropriate information for them to select the most suitable design for their particular needs.

The questionnaire identified that within a WBT the addition of primary and secondary stiffening had a large contribution to the complexity; namely free edges and number of vertices associated with the stiffener profile, cut-outs, scallops, brackets and weld length. Along with the amount of surface area for a given volume, i.e. if the surface area is high, in a small volume then the space is likely to be difficult to coat. Therefore the complexity factors that have been selected on which to base the initial studies on the elements of the Complexity Index are:

- Free edge length associated with all plate and stiffener features, l_{FE};
- Weld length of all plate and stiffener joints, l_W;
- Total surface area of complete structure, A_T;
- Percentage of total area which falls below a minimum offset distance A_{min}.
- Non visible area, A_{nv};
- Stiffener shadow arc length, L_s;

In order to incorporate the influence of structural complexity on the coating process in WBTs, the approach that has been adopted is to first identify a ‘typical’ WBT structure and then investigate methods to measure of the overall structural complexity. This measure could then provide a means of seeking solutions balanced against weight, strength and overall production and through life cost including coatings.

In the first instance, in order to establish the influence of each of the parameters that have been highlighted on the complexity of a structure, a number of simple models were investigated. The case study presented here is the simplest case to provide the insight sought. It is a single stiffener plate combination incorporating a typical longitudinal tee bar stiffener (400 × 150 ×16mm) with associated plating (850mm × 16mm) taken from the midship section of a double bottom WBT of a contemporary tanker design. The values of the structural indices as discussed in Chapter 3.7 for this benchmark stiffener and associated plating are given in Table 5-1. It should be noted that the values are within the expected range other than the area ratio which is higher than would be expected. This indicates a slightly inefficient design, which could be accounted for as this was an early design following the mandatory requirement for double hull tankers, in which cases it is likely that the design team added some 'extra redundancy' to cover unknowns. There will be further discussion on these structural measures during the analysis of the resultant design solutions.

Table 5-1 Values of structural indices for benchmark for plate stiffener combination

z (m^3)	A_r	B	b/t	λ	a/k
1.53E-03	0.323	1.777	53.125	0.246	23.137

This has been used as a benchmark structure against which differing geometries and scantlings, where maintaining the section modulus has been set a design constraint, are compared. This provides a simple means of ensuring 'equivalence' in terms of load carrying capacity with respect to the in-plane stress and similar stiffness of the plate stiffener combinations investigated. To provide insight as to the influence of different stiffener profiles, those shown in diagrammatically in Figure 5-1 were initially investigated.

Using the four typical stiffener profiles without further constraints resulted in a large number of alternative sections due to the variables associated with characterising even these simple sections and the large number of alternative sections possible in the feasible region. In order to reduce the number of variables and cases to be considered, the thickness of the plate and flange for the angle bar and tee bar sections where assumed to be the same and the web thickness to be 60% of this value. This assumption is supported by scrutiny of the scantlings taken from the benchmark vessel.

In the case of the of the offset bulb plate, the alternative sections considered were based on standard sections, ***Corus***, ***(2002)***, but were idealised further in an attempt provide the combined section modulus of the stiffener and associated plating required. However, as would be expected there are no realistic bulb plate sections which are comparable in terms of section properties to the benchmark tee bar which are typical of the stiffeners used in large bulk carriers and oil tankers. These vessels represent approximately one third of the total number of merchant vessel and seventy percent of the total tonnage afloat (***IHS Fairplay 2014***). As a result the bulb stiffener profile has been omitted from the work of this thesis.

To provide a systematic approach, spread across the feasible region of the structural indices that where discussed in Section 3.7, the pseudo aspect ratio, namely stiffener height to flange width, of the different stiffener profiles was varied systematically from 1.0 to 4.0. This variation of the aspect ratio was achieved based on the following simple distortion of both the web height and flange width to create a family of variant family sections indicative of stock sections. If the desired change in aspect ratio as a proportion of the benchmark value is δx, then the corresponding changes to the web height and flange width become:

$$\boldsymbol{h'_w = h_w \cdot \sqrt{(1+\delta_x)}} \qquad 5\text{-}1$$

$$\boldsymbol{f'_w = f_w / \sqrt{(1+\delta_x)}} \qquad 5\text{-}2$$

The associated panel weights provide a simple measure of structural efficiency as given their comparable modulus, the lighter variants can be considered to be more ‘efficient’. Using this approach allows an appreciation of the relationship between the different comparable stiffener-plate combinations, their relative weight and the measures above that can be considered as a measure of ‘complexity’ with respect to ease of coating. These cause and effect studies were undertaken to provide insight into these relationships and subsequently propose a combined measure of complexity.

5.7 Calculation of Complexity Indices

Having introduced the concept of visible area in Chapter 5.5, a simple initial measure of how easy a stiffened panel is to coat, this can be used as basis, along with the other key features of the panel as a means to formulate some simple measures of complexity. These additional measures selected are in keeping with the areas of concern identified within the PSPC and themselves relate to features such as internal and external vertices that have their own requirements as part of the coating process. For example free edge length requires multi-pass grinding to a suitable radius and both this and weld beads require two additional stripe coats.

To calculate complexity production quantities commonly used for work content and cost estimation have been selected as these are readily available for use in modern production software. Accordingly the measures of complexity investigated are:

- Total non-visible area, a_{nv};
- Total stiffener shadow arc length, l_s;
- Total surface area, a_s;
- Total free edge length, l_{fe};
- Total weld length, l_w;

5.7.1 Calculation of Non-Visible Area

To demonstrate how the suggested measures might be applied a portion of structure from a double bottom WBT has been considered as shown in Figure 3-8, and will be used as the basis for cases studies presented in this work. For such a T bar stiffened panel the complexity measure previously outlines are readily calculated. The non-visible area, a_{nv}, per unit length, as shown in Figure 5-8, for a stiffener viewed orthogonally from above can be simply calculated from:

$$\boldsymbol{a_{nv}} = \left(\mathbf{2}(\boldsymbol{f_w} - \boldsymbol{w_t})\right) + \mathbf{2}\boldsymbol{w_h} \qquad \text{5-3}$$

The non-visible area for a simple longitudinally stiffened regular panel requires the total number longitudinal stiffeners, n_{sl}, and there length, L_{sl}, be taken into account. Therefore the total non-visible area for this simple panel is given by:

$$\boldsymbol{A_{nv} = \sum_{i=1}^{n} a_{nv_i} = \left[n \cdot \left[l_s(2(f_w - w_t)) + 2w_h\right]\right]} \tag{5-4}$$

The shadow angle of a given stiffener profile, as discussed previously, is given by:

$$\boldsymbol{\theta_s = 2 \cdot tan^{-1}\left[\frac{0.5f_w - 0.5w_t}{w_h}\right]} \tag{5-5}$$

This allows the subsequent calculation of shadow arc length, l_s, using the ISO 12944 recommended working height and the web height to provide the total effective working height, d_{iso}:

$$\boldsymbol{l_s = \theta_s \cdot d_{iso}} \tag{5-6}$$

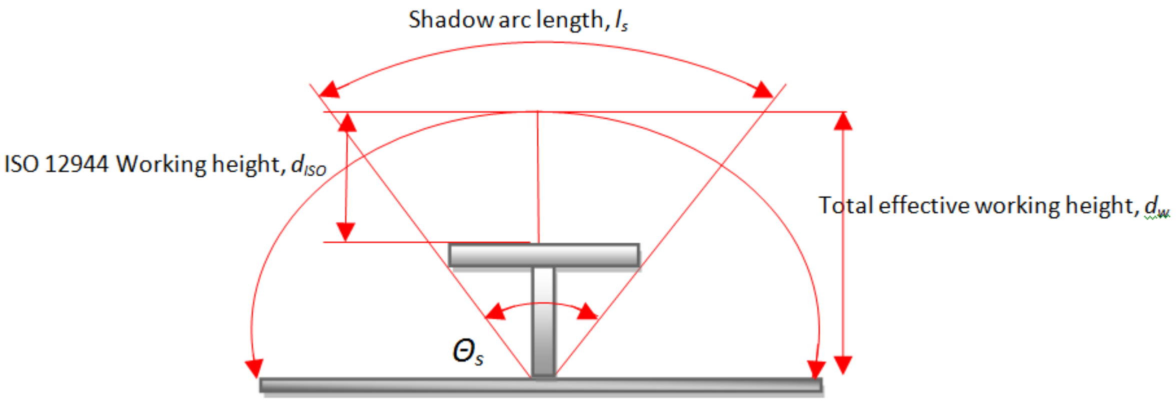


Figure 5-14 Shadow arc length

On the assumption that only longitudinal material is considered, as is the case between web frames in an oil tanker or bulk carrier, the total shadow arc length for n number of stiffeners is given by:

$$\boldsymbol{L_s = \sum_{i=1}^{n} l_{s_i} = n[\theta_s d_w]} \tag{5-7}$$

5.7.2 Calculation of Surface Area

The total surface area of the variant plate stiffener combinations in this study can be calculated simply from:

$$\boldsymbol{A_t = \sum_{i=1}^{n} a_{s_i} + plate\ area = n.a_s + A_p} \tag{5-8}$$

A consideration that is very often omitted from a paint specification is an accurate calculation of the surface area of a given WBT. Painting contractors typically use simple relationships between the volume of the tank and its surface area, ***Momber***, (***2009***), however these methods can only be used to give an approximate estimate of the total surface area to be coated. A more accurate approach for a WBT could be based on quantifying more accurately the area of the plating, stiffening and the area lost at the intersection of different components. For the simple longitudinally stiffened panel considered here this can be considered as:

- Surface area of the plate, A_p;
- Total surface area of the stiffener A_s;
- Total surface area of the intersections, A_i.

Although the area lost at plate to stiffener and stiffener to stiffener intersections may be considered to be inconsequential in a typical tank when undertaking accurate paint requirement estimations this area can be significant and should be taken into account. As a further extension of this argument the area lost to filet weld and the resulting surface area of the filet could also be considered. The assumption that has been made in this study is that the areas lost below the weld and the weld surface are equal to account of the irregularities of the surface of the filet.

$$\boldsymbol{A_p = l_{Plate} \cdot B_{Plate}} \tag{5-9}$$

$$\boldsymbol{A_s = [l_s(2w_h + f_w + (f_w - w_t) + 2f_t)]} \tag{5-10}$$

$$\boldsymbol{A_i = l_{sl} \cdot w_t} \tag{5-11}$$

$$\boldsymbol{A_t = A_p + n(A_s - A_i)} \tag{5-12}$$

5.7.3 Calculation of Free Edge Length

Free edge length calculation is simply determined by the length of the stiffener and the number of external vertices, m.

$$\boldsymbol{l_{fe} = m.l_s} \tag{5-13}$$

$$\boldsymbol{L_{fe}} \sum_{i=1}^{n} \boldsymbol{l_{fe_i}} = \boldsymbol{n[m.l_s]} \tag{5-14}$$

Where *m* is assigned according to stiffener type: for a flat bar, *m* = 2; angle bar, *m* = 3; Tee bar, *m* = 4.

5.7.4 Weld length

Weld length is calculated based on the stiffener to plate connection as well as any welded associated with fabrication with the stiffener profile.

$$\boldsymbol{l_w = [k+2]l_s} \tag{5-15}$$

$$\boldsymbol{L_w = \sum_{i=1}^{n} l_{w_i} = 2\left[l_{plate} + b_{plate}\right] + n[k+2]l_s} \tag{5-16}$$

Where *k* is dependent on stiffener type to account for construction welds, for flat bar is zero and Tee bar is two and Tee and angle bar section stiffeners are both assumed to be fabricated although there is the possibility of using long stalk Tee's and flanged angle bar stiffeners. Given the panel length is common, all the variants will have the same weld length in terms of the connection with plating and the difference in weld length will be due to the inherent work content of the fabricated stiffener in the case of the tee and angle bar profiles. It is noted that if the thickness of the plates used is greater than 20mm then there may be the need for a greater number of weld passes to achieve effective joining.

This insight should allow subsequent development of the approach to allow integration of these factors into a more complete treatment of the associated aspects of inherent work content, material cost, overall production cost and through life considerations.

In the first instance, the approach has been applied to the simple model described previously, including the influence of the alternative stiffener profiles identified. The intention has been to apply the approach to simple 'equivalent' idealised alternative structures to allow the model to be developed and verified in simple steps.

Once the factors that contribute to the complexity measures described are established, an aggregated overall Complexity Index can be used as a formal objective function when seeking solutions that would be easier to coat. To provide a meaningful measure that can be used for comparative purposes between different panels within WBT structures; the proposed approach is that any alternative variant structure is normalised with respect to the benchmark structure rather than based on the absolute value of these measures. Values less then unity suggest improvement with respect to a particular complexity measure and values greater than unity suggest worse solutions.

This approach can then be used to identify whether alternative panel designs provide a reduction in overall complexity relative to the selected benchmark structure, values less than unity indicate an improvement:

$$C'_{L_{fe}} = \frac{l_{FE\ Variant}}{l_{FE_{Basis}}} \tag{5-17}$$

$$C'_{L_w} = \frac{l_{WL\ Variant}}{l_{WL_{Basis}}} \tag{5-18}$$

$$C'_{A_t} = \frac{A_{T\ Variant}}{A_{s_{Basis}}} \tag{5-19}$$

$$C'_{A_{nv}} = \frac{A_{nv\ Varinat}}{A_{nv_{Basis}}} \tag{5-20}$$

$$C'_{L_{arc}} = \frac{L_{arc\ Variant}}{L_{arc_{Basis}}} \tag{5-21}$$

These individual indices can then be aggregated to produce a ‘Complexity Index’ as a compound measure of the overall complexity:

$$CI = \sum_{i=1}^{5} w_i \cdot C'_i = w_1 C_{FE} + w_2 C_{WL} + w_3 C_{As} + w_4 C_{Anv} + w_5 C_{Larc} \tag{5-22}$$

As all the component indices have been normalised they are all of the same order so inherently have the same weighting when aggregated in this manner. To investigate how a different emphasis of these components affects the overall complexity index, an additional weighting term has been introduced to allow the relative importance of each term to be appreciated but in this study the weighting has been set as equal:

$$\sum_{i=1}^{5} w_i = 1 \tag{5-23}$$

5.8 Further Factors Affecting Complexity

As previously discussed the amount of free edge not only affects the complexity of a structure it also adds to the work content. From a production standpoint there is a conflict between aligning brackets to reduce the weld and free edge length and the production accuracy needed to accommodate this alignment. This work has not directly accounted for the brackets that are used to connect the longitudinal material to the transverse webs. The normal practice is to use angle bar stiffeners which are formed by bending a suitably sized and shaped piece of flat plate or by welding on a secondary flat plate.

In practice the orientation of the flange of the bracket is often such that it makes coating of the ‘backside’ of the vertical flange considerably more difficult as shown in Figure 5-15.

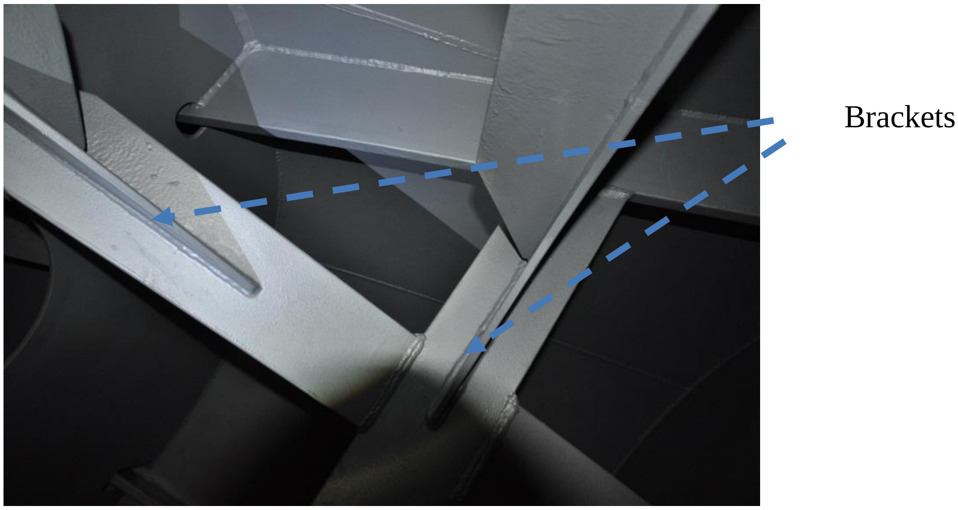


Figure 5-15 Arrangement of brackets

In this case the access to the rear surface of the stiffener was severely restricted as the distance to the steelwork behind was less than 150 mm. The studies within this body of work have shown that it is possible to provide suitable structural solutions that are essentially easier to paint.

Figure 5-16 After-peak WBT

Figure 5-16 shows the WBT from which the picture from which Figure 5-15 is a close up of a particular section of interest. Following the approach of altering the structure to improve access for the coating process the solution would be to alter the spacing of the large primary longitudinal and transverse stiffening to provide better access thus reducing welds and free edge length. However in this case it is difficult to realise any improvements in the area shown in Figure 5-15 as the photograph was taken in stern section of the vessel which has double curvature.

When considering the problem on the scale shown in Figure 5-15, the first study, which examined single stiffeners in isolation, demonstrated that it is possible to alter the dimensions of a stiffener and still provide adequate structural performance. The simplest solution would be to provide a thicker ‘flange’ thus allowing the flange length to be reduced. This would improve the access as well reducing the amount of surface area below the minimum working distance and the effective shadow arc length. This simple example highlights the holistic approach that is required to the design process as decisions taken early in the design process can create problems at the detail design phase

Further inspections on a range of different vessel types highlighted that it is possible to complete the coatings process to a very high standard. It is also possible to consider the future operations of the ship, such as ensuring that all none steelwork items such as cabling are not coated. As shown in Figure 5-17 and Figure 5-18. It should be noted that the pipe in Figure 5-17 is stainless steel and thus does not require coating.

Figure 5-17 Un-coated none steel work items in a tank

Figure 5-18 Un-coated ballast valve nuts and bolts

It should be noted that these pictures were taken on board a large luxury yacht, where initial cost is not of such high importance as in the commercial world. It does however demonstrate that is it possible to achieve consistently high quality finishes, but this standard of work and attention to detail will come at a significantly higher cost than what could be considered as the shipbuilding norm.

5.8.1 Additional Benefits of Reducing Structural Complexity

The work in this thesis has examined the problems that have been created by a lack of understanding of the needs of the coating process. This section will investigate the potential benefits that could be realised if the requirements of the coating process are considered throughout the design process. The fundamental consideration is that if the structure is designed to accommodate the coating process, and then there is a high probability that the selected paint system will be applied to a consistently high quality in line with the specification. This then provides a situation whereby the applied paint film can provide a high level of protection, thus minimising the amount of corrosion, for the entire life of the structure.

If it were possible to ensure that no corrosion would occur then there is the possibility to greatly reduce the cost of the vessel and improve the long term structural performance. This cost saving would be in terms of both the initial cost and the through life costs. If the process of corrosion could be removed completely then there would be no need for the addition of the corrosion allowance or the replacement of corroded plates. In the first instance the removal of the corrosion allowance would reduce the weight of the steel that comprises the 'lightship' of a vessel. The benefits for the building process are a reduction in the cost of steel required and a reduction in the energy needed to produce, move and join the steel work. From an operational perspective this would allow a vessel of the same design to carry more cargo for a given displacement. As there would be no corrosion the need for time consuming inspections would be greatly reduced if not removed altogether, along with the very costly process of replacing badly corroded steel plates ***DNV,*** (***1998***), "*The application of high quality coatings in WBTs at the new building stage is cost effective compared with upgrading by means of steel renewals later on. The application of increased corrosion margin (coating of steel with steel) is not cost effective compared with improving the coating quality"*

5.8.2 Cost Benefits of Improved Design

If the corrosion protection afforded by a paint film could be guaranteed for the expected life time of a vessel then a number of improvements could be employed to reduce the environmental impact of the vessel. By reducing or removing corrosion through design changes to benefit the coating process is may be possible to remove the corrosion allowance this would then require less energy to be consumed in the production of the reduced amount of required steel to build a vessel. An additional but much smaller benefit would be the reduction in the power required to join and move the sections whilst in shipyard. The benefits through the life of the vessel are twofold: reduction in the lightship for a given vessel would lower the power requirements for propulsion needs for a given cargo weight; this reduces the fuel consumption, thus reducing the harmful emissions produced: furthermore there would be a reduction in the need for steel replacement due to corrosion and a less maintenance and repair requirements. An economic benefit to the operator of a vessel is that by reducing the lightship, a vessel is able to carry more cargo for a given deadweight, thus allowing them to generate more revenue. ***OCIMF*** (***2011***) proposes that the steel weight component of the lightship of many vessels could be reduced by up 2% by better structural design and the use of formal optimisation techniques.

To highlight the advantages of reducing the complexity of a given structure, if a typical 60,000 dwt bulk carrier is considered the approximate area of the WBTs is 55,000 m^2 (***Safinah 2010***). Under the IMO PSPC these tanks are to be coated with nominal dry film thickness (DFT) of 320µm of an approved multi-coat scheme (***IMO 2009***). Table 5-2 shows the total amount of paint needed for this typical vessel, using the Safinah Coating Calculator, these calculations are based on three two-pack products which are currently available and have type approval for WBTs. Table 5-2 Paint Usage for Typical 2-Pack Epoxy Paints

	Product		
	A	**B**	**C**
Area to be coated	55,000 m^2		
Vol. Solids (%)	82	70	60
DFT (µm) (per coat)	160	160	160
TSR (m^2/l)	5.1	4.4	3.8
ASR (m^2/l)	1.4	1.2	1.1
% AL	71.9	71.9	71.9
Total litres needed (l)	90,357	105,417	115,000
Number of 20l tins	4,518	5,271	5,750

Where:

TSR is the Theorectical Spread Rate

ASR is the Actual Spread Rate

What is clear is the amount of waste generated by the coating process. For example there will be between 4,500 and 6,000 empty tins for every vessel produced, which must be disposed of. If minimising the surface area was the major focus then it could be argued that there would be a reduction in the amount of paint being required. The views of the author are that the complexity of the structure will have a significant influence on the labour costs to apply the coatings which will potentially offset any paint material savings.

This is reinforced by the author's inspections of WBTs both during building and in-service, as painters then to over apply paint in complex areas, cases of as much as three times the specification are not uncommon as demonstrated in Figure 5-19; the specification called for 320 µm DFT whereas almost 1500 µm DFT was actually applied. This results in a great deal more paint being applied than is actually required.

Figure 5-19 Example of Excessive Paint Thickness

It may be that by reducing the complexity the overall surface area may increase, as fewer but larger stiffeners are required to provide adequate structural performance, it will be easier to apply the specified paint thickness, thus reducing the paint material costs and labour costs. The attendant environmental benefits are a reduction of the waste products and a reduction of the VOC emissions. It should be noted that there is a drive in the industry to increase the volume solids of paint products, in an attempt to reduce VOC emissions.

The lack of suitable quality control procedures and accurate work content compounds the problem. For example if the exact amount of surface area was known within a given tank, then it is not difficult to determine how much paint should be used to achieve the correct coating dry film thickness. Good quality control procedures would highlight under or over use of paints much sooner in the build process, which may allow remedial action to be effected. This could be in the form of improved training for the operators, or simply identifying those operators who are capable of providing a high quality surface finish in more complex areas.

BRSA (***1972***) also highlights the practical aspects of painting, namely that *'coatings cannot be applied at a uniform thickness over an appreciable area by any practical method- brushing, spraying or roller coating.* Therefore it is important during the detailed design stage that the access requirements of the coating process are considered to ensure that the appropriate thickness of paint is applied. The PSPC requires two full coats of paint with a total NDFT of 320 µm, however there is no specified maximum thickness

If the total paint usage could be reduced through better design, then this presents clear benefits both in terms of cost and environmental impact. If it were possible to reduce the paint used in the example shown in Table 5-2 by 10%, then Table 5-3 demonstrates the expected savings in terms of paint and the associated tins, and VOC emissions.

Table 5-3 Potential savings

Product	**A**	**B**	**C**
Paint saved (litres)	9,036	10,542	11,500
Number of Paint tins saved	452	527	575
VOC reduction (tonnes)	3	3.3	3.66

There are a number of indirect savings/reductions that can also be considered which are far harder to quantify; the energy savings as a result of not having to transport the extra paint to the shipyard, a reduction in energy requirements within the yard as the demand placed on the compressors within the yards to supply the air for the blast media and apply the paint will be diminished. Finally there will be less need for the production and disposal of the paint tins. This would also affect the demand for paint, thus paint manufactures would need to look at alternative pricing schemes or as some already do enter into longer term agreements with ship yards and ship owners that seek to maximise the in-service life span of applied coatings.

Experience of the author has shown that to ensure that the specification is met in terms of the DFT applied; applicators tend to over apply to prevent return visits. This can lead to excessive paint thickness which can be as bad if not worse than under thickness. Many of the leading paint manufactures are now specifying a maximum DFT for their products in an attempt to limit the amount of cracking. This cracking is a result of the build-up of internal stresses initially as the solvent is released during the curing process. These stresses can also increase due to the environmental conditions surround the coating. The combination of these factors leads to a situation of cracking as the outer ‘skin’ of the coating cannot resist these stresses. In many cases the paint ‘cracks’ do not penetrate all the way through the paint film thus the steel substrate is still protected. However if the crack does penetrate down to the steel then rapid deterioration is likely due to action of crevice corrosion. Currently the mechanics of this cracking process are not fully understood, in order to address this, a research project has been established Assessment of Ballast Tank Coating (ABTC) which is being funded through the Knowledge Transfer Partnership (KTP).

5.8.3 Operational Benefits of Improved Design

The work presented thus far has focused upon the cost benefits during the building process of the ship. There is also a clear benefit during the operational life of the vessel for WBTs with improved access. The first which underpins the hypothesis of this thesis is that due to the improved working conditions there is a higher probability that the coatings will provide a longer in-service life span, discussions with paint company technical personnel have indicated that the 15 year target life is easily achievable, providing adequate maintenance is undertaken. The provision of better access will allow maintenance work to be satisfactorily undertaken by ships staff providing they are equipped properly in terms of the correct tools for surface preparation and paint application and information of environmental controls.

One aspect that provision of this improved working environment will improve is that of rescue access. There has been a recent focus on the access to and within enclosed spaces as a result of a high number of incidents being reported by the MAIB. There figures indicate that between March 1998 and May 2009, there were 93 fatalities on the MAIB's database. A feature in the Naval Architect (***Allam and Lloyd, 2012***) commented upon the 'Entry into enclosed spaces' conference which was organised to address the extent of the problem and propose measures to reduce the number of incidents.

One aspect that was raised was that during any subsequent investigations following an incident the design of the enclosed space are not critiqued. The article focused principally on the access into tanks rather than the freedom of movement once inside a space. One recommendation made by Michael Lloyd was the increasing the size of the 'typical' manhole, which measures 650 mm x 450 mm, by 75 mm could make a significant difference to the safety and wellbeing of ship's crew. Adam Allan highlighted the placing of cable trays across access holes as an element of bad design; the author has seen many cases of such restriction of access with ships tanks as can be seen in Figure 5-20 and Figure 5-21.

Figure 5-20 Ladders covering manhole

Figure 5-21 Bilge line passing through man hole

It would appear that many of the problems that are seen in practice, where access holes are blocked or restricted are not isolated incidents. Discussions with ship builders would indicate that many of these problems are as result of the lack of feedback between the production and design departments on matters such as these.

Allam and Lloyd (***2012***) note that one disturbing fact that was raised is that more seafarers die as a result of enclosed spaces than do as a result of fire, yet the same breathing apparatus is used when dealing with both scenarios. There is growing momentum to provide ships with specialist equipment which is designed for enclosed space rescue.

Allam and Lloyd (***2012***) also point out that the 'disconnect between designers and the seagoing community' needs to be addressed to improve the operating conditions within enclosed spaces. Therefore there is further merit to re-examine the design process of complex enclosed spaces to include the operational and emergency situation access requirements, following the simple feedback model shown in Figure 4-4. The access requirements for casualty evacuation are likely to be far greater than those of the coating process; therefore any 'design for evacuation' guidelines are likely to be far more stringent than those focusing on the coating process. There is mounting evidence that indicates that the design of enclosed spaces is not providing adequate access, or put another way the complexity of these spaces is at such a level to negatively affect ship emergency operations. Perhaps it is time of the marine industry to be proactive any implement design procedure internally before regulations are imposed by the regulatory authorities.

5.9 Conclusions

This chapter has introduced how the DISPRO four step approach as shown in Figure 5-2, which if successfully implemented, would serve to improve the in-service performance of marine coatings. A link has been proposed between the structural complexity and the structural efficiency of a structure and the performance of the coatings applied to it. Due to the apparent size of the problem faced by the marine coatings industry this project has chosen to focus on the first step of the approach, examining the benefits of simple design changes.

The Complexity Index will allow different designs, which comply with structural requirements, to be given a numerical value based upon a range of geometric factors. Potential designs can then be compared and rated from a coatings perspective meaning that a decision can be made by the design team to select the 'optimum' design solution, which will represent a least cost solution. As a result of improved designs there exists an opportunity to realise significant overall cost savings in terms of labour and materials if the coatings process is properly considered during the design phase.

5.10 Summary

The chapter has expanded upon the results of the industry questionnaire in chapter 3. A four step approach to improving the in service performance has been proposed, which provides both near market and long term goals and objectives, combined with an improvement in the perception and management of the coatings process. Currently there is little consideration given to the coating process during the detail design stage of a vessel that considers the physical tasks that must be undertaken as part of the coating process. The history of structural complexity has been explored as part of the Group Technology development process. The methods for quantifying complexity have been explained along with the key structural constraints which define if a structure is suitable.

6 ASSESSING THE RELATIONSHIP BETWEEN STRUCTURAL ARRANGEMENT AND COMPLEXITY

6.1 Introduction

This chapter builds upon the factors that where identified and described previously. It describes how an Excel model has been built to investigate the influence of each of the factors that have been identified has having an impact on the coating process. The approach is developed from analysis of a range of single stiffener plate combination types, to include investigations of stiffened panels representative of WBT double bottom.

The development of an optimisation routine for the large WBT stiffened panel is described. The results of this optimisation study are presented for the benchmark structure and investigates the possibility of reducing the number of stiffeners.

6.2 Model Development

In the first instance, the approach has been applied to the simple model described previously, including the influence of the alternative stiffener profiles identified. The intention has been to apply the approach to simple, ‘equivalent’ in terms of section modulus, idealised alternative structures to allow the model to be developed and verified in manageable steps. This understanding then allowed integration of these considerations into a more complete treatment of the associated aspects of inherent work content, material cost, overall production cost and through life considerations.

The Excel spreadsheet model developed for this analysis has allowed cause and effect understanding to be gained with respect to the influence of the individual parameters defining the idealised plate stiffener combination on both the structural and complexity indices. This insight will allow the most significant relationships to be understood before further refinement of the approach and possible suggestion of additional measures of complexity. Such understanding is also vital before attempting more formal optimisation of the problem in the future.

Having established the complexity indices and the aggregated overall Complexity Index this can be used as a formal objective function when seeking structural design solutions that will be easier to coat. The design vector for such an optimisation will be the variables defining the plate stiffener geometry as well as key features that in turn influence both the Complexity Index as the objective function and the Structural Indices that will be used to constrain the optimisation problem to a feasible region.

6.3 Single Stiffener Plate Combination Complexity Cause and Effect Study

The results of initial cause and effect study are presented in Figure 6-1 to Figure 6-6. The figures show the individual and combined measures of complexity, as well as weight, to an abscissa of varying pseudo stiffener aspect ratio for the idealised variant sections considered. This then allows the limits of the individual structural constraints that are active to be plotted as a function of the bounding value of stiffener web height to flange thickness aspect ratio. Although the bounding values of the structural constraints are presented, the column slenderness ratio ‘Lambda’ of solutions with aspect rations of 0.5 is outside the allowable limit. Namely all sections are in the feasible region dictated by the other constraints.

Therefore the feasible region has been dictated by the range of aspect ratios considered practical for the variant sections considered, typically 1.5 to 3.0 for angle and tee bar sections, (***Swan 1970)*** as shown by the green shaded area in the following Figures. The upper limit is dictated by buckling and stability considerations. Similarly, in the case of flat plate slab stiffeners an upper limit on aspect ratio of 10 has been applied to avoid proposing stiffeners susceptible to in-plane buckling otherwise known as stiffener tripping. The green shaded area in the figures represents this feasible region of ‘stock’ sections.

In the results presented, the free edge and weld length have not been plotted individually as, has been previously noted, these do not vary with stiffener size only with stiffener profile but are included in the compound complexity function C'_I.

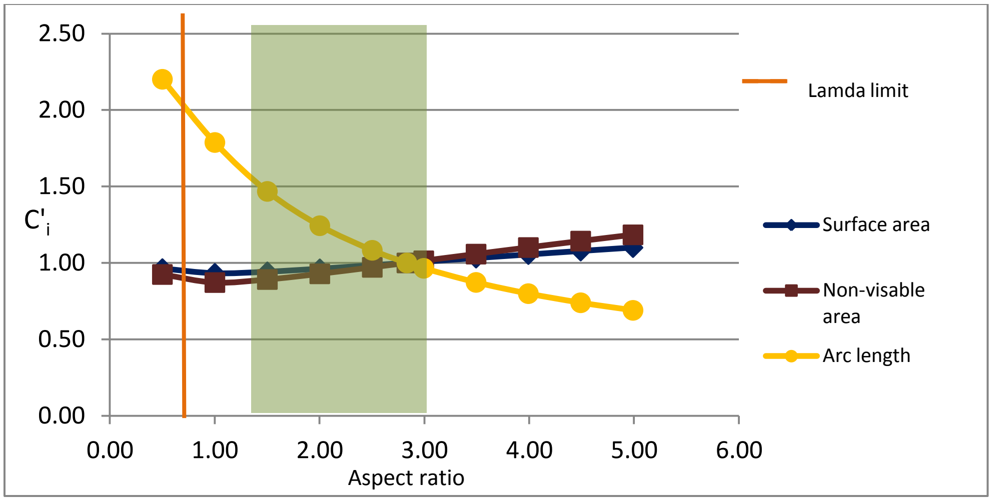


Figure 6-1 Tee bar complexity values

Figure 6-1 shows that as the aspect ratio of the tee bar stiffener increases the overall surface and non-visible areas increase slightly whilst the shadow arc length decreases. This demonstrates that both the non-visible and surface areas are in this case predominately driven by the height of the stiffener web. As the aspect ratio increases, i.e. the web gets bigger and the flange smaller, the stiffener web will provide a more effective distribution of material for a reduction in weight. The reduction in the flange width also accounts for the diminishing value of the arc length. It should be noted that the crossing point represents the values of the benchmark stiffener.

In Figure 6-2 it is interesting to observe that that intersection of the combined complexity index and the weight intersect at the benchmark and that this is at the upper bound of the feasible region as observed in Figure 6-1. This suggests that such stiffener sections inherently provide a solution that is already a very good compromise between structural performance, weight and complexity as shown in Figure 6-2. To achieve any significant benefit to complexity, but with no attendant weight penalty, would mean considering sections of higher aspect ratios where the web would likely behave as an individual plate and become susceptible to in-plane bucking that could also result in the flange becoming out of plane leading to tripping of the complete section. The only way to avoid this would be additional stiffening in the form of gusset plates but this would obviously lead to greater weight and a significantly more complex structure with respect to many production considerations and as such does not provide a sensible solution.

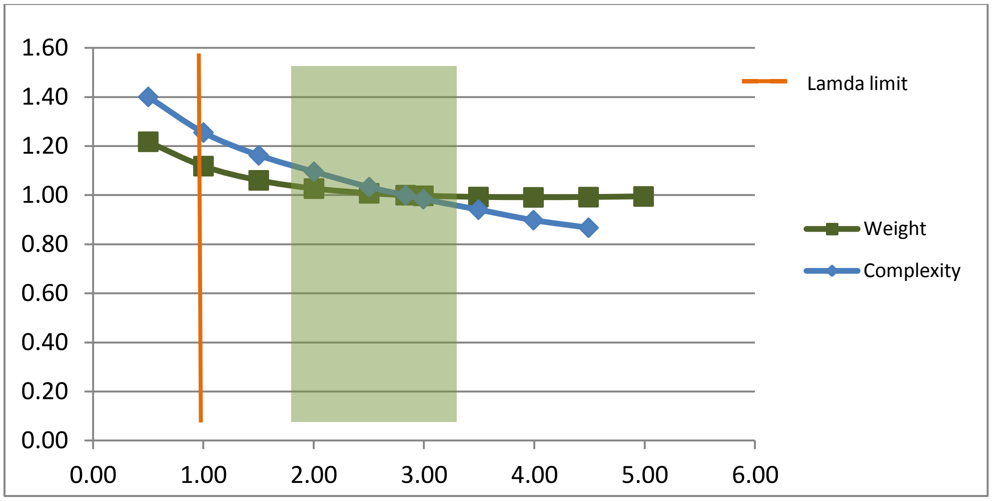


Figure 6-2 Tee bar weight and overall complexity

Further, this demonstrates that there is little real benefit that can be obtained using the same stiffener profile, therefore a means of comparing different profiles is of interest to see the influence of altering both the stiffener type and topology with respect to the base design. Figure 6-3 and Figure 6-4 show the individual complexity indices and the combined complexity index and the weight for the angle bar respectively; again the values have been normalised with respect to those of the benchmark tee bar. As before the feasible region is indicated in green.

If the angle bar results are considered, as would be expected the surface area and the shadow arc length are very comparable to the T bar section as shown in Figure 6-31. The significant difference is that the asymmetric angle bar section demonstrates less non visible area, as effectively one side of the web is no longer ‘hidden’. However, the extra asymmetry would practically result in a section that is more difficult to paint, as one side of the web is effectively deeper than the other making it more difficult to gain access to. This suggests that the degree of asymmetry needs to be considered with respect to complexity.

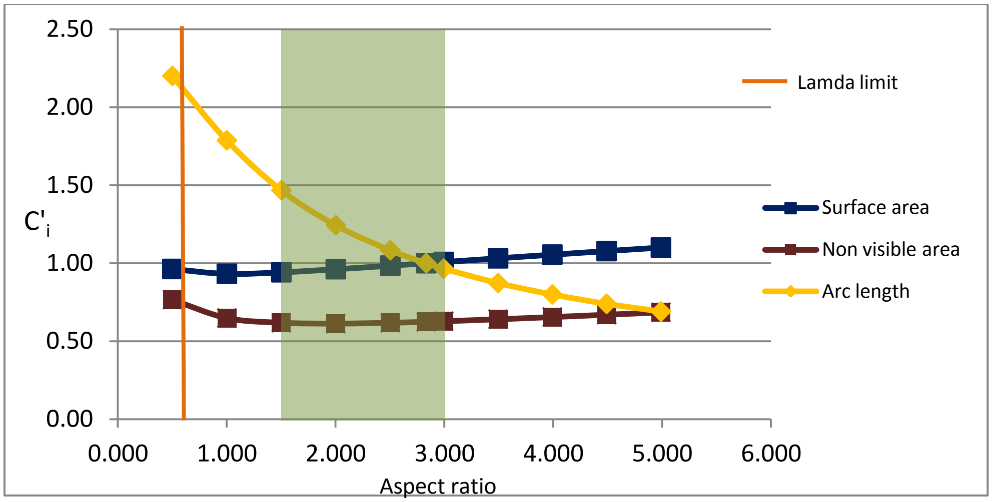


Figure 6-3 Angle bar normalised values

In Figure 6-4 the combined complexity index demonstrates a corresponding reduction in comparison to the benchmark values for the same weight of section. The degree of asymmetry discussed would likely mean this reduction in complexity is possibly misleading, as it is unlikely that it could be realised practically. It is also important to appreciate that for asymmetric sections that tripping of the section becomes an important consideration and that they are generally less structurally effective despite the possible production benefits.

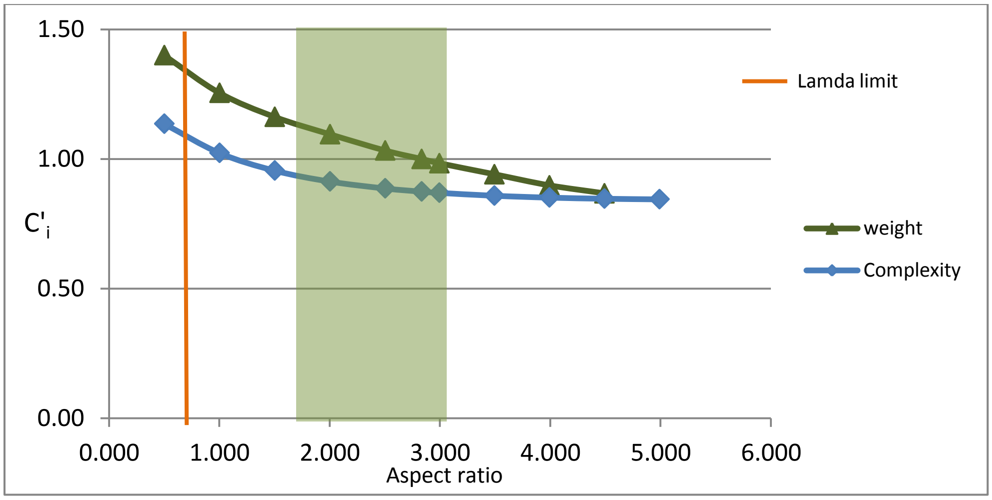


Figure 6-4 Angle bar complexity and weight

In Figure 6-5 the possibility of suggesting significant slab plate stiffeners are presented. Realistically none of these sections are practical replacements for the tee bar benchmark, but have been included to quantify the relationships between complexity and weight that would be expected. Namely, the non-visible area becomes zero and the shadow arc length is minimised as it becomes a consequence of only the thickness of the stiffener. This is accompanied by some reduction in the surface area and accordingly the combined complexity index in Figure 6-6 is significantly reduced.

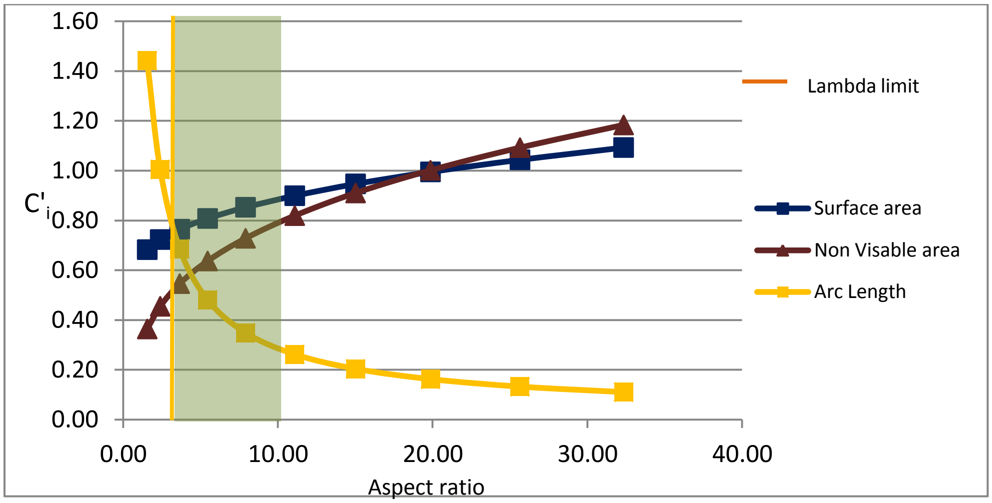


Figure 6-5 Flat bar normalised values

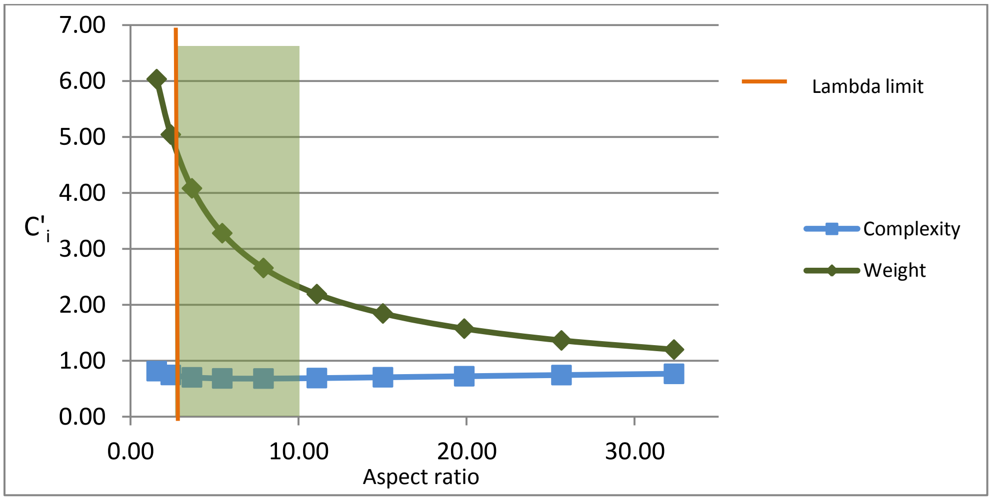


Figure 6-6 Flat bar complexity and weight

Figure 6-6 shows that the weight of such sections is considerably higher than the benchmark due to such ineffective distribution of material. This conclusion would remain true for smaller section flat bar stiffeners where their adoption would be more feasible and these benefits might be achievable, (***Chalmers 1993***); for the longitudinal stiffening considered here equivalent slab plate sections would not be possible.

Analysis of all of these graphs shows that although it is possible to use other profiles to attempt to reduce the value of one or more of the factors that influence the complexity of a structure, in every case there will again be a significant weight penalty. Although ***Hargroves et al.*** (***1975***) suggested that the shipbuilding industry would be willing to accept a small increase in overall weight, it as a whole is highly unlikely to adopt a redesign concept that will result in substantially higher capital investment in new buildings driven by material costs.

It also not felt that these factors fully represent the true nature of the complexity of a structure and how an operator interacts with it when involved in the coating process. This element of the problem was introduced as part of the structural interaction in Chapter 5.

6.4 Investigation of the Structural Performance of Single Stiffener Plate Combinations

The initial study achieved equivalence by ensuring that each stiffened panel provided the same section modulus. It was however felt necessary to carry out numerical analysis of the different stiffened panel's structural behaviour. ***Benson* (*2011*)** developed '*AutoPanel*' which is a program that builds a Finite Element (FE) model based on the principal dimensions that are input via an Excel spread sheet. The program allows the ultimate strength of the plate stiffener combination to be assessed. In constructing the FE models the following settings where adopted, yield strength of steel set as 245MP; boundary conditions where fully fixed one end, with the edges and opposing end only allowed to move in the *X* plane, the imperfections included where average.

The program assesses the structural response of the tee, angle and flat bar sections using the dimensions of those discussed in the previous section. Figure 6-7 shows the load shortening curves for the tee bar plate stiffener combinations with aspect ratios from 0.5 to 5 as designated by ARx_x in Figure 6-7. The results show that the stiffener plate combination of 0.5 and 1.0 have greater ultimate strength but the post collapse behaviour is worse due to buckling and tripping of the flanges, which would reflect the fact that the column slenderness for those panels was very close to the acceptable limits previously discussed.

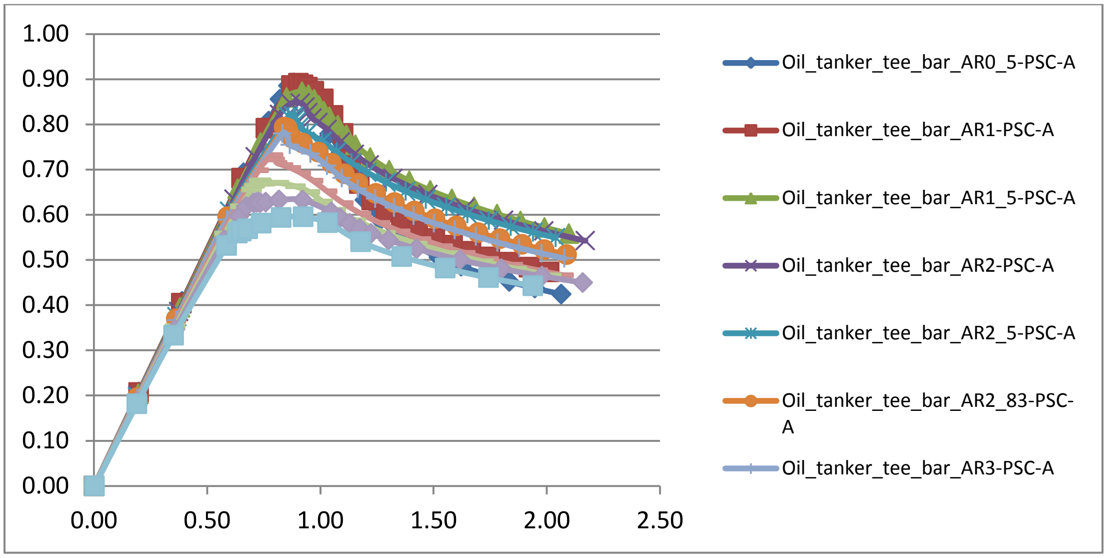


Figure 6-7 Tee bar ultimate strength curves for different aspect ratios

Figure 6-8 shows those stiffeners in the feasible region, those stiffeners with an aspect ratio between 1.5 and 3. Although the ultimate strength of the lower aspect ratio plates is higher, when the increased weight, as shown in Figure 6-2, is considered then they do not provide a ‘better’ or more efficient structural solution.

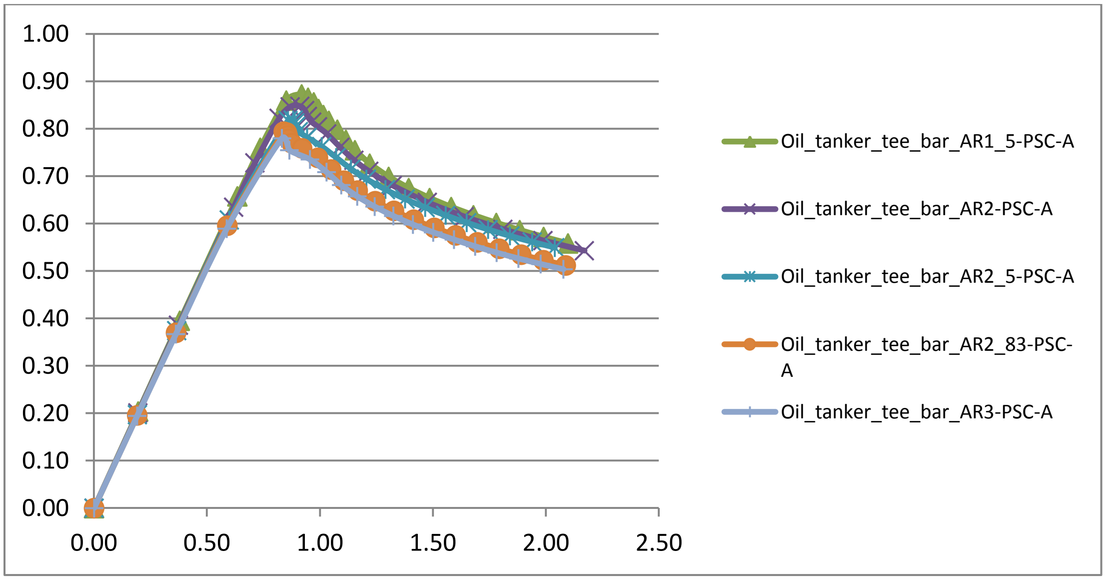


Figure 6-8 Ultimate strength of plates in the feasible region

The *AutoPanel* program produces finite element plots for each of the stiffeners. Each point on the ultimate strength graphs in Figure 6-7 and Figure 6-8 represents an individual step in the finite element analysis process. Displaying all of these plots is unfeasible; as such a typical plot for the benchmark structure is shown in Figure 6-9, and Figure 6-10. The first plot shows the levels of stress before failure and the second at the point of failure. In should be noted that the distortion scale factor has been increased to allow visual recognition of the distortion of the plate stiffener combinations.

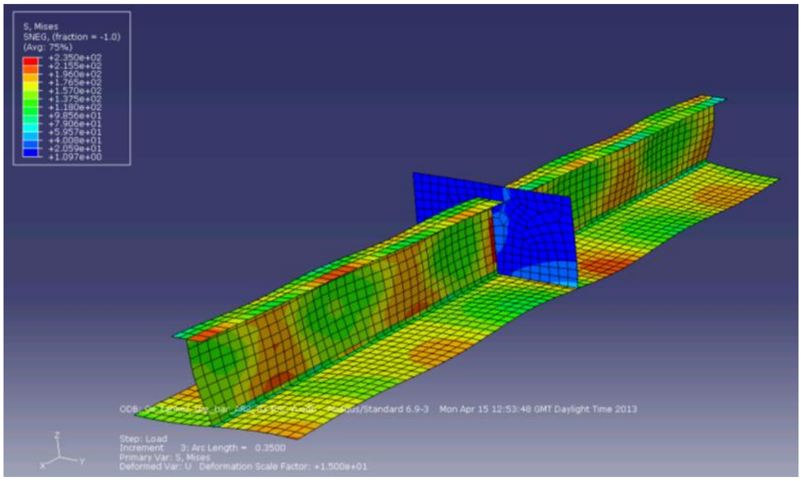


Figure 6-9 T bar stiffener Abaqus plot before failure

Figure 6-10 shows the localised areas of increasing stress and the plate beginning to buckle; this is accompanied with deformation of the stiffener web and flange.

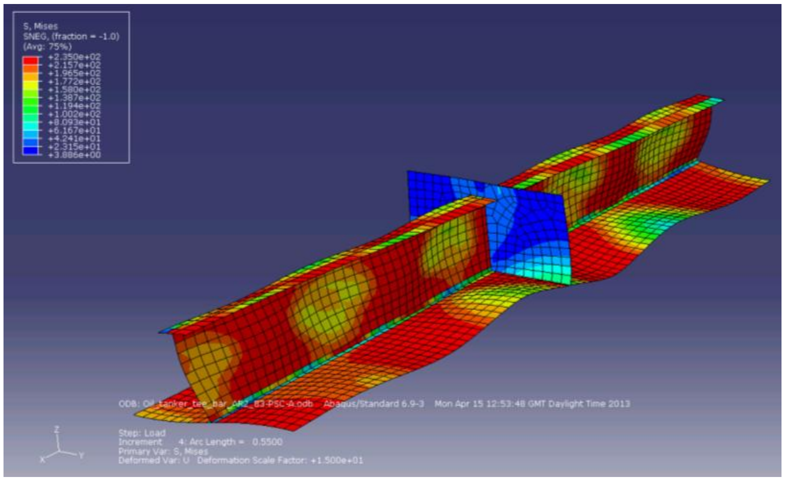


Figure 6-10 T bar stiffener Abaqus plot before failure

Figure 6-10 shows how overall the stress levels are far higher throughout the plate stiffener combination, with buckling occurring in both the plate and the web of the stiffener.

The results of the single stiffener study where based upon achieving equivalence in terms of section modulus, which results in increased values of β as the aspect ratio increased. Therefore it is not possible to plot the results for column slenderness against ultimate strength for constant values of plate slenderness. A subsequent study was undertaken for the stiffeners within the feasible region whereby an addition variable was created for the plate thickness to allow the plate slenderness to be altered in discrete steps whilst maintain section modulus. The stiffeners used in this study only covered a small portion of the range proposed by Chalmers in Figure 3-9, however the influence of the plate slenderness on the ultimate strength is clear to see.

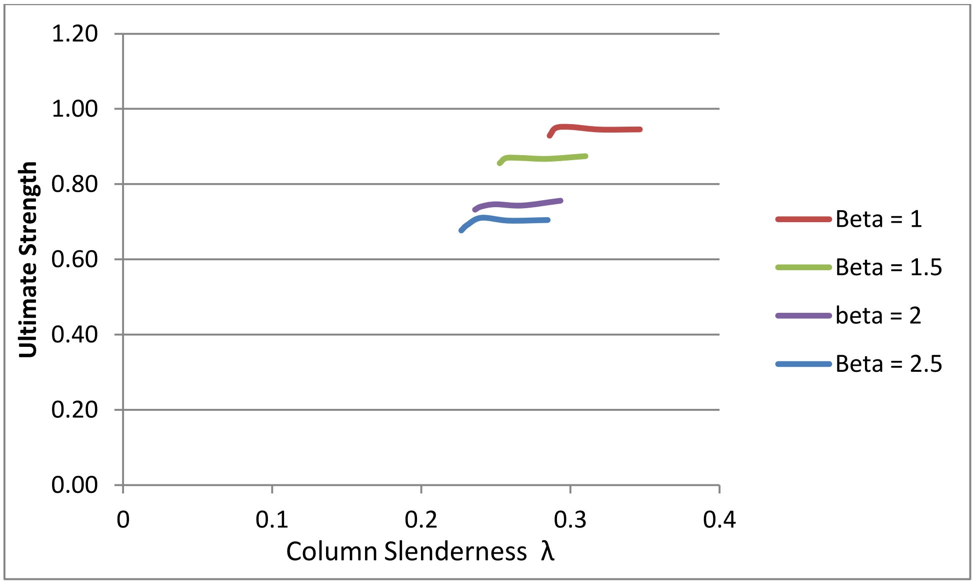


Figure 6-11 Column Strength curves for Constant Beta

The influence of the plate and column slenderness ratios will be discussed further in Chapter 7, including the influence these parameters have on the complexity and ultimately on the costs associated with production.

6.5 Consideration of the Investigation of the Influence of Surrounding Structure

In addition to the fundamental factors that have been discussed and selected as a means to quantify complexity that are direct measures of the plate geometry, there is a need for an additional measure related not just to the geometry but also the interaction between the arrangement of the structure and the physical activities of the coating process. To extend the visible arc concept previously discussed, the interaction between the working arcs of adjacent stiffeners becomes increasing complicated for larger panels and when considering transverse structural items. Thus to capture some of the subtleties of the interaction between coating process operators and the structure, the extent of surface area that does not provide adequate standoff has been calculated. If the stiffener web height and spacing is greater than the minimum requires standoff, d_{iso}, then there is negligible effect as shown in Figure 6-12.

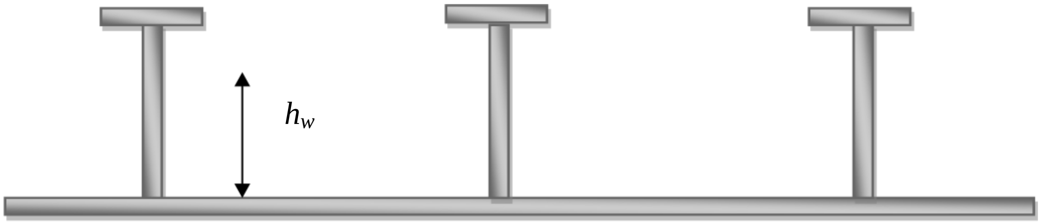


Figure 6-12 Stiffeners with spacings and web height greater larger than d_{iso}

If the web height is less than the minimum standoff then access to the backside of the flanges becomes restricted as shown in Figure 6-13.

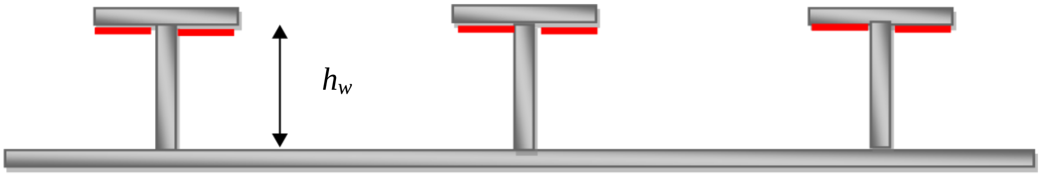


Figure 6-13 Stiffeners with web height less than d_{iso}

If the web height and the distance between the flanges is less than the minimum standoff then access to the backside of the flanges becomes restricted as shown in Figure 6-14.

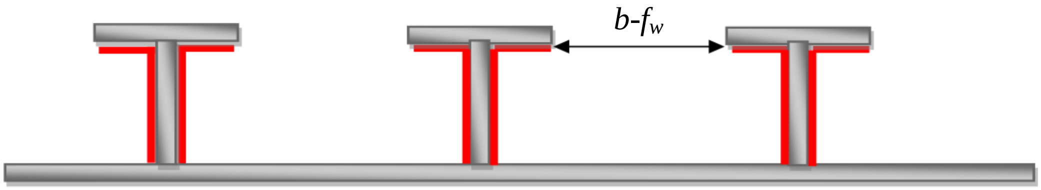


Figure 6-14 Stiffeners with web height and flange distance less than d_{iso}

If the web height and the stiffener spacing is less than the minimum standoff then access to the backside of the flanges becomes restricted as shown in Figure 6-15

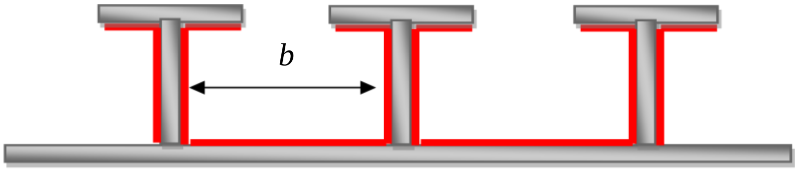


Figure 6-15 Stiffeners with web height and stiffener spacing less than $\mathbf{d_{iso}}$

This results in distinct regimes as shown in Figure 6-15 to 6-15:

- $h_w < d_{iso}$
- $b\text{-}f_w < d_{iso}$
- $b < d_{iso}$

For $h_w < d_{iso}$ the associated amount of area is;

$$\boldsymbol{a_{web} = nl_{sl}[2(f_w - w_t)] + nl_{st}[2(f_w - w_t)]} \qquad 6\text{-}1$$

For $b\text{-}w_f < d_{iso}$ the associated amount of area is;

$$\boldsymbol{a_{stiffener} = nl_{sl}[2w_h + (f_w - w_t)] + nl_{st}[2w_h + (f_w - w_t)] - \left[(nS_l \times nS_t) \times \left((w_h \times w_t) + (w_f - w_t)\right)\right]} \qquad 6\text{-}2$$

For $b < d_{iso}$ the associated amount of area is;

$$\boldsymbol{a_{flange} = nl_{sl}[2w_h + 2(f_w - w_t)] + nl_{st}[2w_h + 2(f_w - w_t)] - \left[(nS_l \times nS_t) \times \left((w_h \times w_t) + (w_f - w_t)\right)\right]} \qquad 6\text{-}3$$

The first describes the scenario where the height of the web is less than that of the minimum recommended by the ISO 12944 (d_{iso}). The second where the distance between the flanges of the stiffeners is less than and the third is where the stiffener spacing is less than d_{iso}. These three regimes cover the coating access problems associated with short stiffeners, stiffeners with wide flanges and closely spaced stiffeners. Therefore:

$$\boldsymbol{A_{min} = f\ [d_{iso}, b, f_w, h_w]} \qquad 6\text{-}4$$

And is calculated testing for the three conditional causes stated above. The problem is that typical longitudinal and transverse stiffener spacings are similar to the standoff distance recommended by ISO 12944, namely 600 mm. Therefore if the influence of stiffener dimensions are taken into account access is generally far from ideal and such complexity is to the determent of the coating process.

Before any calculations are carried out consider the three levels of access limitation; both the area on the reverse of the webs and the limitation of access to the 'bay' can be limited by using high aspect ratio tee stiffeners, this solution will also provide a good structural solution as it maximises the depth of the web which is dominant in providing moment of inertia.

The issue of stiffener spacing was discussed in more detail in chapter 4, briefly conventional wisdom has converged on a solution whereby typically stiffeners are spaced every 600 mm. Based on the recommendations based on ISO 12499, this spacing does not provide adequate access for surface preparation and paint application activities. To calculate the amount of area below the minimum specified distance was then added to the Complexity Index presented below to provide a more representative measure of the complexity of a given space, as shown in Equations 6-5 and 6-6.

$$\boldsymbol{C_{Am} = \frac{A_{min}'_{Variant}}{A_{min}'_{Basis}}} \qquad 6\text{-}5$$

$$\boldsymbol{CI = \sum_{i=1}^{6} w_1 C_{FE} + w_2 C_{WL} + w_3 C_A + w_4 C_{Am} + w_5 C_{Anv} + w_6 C_{Larc}} \qquad 6\text{-}6$$

By using multiple IF statements in Excel it was possible to determine the smallest distance between two elements on the orthogonally stiffened panel. It was then possible to determine the percentage of the total surface area that these areas represented. This worked for relatively simple structures where only one of the principle dimensions fell below the threshold, with manual interaction required to achieve the desired result. With the inclusion of this calculation the physical interaction between an operator and the structure will be better represented. An additional point to consider in this context is that of limiting the maximum height of the stiffeners. Although maximising the height of the web provides a greater amount of second moment of area, if the height becomes too large, greater than perhaps 750 mm, then moving between one bay and the next will be more difficult for the coatings operator.

6.6 Initial Stiffened Panel Complexity Cause and Effect Study

To expand the study, a panel between frames from the ‘typical’ WBT was selected to form the basis for an extended cause and effect study. The stiffeners on the panel are the same scantlings as those in the last study. The panel is 16.14 m by 3.8 m and represents the longitudinal structure between transverse frames on one side of the vessel in way of the double bottom tank. The stiffeners are fabricated tee bar stiffeners 425 × 11 × 150 ×16 mm with a spacing of 850 mm, equating to 18 stiffeners over the complete panel. The relationship between the complexity measures has again been considered but now with respect to the number of stiffeners. Additionally the extent of the area below the minimum working distance has been included as well as the free edge and weld length. Again graphs for the attributes discussed previously have been plotted with the addition of the amount surface area that has restricted access to it:

- Free edge length associated with all plate and stiffener features, l_{FE};
- Weld length of all plate and stiffener joints, l_W;
- Total surface area of complete structure, A_T;
- Percentage of total area which falls below a minimum offset distance A_{min}.
- Non visible area, A_{nv};
- Stiffener shadow arc length, l_s;

The complexity factors have been normalised with respect to the initial design point i.e. the ‘typical’ tanker plate stiffener combination, with the weighting factors set as equal, and plotted against the number of stiffeners whilst maintaining the section modulus. Those plate stiffener combinations that did not meet the structural acceptance criteria have not plotted. Table 6-1 shows the results of the from the first panel study where the web height was idealised by being altered in discrete 25 mm steps. The flange size was selected to maintain aspect ratio, at 2.82, and thickness selected to provide required section modulus as the number of stiffeners was altered. It should be noted that having variables for the thickness of the web, flange and plate, proved to very time consuming, to combat this plate thickness was set as a the only variable, and fixed ratios determined to both the flange and the web thickness. The study examined the influence of both increasing and reducing number of stiffeners, thus the study ranges from 20 to 12 stiffeners, with panel 3 representing the benchmark panel with 18 stiffeners. The values of total free edge etc are relative to the bench mark.

Table 6-1 Initial Panel Complexity Factors

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9
Web Height (m)	0.375	0.4	0.425	0.45	0.475	0.5	0.525	0.55	0.575
Flange Width (m)	0.133	0.142	0.15	0.159	0.168	0.177	0.186	0.195	0.203
Thickness (m)	0.0179	0.0168	0.016	0.0155	0.0152	0.0152	0.0154	0.0159	0.0166
Aspect ratio	2.820	2.817	2.833	2.830	2.827	2.825	2.823	2.821	2.833
Number of Stiffeners	20	19	18	17	16	15	14	13	12
Total Free Edge (m)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722	0.667
Total Weld Length (m)	1.097	1.048	1.000	0.952	0.903	0.855	0.806	0.758	0.709
Total surface Area (m^2)	0.991	0.998	1.000	1.000	0.996	0.988	0.977	0.962	0.943
Non visible area (m^2)	0.974	0.992	1.000	1.003	0.998	0.987	0.968	0.942	0.908
Panel weight (tonnes)	1.111	1.048	1.000	0.969	0.948	0.943	0.948	0.969	0.998
Total arc length (m)	1.065	1.038	1.000	0.968	0.933	0.896	0.856	0.813	0.763
Total area below min distance (m^2)	0.968	0.992	1.000	1.007	1.006	0.996	0.979	0.954	0.917
Complexity (CI)	1.034	1.021	1.000	0.979	0.954	0.926	0.894	0.859	0.818

Figure 6-16 and Figure 6-17 demonstrate how all of the complexity factors increase as the number of stiffeners increases. The limiting factor in this study was the plate buckling, β, exceeding the upper bound constraint of 2.5 for less than 12 stiffeners. Details of the exact stiffeners sizes can be found in Appendix B. As would be expected weld length, free edge length and the total arc length have a linear response to the number of stiffeners. It is interesting to note that the response of the surface area and non-visible area to the number of stiffeners is such that it can be reduced by either increasing or reducing the number of stiffeners. By increasing the number of stiffeners the individual stiffeners become smaller, with a corresponding reduction in surface area. Whereas reducing the number of stiffeners reduces the overall surface area despite the stiffeners becoming larger.

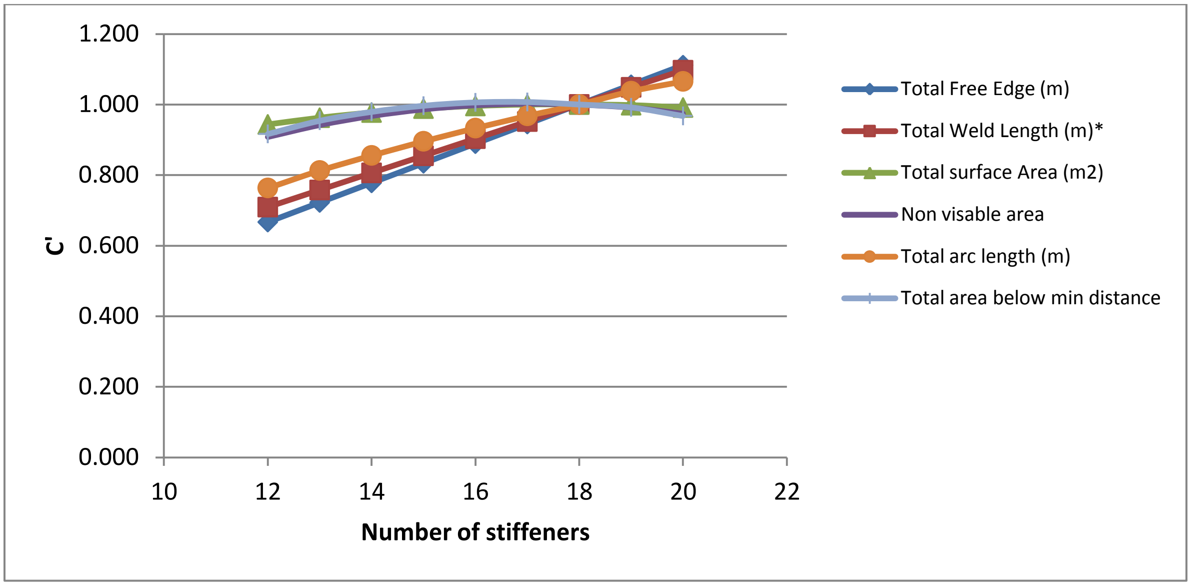


Figure 6-16 Initial plate study complexity factors

Figure 6-17 shows plots of the aggregated complexity index, *CI*', and weight as the number of stiffeners is varied. If weight is plotted against complexity it is clear that there is certainly scope to reduce the complexity of a design and reduce weight. This is considered to add credence to the contention that the needs of the coating process should be an integral consideration throughout the design process, and can be included without penalising other aspects of design, whilst actually resulting in both newbuild and operational benefits.

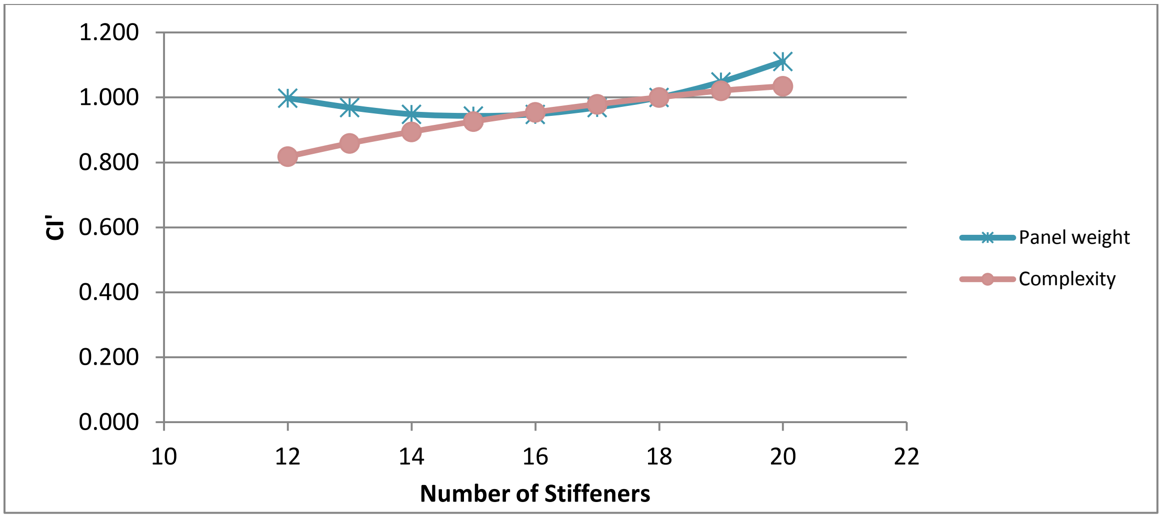


Figure 6-17 Initial plate study weight and complexity

Table 6-2 shows the potential percentage savings for each of the complexity factors for each of the different panels when structural equivalence is ensured by maintaining the section modulus.

Table 6-2 Initial Panel percentage reductions

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9
Stiffener Number	20	19	18	17	16	15	14	13	12
Total Free Edge	-11.1	-5.6	0.0	5.6	11.1	16.7	22.2	27.8	33.3
Total Weld Length	-9.7	-4.8	0.0	4.8	9.7	14.5	19.4	24.2	29.1
Total stripe coat length	-11.1	-5.6	0.0	5.6	11.1	16.7	22.2	27.8	33.3
Total surface Area	0.9	0.2	0.0	0.0	0.4	1.2	2.3	3.8	5.7
Non visible area	2.6	0.8	0.0	-0.3	0.2	1.3	3.2	5.8	9.2
Panel weight	-11.1	-4.8	0.0	3.1	5.2	5.7	5.2	3.1	0.2
Total arc length	-6.5	-3.8	0.0	3.2	6.7	10.4	14.4	18.7	23.7
Total area below min distance	3.2	0.8	0.0	-0.7	-0.6	0.4	2.1	4.6	8.3
Complexity	-3.4	-2.1	0.0	2.1	4.6	7.4	10.6	14.1	18.2

Further investigation of the multiple stiffened panels was needed to ensure that realistic solutions were presented. Closer inspection of the results of this study noted that as the web height increased the flange width also increased to maintain the overall aspect ratio and the thickness of the web reduced. This is contradictory to accepted convention, namely as the web gets larger the thickness should increase proportionally to prevent problems with buckling or tripping of the stiffener web.

6.7 Further Stiffened Panel Complexity Cause and Effect Study

A second study was undertaken where the thickness was incrementally increased by 0.5 mm as the number of stiffeners was altered. Again the web height and flange sizes where selected accordingly to provide the required section properties. It should be noted that in some cases the thickness was further rationalised to achieve this outcome. Table 6-3 shows the results of this study which represents what is considered a more realistic range of solutions. Again the results have been normalised relative to the benchmark structure.

Table 6-3 Second Panel Complexity factors

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8
Web Height (m)	20	19	18	17	16	15	14	13
Flange Width (m)	0.400	0.410	0.425	0.430	0.440	0.450	0.460	0.470
Thickness (m)	0.142	0.145	0.15	0.152	0.155	0.16	0.162	0.166
Aspect ratio	0.0164	0.0164	0.016	0.0165	0.0167	0.017	0.0175	0.018
	2.82	2.83	2.83	2.83	2.84	2.81	2.84	2.83
Number of Stiffeners	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722
Total Free Edge (m)								
Total Weld Length (m)	1.097	1.048	1.000	0.952	0.903	0.855	0.806	0.758
Total surface Area (m^2)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722
Non visible area (m^2)	1.027	1.011	1.000	0.975	0.955	0.935	0.910	0.887
Panel weight (tonnes)	1.045	1.017	1.000	0.955	0.920	0.884	0.841	0.798
Total arc length (m)	1.044	1.033	1.000	1.013	1.011	1.014	1.026	1.037
Total area below min distance (m^2)	1.092	1.043	1.000	0.951	0.900	0.861	0.803	0.755
Complexity (CI)	1.046	1.016	1.000	0.956	0.918	0.889	0.839	0.798
Web Height (m)	1.070	1.032	1.000	0.956	0.914	0.876	0.830	0.786

Figure 6-18 demonstrates how all of the complexity factors continue to increase as the number of stiffeners increases, however the sensitivity is slightly less when compared to the previous multiple stiffener study.

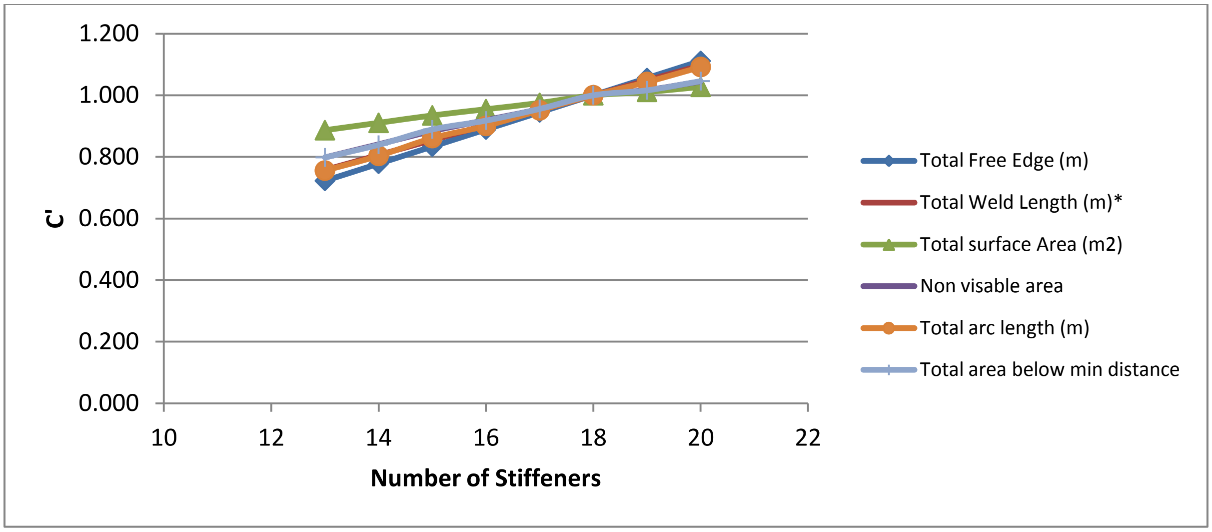


Figure 6-18 Second study complexity factors

The most significant divergence between this and the first panel study is shown in Figure 6-19, where the complexity index and weight plots are shown. It demonstrates that although it is still possible to reduce the complexity there is much less opportunity to reduce the weight of the panel. It is likely that by reducing the number of stiffeners there will be a slight overall gain in the weight.

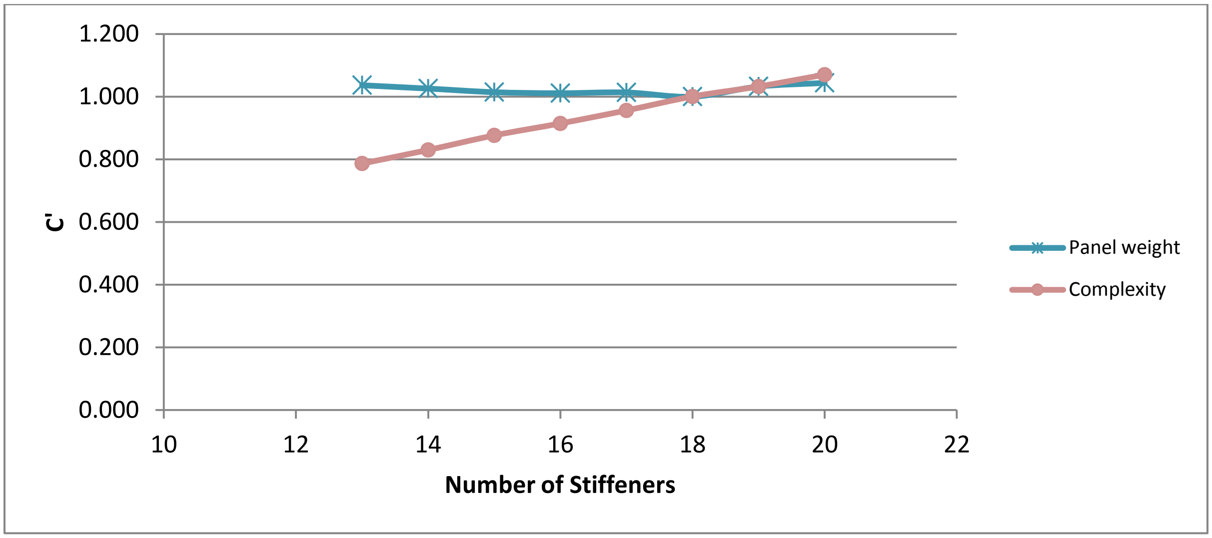


Figure 6-19 Second study on complexity and weight

Table 6-4 shows the potential percentage savings for each of the complexity factors for each of the different panels.

Table 6-4 Second Panel study percentage savings

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8
Web Height (m)	0.375	0.4	0.425	0.45	0.475	0.5	0.525	0.55
Flange Width (m)	0.133	0.142	0.15	0.159	0.168	0.177	0.186	0.195
Thickness (m)	0.0179	0.0168	0.016	0.0155	0.0152	0.0152	0.0154	0.0159
Aspect ratio	2.82	2.82	2.83	2.83	2.83	2.82	2.82	2.82
Number of Stiffeners	20	19	18	17	16	15	14	13
Total Free Edge (m)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722
Total Weld Length (m)	1.097	1.048	1.000	0.952	0.903	0.855	0.806	0.758
Total surface Area (m^2)	0.991	0.998	1.000	1.000	0.996	0.988	0.977	0.962
Non visible area (m^2)	0.974	0.992	1.000	1.003	0.998	0.987	0.968	0.942
Panel weight (tonnes)	1.111	1.048	1.000	0.969	0.948	0.943	0.948	0.969
Total arc length (m)	1.065	1.038	1.000	0.968	0.933	0.896	0.856	0.813
Total area below min distance (m^2)	0.968	0.992	1.000	1.007	1.006	0.996	0.979	0.954
Complexity (CI)	1.034	1.021	1.000	0.979	0.954	0.926	0.894	0.859

This study shows that there is still opportunity to reduce the free edge and weld length but that this is likely to result in a small overall increase in the weight of the panel. Therefore a cost benefit analysis needs to be undertaken to determine whether the increase in steelwork costs can be offset against a reduction in the work content and the related labour costs, with the associated potential increases in operating costs as a result of a heavier lightship.

As the labour required to perform the coating process represents a significant proportion of the overall labour cost of building a ship, there is clear evidence to support the views of ***Rigo***, (***2001***) that an optimum design solution cannot be found if the objective function is to minimise the weight of the structure. A truly optimised solution will be one that delivers a minimum cost solution where all of the design, production and operational costs are accounted for.

This study has highlighted the limits of the increasing the stiffener spacing. The sensible lower limit based upon the structural constraints on the number of stiffeners would appear to be around fourteen stiffeners which translates to a stiffener spacing of 1076 mm for this panel. This represents an increase in stiffener spacing of approximately 220 mm, thus there is a clear indication that increasing the longitudinal stiffener spacing to a greater than the ISO minimum working distance will provide improvements to the coating process. Therefore based upon the conventional approach there is an opportunity to realise some of the benefits in terms of complexity and weight reduction.

6.8 A Proposed Approach to Quantify Overall Compartment Complexity

The previous studies have investigated the complexity of single and multiple plate stiffener combinations. In calculating complexity, rather than using more complex feature based measures, production quantities commonly used for work content and cost estimation have been selected as these are readily available for use in modern production software. The primary level is the complexity factors for an individual stiffener. The secondary level is the summation of the complexity factors for all of the stiffeners on a panel. At the tertiary level it is summation of all of the panels in a compartment. This hierarchy is shown in Table 6-5 and could be extended in an attempt to provide a measure for the complete ship.

Table 6-5 Complexity measures and associated hierarchy

Level	Structural component	Complexity measures				
Primary	i^{th} stiffener and associated plating	a_{nv_i}	l_{s_i}	a_{s_i}	l_{fe_i}	l_{w_i}
Secondary	j^{th} panel	$A_{nv_j} = \sum_{i=1}^{n} a_{nv_i}$	$L_{s_j} = \sum_{i=1}^{n} l_{s_i}$	$A_{t_j} = \sum_{i=1}^{n} a_{s_i}$	$L_{fe_j} = \sum_{i=1}^{n} l_{fe_i}$	$L_{w_j} = \sum_{i=1}^{n} l_{w_i}$
Tertiary	Compartment or 3D unit	$\sum_{j=1}^{n} A_{nv}$	$\sum_{j=1}^{n} L_s$	$\sum_{j=1}^{n} A_t$	$\sum_{j=1}^{n} L_{fe}$	$\sum_{j=1}^{n} L_w$

The intention here is to consider the problem at a compartment level and to ensure changes suggested are compatible with the overall structural design of the vessel and implications for the hull girder. Putting the emphasis on summating the constituent panels within a compartment allows future development to account for more complex shapes such as those found in the ends of a ship. In essence it is possible to separate a complex shape into a number of discrete panels and build up an entire space in this manner.

This arrangement would hold true for the majority of the vessel especially within the parallel mid body of the vessel, where the ship can be viewed as a series of cube like sections. Considering more complex sections of a vessel such as the fore and after peak tanks, which have large amounts of curvature in the panels that constitute the compartment it may be possible to divide panels with curvature into a number of smaller 'flatter' panels. In this case complexity can be said to be a function of the number of 'flat' panels required to define a space.

Further exploration of summing the complexity of a space and ultimately a ship has shown how ***Caprace*** and ***Rigo*** (***2010***) investigated the complexity of the steel structure within ten passenger ships. The study used equation 6-7 to calculate the complexity of some 3500 structural sections each one containing 500 individual steel components.

$$\boldsymbol{C_T = \frac{w_1 C_{sh} + w_2 C_{as} + w_3 C_{mt}}{w_1 + w_2 + w_2}} \qquad \text{6-7}$$

Where C_{sh} is the shape or manufacturing complexity;

C_{as} is the assembly sequence or process complexity;

C_{mt} is the material complexity.

The authors note that the areas of highest complexity is generally located in the bottom part of the vessels as well and the fore and aft sections were large amounts of curvature exists. The use of the three elements of the complexity index can lead the designer to revise the appropriate design variables in order to reduce the global complexity of the ship during the design space. The paper also notes that the ships structure may be altered in such a way as to standardise the scantlings and simplify the shape of the components, to eliminate unnecessary welding and other sources of production costs.

6.9 Seeking Solutions to Reduce the Complexity of Water Ballast Tank Structures

The insight gained from the cause and effect studies highlighted the relationships between the topology of the structure and its complexity and weight. Due to the time consuming nature of these studies a more efficient method was needed to explore a large range of design solutions. In order to reach an optimum workable design a designer needs a certain degree of experience when considering the trade-off between these criteria. ***Pike***, (***1985***) defined the three basic components that are required to optimize a given industrial process. First, a mathematical model is required, and the process variables which can be manipulated and controlled must be known. Secondly, an economic model of the process is required. This is an equation that represents the profit made from the sale of products and costs associated with their production, such as raw materials, operating costs, fixed costs, etc. Finally, an optimization procedure must be selected which locates the values of the independent variables of the process to produce the maximum profit or minimum cost as measured by the economic model. Also, the constraints in materials, process equipment, manpower, etc. must be satisfied as specified in the process model.

Traditional numerical optimisation methods used scalar optimisation criterion, which are known as objective functions, measures of merit, or cost functions ***Parsons*** and ***Scott*** (***2004***). For concept designs were there are a large number of conflicting criteria there is no single optimum, what tends to be produced is a set of solutions often known as the Pareto optimum. To arrive at a single answer within the Pareto set requires a large amount of time to consider every one of the solutions, this become increasingly difficult if there are more than three criteria.

The design vector characterising the scantlings of the plate and associated stiffener were defined as:

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{f_t} \\ \boldsymbol{f_w} \\ \boldsymbol{w_t} \\ \boldsymbol{w_h} \\ \boldsymbol{t_p} \end{bmatrix} \tag{6-8}$$

In this case the design vector was initially applied to a single plate tee stiffener combination. The individual objective functions investigated to minimise were:

$$\boldsymbol{f_1(X) = \mathit{Complexity\ Index}} \tag{6-9}$$

$$\boldsymbol{f_2(X) = \mathit{Weight}} \tag{6-10}$$

The constraint set limiting scantlings and structural indices was defined as:

$$\boldsymbol{0.100 \le w_h \le 0.700} \tag{6-11}$$

$$\boldsymbol{0.009 \le w_t \le 0.030} \tag{6-12}$$

$$\boldsymbol{0.075 \le f_w \le 0.500} \tag{6-13}$$

$$\boldsymbol{0.010 \le f_t \le 0.030} \tag{6-14}$$

$$\boldsymbol{2 \le \frac{w_h}{f_w} \le 3} \tag{6-15}$$

$$\boldsymbol{25 \le \frac{w_h}{w_t} \le 45} \tag{6-16}$$

$$\boldsymbol{8 \le \frac{f_w}{f_t} \le 25} \tag{6-17}$$

$$\mathbf{z = 2.42x10^{-2}} \tag{6-18}$$

$$\mathbf{1.0} \leq \boldsymbol{\beta} \leq \mathbf{2.5} \tag{6-19}$$

Where:

$$\boldsymbol{\beta} = \frac{\boldsymbol{b}}{\boldsymbol{p_t}} \cdot \sqrt{\frac{\boldsymbol{\sigma_y}}{\boldsymbol{E}}} \tag{6-20}$$

$$\mathbf{0.1} \leq \boldsymbol{\lambda} \leq \mathbf{0.45} \tag{6-21}$$

$$\boldsymbol{\lambda} = \frac{\boldsymbol{l_{eff}}}{\boldsymbol{\pi k}} \cdot \sqrt{\frac{\boldsymbol{\delta_y}}{\boldsymbol{E}}} \tag{6-22}$$

$$\boldsymbol{A_r} = \frac{\boldsymbol{A_{stiffener}}}{\boldsymbol{A_{stiffener}A_{plate}}} \tag{6-23}$$

$$\boldsymbol{A_r} \geq \mathbf{0.1} \tag{6-24}$$

Scott and Parsons (***2004***) present a sound definition of the difference between Multicriterion versus multidisciplinary, as they are not synonymous and are often confused. Multicriterion optimisation refers to a number of specific criteria greater than one used to make the design optimisation decision. This is a particular type of mathematical programming optimisation problem. Multidisciplinary optimisation or multidisciplinary design optimisation (MDO) is an overall philosophy or approach to engineering design that focuses on system wide optimisation in lieu of using only subsystem optimisation within each discipline.

Adopting a system wide optimisation approach often returns results which are at least as good as, and often better than isolated optimisation within each discipline or subsystem. Multicriterion optimisation problems are found in many different fields not only in engineering. They exist where ever decisions are needed between two or more competing objectives, which in this case are minimising the complexity and the weight of a structure.

Rigo, (***2001***) presents a clear and concise review of the development of the optimisation process for the design of ship structures. He discusses the different meanings attached to ‘ship structural optimisation’ based on the group carrying out the process. He also notes that the most of methods deal with mathematical optimisation tools and methods for predicting limit states for aspects such as strength or deflection. There are few articles in the public domain that create a cost objective function for the construction of a ship or structure.

When conflicting multiple criteria are present, the most common definition of an optimum is Pareto optimality, which was articulated by the Italian-French economist V. Pareto in 1906. This is also referred to as Edgeworth-Pareto optimality (***Stadler 1988***, ***Statnikov 1999***):

"A point is Pareto optimal if it satisfies the constraints and is such that no criterion can be further improved without causing at least one of the other criteria to decline".

It should be noted that this highlights the conflicting nature of the relationships between the criteria. A solution can be classed as Pareto optimal if it satisfies the constraints and one criterion remains constant while at least one of the other criteria declines. These definitions typically result in a set of optimal solutions rather than a single unique solution. The difficulty with this method that arises is that a design team will typically require a single result that provides a suitable compromise between the different conflicting criteria.

A distinction can be drawn between two different approaches when considering the role of the decision maker, a priori approach requires all knowledge about the relative importance of the objectives before staring the process. Whereas a posteriori approach delivers a large representative set of Pareto optimal solutions from which it is possible to select a preferred one. In an interactive approach some Pareto optimal solutions are produced with feedback from the decision maker, this allows better tuning of the preferred combinations of the objectives.

Total cost is comprised of material, labour and consumable costs thus:

$$\boldsymbol{FC = F_{MAT} + F_{CONS} + F_{LAB}} \tag{6-25}$$

Where:

$$\boldsymbol{F_{MAT} = \gamma . L . B . \left[C_1 . \delta + C_2 \frac{(h.d+w.t)_X}{\Delta_X} + C_3 \frac{(h.d+w.t)_Y}{\Delta_Y} \right]} \tag{6-26}$$

$$\boldsymbol{C_1 = C_1^0 [1 + \Delta C_1 (\delta - E_0) 10^3]} \tag{6-27}$$

$$\boldsymbol{C_2 = C_1^0 \left[1 + \alpha_X . \Delta_{C_2}\right]} \tag{6-28}$$

$$C_3 = C_1^0\left[1 + \alpha_Y \Delta_{C_3}\right] \tag{6-29}$$

And

$$F_{CONS} = L.B.\left[\frac{2-\alpha_X}{\Delta_X} + \frac{2-\alpha_Y}{\Delta_Y}\right].C_8 \tag{6-30}$$

$$C_8 = C_8^0[1 + \Delta C_8] \tag{6-31}$$

And

$$F_{LAB} = \varepsilon.k.C_1^0.WLOAD \tag{6-32}$$

$$F_{LAB} = L.B.\left[\frac{1}{\Delta_X}.P_4 + \frac{1}{\Delta_Y}.P_5 + \frac{1}{\Delta_X.\Delta_Y}(P_6 + \beta_X.\beta_Y.P_7) + \frac{1-\alpha_X}{\Delta_X}.P_9(X) + \frac{1-\alpha_Y}{\Delta_Y}.P_9(Y) + P_{10}\right] \tag{6-33}$$

$$P_4 = P_4^0[1 + (d_X - E_0).10^3.\Delta P_4] \tag{6-34}$$

$$P_5 = P_5^0[1 + (d_Y - E_0).10^3.\Delta P_5] \tag{6-35}$$

$$P_9(X) = P_9^0[1 + (d_X - E_0).10^3.\Delta P_9] \tag{6-36}$$

$$P_9(Y) = P_9^0[1 + (d_Y - E_0).10^3.\Delta P_9] \tag{6-37}$$

$$P_{10} = P_{10}^0[1 + (\delta - E_0).10^3.\Delta P_{10}] \tag{6-38}$$

The approach currently the most comprehensive cost model for panels however it is the authors belief that that this approach also tends towards lower weight solutions as the term C_1^0 is a measure of the cost per kg of a plate at a specified thickness.

Recently works of ***Rigo*** (***2001***), ***Caprace*** and ***Rigo*** (***2010***), ***Caprace et al***. (***2010***), ***Caprace*** and ***Rigo*** (***2011***) discuss the issues associated with the practice of designs that are optimised for minimum weight, rather than for a minimum cost. As the cost of steel is one of the major expenditure around 8% of the cost of the vessel in shipbuilding, there is a belief that minimising the steel weight will provide the most cost effective means of building a ship. The labour cost accounts for almost double that of the steel weight; and those minimum weight solutions often increase the work content of a given structure. The cost of redesigning for a minimum cost solution must also be accounted for thus an appropriate balance must be sort. Despite an extensive amount of work to develop software to determine an optimised initial design where the objective function is that of lowest overall cost, the work does not take into account the coating process, as it tends to focus on the labour content of the steelwork department.

6.10 Formulation of Optimisation Problem of Single Stiffener Plate Combinations

Pike (***1985***) provides a succinct overview of the development of the Generalized Reduced Gradient (GRG). This method if one of a range of techniques called reduced-gradient or gradient projection methods. The process used is based on extending methods for linear constraints to apply to nonlinear constraints. The variables are adjusted so the active constraints continue to be satisfied as the procedure moves from one point to another. The ideas for these algorithms were devised by ***Wilde*** and ***Beightler*** (***1967***) using the name of *constrained derivatives*, by ***Wolfe*** (***1963***) using the name of the *reduced-gradient method* and extended by ***Abadie*** and ***Carpenter*** (***1969***) using the name *generalized reduced gradient.*

The idea of generalized reduced gradient is to convert the constrained problem into an unconstrained one by using direct substitution. If direct substitution were possible it would reduce the number of independent variables to (n-m) and eliminate the constraint equations. However, with nonlinear constraint equations, it is not feasible to solve the m constraint equations form of the independent variables in terms of the remaining (n-m) variables and then to substitute to these equations into the economic model. Therefore, the procedures of constrained variation and Lagrange multipliers in the classical theory of maxima and minima are required. There, the economic model and constraint equations were expanded in a Taylor series, and only the first order terms were retained. Then with these linear equations, the constraint equations could be used to reduce the number of independent variables.

The GRG method was deemed to be most suitable due to the non-linear but continuous nature of the relationships that were developed during the cause and effect studies. The initial optimisation study sought to find a solution for each of the competing objectives, in this case complexity and weight, in order to establish their influence on the final solution for the single plate stiffener combinations. The problem was constructed in two concurrent problems with both minimum complexity and minimum weight as the objective functions.

A spread sheet was constructed, where the main dimensions of the stiffener namely; web height and thickness and flange width and thickness, where set as the design variables. Constraints were placed on the ratios between web height and flange width, and also between web height and thickness and flange width and thickness following the lessons learnt in both of the panel cause and effect studies. The section modulus of the original plate stiffener was calculated and also used as a constraint to ensure any solution provided adequate strength and stiffness. The structural indices discussed previously have also been used as constraints to ensure that structurally un-sound solutions are not presented, the resultant stiffener dimensions are shown in Table 6-6.

Table 6-6 Stiffener dimensions for initial optimisation study

	Benchmark $f_b(X)$	Complexity $f_1\,(X)$	Weight $f_2(X)$
Web Height (m)	0.425	0.376	0.373
Flange width (m)	0.150	0.125	0.187
Flange thickness (m)	0.016	0.016	0.023
Web thickness (m)	0.010	0.015	0.009
Relative complexity	1.000	0.921	1.099
Weight (tonnes)	0.989	1.050	0.974

The results of this study confirmed the cause and effect study’s findings that indicated the benchmark structure provides a good balance between the conflicting needs of steelwork and coating processes. Note the web heights are similar for both cases, however the flange widths vary significantly. Smaller flange widths reduce the total arc length and non-visible area and hence reducing the complexity. Table 2 shows the results of the minimum complexity objective function based on equal weighting of all the complexity factors in the aggregated total complexity. It shows that in this instance how the minimum complexity solution leads to a heavier plate stiffener combination.

These results confirm those that were presented earlier and that the topology of tee bar stiffeners has developed over time to very close to an optimum with respect to these considerations. There is a possibility of reducing the complexity of a stiffener plate combination but this will cause an increase in weight. There is only a very small opportunity to reduce the weight of the structure. This demonstrates the inherent conflict between weight and complexity.

What was very interesting to note from this study was that the initial design taken from the 'typical oil tanker' was somewhat removed from both of the solutions returned by the either of the optimisers. The results of this study indicated that the benchmark structure was not particularly optimum. Closer inspection of the structural performance as shown in Table 5-1 confirmed this in particular the area of stiffener to area of plate and stiffener ratio is, as the typical range is 0.1 to 0.2. Further investigation has proposed that the 'typical' oil tanker was one of the first designs for double hull tankers after OPA 90 was introduced. As a result of the relative lack of previous experience designers erred on the side of caution with these designs in the early days, resulting in relatively inefficient solutions.

6.11 Formulation of Optimisation Problem of Multi-stiffener Plate Combinations

6.11.1 Minimum Steelwork Costs Objective Function

The previous optimisation study was extended to a multi-stiffener panel where a number of discrete cases were taken with differing stiffener numbers in order to identify solutions with more beneficial longitudinal stiffener spacings. The design vector in this case becomes:

$$\boldsymbol{X} = \begin{bmatrix} \boldsymbol{f_t} \\ \boldsymbol{f_w} \\ \boldsymbol{w_t} \\ \boldsymbol{w_h} \\ \boldsymbol{t_p} \end{bmatrix} \qquad \text{6-39}$$

For $n = 14,15,16,17,18$ stiffeners as discrete cases.

In the calculation of the Complexity Index objective function in Equation 5-22, the first two terms vary as a function of the number of stiffeners. The weight objective function now also relates to the cross sectional area of the total number of stiffeners, *n*, and the entire plate cross sectional area and length associated with the panel. The objective functions previously considered were extended to also include cost as the inclusion of production cost is an important consideration in when seeking improved solutions, ***Pike*** (***1985***) and ***Parsons and Scott*** (***2004***). The additional cost objective functions were defined as:

$$\boldsymbol{f_3(X) = Steelwork\ costs} \tag{6-40}$$

$$\boldsymbol{f_4(X) = Coating\ costs} \tag{6-41}$$

$$\boldsymbol{f_5(X) = Total\ costs} \tag{6-42}$$

The same constraint set was employed as in the previous case, namely Equations 6-9 to 6-19 were applied to the panel to again ensure solutions were constrained to a feasible range of structural solutions.

The general multi-objective function problem was also considered:

$$\boldsymbol{F(X) = \sum_{i=1}^{4} f_i\,(X)} \tag{6-43}$$

A solution was sought on the basis of a normal weighted sum optimum, namely

$$\boldsymbol{P[f_i\,(X)] = \sum_{i=1}^{4}\left[w_i \frac{f_i(x)}{f_i^0}\right]} \tag{6-44}$$

or as:

$$\boldsymbol{P[f_i\,(X)] = \sum_{i=1}^{4}\left[w_i f'_i(X)\right]} \tag{6-45}$$

for the cases where i = 1 to 2 and i = 1 to 4. However to provide the insight sought in this study, the emphasis was placed on the individual objective functions as well as simply an aggregate cost function.

Detailed cost estimation models are not readily available in the public domain. The model proposed by ***Rigo***, (***2001***) provides a means of estimating the material, labour and consumables costs at a level consistent with the current study. ***Rigo***, (***2001***) states that the practice of optimisation for a minimum weight solution cannot be justified; it should be replaced by a least construction cost or, even better a minimum global cost, to include the in-service operation costs.

This echoes the proposal of ***Pike***, (***1985***) that to achieve a true optimum for any problem the economies associated with it must be included. ***Rigo***, (***2011***) presented the following method an objective function for estimation of the cost of building section of a ship as was described in Equation 6-25.

6.11.2 Minimum Coating Costs Objective Function

Following the approach of ***Rigo***, (***2001***), a cost estimation model of the coating process has been calculated for the different design solutions, this provides an estimate of the complete production cost, when taken with the steelwork cost previously defined. It is that if the coating process was easier to undertake then there is a higher probability that the finish of the coatings that are applied to that structure will be of a higher and more consistent quality, thus benefiting their in-service effective life span. Providing a measure of structural complexity not only gives an estimation of the cost of the application but also potentially provides an indication of the likely in-service performance of the applied coatings.

The cost of coating a structure is not conventionally included during the design process, but it is accepted that more complex designs require a greater labour input. Following a similar approach to that of Rigo, the cost of the coating process has been broken down into:

- Surface preparation and cleaning;
- Paint application;
- Inspection and ventilation.

To calculate the cost of the surface preparation and paint application activities they can be further broken down into materials and labour cost. The cost of the materials for surface preparation is based upon the method used, i.e. blasting or power tooling and the respective productivity rates for each method. There is an associated material consumption of either blast media or tooling discs and therefore a cost related. In order to completely cost the process would also require calculation of the power consumption for each of these processes. All of these are principally dependent on the overall surface area that needs preparing, but will also be affected by the complexity of the surface.

The cost of labour is dependent on the cost of labour per hour and the productivity of the workers, which is directly related to the complexity of the space. In addition to the overall cost of preparing the surfaces, is the time and cost required to grind the free edges within the WBT. At this stage the total coating labour costs have been multiplied by the relative complexity to provide an estimate of the influence of complexity on the coating process.

In terms of paint application again there is a distinction between material and labour costs, with both being affected by the complexity of the structure. Surveys of WBTs undertaken by the author would indicate that to ensure that the minimum DFT is achieved, more paint is applied to ensure that repeat applications are not required.

It should be noted there is very little published data on productivity rates for surface preparation and/or paint application. Estimates have been made in conjunction with the industrial partners involved with the project. This study has examined the relative benefits that could be achieved by using alternative designs, hence the actual productivity rate or cost per unit area is only needed for comparative purposes. Even for flat steel panels accurately predicting productivity rates for the coating process is very difficult. A range of typical rates are available for surface preparation rates and blast media consumption, but these do not directly account for any complexity within a given space. Coatings contractors typically apply conversion factors for different areas of a vessel e.g. outer hull, accommodation, tanks and machinery spaces. However, these factors are only applied at the macro scale and are based on experience rather than the actual topology of the structure.

The inspection costs are very much driven by time which is highly influenced by the overall number of structural items within a WBT as the PSPC defines how many reading are to be taken over the measured area. At this initial stage the inspection costs have not been calculated. Similarly it has been assumed that as ventilation is dependent of the overall volume of a given tank hence that the ventilation requirements will not change. However it is likely that reduction of complexity will remove ‘dead’ areas and thus improve the flow of air and promote better curing of the applied coatings. The coating cost method proposed is based on:

$$\textit{Coating costs} = \boldsymbol{FC_{Paint} = P_{Mat} + P_{lab}} \tag{6-46}$$

Where:

$$\boldsymbol{P_{Mat} = M_{Prep} + M_{Paint}} \tag{6-47}$$

$$\boldsymbol{P_{Lab} = L_{Prep} + L_{Paint}} \tag{6-48}$$

$$\boldsymbol{M_{Prep} = \frac{A_T}{Ab_{cons}} \cdot Ab_{cost} + \left[\frac{L_{fe}}{e_{cost}}\right]} \tag{6-49}$$

$$\boldsymbol{M_{paint} = \left[\frac{A_t}{(S \cdot L \cdot n_c)} \cdot Pt_{cost}\right] + [(L_{Fe} + L_{wl}) \cdot (e_t) \cdot s_w \cdot Pt_{cost}]} \tag{6-50}$$

$$\boldsymbol{S = \frac{1000 \cdot VS}{DFT}} \tag{6-51}$$

$$\boldsymbol{L_{prep} = \left[\frac{A_T}{SP_{prod}} \cdot CI\right] \cdot PL_{cost}} \tag{6-52}$$

$$\boldsymbol{L_{paint} = \left[\frac{A_T}{P_c} \cdot \left[(L_{Fe} + L_{wl}) \cdot e_p\right]\right] \cdot CI} \tag{6-53}$$

Where:

P_{mat} = Coating process material costs
P_{lab} = Coating process labour costs
M_{prep} = Surface preparation material costs
M_{paint} = Protective coating material costs
Ab_{cons} = Abrasive blasting material usage (kg/m^2)
Ab_{cost} = cost of abrasive blasting materials
e_{cost} = cost of edge grinding (€/m)
S = Actual paint spread rate
L = paint loss factor
N_c = number of applied coats
VS = volume solids of the paint
DFT = required dry film thickness (DFT) in microns
Pt_{cost} = cost of protective coating (€/litre)
e_t = cost of stripe coating (€/m)
s_w = average width of stripe coat
L_{prep} = surface preparation labour costs (€/day)
L_{paint} = protective coating application labour costs (€/day)

SP_{prod} = surface preparation production rate (m^3/h)
CI = Complexity Index
PL_{costs} = surface preparation labour cost (€/day)
P_c = Paint application cost (€/m^2)

The major difficulty of this approach is quantifying the through life benefits that can be attributed to improving the design of a WBT to incorporate the coating process. These could include an increase in the service life of applied coatings, leading to a reduction in the maintenance and repair costs to both the coatings and the steel substrate.

As described previously, in the cause and effect studies on the influence of the surrounding structure, the lower bound in terms of number of stiffeners was fourteen stiffeners and that although it is structurally possible to provide solutions with more stiffeners than the benchmark they did not provide any benefits. Therefore the feasible region that was selected for further investigation was taken as between fourteen and eighteen stiffeners.

To explore the influence of complexity and weigh on the cost associated with producing a panel two cost based optimisation routines have been developed. The steelwork objective function uses the ***Rigo***, (***2001***) approach, with the coatings objective following a similar approach as shown above. The models produced provide solutions for the given number stiffeners for each of the objective functions namely:

- Minimum absolute complexity;
- Minimum weight;
- Minimum steelwork costs;
- Minimum coating costs.

The solver was tested to ensure it returned a globally optimum solution by varying the starting point throughout the acceptable range of stiffener sizes. The following section describes each of these different objective functions in turn. Applying the approach to the complete keel panel for the different objective functions yields the results shown in Table 6-7.

Table 6-7 Optimisation of benchmark panel

	Benchmark panel $f_b(X)$	Minimum Complexity $f_1\,(X)$	Minimum Weight $f_2(X)$	Minimum Steelwork Costs $f_3(X)$	Minimum Coating Costs $f_4(X)$
Complexity CI	1	0.93	1.29	1.29	0.93
Weight (tonnes)	11.49	12.34	10.61	10.61	12.34
Steelwork Costs (€)	13,053	13,522	12,207	12,207	13,522
Coating Costs (€)	3,502	3,334	3,515	3,515	3,334
Total Costs (€)	16,555	16,856	15,722	15,722	16,856

The results of this study show that depending on which objective function is chosen it is possible to realise the improvements shown in Table 5 by altering the dimensions of the Tee bar stiffeners.

Table 6-8 Potential Savings based on alterative objective functions

Percentage Savings	Benchmark $f_b(X)$	Minimum Complexity $f_1\,(X)$	Minimum weight $f_2(X)$	Minimum Steel work $f_3(X)$
Complexity CI	0.00	7.06	-29.46	-29.46
Weight (tonnes)	0.00	-7.41	5.53	5.53
Steelwork Costs(€)	0.00	-5.25	5.21	5.21
coating Costs (€)	0.00	7.80	-9.20	

reduces the number stiffeners whilst calculating each of the above objective functions. The solver was tested to ensure it returned a globally optimum solution by varying the starting point throughout the acceptable range of stiffener sizes. The following section describes each of these different objective functions in turn.

6.11.3 Complexity Resulting from Weight and Complexity Optimisation

The complexity that results from both optimisation for complexity index, *CI*, and weight objective functions are shown in Figure 6-20. This demonstrates the trend of increasing complexity of the panel as more stiffeners are added. This study shows how seeking a minimum weight solution will return design solutions with considerably higher complexity than the results study focusing on minimum complexity

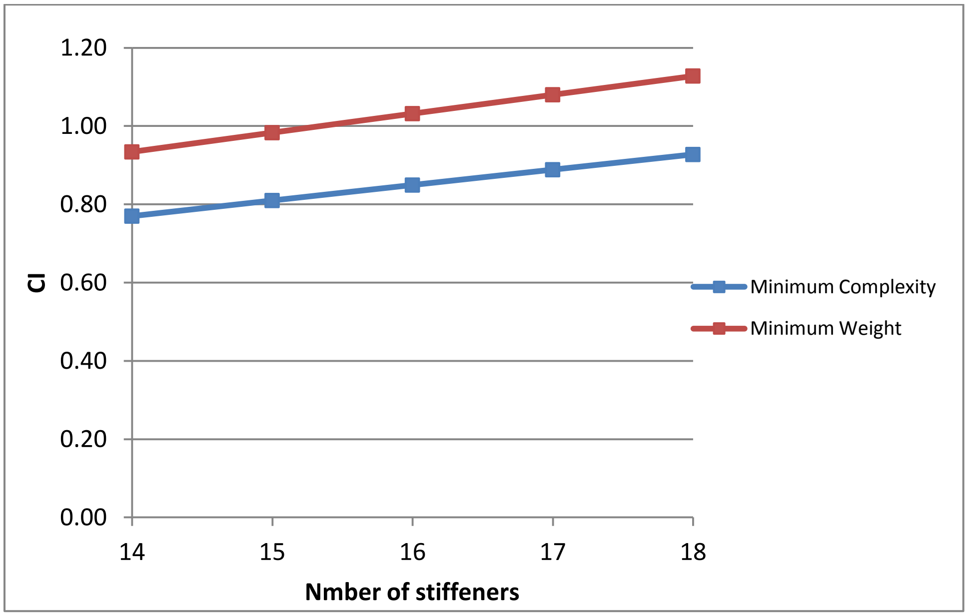


Figure 6-20 Minimum absolute complexity

6.11.4 Weight Resulting from Complexity and Weight Optimisation

The minimum weight solution seeks to minimise the overall weight of the panel whilst still providing the required section modulus. Figure 6-21 shows how the response of the weight for both the minimum weight and complexity objective functions, is relatively insensitive with respect to the number of stiffeners; this confirms the results of the second stiffened panel study in ***Wright et al***. (***2013***). In this case there is little opportunity to reduce the weight of a panel by reducing the number of stiffeners. Similarly it is demonstrated that less complex designs have an associated weight penalty.

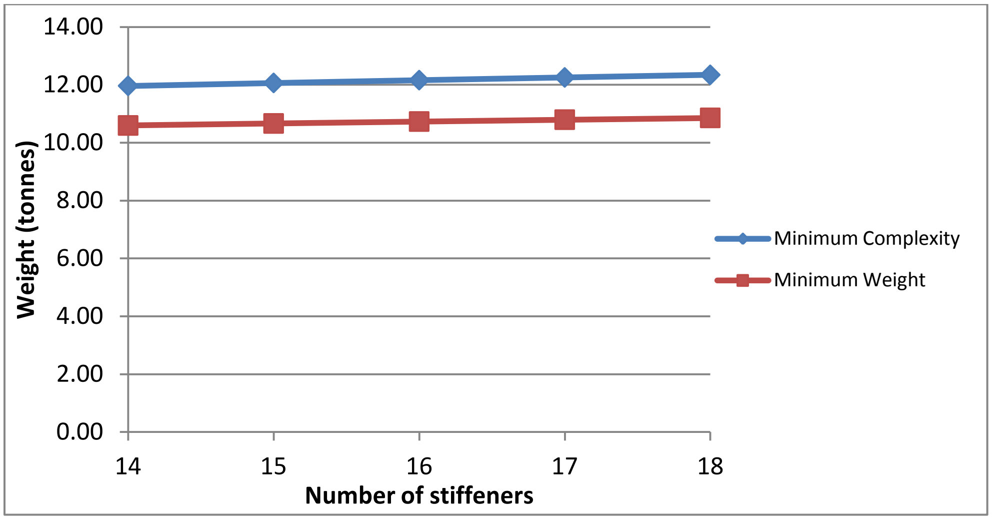


Figure 6-21 Minimum weight solution

Figure 6-20 and Figure 6-21 highlight the conflicting nature of the different objective functions as the solution for minimum complexity returns the heaviest panel and the lightest panel returns the most complex panel. This goes somewhere to verifying the shape of the graphs presented in the cause and effect studies. A level of agreement has been found with the second stiffened panel which indicated that was highly unlikely that both the complexity and the weight could be reduced.

6.11.5 Steelwork Cost Resulting from Coating Costs and Steelwork Cost Optimisation

As has been discussed the steelwork cost solution presented by ***Rigo***, (***2001***), is comprised of material costs, labour costs and overhead costs. Consideration is given to varying work content as a result of joining different plate thicknesses, the different prices associated with plates and bulb plate stiffeners, the cost of welding consumables and the work content as a result of the secondary detail such as intersecting stiffeners and brackets. Figure 6-22 shows the application of this approach to the current problem.

In this case the objective function appears to be dominated by the material costs as there is no transverse material and hence no cost associated with the labour intensive process of these structures. Additionally this approach assumes that the stiffeners themselves are variations on a standard form. This means that the calculated labour content will be lower than the actual effort required to fabricate tee bars of differing plate thicknesses. However as this study is examining relative benefits between alternative design solutions, it has been considered appropriate for such a comparative study.

Based upon this approach optimisation for steelwork costs and weight results in the same stiffener topology being identify for both objective functions, as a result of the dominance of material costs.

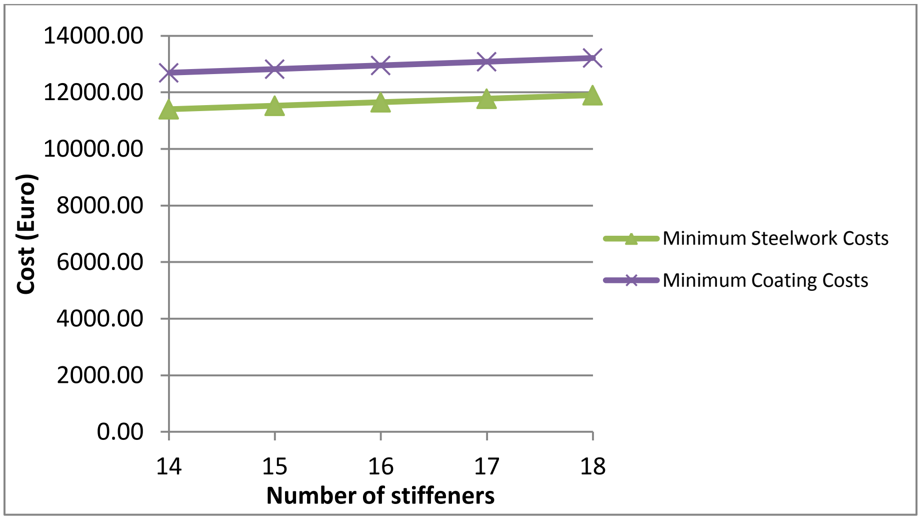


Figure 6-22 Minimum steelwork costs

This study shows that, although the response to reducing number of stiffeners is quite flat, there are cost benefits to reducing the number of stiffeners principally driven by minimising the material costs. This is influenced by the reduction in work load and labour cost as a result of reduced weld length. The reduction in coating process costs mirror those of the steelwork costs, which in this case is driven by a reduction in the free edge preparation and stripe coating length. It should be noted that although edge grinding is essentially a steelwork task it has been included in the coating process, as it is a requirement of the ***IMO PSPC***, (***2007***) rather than one of structural importance.

6.11.6 Coating Cost Resulting from Steelwork Cost and Coating Costs Optimisation

Figure 6-23 shows that in this study there are definite benefits and cost savings to both the steelwork and coating processes that can be realised by reducing the number of stiffeners. There is a small difference between the solution for minimum coating cost and minimum steel work cost, with a definite split between steelwork and coating focused activities. Again the benefit is directly attributable to the reduction in work content through the removal of stiffeners, namely as a consequence of reduction of free edge and weld length.

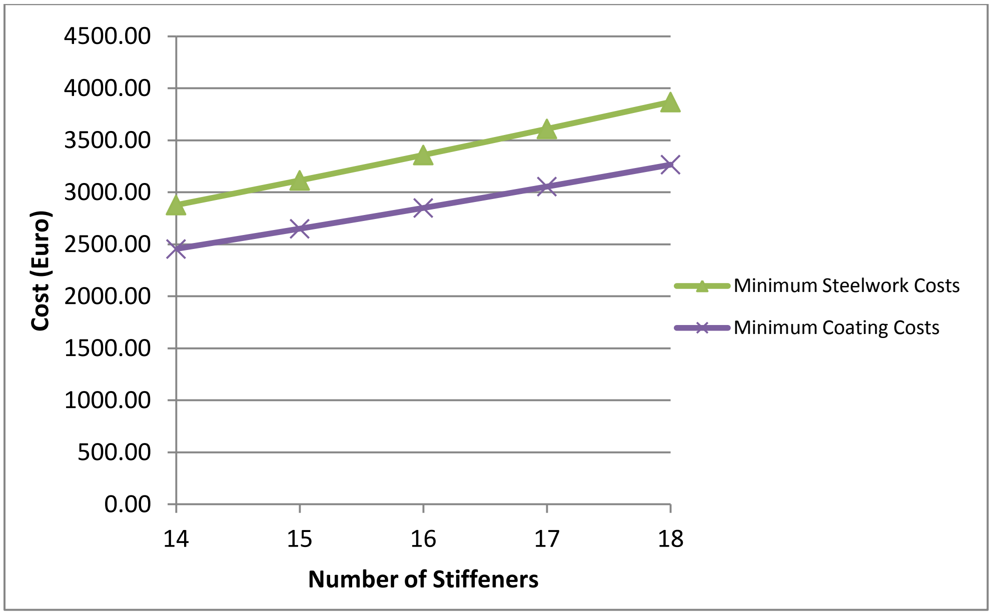


Figure 6-23 Minimum coating costs

The difference between the two solutions is a result of the topology of the stiffeners in each case. Those of the steelwork solution have a larger aspect ratio, namely web height to flange width, with thicker flanges and thinner webs than the solution for the coating process. These factors result in the steelwork solution having a higher complexity, driven by total arc length and non-visible area. This combined with the greater surface area leads to an increase in costs.

6.12 Verification of Proposed Multi-Stiffener Plate Solutions

The optimisation study for the double bottom plates in the previous section presented a number of different solutions that met the structural constraints applied, principally that the same section modulus was provided in all cases. Examining the double bottom panel in question reducing the numbers of stiffeners would increase the stiffener spacing such that a reduction from 18 stiffeners to 14 would increase the stiffener spacing increasing from 849 mm to 1076 mm. The results of the studies within this work have been separated in those with a spacing of less than 1000 mm and those with which are greater.

In order to ensure that the structural behaviour of the different design solutions that have been proposed within this work, Finite Element models have been developed for five bays of the keel plate of the double bottom structure, to ensure that the middle bay, which is of interest in this case, is not influenced by any of the boundary conditions. It is difficult to determine what portion of the in-plane load as result of hogging or sagging moments would be applied to double bottom panel considered Thus the performance of the panel was investigated by applying a given displacement rather than a specified in-plane load. As the structural performance beyond the point of failure is of interest in this case, the displacement has been applied using the arc length or modified Riks method. The models were constructed such that one end was constrained in all six degrees of freedom, whilst the other end and the edges were constrained to move only in the longitudinal direction in which the displacement was to be applied. An example of one of the Finite Element plots is shown in Figure 6-24.

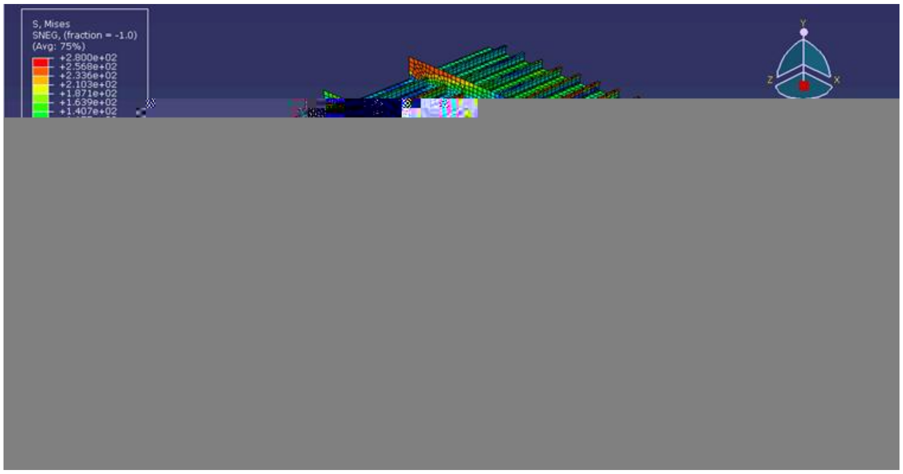


Figure 6-24 Example of finite element model of keel panel

Smith et al*. (*1991*)** noted how both theoretical and experimental investigations have demonstrated how the initial imperfections within a plate have a significant influence on the strength and stiffness of a plate. Following the approach adopted by ***Benson (***2012***) which builds upon the work undertaken by ***Dow*** and ***Smith*** (***1984***), the plates used in this study have been assumed to have average levels of initial imperfections. This is believed to represent what would be classed as a good standard of shipbuilding practice, in terms of accuracy control and distortions due to welding heat input.

The panel in question forms part of the midship section, and overall hull girder system. As a result it is important to understand the complete structural performance of the panel, not just its strength. Therefore analysis of the progressive collapse performance is required. These results for the panels with less than a 1000 mm spacing are shown in Figure 6-25. They demonstrate the pre-collapse stiffness, the point of collapse, or the ultimate strength, and the post collapse behaviour.

These results demonstrate that all of the panels of interest have the same failure mode, namely plate buckling. This is as would be expected with plate slenderness ratios of 1.7, and is demonstrated by the shape of the progressive collapse results. Also, when compared to the benchmark panel, the overall collapse strength of the panels is very similar. The post-collapse behaviour of the panel with eighteen optimised stiffeners is slightly better than the others. This is a result of reduction of the column slenderness ratio, as this measure determines the post collapse behaviour of the panel. Lower values of column slenderness result in post collapse responses closer to that of yielding rather than buckling.

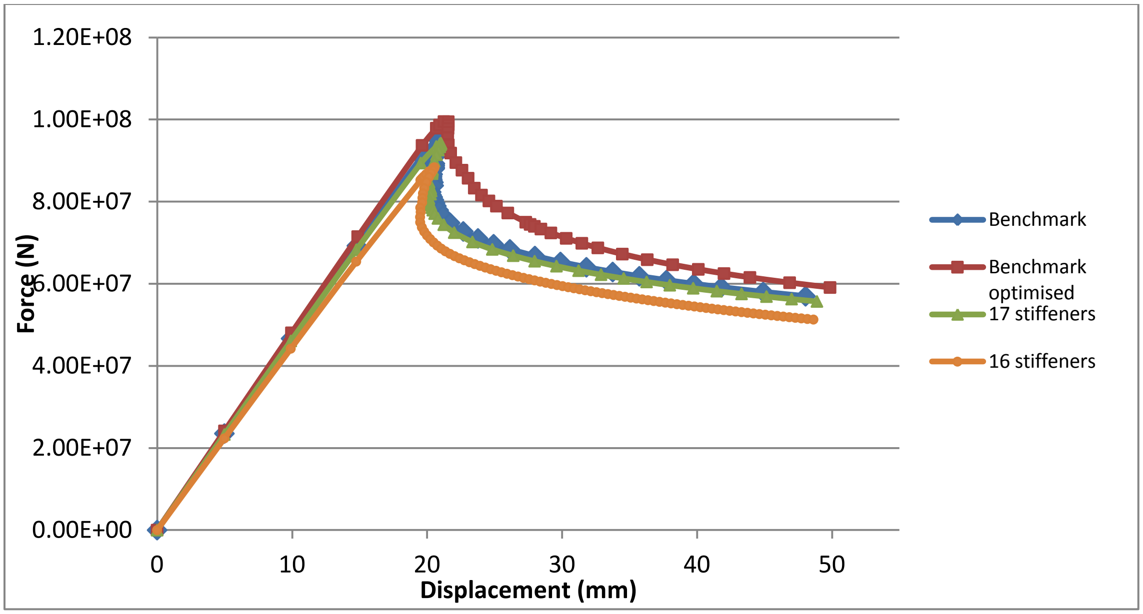


Figure 6-25 Stress Stain Curves for Stiffened Panels less than 1000 mm spacing

Figure 6-26 shows the ultimate strength plots for those panels which are have stiffener spacings of greater than 1000 mm. Again these plots are grouped together, albeit with a reduced ultimate strength. This reduction is driven by the increase in plate slenderness ratio as the column slenderness ratio alters very little across the different design solutions.

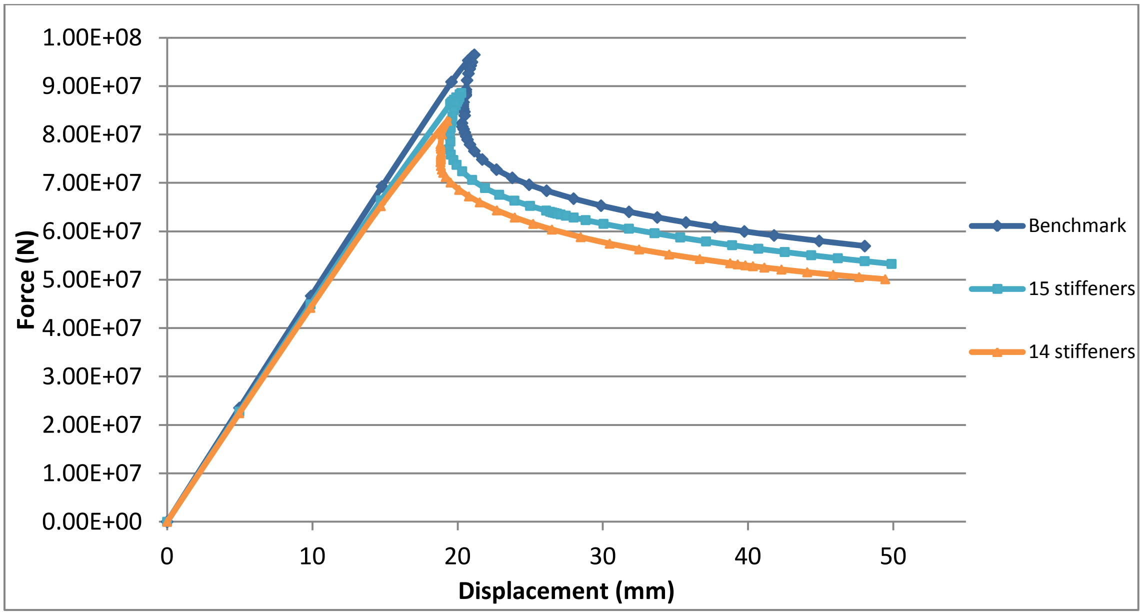


Figure 6-26 Stress stain curves for stiffened panels with greater than 1000 mm spacing

There is relative reduction in performance when the plate slenderness ratio becomes greater than two, this corresponds to the cases of fewer than sixteen stiffeners. The overall reduction in ultimate strength is in the region of 10% which was deemed acceptable to further investigate the potential benefits in terms of cost saving that could be realised by reducing the number of stiffeners on a panel. The influence on production costs of the plate and column slenderness ratios will be discussed further in the following Chapter.

6.13 Conclusions

This Chapter has sought to provide a measure of the relative complexity of different stiffener sections to provide an indication of their relative ease of coating; the intention to quantify the relationship between typical ship structural configurations and the physical activities of the coating process. The results presented from this initial study demonstrate that there is only a relatively small feasible region in the design space within which alternative stiffener types and scantlings can be proposed to seek such benefit with respect to coating activities. As a simple measure of structural 'efficiency' the weight also provides a means to quantify the relative merits of these alternative sections and quantify what might be considered to be accepted knowledge in terms of the relative merits of different stiffener sections.

It is very interesting to note that the benchmark structure when examined as an individual stiffener plate combination and as an entire panel assembly is very close to the upper feasible bound of structural constraints and that there is no simple means to improve its performance further with respect to both weight and complexity; it is evident that structural solutions have not evolved by chance. This demonstrates that although coating has not conventionally been explicitly considered the sections that have evolved offer little opportunity for improvement with respect to ease of coating.

The relationship between fundamental structural performance, weight and complexity with respect to production cost, has been examined following the approach proposed by ***Rigo***, (***2001***). The resultant optimisation problem delivered solutions for the four different objective functions. The results of the work reinforce the beliefs of ***Rigo***, (***2010***) that focusing on steel weight will not return the lowest cost solution. To achieve a truly minimum cost solution all elements of the production process including paint must be included. The results have shown that considerable savings can be achieved through the reduction of the number of stiffeners.

6.14 Summary

This chapter has charted the development of a number of models that have analysed the complexity of a range of stiffened panels, beginning with a single stiffener plate combination cause and effect study including a panel cause and effect study through the development of a number of different objective functions, namely minimum complexity, minimum weight, minimum steelwork costs and minimum coating costs.

The next chapter further investigates the nature of the cost savings that have been shown in this chapter. It also examines the wider production benefits that could be achieved as a result of considering a number of different design methodologies and their influence on the coating process.

7 FURTHER INVESTIGATION OF PROPOSED NEW DESIGNS

7.1 Introduction

This chapter builds upon the previous work as it investigates the influence that the plate and column slenderness ratios have on the total production costs. The optimisation routines that have been developed for panels have been applied to the double bottom compartment, the potential cost savings and strength predictions are discussed. In addition to this the potential cost savings are presented, if the entire midship section is optimised for the five different objective functions.

7.2 Understanding the Influence of Beta and Lambda on Production Costs

Normal ship design practice is to produce load shortening curves for a stiffened panel which plots the ultimate strength of a panel for a range of either plate slenderness ratios, β, for fixed column slenderness, λ, ratios or vice versa, (***Chalmers***, ***2003***). Plate slenderness ratio is defined as:

$$\boldsymbol{\beta} = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}} \qquad 7\text{-}1$$

To maintain plate slenderness ratio the plate thickness is increased in proportion to the plate width. The column slenderness ratio is maintained by varying the topology of the stiffeners to provide the required second moment of area, as described by:

$$\boldsymbol{\lambda} = \frac{l_{eff}}{\pi k}\sqrt{\frac{\sigma_y}{E}} \qquad 7\text{-}2$$

Where *k* is the radius of gyration;

$$\boldsymbol{k} = \sqrt{\frac{I}{A_t}} \qquad 7\text{-}3$$

Having developed and understood the influence of plate and column slenderness ratios for this panel on the structural performance, the intention is to consider how these factors relate to production costs. As the for the ship builder the ultimate goal is to seek methods of reducing the cost of building a ship, in terms of low production time with high quality.

The previous chapter developed the different objective functions for complexity, weight, steelwork costs and coating costs, these have been plotted for panels where plate and column slenderness ratios have been selected as fixed constraints. The results have been normalised relative to the benchmark mark values, namely values less than one represent a relative improvement as shown in Figure 7-1.

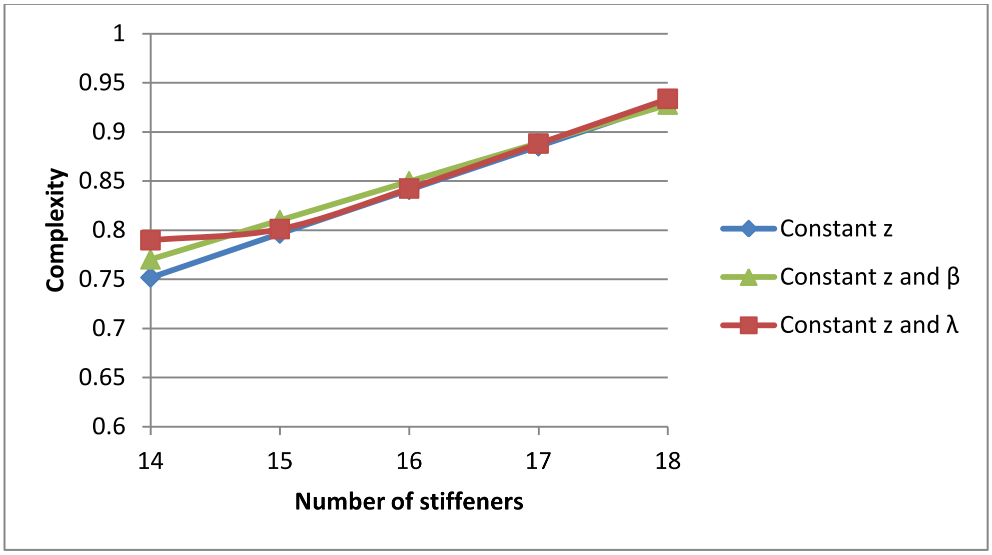


Figure 7-1 Complexity values for the different design constraints

Generally the geometry of the stiffeners, specifically in terms of their aspect ratios, are very similar thus the different structural approaches have little effect on the complexity for a given number of stiffeners. When either plate or column slenderness ratios are constrained to that of the benchmark for either a minimum complexity or weight objective function the results are all but identical.

Figure 7-2 shows the potential weight savings for each of the different structural methodologies compared to the benchmark with minimum weight objective function.

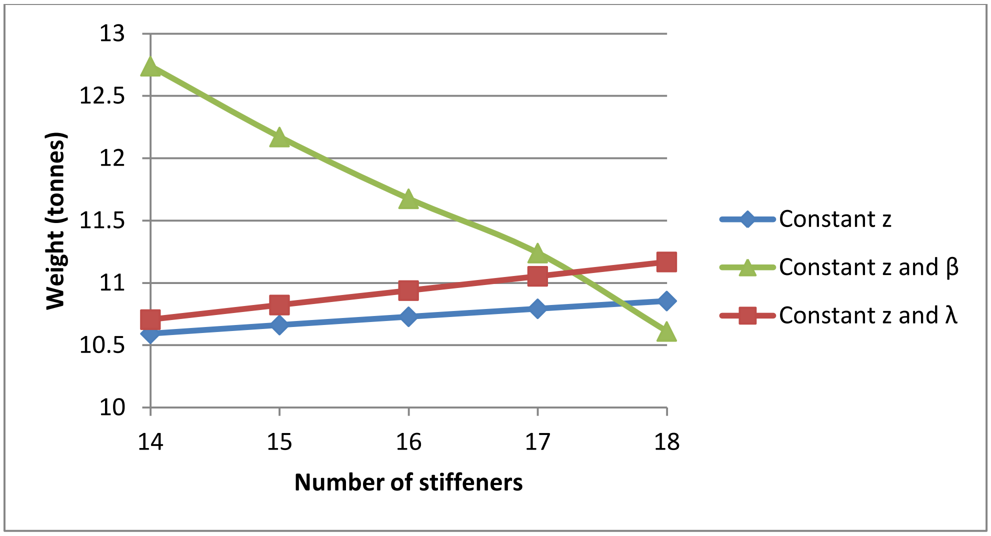


Figure 7-2 Panel weights for the different design constraints

Constraining the plate slenderness ratio results in, as would be expected, a heavier solution. This is due to the stiffener profile being the same as for constrained section modulus alone, but with greater plate thickness. The difference between the constant section modulus and constant column slenderness results are due to slight variations in the distribution of material to satisfy the different constraints.

Given the objective of reducing building cost of a ship, the results for the minimum steelwork cost objective function are shown in Figure 7-3.

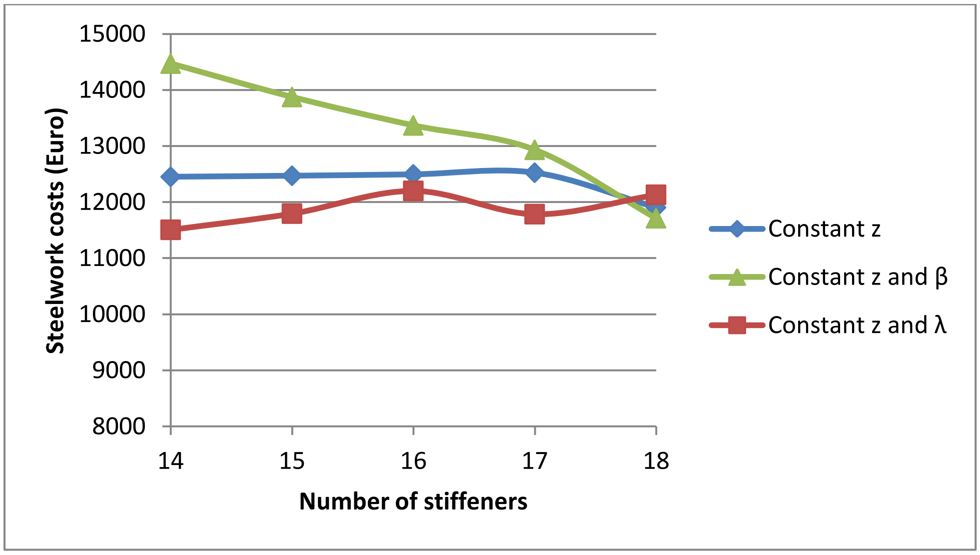


Figure 7-3 Panel steelwork costs for the different design constraints

There is a distinct separation between the results for the three objective functions. This is principally driven by the steel material costs as a result of the differences in weight provided by the different steelwork objective functions. The last case considered examined the potential benefits to the coating costs based upon the different objective functions as shown in Figure 7-4.

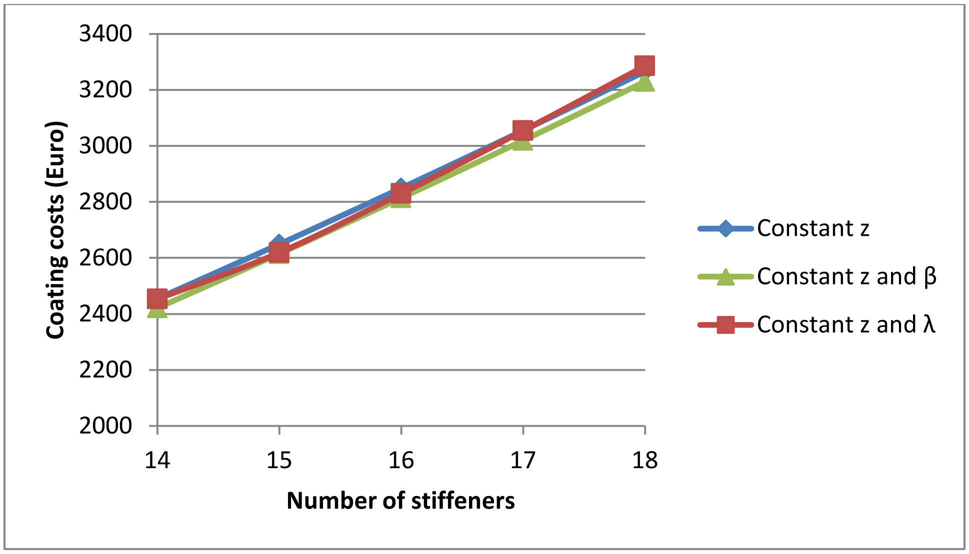


Figure 7-4 Panel coating costs for the different design constraints

In this case there are more pronounced savings as the number of stiffeners are reduced. This is principally driven by the reduction of the requirement for edge grinding and the application of stripe coats. There is also a significant reduction in the overall surface area that requires preparation and paint application, which affects both the labour content and coating material usage associated with the panel.

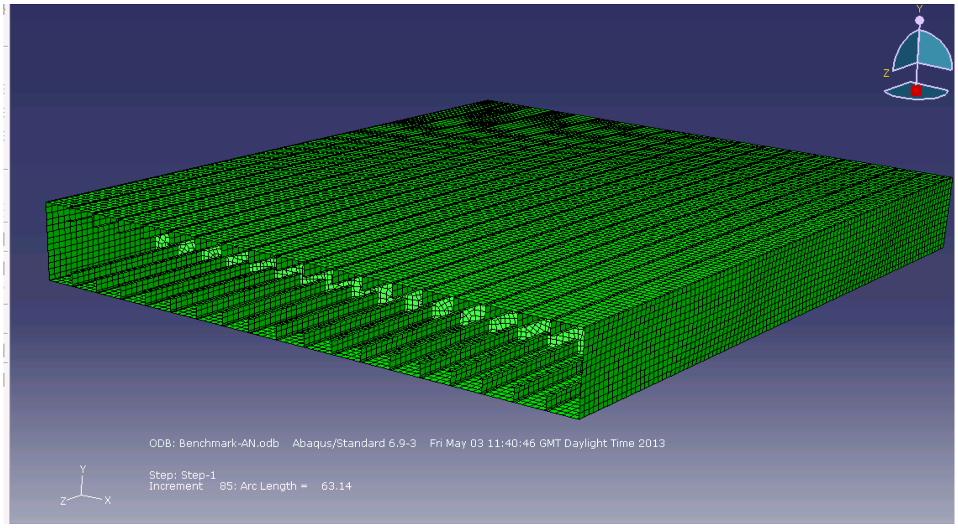
The principal driver between the conflicting result for the steelwork and the coating processes is down to either minimising weight and therefore steelwork material costs or minimising complexity as a result of lower aspect ratio stiffeners. In all cases the number of stiffeners reduces the work content, from a purely steelwork perspective this is a reduction of the weld length, and with respect to the coating process terms the work content reduction comes from decreasing the free edge that requires preparation and the associated application of stripe coats.

When examined, the cost associated with producing a panel of the different designs, the results have shown the influence that constraining plate and column slenderness ratios have in combination with the section modulus. Constraining the column slenderness leads to less complex and therefore lower relative cost solutions in terms of the coating process. Constraining the plate slenderness ratio provides panels that have a higher cost associated with them driven by the material weight. The most important conclusion that can be drawn is that regardless of which constrains are applied, it is possible to design stiffened panels that provide adequate structural performance whilst reducing the associated production costs.

7.3 Optimisation of a Compartment

Having investigated the cost savings for a single panel, the ultimate goal of this work is to demonstrate the potential cost savings that could be realised for all of a ships ballast tanks if the coating process is considered during the design phase. It is however very time consuming and costly to produce entire ship finite element models, to verify the different approached to alternative stiffener spacing for the whole ship is currently unrealistic. The proposed approach is to continue to build up knowledge in a gradual stepwise approach, thus a double bottom section will be modelled to explore the influence of the alternative design methodologies.

To achieve this, the optimisation program that has been developed was applied to the double bottom structure of the benchmark tanker. The topology of both the keel panel and the inner hull panel were entered into the optimisation routine. The resultant dimensions for the varying number of stiffeners and different constraints, section modulus, plate and column slenderness, were then used to construct the double bottom structure in ABAQUS using, the AutoHull program developed by ***Benson***, (***2012***) as shown in Figure 7-5. This allowed a relatively simple process of constructing a complex FE model, from which is possible to determine the ultimate strength of the structure. It should be noted that the dimensions of the minimum coating cost objective function have been used for these models.



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ODB: Benchmark-AN.odb    Abaqus/Standard 6.9-3    Fri May 03 11:40:46 GMT Daylight Time 2013

Step: Step-1
Increment     85: Arc Length =     63.14
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Figure 7-5 Benchmark double bottom structure

As would be expected the objective functions described previously for the panel study return very similar results albeit with a higher magnitude, as the double bottom is essentially two panels supported by the appropriate transverse structure. As a result of this only the cost objective functions will subsequently be discussed for the alternative structural methodologies and compared with the ultimate strength of the compartment.

7.3.1 FE Analysis of Double bottom structure

In order to investigate the structural behaviour of the different design solutions, Finite Element models where developed following the same approach as for the single panel, namely the model consists of five bays, a displacement was applied in-plane applied using the arc length or modified Riks method. Again the models were constructed such that one end was constrained in all six degrees of freedom, whilst the other end and the edges were constrained to move only in the longitudinal direction in which the displacement was to be applied.

Figure 7-6 shows the progressive collapse performance of the double bottom designs for 18 stiffeners, the benchmark and 16 stiffeners. The results are very much the same as those of the keel panel study, in that all of the models demonstrate a bulking collapse failure mode with similar levels of ultimate strength. Again those panels where the plate slenderness ratio, β, was constrained to that of the benchmark, exhibit greater strength characteristics than those where the column slenderness is constrained. This is driven by the failure mode of the structure, as the number of stiffeners is reduced the plate thickness must increase accordingly to maintain the plate slenderness ratio. As the plate thickness increases the contribution to the second moment of area also increases with a corresponding reduction in the height of the neutral axis and hence increase in y_{max}, thus providing the same section modulus. As the structure is failing as a result of plate buckling, increasing the plate thickness will facilitate a higher point at which failure occurs.

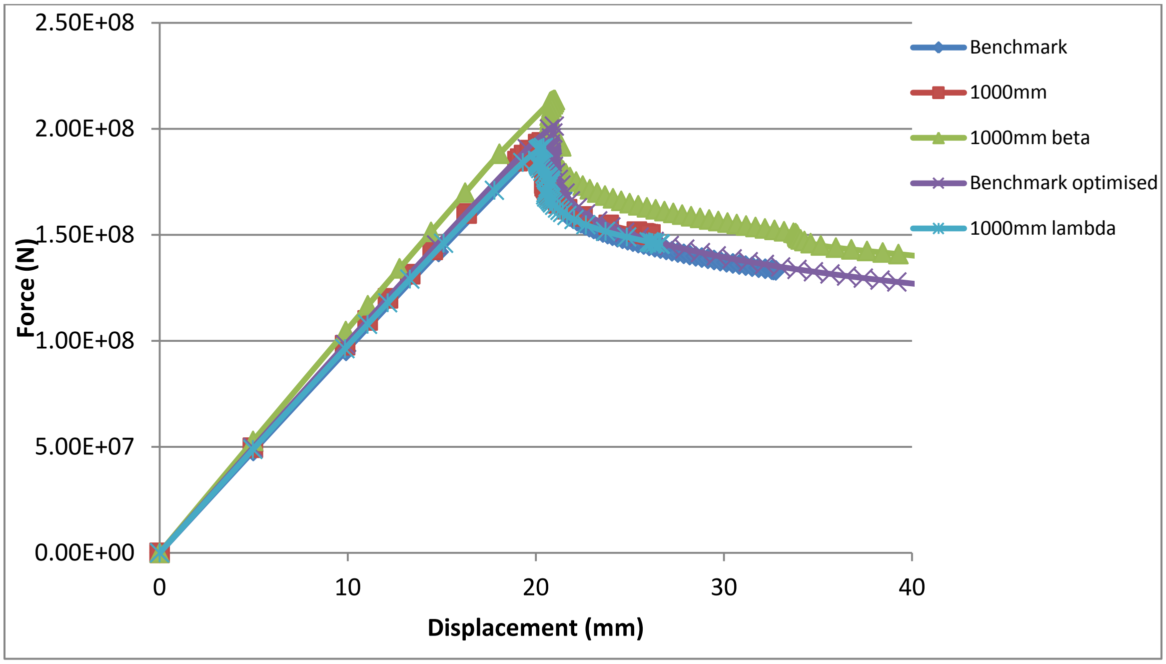

Figure 7-6 Progressive collapse performance for the different objective functions for stiffener spacings below 1000 mm

Figure 7-7 shows the progressive collapse performance of the double bottom designs which have stiffener spacing above 1000 mm. The results shown that those panels with constrained plate slenderness demonstrate greater ultimate strength.

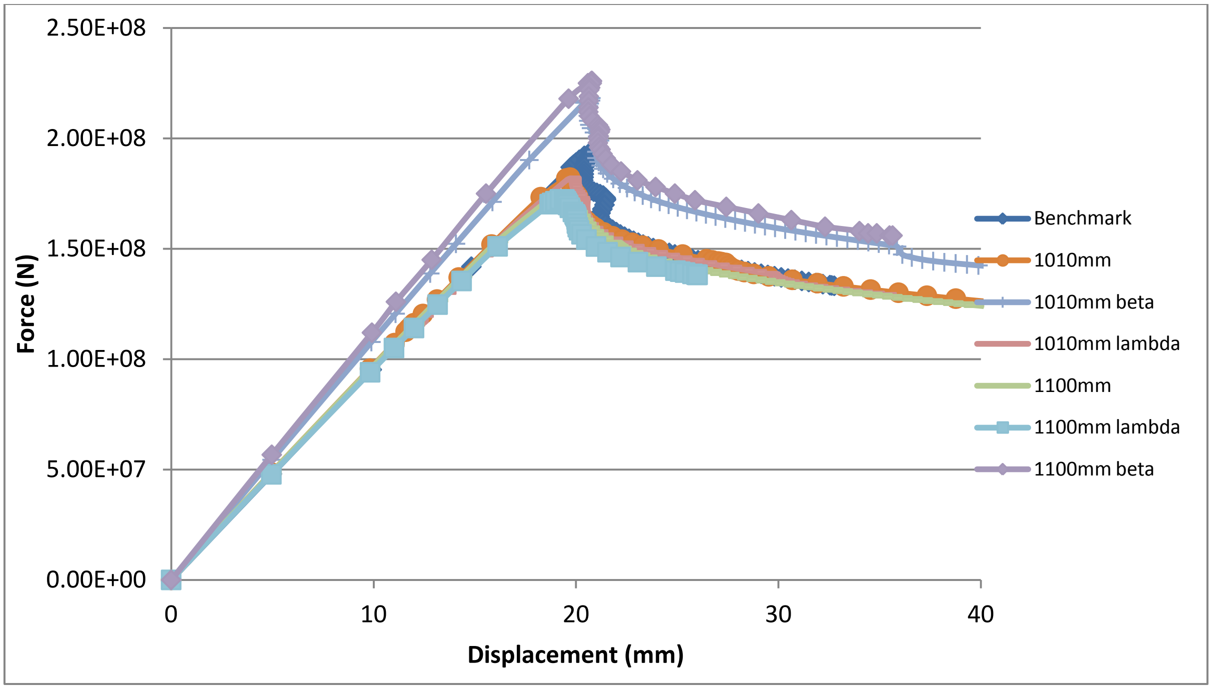

Figure 7-7 Progressive collapse performance for the different objective functions beyond 1000 mm stiffener spacing

Figure 7-8 shows FE graphical outputs of the double bottom and confirms that the failure mode as that of plate buckling as would be expected. The buckling of the inner panel near the end should be disregarded as the stresses in this region are likely to higher as a result of the constraining nature of the boundary condition at the end of the model. It should also be noted that the deformations have been magnified by a factor of ten to allow better visual representation of the failure.

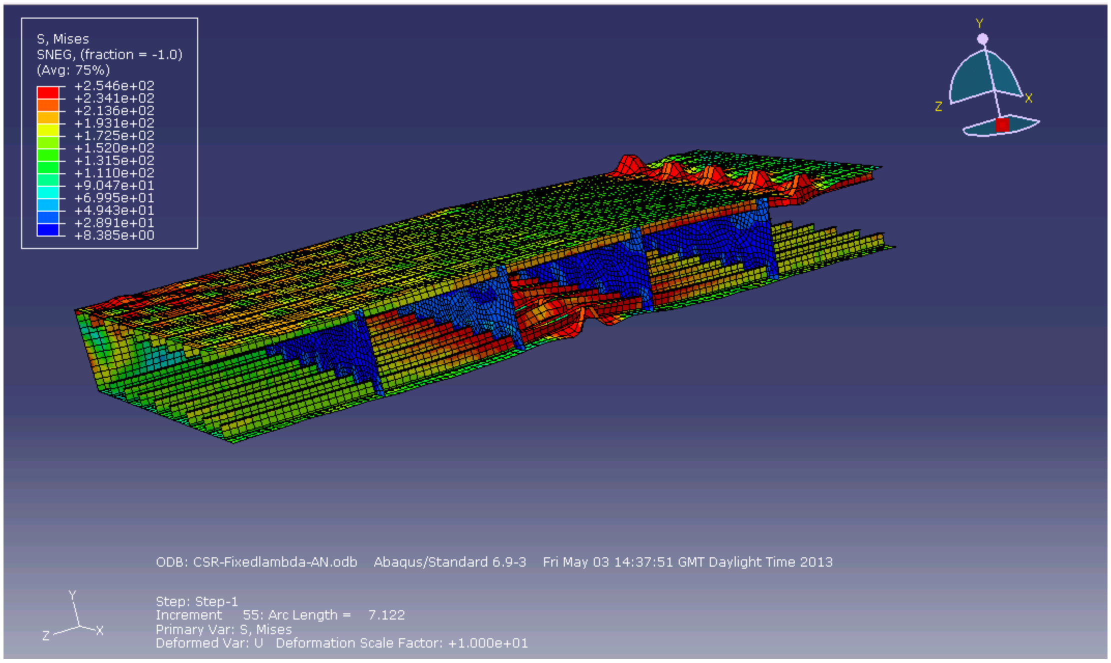

Figure 7-8 FE graphical output for benchmark structure

Table 7-1 shows the difference in the maximum load carrying ability of each of the structures output from the minimum coating cost objective function compared to that of the benchmark. It demonstrates how the ultimate strength of the panel could be increased by as much as 16% for the case of 14 stiffeners and fixed β

Table 7-1 Double bottom maximum force values

Method	Ultimate Strength (N)	% change	Relative change
Benchmark (18)	1.94E+08	0	1
16 stiffeners, fixed z	1.94E+08	-0.41	1.00
Benchmark optimised (18)	2.01E+08	3.42	1.04
16 stiffeners, fixed β	2.14E+08	9.02	1.10
16 stiffeners, fixed λ	1.91E+08	-1.65	0.98
15 stiffeners, fixed z	1.82E+08	-6.65	0.94
15 stiffeners, fixed β	2.18E+08	10.95	1.12
15 stiffeners, fixed λ	1.82E+08	-6.87	0.94
14 stiffeners, fixed z	1.75E+08	-11.10	0.90
14 stiffeners, fixed β	2.26E+08	13.99	1.16
14 stiffeners, fixed λ	1.72E+08	-12.75	0.89

7.3.2 Minimum Total Cost Objective Function

As previously discussed the ultimate goal is to identify designs that provide minimum cost solutions when all of the factors included in the production of a panel, block or entire ship are considered. Simply adding the coating and steelwork costs together provides an indication of the total production costs of a double bottom. Shipbuilders are more likely to embrace a new design philosophy if it not only demonstrates total cost saving but shows improvements to the steelwork process.

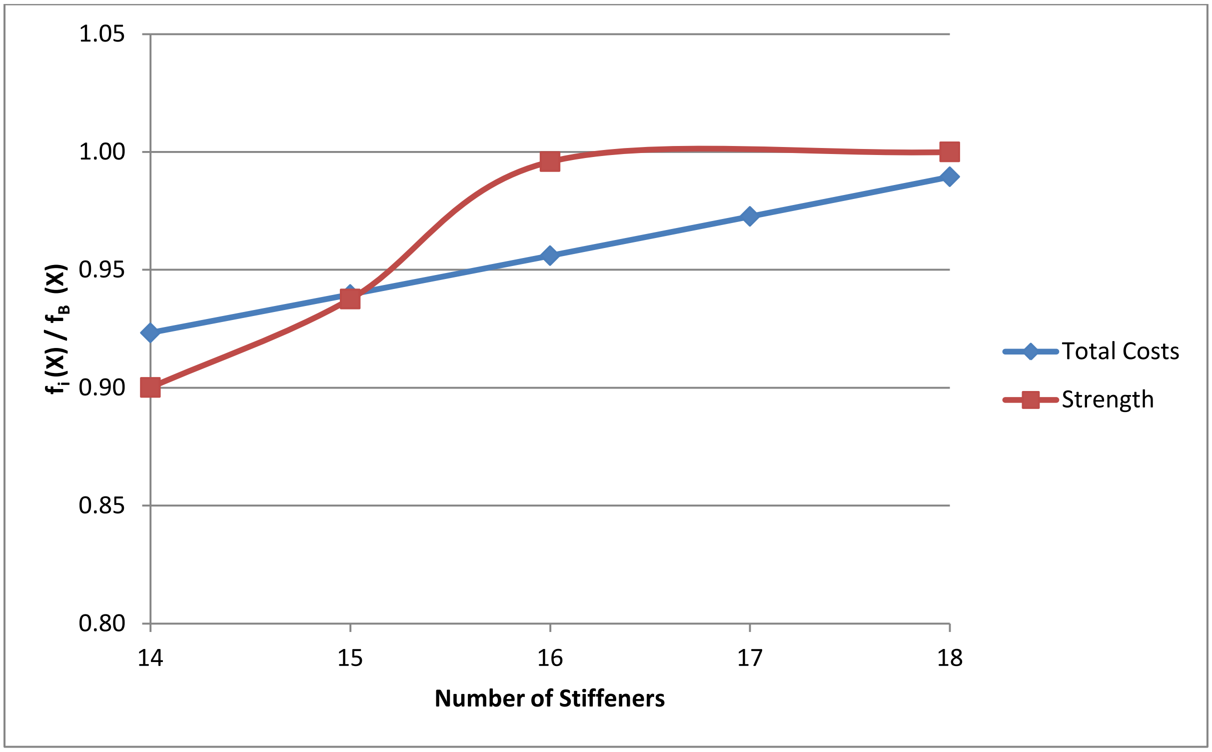

Figure 7-9 Total costs of producing a double bottom section with constrained section modulus

Figure 7-9 shows that it is possible to produce a double bottom compartment with savings of up to 7%, by reducing the number of stiffeners to 14. This however comes with an inevitable penalty in this case a reduction in the ultimate strength of the compartment of 10%. There is however the possibility of reducing the number of stiffeners to 16, whilst still providing a 4% reduction in total costs whilst maintaining the overall strength of the panel.

7.4 Optimisation of the Complete Benchmark Midship Section

Having investigated the benefits for a plate and a single compartment and found that the structural performance acceptable, the final element is to explore the benefits that could be realised by optimising the entire midship section, this represents approximately 60% of the total length of ship. It is common for shipbuilders to construct vessels of similar sections, following the process of standardisation previously discussed. In this case a cargo hold and its associated WBTs are comprised of a number of bays made up of the longitudinal material between the frames and both sides of a web frame. Normal practice is to attach stiffeners to one side of the web frame, thus the calculations carried out are for two bays of the vessel i.e. either side of the centreline bulkhead, including all of the longitudinal material and both the stiffened and un-stiffened areas of one web frame.

The midship optimiser program for the ship is a direct development of that which was used for the double bottom structure. The midship section was broken down into separate panels; a separate worksheet was created for each panel, with the principal dimensions for each panel being controlled by a central input worksheet.

In many cases the thickness of the plates within what has been defined as a panel vary. Although it would be possible to create panels wherever the plate thickness varies this would lead to a large number of panels. In addition to this the thickness does not vary a great deal throughout anyone panel. To combat this, the average thickness of the individual plates forming the panel was used. In the majority of the panels the type and dimensions of the stiffener does not vary across the panel. There are, however a couple of panels where the stiffener type and size alters. In all cases the most widely occurring stiffener size and type has been used, as such some of the angle bar stiffeners that occur in the wing tanks have been replaced with equivalent tee bar stiffeners. Although this does not give a highly accurate solution the results are comparative rather than absolute.

Figure 7-10 shows the midship section of the benchmark tanker and shows that the stiffeners used on the web frames are flat bar stiffeners. To allow the optimiser program to deal with these stiffener types is was necessary to remove the aspect ratio and flange thickness ratio constraints.

Also to note is that as the flat bar stiffeners are relatively short in length, they have a maximum length of 2 m, it is possible to relax the height to thickness ratio of 1:10 as there is little chance of stiffener tripping.

The normal procedure in an oil tanker of the type used as the benchmark would be to coat the cargo spaces in accordance with the IMO PSPC COT, which is to paint the flat inner bottom of the tank up to 0.3m, the deckhead and the tank vertical structure down to 10% of the total height but no more than 3m. In this model only the area associated with the under-deck stiffeners has been included, as such the centreline bulkhead has been optimised but the number of stiffeners has not been altered.

Figure 7-10 shows how the midship section of the benchmark oil tanker was broken down in the ten panels that where then used to form the basis of the optimisation study, it should be noted that the panels in the side shell areas of the vessel namely 6,7 and 8, where considered twice to account for the inner and outer skins.

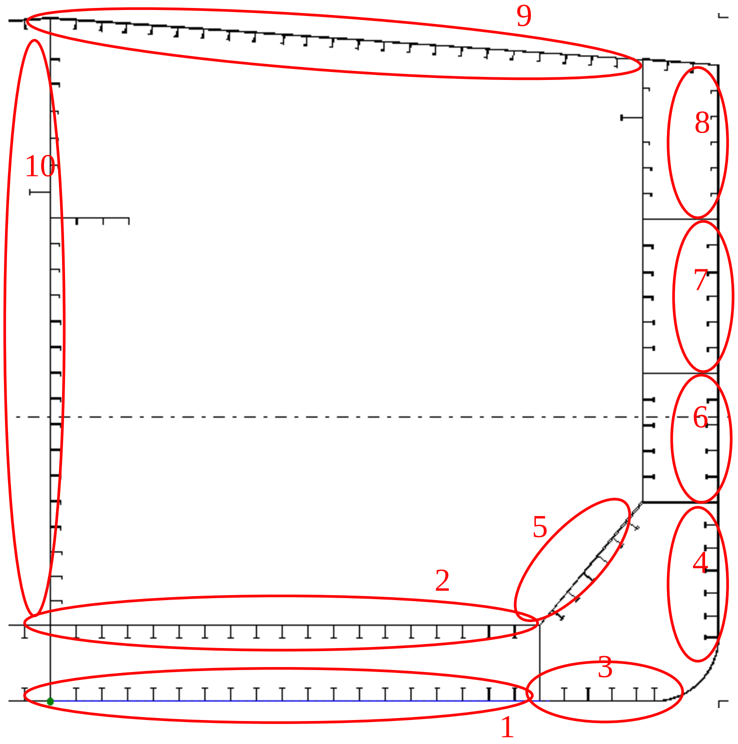

Figure 7-10 Benchmark Midship Section

The midship section was broken down into the following panels:

- Keel plate - 1;
- Inner bottom plate - 2;
- Turn of bilge bottom - 3;
- Turn of bilge side - 4;
- Hopper plate - 5;
- Lower wing tank - 6;
- Middle wing tank - 7;
- Upper wing tank - 8;
- Deck plate - 9;
- Centreline bulkhead - 10.

Investigation of the values of the structural indices that have been previously discussed highlighted that a number of the panels exhibited values that are outside of the constraints that have previously been defined. Principally these where; the aspect ratio of the stiffeners being in excess of three and the column slenderness ratio being higher than 0.45. This presents difficulties when running the optimisation routines for these panels using the previous constraints. The panels concerned are the three wing tanks and the centreline bulkhead. To ensure a like for like comparison the constraints in question were relaxed to the values presented by the benchmark midship section, namely in the wing tanks, the aspect ratio and the column slenderness ratio are 3.33 and 0.46 respectively. Thus upper limits were increased from 3 to 3.5 and 0.45 to 0.5 respectively.

7.4.1 Cost Savings for the Benchmark Structure

The costs breakdown for the optimised panels of the entire midship section is shown in Table 7-3 Results for Optimisation within 1000 mm stiffener spacing limit. The results show the potential benefits that could be realised depending on which objective function is used.

Table 7-2 Benchmark Midship Section Costs Breakdown

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost	Min Total Cost
Cost Savings %					
Steelwork cost reduction	-3.18	2.87	2.83	-3.18	2.52
Coating cost reduction	2.10	-13.08	-12.94	2.10	-8.55
Total cost reduction	-2.14	-0.26	-0.27	-2.14	0.35
Cost of steelwork materials	-4.59	4.15	4.08	-4.59	3.63
Weight	-4.61	2.66	2.59	-4.61	2.45
Cost of coating materials	2.06	-2.04	-1.98	2.06	-2.09
Cost of coating labour	2.43	-18.16	-17.98	2.43	-11.67
Cost of surface preparation materials	2.06	-2.04	-1.98	2.06	-2.09
Cost of surface preparation labour	3.60	-18.70	-18.49	3.60	-12.37
Cost of edge grinding	0	0	0	0	0
Cost of coating process labour	2.57	-18.23	-18.04	2.57	-11.75

Examination of the results shows that the high cost of the coating process when optimised for weight or steelwork content has been driven up by the increase in the labour costs for surface preparation and paint application. The reason for the relatively high costs of surface preparation labour is due to the greater amount of surface areas and relative complexity returned by the solutions for weight and steelwork costs. As the number of stiffeners has not reduced there is no saving for edge grinding

The higher level of complexity for the weight and steelwork optimisers is due to the solver returning Tee bar stiffeners that have shorter web heights and larger flanges resulting in greater non visible area and arc length as a result of the lower stiffener aspect ratio. It is interesting to note that the objective function for steelwork returns a slightly more costly coating process than the weight only objective function. This is principally driven by the slight difference in the stiffener dimensions for the wing tanks. This study has principally focused on longitudinal material, not grillage structures; as such the cost of the material mass of the steel within the structure has a greater influence on the total costs than the labour content. Thus from a steelwork point of view the minimum weight objective function returns the lowest cost solution, which is as would be expected.

This study highlights that selecting either the coating or the steelwork process alone will not deliver the lowest total cost solution. Due to the difference in the magnitude of the two processes, the total cost objective function will tend towards solutions of the minimum steelwork costs. However it does highlight the need to consider the coating process, as it is fundamental element of the total production costs, when evaluating potential design solutions.

What can be concluded from this study is that although the benchmark structure does not provide a true optimum, it does strike a good balance between the competing aspects of steelwork and coating activities. It is unlikely that optimisation design effort would or indeed should be expended to provide a design solution with such a marginal production cost saving.

7.4.2 Cost Savings Through Reduction of Number of Stiffeners

By reducing the number of stiffeners on each panel using 1000 mm as a maximum stiffener spacing, the potential savings for the entire midship section are shown in Table 7-3. It should be noted that not all panels were able to exploit the benefits of increasing the stiffener spacing. This was most evident in the upper and lower wing tanks where only 5 stiffeners are present, as removing one stiffener then increased the spacing beyond 1000 mm.

Table 7-3 Results for Optimisation within 1000 mm stiffener spacing limit

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost	Min Total Cost
Cost Savings %					
Steelwork cost reduction	-1.7	6.1	6.0	-1.7	5.61
Coating cost reduction	18.52	3.51	3.58	18.52	5.70
Total cost reduction	1.98	5.54	5.52	1.99	5.63
Cost of steelwork materials	-5.04	5.96	5.88	-5.02	5.25
Cost of fabrication consumables	7.14	7.14	7.14	7.14	7.14
Work load for steel work	6.39	6.39	6.39	6.39	6.39
Cost of labour for steelwork	6.39	6.39	6.39	6.39	6.39
Weight	-3.96	5.25	5.15	-3.95	4.92
Cost of coating materials	5.93	1.92	1.95	5.92	1.90
Cost of coating labour	22.98	2.28	2.38	22.99	5.37
Cost of surface preparation materials	5.93	1.92	1.95	5.92	1.90
Cost of surface preparation labour	18.11	-2.89	-2.79	18.11	-0.19
Cost of edge grinding	14.73	14.73	14.73	14.73	14.73
Cost of coating process labour	22.37	1.63	1.72	22.38	4.66

This table shows that definite savings can be made in terms of the reduction of labour costs for the different objective functions. In terms of steelwork, which is principally driven by the reduction in weld length, there are potential savings of approximately 5%. Considering the coating process the savings are relatively much higher, due to the reduction in surface area, but principally driven by the reduction in free edge and weld length which has a significant impact on the complexity of the structure. This study further reinforces the need to consider the total production cost, including coatings, of a given structure rather than focus on minimising one aspect of the production process, such as steel weight or weld length, which have been used in the past.

Examining the results from this study highlights that even with the associated reduction in the work content, as stiffeners are removed thus reducing the stripe coating length, the surface preparation and coating labour costs increase when a minimum steelwork cost solution is sought. This is a result of the reduction of aspect ratio, due to the increase in flange width and reduction in web height, which has an associated effect on the total arc length and non-visible area; these factors then drive up the overall complexity of the panels which influences the labour costs of the coating process.

This shows that the steelwork objective functions return a slightly lower surface area as a result of the reduction of the number of stiffeners. However the labour costs associated with applying paint to the surfaces are higher due to the added complexity of the steelwork focused structures. This highlights the importance of understanding the impact of each of the factors that contribute to the complexity of a structure and the interaction between them. For example if minimising the surface area was determined to be of the greatest importance during the design phase, as this reduces the total amount of paint required therefore minimising paint material costs.

This study highlights the potential problem of a surface area based approach, as although the surface area is reduced the overall complexity of the structure has increased, resulting in a more difficult working environment, ultimately this leads to higher costs as more time is required to successfully paint the structure. However more data collection is required to quantify the link between structural complexity and worker productivity.

7.4.3 Cost Savings from Increased Stiffener Spacing

A number of the panels within this midship section are unable to fully exploit the benefits of increasing the stiffener spacing. For example the keel and inner bottom panels can be reduced from 18 stiffeners to 16 with a stiffener spacing of 949mm. Designing a panel with 15 stiffeners would increase the spacing to 1009mm, whereas 14 stiffeners would increase the spacing to 1076mm.

Table 7-4 shows the potential savings of increasing the stiffener spacing to 1009 mm in the double bottom structure. It should be noted that it was not possible to remove any stiffeners from any additional panels as this would in most cases result in larger stiffener spacings to the point the design would require thick plates to achieve the require section modulus.

Table 7-4 Stiffener Spacing Increased to 1009 mm

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost	Min Total Cost
Cost Savings %					
Steelwork cost reduction	-1.0	6.3	6.5	-1.0	6.1
Coating cost reduction	23.3	8.7	8.1	23.3	10.4
Total cost reduction	3.2	6.8	6.8	3.2	7.0
Cost of steelwork materials	-4.8	5.7	6.0	-4.8	5.4
Cost of fabrication consumables	8.2	8.2	8.2	8.2	8.2
Work load for steel work	7.5	7.5	7.5	7.5	7.5
Cost of labour for steelwork	7.5	7.5	7.5	7.5	7.5
Weight	-3.3	4.1	4.3	-3.3	4.1
Cost of coating materials	7.4	3.6	3.4	7.4	3.3
Cost of coating labour	28.9	8.4	7.7	28.9	11.0
Cost of surface preparation materials	7.4	3.6	3.4	7.4	3.3
Cost of surface preparation labour	22.5	2.1	1.3	22.5	4.1
Cost of edge grinding	19.3	19.3	19.3	19.3	19.3
Cost of coating process labour	28.1	7.6	6.9	28.1	10.1

The results of this study show the potential to reduce the overall cost of the structure by between 3% and 7% depending on which objective function is used. Interestingly the steelwork, weight and total cost objective functions return saving in all processes, whereas the coatings focused objective functions provide large coatings cost savings but at the expense of weight, thus driving up steelwork costs.

Analysis of the results of the optimisation routine also highlights a further potential production benefit, the thickness of the web and the flange on the stiffeners is very similar, the required thickness is less than 0.25mm different. The benefit of this comes as a result of scheduling work and material flow during the building process, in that if the same thickness of plate is required for the fabricated tee bar stiffeners then it would be possible to standardise the process. In this case it would be possible to use one thickness of plate for both the stiffener and the shell plate, thus provide further if only marginal benefits

7.4.4 Cost Savings from Further Increases in Stiffener Spacing

Table 7-5 shows the results from a study where the maximum allowable stiffener spacing was increased to 1080 mm, it should be noted that not all panels utilise the maximum allowable spacing as the structural constraints are reached before the maximum stiffeners spacing, the actual spacing's can be found in the Appendix C.

Table 7-5 Percentage savings for 1080 mm stiffener spacings

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost	Min Total Cost
Cost Savings %					
Steelwork cost reduction	-0.33	6.98	6.89	-0.30	6.80
Coating cost reduction	28.56	14.33	12.23	28.56	15.25
Total cost reduction	4.56	8.43	7.96	4.59	8.45
Cost of steelwork materials	-4.54	5.80	5.68	-4.50	5.54
Cost of fabrication consumables	10.25	10.25	10.25	10.25	10.25
Work load for steel work	9.41	9.41	9.41	9.41	9.41
Cost of labour for steelwork	9.41	9.41	9.41	9.41	9.41
Weight	-2.21	4.99	4.59	-2.19	4.89
Cost of coating materials	8.44	4.51	3.92	8.42	4.54
Cost of coating labour	35.70	15.53	12.71	35.71	16.88
Cost of surface preparation materials	8.44	4.51	3.92	8.42	4.54
Cost of surface preparation labour	26.42	6.52	3.69	26.42	7.62
Cost of edge grinding	24.89	24.89	24.89	24.89	24.89
Cost of coating process labour	34.51	14.36	11.54	34.52	15.68

The results of this study show that it is possible to provide savings in all aspects apart from a small increase in weight when focusing on coatings. The study shows that it may be possible to reduce the overall cost of the structure by over 8%. This figure is driven by the significant reductions in the cost of the coating process, as these costs have been based upon a number of assumptions it is unwise to take these numbers as absolute; there do however give an indication of relative potential saving.

When considering the results from these studies it is interesting to note that there is little opportunity to realise any significant cost savings by merely optimising the benchmark structure, which follows the results of the single stiffener study conclusion that the design has not been arrived at by chance. By optimising the structure and remaining within the 1000 mm limit it is possible to reduce total production costs by almost 12% which would offer a significant saving to a ship builder and potentially and owner. Increasing the spacing to 1009 mm does not provide much in the way of further cost savings compared to the 1000 mm spacing limit. By increasing the spacing to 1080 mm enables removal of an additional stiffener from the double bottom, one from either side of the lower and upper wings and two from either side of the middle wing.

It is also worth noting that some shipyards are using sections which are supplied from the steel mill with 'pre-rounded' edges, which drastically reduce the labour bill for edge grinding; this is especially true of bulb plate sections. It should also be noted that this study does not directly account for the consumables associated with the edge grinding process, for completeness it could be included in the cost per meter estimate.

7.5 Conclusions

This work has focused on developing the methodology for cost savings on predominantly longitudinally stiffened panels. The approach taken by the steelwork process in a given yard will determine the influence of the labour cost savings by removing weld length metres. There are two principal construction methods, one method employs an automatic panel line where stiffeners are attached to plate using an automated process, and then the grillage structure is placed over the previously attached stiffeners. The notches cut in the grillage structure tend to be large to accommodate the distortions of the stiffeners. There is little opportunity for savings with this method as all welds tend to undertaken during the same pass with multiple welding robots. Reducing the number of stiffeners could lead to increased inefficiencies as weld robots are sitting idle in current plant, although savings could be made for future welding plant.

The results have shown that considerable savings can be achieved through the reduction of the number of stiffeners. It has also been shown that by increasing the stiffener spacing that significant further cost savings can be achieved for single panels, compartments and an entire midship section. Detailed analysis for the panels and compartment has shown that the proposed structurally feasible region proposed is acceptable. It may be possible when a complete grillage is considered to design structures that do not have an associated weight penalty, by considering the spacing of the transverse stiffeners or webs.

7.6 Summary

This chapter has sought to apply the methodologies that have been developed throughout this work to understand the influence of the plate and column slenderness ratios on both the production costs of a panel. This approach has then been applied to a compartment of the double bottom of the vessel, to determine the cost implications.

This work has highlighted the delicate balance between strength, weight and the overall production costs associated with constructing midship section of a ship. It has explored the influence of the plate and column slenderness ratios on both strength and costs. The values of both measures are closer to the upper limits. Most notably when the plate slenderness increases beyond 2 there is a significant reduction in the overall strength of the structures, however constraining it the benchmark, 1.7, produces panels with improved strength characteristics but the cost of being considerably heavier.

Through the development of an optimisation routine the competing nature of the steelwork and coating processes as objective functions has again been highlighted, whether that be purely focused on weight and complexity or the steelwork and coating process costs. The results of the work reinforce the beliefs of ***Rigo***, (***2001***) that focusing on steel weight will not necessarily return the lowest cost solution. To achieve a truly minimum cost solution all elements of the production process including paint must be included.

The final element has been to optimise the entire midship section of the vessel and examine the potential cost savings that could be realised, should a design for coatings approach be adopted. The final chapter of this work presents the overall conclusions and provides direction for future work.

8 SUMMARY, CONCLUSIONS AND FUTURE WORK

8.1 Summary

The nature of this work was such that there was a great deal of potential avenues for exploration. The development of WBTs from initial fixed weights used in wooden sailing vessels to the highly complex spaces seen in modern ship designs was considered. In addition to this a significant amount of knowledge on what could be considered as good design practice for consideration of the coating process has been identified.

The important points to takeaway are that areas which do not provide appropriate access the surfaces within them are likely in time lead to paint failures as a result of either insufficient or excessive paint thickness. Edges and welds should be minimised as the time and labour required to prepare and coat these areas using the methods required, brush and roller, are far greater than applying coatings by spray methods to other areas. Currently the problem remains that due to lack of importance afforded to the coating process, this knowledge is not being applied in practice so the potential benefits are never realised, as coatings are not seen as a value adding process.

The lack of investment of both time and money in the coating process and the fact the methods currently used to prepare surfaces and apply paint is largely the same as that used since 1950's, is believed to be one of the key drivers for the lack of respect that is often given to the coating process. As shipyards continue to strive to reduce their costs and with a greater focus placed on the reducing environmental impact, the importance of the coating process has begun to be recognised.

The recent adoption of the IMO PSPC has forced shipbuilders to reconsider their appreciation of the coating process within WBT's however current industry research is being focused on identification of new processes and products. The major paint companies continually strive to develop new improved products however the design space in which they can operate is tightly constrained, and the time required to develop a new paint product precludes any major innovations in the next 5-8 years. However before any benefits of these products or processes can be realised an improvement in the management systems employed for coatings must be made to bring the process under control.

The PSPC proposed a link between structural design complexity and coating performance; before it is possible to reduce complexity it was necessary to define a method of quantifying it, this lead to the development of the Complexity Index. This process involved both observing the coating process first hand and obtaining the views of both operators and designers as to what element of a structure contributed to the overall complexity. This tool allows a quantative assessment to be carried out on different design options. This index gives an indication of the difficulty an operator would encounter during the surface preparation and paint application processes. This work is the first of its kind to consider the needs of the coating process during the ship design process. The connection between the physical layout of a structure and the physical tasks that are needed to provide suitable protection for the expected asset life span has been defined and developed.

The ship structural design process has been reviewed in order to define the appropriate methods used for load prediction and the modes of failure which are likely to occur. During this a set of suitable assessment criteria for use on single and multiple stiffener plate combinations was identified and their relevance discussed. The assessment criteria that have been defined were used to identify a suitable design space within which alternative designs that provide improved solutions for the needs of the coating process that were investigated.

The review highlighted that current structural design methods do not consider the effect of applied protective coatings, assumptions are made as to the length of time that applied coatings provide protection. If the application of coatings is given greater importance then it is possible that the levels of uncertainty as to coating lifespan and therefore rates of corrosion could be significantly reduced. Ultimately this would result in safer more predictable ships structures.

Studies have been undertaken which have highlighted the problems that continue to exist with respect to the perception of protective coatings within shipbuilding. It is clear from analysis of the coating surveys that attitudes and practices have certainly not improved by any significant degree over at least the last the 15 years. This work through insight gathered from the industry at large has highlighted the varying perception of what is and isn’t difficult to paint. Most notably the difference of opinion of those designing and those applying paint to ships structures.

The development of the Complexity Index enables different designs, which comply with structural requirements, to be given a numerical value based upon a range of geometric factors. The Complexity Index was applied to a range of single stiffener plate combinations, typically used in shipbuilding, to determine the benefits that could be realised by altering the design of ‘standard’ sections in terms of the coating process. This review concluded that the stiffeners sizes and shapes currently being used strike a good balance between structural performance and ‘coatability’.

Potential designs were then compared and rated from a coatings perspective meaning that a decision can be made by the design team to select the ‘optimum’ design solution. As a result of improved designs there exists an opportunity to realise significant overall cost savings in terms of labour and materials if the coatings process is properly considered during the design phase.

The lack of suitable feedback between the production departments has been emphasised, including painting, and ship designers. Observations from the initial shipyard surveys which included the benefits of providing improved access within a WBT were implemented by the design team in the partner shipyard on the next ship with only a modest amount of additional effort.

From the beginning equivalent structural performance has been maintained by ensuring that the section modulus of all of the alternative structural solutions was equal to that of the benchmark structure. In addition to this a number of common indicators of structural performance including plate buckling and column slenderness ratios were used to define a feasible design space. As the knowledge of the interaction between the structure and the coating process increased additional constraints were added in order to ensure that the proposed designs provided solution that did not present production issues.

Expanding upon the knowledge gained looking at single stiffener plate combinations a stiffened panel from a double bottom section of an oil tanker was studied. A number of studies examined whether improvements could be realised by altering both the stiffener topology and the number of stiffeners. Cause and effect studies highlighted that it is possible to provide up to 20% reductions in the complexity of the panel by decreasing the number of stiffeners.

This provides two attendant benefits; firstly the increased spacing between the stiffeners provides improved access and therefore working conditions on the panel. Secondly by removing stiffeners from the panel there is a reduction in the amount of weld and free edge length on the panel. The act of preparing and painting edges is cited as one of the major cost drivers in protecting WBTs by shipbuilders. In practice this make perfect sense, if the process of painting a room in your house is considered; applying the emulsion to the main body of the walls and ceiling takes relatively speaking no time at all. The majority time is used during the ‘stripe coating’ process i.e. applying the gloss to the door frames and skirting boards and ‘cutting in’ between gloss and emulsion.

The initial single stiffener and stiffened panel studies examined the relationship between complexity and weight. Developing the argument further, an optimisation routine was developed to examine the influence of a number of different objective functions on the overall topology of the structure. These objective functions sought to minimise:

- Complexity;
- Weight;
- Steelwork cost;
- Coating process cost.

The calculation of the steelwork content used the approach present by ***Rigo*** (***2001***). The calculation of the work content of the coating process followed a similar approach to the steelwork, in that the surface preparation and paint application processes are separated into material use and labour content.

The proportions between steelwork and the coating process are what would be expected, i.e. the coating process accounts for between 25-30% of the total costs. However when calculating the steelwork costs the material costs are also included in the labour cost calculation. Due to high price of steel it is the opinion of the author that this approach drives the resultant solution towards that of minimum weight solutions. This is evidenced when examining the costs predictions for a given panel or compartment, where the steelwork labour costs are greater than the entire coating process costs.

When minimum total cost is chosen as the objective function the topology the resultant stiffeners are different to that of the steelwork cost, highlighting how a balance between the two process has been reached. Due to the influence of steel material costs on the steelwork process as the overall weight of the panels increase the topology of the resultant stiffeners tend towards that of the minimum steelwork cost objective function.

This study demonstrated that it is possible to reduce the production cost of building a ship, both in terms of the steel work and the coating process work content, despite increase in weight. By increasing the longitudinal stiffener spacing the studies were able to indicate that the potential cost savings that could be as high as 8% overall with a 15% reduction of coating labour costs. Depending on the build strategy employed at a given ship yard it may well be possible to increase this.

Having explored the defined design space using the structural indices Finite Element Analysis (FEA) was used to confirm the structural performance of all of the analysis that was undertaken from the load shortening of the single stiffener plate combinations, the single stiffener plate and the double bottom structure.

8.2 Future Work

The work within this thesis has looked at alternative structural solutions which will take a significant amount of design effort, plus a change in attitude of the wider shipping industry to realise the benefits.

There are a number of nearer market opportunities that could be realised. Principally these are to develop tools that offer improvements to operators within the confines of the current designs. The options fall into three areas; spray equipment that is easier to use in confined spaces; spray equipment that requires a shorter standoff distance, and methods of reducing the costs associated with touch and repair.

Spray equipment that is smaller/lighter would be easier for an operator to handle in restricted areas and is likely to increase the quality of the work carried out. In conjunction with this spray equipment that atomises the liquid paints in a shorter distance, thus reducing the standoff distance that an operator would need. This would almost certainly need to be developed in conjunction with a paint manufacturing company as there are significant gains that could be realised by considering the needs of the spray painter operator. The difficulty is that the marine industry is a small part of the sales of the major spray equipment manufacturers; it is difficult to see how potential returns could justify the investment of large amounts of money. I believe it requires one of the large marine coating manufactures to take the lead.

Recently portable vacuum blasting machines are being used more regularly; the use of such tools will improve the surface cleanliness and subsequent performance of any repairs completed due to the surface cleanliness provided. However it needs to be used with care, as improving the ability to repair damage can lead to situations where it is deemed acceptable to cause damage, which is the opposite message that this thesis is trying to convey.

8.2.1 Development of the Proposed Approach

This section is broken down into two sections, firstly future work that should be conducted to address the three other areas that were highlighted during the initial phase of the project. The second section covers work which should be conducted to develop the methodology proposed in this work and also areas that need to be addressed by individual areas of the shipbuilding industry.

This work has looked at the potential benefits of reducing complexity and the cost associated with the coating process during the newbuilding of ships. To fully understand the relationship between the complexity of a given structure and the productivity of both the surface preparation and paint application processes significant amounts of data is required. This requires working partnerships to be formed both between shipyard departments and with external painting contractors. This should be separated in different areas to determine the influence of complexity on such things as:

- abrasive blasting process for a range of different blasting systems;
- hand tooling;
- paint application by spray equipment;
- paint application by brush and roller;
- inspection including but not limited to steelwork, surface cleanliness and paint application.

In time this would allow relationships to be defined, ultimately leading to a system whereby a designer has a set of guidelines or a built-in monitoring tool that will determine the complexity of a structure and provide warning when it exceeds a given threshold. One attended benefit that could easily be over looked is that of improving the working environment for the steelworkers. In that reduction of complexity by increasing the working distance between items within a given space would provide similar improvements in the quality and repeatability of the steelwork process.

Although this work has focused on newbuild cost savings potential the largest benefits of improved coating performance lie in reducing the through life costs of a ship. The very nature of shipping industry in terms of ownership profiles and priorities means that at best, if the approach presented in this work were adopted, it would be a number of years before any of the cost benefits were seen. It may be the case as some owners do not keep a ship for its entire operating life that the benefits are never actually seen.

It is this that would present the greatest barrier to this approach being widely adopted, as oil tankers and bulk carriers are deadweight carriers, in that they reach their maximum capacity in terms of weight before they are ‘full’ then an increase in steelmass will reduce the cargo carrying capability of the vessel for the same displacement. This then reduces the potential revenue that an owner can generate from that vessel. To offset this revenue reduction would require a similar reduction in the initial capital cost of a ship, but this is subject to wider market forces which is another topic entirely.

This study has explored the influence of the structural limits that are often used in ship design namely, plate and column slenderness ratios, β and λ on not only the structural performance but also the production costs. The FEA of the optimised panels and double bottoms, showed a reduction in ultimate strength of a panel when the plate slenderness ratio exceeds two. The benchmark structure was chosen as it was thought to represent a modern contemporary design for a double hull tanker. This work has highlighted the relative inefficiencies of the design of the benchmark structure, to truly explore what structural performance and total production benefits could be possible it would be necessary to define the operational requirements of the ship and design a structure to meet these needs.

Following this it would be possible to develop a mathematical model of the midship section to assess the structural performance of the benchmark and the influence of factors such as the relaxing the structural constraints of the stiffeners in way of the neural axis of the vessel, thus considering all of the panels within the midship section as part of the structural system.

When considering the orientation of stiffeners and brackets to aid with drainage, this work has made assumptions on the topology to simplify the studies, i.e. angle bar stiffeners replaced with tee bar versions. The problem arises as Tee bar stiffeners create problems in terms of water traps on the upper side. However to provide the same structural performance an angle bar requires a large flange which creates problems for the applicators in terms of access to the inner most surfaces.

The body of this work is founded on the development of a tool to calculate the complexity of a given structure and then propose an alternative suitable design that will reduce the complexity. This idea was further developed to provide an indication of what potential cost savings in the coating process could be achieved by adopting the alternative design. The methodology calculates the complexity of a compartment by simple addition of the complexity of the panels that make up the compartment. Currently the program does not account for the brackets that are used to transfer loads between longitudinal and transverse structure. Further investigation is needed into the types of brackets typically used, and their positioning on complexity, it is expected that in light of the findings of this work that there will scope of improvement in terms of reducing complexity and cost.

The simple lessons learnt in the oil tanker double bottom can be applied to a more complex space; the number of stiffeners should be rationalised and reduced wherever possible and access both to the individual surfaces and within the tank should be considered during the design phase. Further work is needed to develop the approach for different areas of the vessel for example it may be possible to further relax the structural constraints for less highly stressed areas near natural axis.

The current incarnation of this tool is based in Microsoft Excel, and provides relative results in relation to a given benchmark structure. In order to allow the program to be more widely useable, a phase of development is required. The intention is that this program could be used by a structural designer to identify any potential cost saving by altering their proposed design. In time the program could be imbedded into one of the ship design software packages to predict a build cost for a proposed design whilst also identifying any cost saving changes that could be made.

Principal to this would be the development of a more user friendly interface and results display. One aspect of this is developing the influence the user has on the results, in terms of applying a user weighting to the different elements that influence the complexity and ultimately the cost of producing a given structure. Discussion with potential end users of this program has indicated their preference for an upfront display where principal dimensions are entered and results displayed. Initial investigations have shown that python programming language could be used to achieve this.

8.2.2 Secondary Steelwork

It is highly likely that regulations similar to the PSPC will be applied to alter areas of ships, following the precedent of the adoption of such regulations to WBTs and Cargo Oil tanks and the guidlines for void spaces. One area that such regulations could be applied to is that of the duct keel spaces on board a ship. These spaces are located along the centre of the vessel in the double bottom, and contain the pipe work necessary to undertake ballasting and operational fuel transfers. These spaces suffer from many of the same problems as the WBT double bottom but with the added issues associated with the addition of the required pipework. The provision of adequate access to all of the surfaces within these spaces is even more difficult due to the inclusion of the pipework.

The duct keel spaces also contain cable trays for the provision of lighting and measuring of the contents of the WBTs, Fuel oil tanks and Cargo Oil tanks. All of these items combined make the painters job very arduous in these spaces. It may be that in these areas due to the amount of piping and cable trays that are required that it is impossible to provide adequate access for the coating process. The decision is then one of scheduling, would it be better to paint the steelwork structures prior to the installation of some or all of the pipe and or cable trays. The difficulty then is how to impress upon the outfitting team the importance of not damaging the applied coatings. The major issue with this approach it that of in-service maintenance, if access cannot be gained to either the steel structure or some area of the pipework surfaces then it is very difficult to undertake maintenance. The second approach is to pre-outfit as much of the section as possible prior to painting, with this approach more design effort is required to ensure that all surfaces can be accessed. The advantage of this approach is that the applied coatings are far less likely to be damaged due to reduction in the outfitting activities that will take place after painting.

8.2.3 Novel Technologies

The third element that the DISPRO project identified was that of the use of alternative or novel materials and technologies. This has not been the main focus of this work however during the course of the project a number of items have been identified as areas for further work. There are three areas of interest for the shipbuilding community in the use of alternative materials; the use of novel structural panels, the use of adhesives for the attachment of none structural items and the use of none metallic materials for items such as ladders and walkways.

Sandwich panels such as the SPS panel have been used with reported good results for car decks in Ro-Ro ferries. This difficulty in utilising this type of technology in ballast tanks can be separated into three distinct areas. Firstly the joining of individual panels is difficult due to the affect the heat would have on the elastomer core of the panels, related to this are the current problems that occur with work scheduling in terms of the attachment of brackets etc. Secondly, the panels on car decks have been designed for the local loading of car and trucks, the difficulty in applying them to WBTs is related to their ability to handle and transfer the global ship hull girder loads. Finally is the issue of producibility the panels are currently flat and produced in ‘standard’ sizes. The WBTs in the ends of a vessel are far from flat therefore production of panels with curvature in two planes may be difficult and the issue of connection becomes even greater.

Without doubt work will continue in this area and the applicability of these types of panels will increase, however it will be some time, if ever, before this type of technology is widely used in the main hull girder of a vessel.

A growing interest has been identified in the use of industrial adhesives, rather than conventional welding, bolting or riveting. The use of such technology would help to reduce the great deal of damage that is done to applied coatings during the shipbuilding process, as in many cases building work often begins before the engineering process has been fully completed. This results in the need for additional extra brackets and pipe hangers for auxiliary piping and wiring systems. These are often required once the coating process has been completed for a given space/block.

Work has been undertaken to investigate the use of adhesives to glue these secondary items. In the USA a large proportion of the truck trailers that are produced use adhesives rather than more traditional rivets or bolts. Henkel claim to produce adhesives that make the truck bodies stronger, more reliable, quieter and better looking. Henkel’s bonding products are based on two-part Acrylic chemistry. The drawback of drawing parallels between truck bodies and shipbuilding is the expected life span. A typical truck body has a service life of around 15 years which is 10 years less than that of a ship.

There is still a great deal that is unknown know about the long term performance of adhesives. The solar industry has perhaps the most long term in-service data for structural adhesives. Hughson Chemicals produce a product that is used to bond the solar lenses into their supporting frame. The sun causes accelerated aging of many adhesives leading to a loss of inherent properties. The Lord Corporation who now own Hughson Chemicals, who appears to be a major player in this industry has over 40 years of experience in adhesives that are able to withstand harsh environments. Further investigations are on-going in this area to identify products which have a proven long term track record, which may be suitable for secondary steel items.

A final area that could yield operational cost saving to ship owners is that of none metallic materials for secondary structural items. The protective coatings that protect of means of access are highly likely to suffer from mechanical damage during service. It is also noted that the ladders, rails, walkways, gratings, stanchions, etc., that form the means of access will often be fabricated from square and flat bar sections, the edges of which are an inherent weak point in any coating system, especially where abrasion or mechanical damage is a possibility.

It should be noted that some class regulations do allow the use of plastic ladders/gratings and walk ways for access and these may be considered to ensure the Permanent Means of Access (PMA) remain corrosion free for the expected life. It is envisaged that this aspect would be examined during a details investigation of the integration of the secondary steelwork items as described above.

8.2.4 Planning and Work Scheduling

The importance of well thought out and scheduled work planning cannot be over stressed. The costs that can be attributed to unnecessary rework within the coating process are huge. It is hoped that as the importance of applied coatings increases that more effort will be invested to ensure that avoidable rework is minimised. To achieve this, the needs of the coating process must be considered during the ship production process. Simple elements of this are ensuring that the applied coatings have sufficient time to properly cure. This is very much depended on the prevailing environmental conditions, for example paint curing time is principally driven by the ambient temperature, however this is not a linear relationship. This means that the required curing time differs significantly between summer and winter.

Training systems have been implemented in other industrial areas such as ICATS, SSPC and the Train the Painter program, yet there are currently no mandatory requirement for training and certification of blasters and painters, there are under the PSPC such requirements for the inspectors. It would seem odd that there are requirements to find sub-standard work rather than invest in suitable training of painters. If the painters were trained to a higher standard, then the likelihood of instances of substandard work would be reduced.

Currently due to the very nature of the coating process there is very little formal quality control. This is evidenced by the fact that the PSPC requires 320 μm within the 90/10 rule, in order to ensure that revisits to an area are minimised it is common for painters to apply significantly more paint than required. The working environment within a WBT makes the application of QC processes very difficult, however one such method could stem from this work.

The complexity calculator can be used to accurately determine the surface area of a given panel or tank. Then based upon the desired paint thickness it would then be possible to determine how much paint should be used to achieve the desired dry film thickness, accounting for paint chemistry and suitable loss factors. If suitable records are kept of the use of the number of tins of paint for a given area or space then this would provide an early high level indication of the thickness of the applied paint film.

8.3 Areas for Industrial Focus

The final part in this section is directed towards the wider shipbuilding industry. This research project has examined an area that to date has not been well investigated. The project highlighted four areas during the initial stages of the project that were seen as key hurdles to improving the performance of applied coatings not just in ships WBTs but in a broader sense in ship building. This project has focused on the improvements that could be realised by altering the stiffener spacing within an oil tanker double bottom. Although the space that has been investigated is relatively simple when compared to a forepeak tanks for example, the results highlight the impact of free edges and weld length on both the construction and coating processes.

The work presented in this thesis could be seen as only the beginning of a new avenue for future research as it has served to highlight the enormity of the problem faced by ship designers in achieving a truly optimal ship design. This is principally due to the competing nature of different influencing factors. It is hoped that this project will form a platform from which further studies into improving the performance of coatings within shipping. With this in mind the author has these remarks which pertain to each of the different stakeholder groups who were involved in the project.

8.3.1 Classification Societies

It is recommended that classification societies investigate the development of guidelines for minimum standoff between structural items. It is envisages that this would be broken down into two different sections; one ensuring there is adequate standoff between primary and secondary steelwork; with the second focusing on the standoff between steelwork and secondary items such as pipework, and the standoff between different section of pipework. It is also suggested that Class look at the rules on the maximum stiffener spacing and encourage its clients to utilise wider spacing’s to realise the benefits proposed in this project

8.3.2 Shipbuilders

During the project IHC have been proactive in adopting some of the design ideas that have been generated. Designs have been developed that improve the access within WBTs by the provision of larger access holes, which has been well received by the coatings process operators. They have also trialled designs that remove as much of the stiffeners from WBTs, although this improved the working conditions within the WBT it simply moved the problem to the void spaces which surrounded the WBT. Which although these spaces are subject to a far less aggressive environment and only require one coat of paint, they are still very challenging to paint. Looking at the problem from a more localised approach; studies need to been undertaken to assess the potential benefits of reducing the number of stiffeners. In addition to this research need to be undertaken to determine the number of lightening holes provided.

Data collected by ***Baldwin*** (***1995***) looked at the productivity of the coating process for different areas of vessel at different locations within the building process. The data showed that painting activities undertaken in a dedicated paint cell have the highest productivity rates and that the flat side of the hull requires the least man hour input. The difficulty with drawing any further conclusions is the lack of raw data, as much of the painting work, is and remains the case, undertaken by sub-contractors and as such detailed records are not kept and disclosed to the shipyard.

It is therefore of paramount importance that accurate records are kept of the production rates of the surface preparation and paint application processes. Undertaking this would hopefully provide actual verification of the hypothesis of this thesis.

A significant amount of damage is done to applied coatings during the removal of access scaffolding from ships tanks. One potential solution would be to use a contractor for both paint application and scaffolding removal, with that company responsible for any rework that is required as a result of a lack of care when removing the scaffold. The reasoning being that if those who are moving the staging are involved with the coating process then they are more likely to be more sympathetic to the applied coatings, therefore cause less damage. A second solution would be to consider how a space could be design to incorporate the require staging

8.3.3 Paint Manufactures

In terms of the findings of this project for the development of coatings, there are two elements that should be investigated. The first that perhaps most difficult how be the development of coatings can atomise in a shorter distance thus making the job of the painter easier as they could operate more effectively in confined spaces. It is thought that this would and should be undertaken in conjunction with a spray equipment manufacturer, and could involve a means of switching between normal operation and confined working modes, perhaps by reducing the pressure in the paint line thus allowing the paint to atomise in a shorter distance for difficult to reach areas.

This project has highlighted the impact that the stripe coating of edges and weld has on the time taken to undertake the painting of a tank. Thus there is merit to the investigation of the development of paints that that aid the stripe coating process by either removing the need of two coats with edge retentive coatings or reducing the drying time.

8.3.4 Coating Subcontractors

It is the author’s belief that the biggest benefits to the performance of applied coatings through the life of a vessel will be made if agreements can be reached between shipbuilders and paint sub-contractors to accurately determine the productivity rates for different levels of complexity.

This would require a joint working party whereby quantitative feedback can be gained for design alterations. The benefits of this approach would be that better estimating of work content from general arrangement drawings would be possible, allowing improvements in work planning. It would be a competitive advantage to a coating contractor to be in a position to provide the services of scaffold erection and removal, and employ workers would understand/appreciate the coating process when removing the staging from tanks and other confined spaces.

8.4 Final Remarks

The work within this thesis has shown that until recently the coating process has been considered a value adding element of the ship building process. It has been demonstrated that there is the opportunity to provide significant gains to the shipbuilding industry by considering the coatings and the processes required to apply them as integral elements of the process.

There are potential cost savings for shipbuilders due to a reduction in labour costs, a significant proportion of this is avoidable rework associated with repairing damaged coatings, but also in the reduction of the time required to apply coatings by considering the structures to be painted and the operators working environment.

By apply coatings in a consistent manner in line with the manufactures guidelines on a more regular basis, then the likelihood is that the coatings will provide the intended in-service lifespan. This will provide shipowners with through life cost benefits in terms of reducing or removing the need for steel replacement as coating system provide a more reliable protection time span.

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10 APPENDICES

Contents

10.1 Appendix A Distributed Questionnaire

This question has been prepared aim with the DISPRO project (Design to Improve Structural PROection). This project is seeking to reduce structural complexity to make the processes of surface preparation and paint application easier. The basis for this work is the idea that if the structure is simplified it will be easier to apply paint consistently to the desired thickness, which will result in the paint will lasting longer whilst in service.

I would appreciate it if you would provide your name and company you work for, please note that any information provided will be treated in strictest confidence.

Name ____

Employer ____

What is your role within the shipbuilding or coatings industry?

1. Structural Designer __
2. Paint applicator __
3. Surface preparation __
4. Paint manager __
5. Coatings Manufacturer __
6. Technical advisor __
7. Other please specify __

____

___

How long have you been in your current role? _______

How long have you been in the shipbuilding or coatings industry?_______

What was your role before this one?

____

____

Where on a ship would you say are the most difficult areas are to prepare and apply paint?

____

____

____

____

What would you say makes these areas difficult to undertake adequate surface preparation?

1. Limited access to all surfaces in a compartment __
2. Arrangement of steel work to coat __
3. Amount of surface area to be coated __
4. Free edge length __
5. Weld length __
6. Other, please specify ____________________________________
   ____
   ____
   ____

What would you say makes these areas difficult to apply consistent thickness of paint to the surface?

1. Limited access to all surfaces in a compartment __
2. Arrangement of steel work to coat __
3. Amount of surface area to be coated __
4. Free edge length __
5. Weld length __
6. Other, please specify ____________________________________
   ____
   ____
   ____

Would a change in any of these factors make your job easier? If so which ones and how?

____

____

____

____________-

____

____

What other changes do you think would make the application of paint easier?

-

____

____

____

____

____

Please rate the following pictures on a scale of 1~5 in terms of difficult they would be to apply paint to, and provide and suggestions of how it could be improved.

1 = virtually impossible to consistent dry film thickness

5 = very easy to achieve consistent dry film thickness

Rating_____________

Comments

____

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Rating______

Comments

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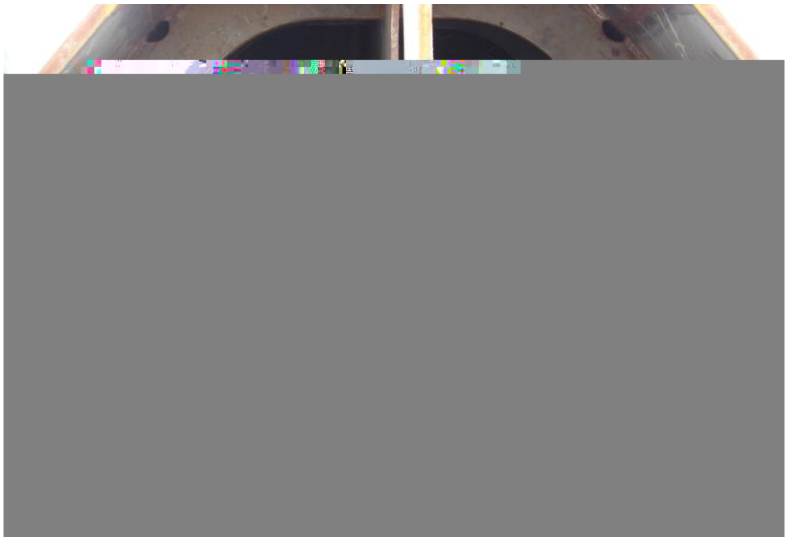

Rating ________

Comments

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Rating ________

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Any other comments

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10.2 Appendix B Results of the Different Plate Stiffener Combinations

Results for Initial multiple Tee bar stiffener plate combinations

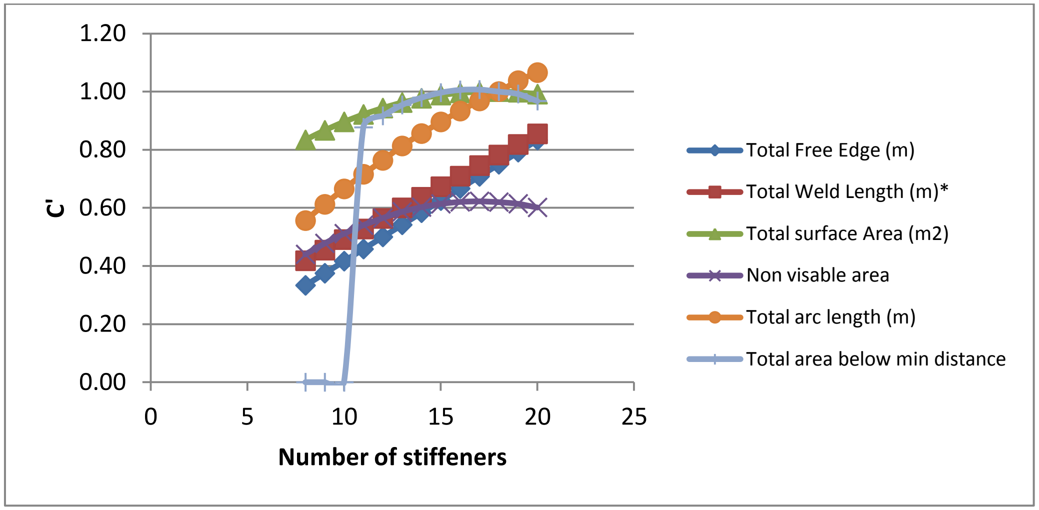
T' stiffener web aspect ratio fixed

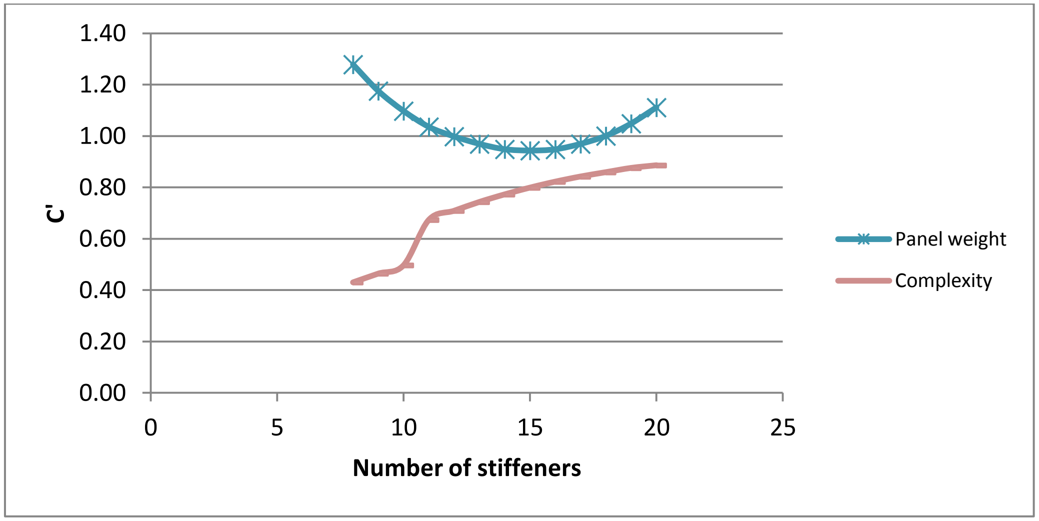
	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9	Panel 10	Panel 11	Panel 12	Panel 13
web	0.375	0.4	0.425	0.45	0.475	0.5	0.525	0.55	0.575	0.6	0.625	0.65	0.675
flange	0.133	0.142	0.15	0.159	0.168	0.177	0.186	0.195	0.203	0.212	0.221	0.23	0.239
thickness	0.0179	0.0168	0.016	0.0155	0.0152	0.0152	0.0154	0.0159	0.0166	0.0175	0.0189	0.0207	0.0231
aspect ratio	2.820	2.817	2.833	2.830	2.827	2.825	2.823	2.821	2.833	2.830	2.828	2.826	2.824
	20	19	18	17	16	15	14	13	12	11	10	9	8
Total Free Edge (m)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722	0.667	0.611	0.556	0.500	0.444
Total Weld Length (m)*	1.097	1.048	1.000	0.952	0.903	0.855	0.806	0.758	0.709	0.661	0.612	0.564	0.515
Total stripe coat length (m)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722	0.667	0.611	0.556	0.500	0.444
Total surface Area (m2)	0.991	0.998	1.000	1.000	0.996	0.988	0.977	0.962	0.943	0.921	0.896	0.867	0.834
Non visible area	0.974	0.992	1.000	1.003	0.998	0.987	0.968	0.942	0.908	0.869	0.822	0.769	0.708
Panel weight	1.111	1.048	1.000	0.969	0.948	0.943	0.948	0.969	0.998	1.035	1.097	1.175	1.278
Total arc length (m)	1.065	1.038	1.000	0.968	0.933	0.896	0.856	0.813	0.763	0.716	0.665	0.612	0.556
Total area below min distance	0.968	0.992	1.000	1.007	1.006	0.996	0.979	0.954	0.917	0.877	0.000	0.000	0.000
Percentage of total	0.976	0.994	1.000	1.007	1.010	1.008	1.002	0.991	0.972	0.952	0.000	0.000	0.000
Complexity	1.034	1.021	1.000	0.979	0.954	0.926	0.894	0.859	0.818	0.776	0.592	0.552	0.510
section modulus	1.000	1.003	1.000	0.999	0.996	0.997	0.997	1.001	1.001	0.997	1.001	1.000	0.999
Area ratio	0.301	0.305	0.306	0.307	0.306	0.303	0.299	0.293	0.286	0.277	0.266	0.253	0.238
Beta	1.436	1.508	1.588	1.676	1.774	1.885	2.011	2.155	2.320	2.514	2.742	3.016	3.351
b/t	42.937	45.084	47.457	50.093	53.040	56.355	60.112	64.405	69.36	75.14	81.97	90.16	100.18
landa	0.171	0.161	0.154	0.148	0.143	0.139	0.136	0.134	0.133	0.132	0.133	0.134	0.137
a/k	16.036	15.156	14.446	13.869	13.404	13.040	12.763	12.569	12.45	12.41	12.46	12.59	12.840

Results for Initial multiple Angle bar stiffener plate combinations

	Angle bar fixed ratio												
	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9	Panel 10	Panel 11	Panel 12	Panel 13
web	0.375	0.4	0.425	0.45	0.475	0.5	0.525	0.55	0.575	0.6	0.625	0.65	0.675
flange	0.133	0.142	0.15	0.159	0.168	0.177	0.186	0.195	0.203	0.212	0.221	0.23	0.239
thickness	0.0179	0.0168	0.016	0.0155	0.0152	0.0152	0.0154	0.0159	0.0166	0.0175	0.0189	0.0207	0.0231
aspect ratio	2.82	2.82	2.83	2.83	2.83	2.82	2.82	2.82	2.83	2.83	2.83	2.83	2.82
	20	19	18	17	16	15	14	13	12	11	10	9	8
Total Free Edge (m)	0.83	0.79	0.75	0.71	0.67	0.63	0.58	0.54	0.50	0.46	0.42	0.38	0.33
Total Weld Length (m)*	0.85	0.82	0.78	0.75	0.71	0.67	0.64	0.60	0.56	0.53	0.49	0.45	0.42
Total stripe coat length (m)	1.11	1.06	1.00	0.94	0.89	0.83	0.78	0.72	0.67	0.61	0.56	0.50	0.44
Total surface Area (m2)	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.94	0.92	0.90	0.87	0.83
Non visible area	0.60	0.61	0.62	0.62	0.62	0.61	0.60	0.59	0.57	0.54	0.51	0.48	0.44
Panel weight	1.11	1.05	1.00	0.97	0.95	0.94	0.95	0.97	1.00	1.04	1.10	1.18	1.28
Total arc length (m)	1.07	1.04	1.00	0.97	0.93	0.90	0.86	0.81	0.76	0.72	0.67	0.61	0.56
Total area below min distance	0.97	0.99	1.00	1.01	1.01	1.00	0.98	0.95	0.92	0.88	0.00	0.00	0.00
Percentage of total	0.98	0.99	1.00	1.01	1.01	1.01	1.00	0.99	0.97	0.95	0.00	0.00	0.00
Complexity	0.89	0.88	0.86	0.84	0.82	0.80	0.77	0.74	0.71	0.67	0.50	0.46	0.43
sec mod	0.90	0.95	1.00	1.05	1.10	1.16	1.22	1.29	1.36	1.42	1.50	1.58	1.66
Area ratio	0.30	0.30	0.31	0.31	0.31	0.30	0.30	0.29	0.29	0.28	0.27	0.25	0.24
Beta	1.44	1.51	1.59	1.68	1.77	1.89	2.01	2.15	2.32	2.51	2.74	3.02	3.35
b/t	42.94	45.08	47.46	50.09	53.04	56.35	60.11	64.41	69.36	75.14	81.97	90.17	100.19
lambda	0.17	0.16	0.15	0.15	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.14
a/k	16.04	15.16	14.45	13.87	13.40	13.04	12.76	12.57	12.46	12.42	12.46	12.60	12.84

Plots of the results for Initial multiple Angle bar stiffener plate combinations





Results for Second multiple Tee bar stiffener plate combinations

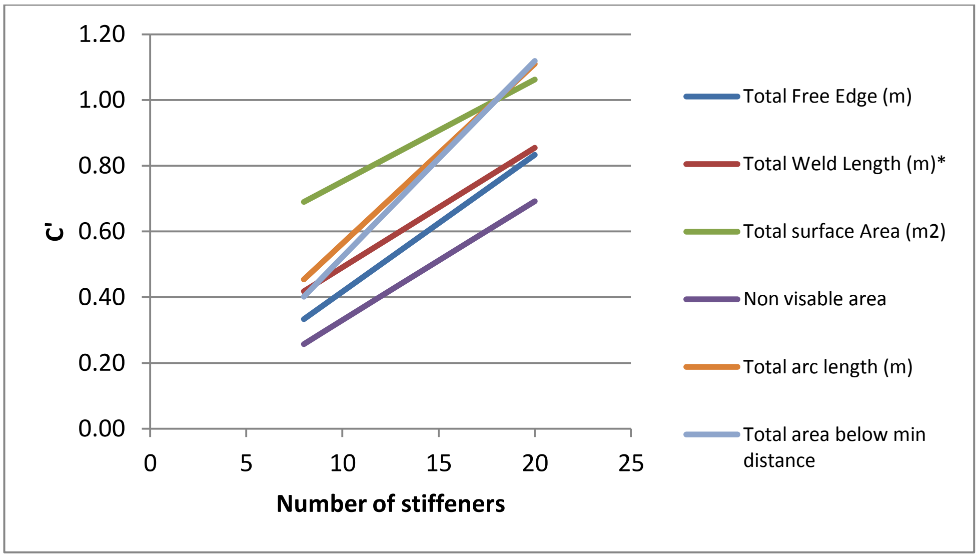
T' stiffener web aspect ratio fixed

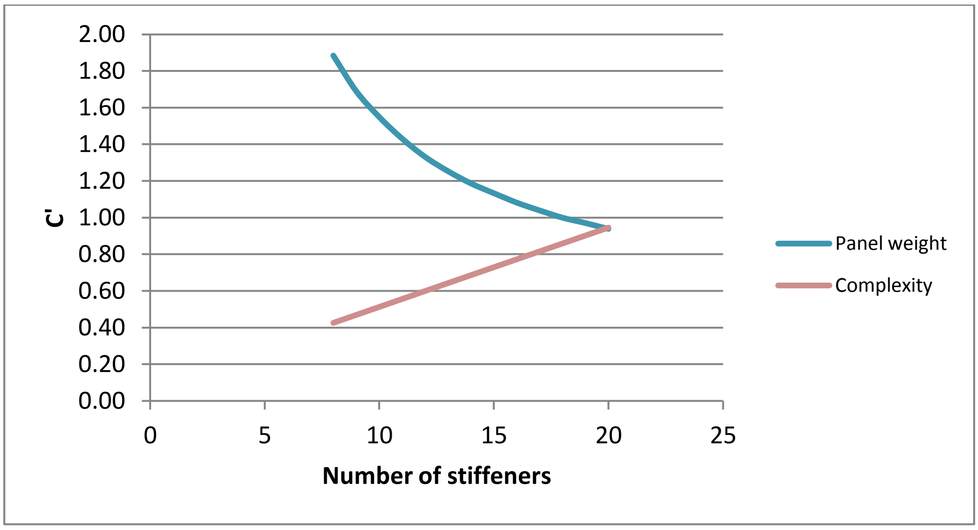
	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9	Panel 10	Panel 11	Panel 12	Panel 13
web	0.4	0.41	0.425	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.51	0.52	0.53
flange	0.142	0.145	0.15	0.152	0.155	0.16	0.162	0.166	0.17	0.173	0.179	0.184	0.187
thickness	0.0164	0.0164	0.016	0.0165	0.0167	0.017	0.0175	0.018	0.0185	0.0195	0.0197	0.0209	0.0228
aspect ratio	2.82	2.83	2.83	2.83	2.84	2.81	2.84	2.83	2.82	2.83	2.85	2.83	2.83
	20	19	18	17	16	15	14	13	12	11	10	9	8
Total Free Edge (m)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722	0.667	0.611	0.556	0.500	0.444
Total Weld Length (m)*	1.097	1.048	1.000	0.952	0.903	0.855	0.806	0.758	0.709	0.661	0.612	0.564	0.515
Total stripe coat length (m)	1.111	1.056	1.000	0.944	0.889	0.833	0.778	0.722	0.667	0.611	0.556	0.500	0.444
Total surface Area (m2)	1.027	1.011	1.000	0.975	0.955	0.935	0.910	0.887	0.861	0.833	0.811	0.781	0.749
Non visible area	1.045	1.017	1.000	0.955	0.920	0.884	0.841	0.798	0.753	0.703	0.665	0.611	0.552
Panel weight	1.044	1.033	1.000	1.013	1.011	1.014	1.026	1.037	1.045	1.078	1.070	1.108	1.177
Total arc length (m)	1.092	1.043	1.000	0.951	0.900	0.861	0.803	0.755	0.706	0.652	0.599	0.550	0.492
Total area below min distance	1.046	1.016	1.000	0.956	0.918	0.889	0.839	0.798	0.755	0.702	0.662	0.611	0.549
Percentage of total	1.018	1.005	1.000	0.980	0.961	0.951	0.922	0.901	0.876	0.842	0.815	0.782	0.733
Complexity	1.070	1.032	1.000	0.956	0.914	0.876	0.830	0.786	0.742	0.694	0.651	0.603	0.550
sec mod	1.002	1.002	1.000	0.999	0.997	1.004	1.004	1.005	0.998	1.003	0.999	0.998	1.001
Area ratio	0.316	0.310	0.306	0.296	0.288	0.281	0.271	0.260	0.249	0.237	0.227	0.212	0.196
Beta	1.568	1.646	1.733	1.829	1.937	2.058	2.195	2.352	2.532	2.743	2.993	3.292	3.658
b/t	46.864	49.207	51.797	54.675	57.891	61.509	65.610	70.296	75.704	82.012	89.468	98.415	109.350
lambda	0.274	0.269	0.260	0.260	0.257	0.253	0.251	0.249	0.248	0.247	0.242	0.243	0.246
a/k	25.689	25.231	24.446	24.415	24.096	23.759	23.576	23.384	23.256	23.237	22.720	22.834	23.144

Results for Second multiple Angle bar stiffener plate combinations

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9	Panel 10	Panel 11	Panel 12	Panel 13
web	0.4	0.41	0.425	0.43	0.44	0.45	0.46	0.47	0.48	0.49	0.51	0.52	0.53
flange	0.142	0.145	0.15	0.152	0.155	0.16	0.162	0.166	0.17	0.173	0.179	0.184	0.187
thickness	0.0164	0.0164	0.016	0.0165	0.0167	0.017	0.0175	0.018	0.0185	0.0195	0.0197	0.0209	0.0228
aspect ratio	2.82	2.83	2.83	2.83	2.84	2.81	2.84	2.83	2.82	2.83	2.85	2.83	2.83
	20	19	18	17	16	15	14	13	12	11	10	9	8
Total Free Edge (m)	0.83	0.79	0.75	0.71	0.67	0.63	0.58	0.54	0.50	0.46	0.42	0.38	0.33
Total Weld Length (m)*	0.85	0.82	0.78	0.75	0.71	0.67	0.64	0.60	0.56	0.53	0.49	0.45	0.42
Total stripe coat length (m)	1.11	1.06	1.00	0.94	0.89	0.83	0.78	0.72	0.67	0.61	0.56	0.50	0.44
Total surface Area (m2)	1.03	1.01	1.00	0.98	0.95	0.93	0.91	0.89	0.86	0.83	0.81	0.78	0.75
Non visible area	0.65	0.63	0.62	0.59	0.57	0.55	0.52	0.49	0.47	0.44	0.41	0.38	0.34
Panel weight	1.04	1.03	1.00	1.01	1.01	1.01	1.03	1.04	1.04	1.08	1.07	1.11	1.18
Total arc length (m)	1.09	1.04	1.00	0.95	0.90	0.86	0.80	0.76	0.71	0.65	0.60	0.55	0.49
Total area below min distance	1.05	1.02	1.00	0.96	0.92	0.89	0.84	0.80	0.75	0.70	0.66	0.61	0.55
Percentage of total	1.02	1.01	1.00	0.98	0.96	0.95	0.92	0.90	0.88	0.84	0.82	0.78	0.73
Complexity	0.92	0.89	0.86	0.82	0.79	0.76	0.72	0.68	0.64	0.60	0.57	0.52	0.48
sec mod	0.94	0.97	1.00	1.02	1.05	1.09	1.12	1.15	1.18	1.23	1.28	1.32	1.37
Area ratio	0.32	0.31	0.31	0.30	0.29	0.28	0.27	0.26	0.25	0.24	0.23	0.21	0.20
Beta	1.57	1.65	1.73	1.83	1.94	2.06	2.19	2.35	2.53	2.74	2.99	3.29	3.66
b/t	46.86	49.21	51.80	54.67	57.89	61.51	65.61	70.30	75.70	82.01	89.47	98.41	109.35
lambda	0.27	0.27	0.26	0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.24	0.24	0.25
a/k	25.69	25.23	24.45	24.42	24.10	23.76	23.58	23.38	23.26	23.24	22.72	22.83	23.14

Plots of the results for Second multiple Angle bar stiffener plate combinations





10.3 Appendix D Principal dimensions of the panels, stiffeners and web frames

Panel sizes				Stiffener sizes	
Keel	Width	16.14		Web height	0.425
	Length	3.85		Flange width	0.15
	Thickness	0.016		Flange thickness	0.016
	No stiffeners	18		Web thickness	0.011
Inner Bottom	Width	16.14		Web height	0.425
	Length	3.85		Flange width	0.15
	Thickness	0.016		Flange thickness	0.016
	No stiffeners	18		Web thickness	0.011
Turn of bilge bottom	Width	3.76		Web height	0.425
	Length	3.85		Flange width	0.15
	Thickness	0.016		Flange thickness	0.016
	No stiffeners	5		Web thickness	0.011
Turn of bilge side	Width	4.45		Web height	0.425
	Length	3.85		Flange width	0.15
	Thickness	0.016		Flange thickness	0.017
	No stiffeners	6		Web thickness	0.0117
Hopper	Width	5.26		Web height	0.425
	Length	3.85		Flange width	0.15
	Thickness	0.016		Flange thickness	0.017
	No stiffeners	6		Web thickness	0.0117
Lower wing	Width	4.25		Web height	0.385
	Length	3.85		Flange width	0.125
	Thickness	0.016		Flange thickness	0.018
	No stiffeners	4		Web thickness	0.011
Middle wing	Width	5.1		Web height	0.35
	Length	3.85		Flange width	0.1
	Thickness	0.016		Flange thickness	0.017
	No stiffeners	5		Web thickness	0.012
Upper wing	Width	5.1		Web height	0.3
	Length	3.85		Flange width	0.09
	Thickness	0.016		Flange thickness	0.018
	No stiffeners	5		Web thickness	0.011
Deck	Width	19.5		Web height	0.3
	Length	3.85		Flange width	0.09
	Thickness	0.016		Flange thickness	0.018
	No stiffeners	22		Web thickness	0.011
Centerline bulkhead	Height	19.5		Web height	0.3
	Length	3.85		Flange width	0.09
	Thickness	0.016		Flange thickness	0.018

	No stiffeners	22		Web thickness	0.011

Web frame				Stiffener sizes	
Double bottom	Width	16.14		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	18		Web thickness	0.013
Bilge bottom	Width	6		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	5		Web thickness	0.013
Lighting hole inner	Width	2		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	3		Web thickness	0.013
Lighting hole lower	Width	3		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	3		Web thickness	0.013
Lighting hole upper	Width	2		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	3		Web thickness	0.013
Lower wing	Width	4.25		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	4		Web thickness	0.013
Middle wing	Width	5.1		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	5		Web thickness	0.013
Upper wing	Width	5.1		Web height	0.2
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	5		Web thickness	0.013
Deck web	Width	19.5		Web height	0
	Height	2		Flange width	0
	Thickness	0.016		Flange thickness	0
	No stiffeners	0		Web thickness	0
Centreline web	Height	19.5		Web height	0
	Width	2		Flange width	0

	Thickness	0.016		Flange thickness	0
	No stiffeners	0		Web thickness	0

10.4 Appendix E Results of Optimization Studies

Optimized Benchmark

	Benchmark	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Total surface area	2333.4	1984.3	2274.8	2072.4	2144.4
Total non visible area	973.1	902.2	1010.8	1026.6	903.5
Total arc length	18180.2	17167.7	26188.9	28811.6	17362.3
Total free edge length	4586.0	4586.0	4586.0	4586.0	4586.0
Total weld length	5846.5	5479.2	5767.2	5479.2	5701.5
Total area below working distance	179.1	162.1	238.7	251.0	162.0
Absolute complexity	31439.6	30281.4	39558.3	42226.8	30475.0
Complexity including weighting	5240.0	5047.0	6593.2	7037.9	5079.3
Relative complexity	61.0	41.3	64.4	48.5	56.3
Weight	213.5	219.8	207.0	207.2	219.8
Production costs					
Cost of steelwork materials	5672.2	5730.9	5601.5	5600.4	5721.7
Cost of fabrication consumables	2236.9	2236.9	2236.9	2236.9	2236.9
Work load for steel work	2848.4	2848.4	2848.4	2848.4	2848.4
Cost of labour for steelwork	5696.8	5696.8	5696.8	5696.8	5696.8
Weight objective function	236.0	241.4	243.6	244.5	241.1
Cost of coating materials	3555.8	3467.8	3575.1	3602.1	3464.5
Cost of coating labour	27380.6	26059.3	31399.7	32924.3	26074.7
Cost of surface preparation materials	648.2	632.1	651.7	656.6	631.5
Cost of surface preparation labour	5000.2	4746.5	5706.3	5977.2	4748.1
Cost of edge grinding	2293.0	2293.0	2293.0	2293.0	2293.0
Steelwork costs	13605.9	13664.5	13535.2	13534.1	13655.4
Coating Costs	38877.8	37198.6	43625.8	45453.1	37211.8
Total costs	52483.7	50863.2	57161.1	58987.2	50867.2

	Benchmark	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Cost Savings %					
Steelwork cost reduction	0	-0.43	0.52	0.53	-0.36
Coating cost reduction	0	4.51	-10.88	-14.47	4.48
Total cost reduction	0	3.19	-8.18	-11.03	3.18
Cost of steelwork materials	0	-1.02	1.26	1.28	-0.86
Cost of fabrication consumables	0	0.0	0.0	0.0	0.0
Work load for steel work	0	0.0	0.0	0.0	0.0
Cost of labour for steelwork	0	0.0	0.0	0.0	0.0
Weight	0	-2.88	3.11	3.04	-2.88
Cost of coating materials	0	2.54	-0.54	-1.28	2.64

Cost of coating labour	0	5.07	-12.80	-16.84	5.01
Cost of surface preparation materials	0	2.54	-0.54	-1.28	2.64
Cost of surface preparation labour	0	5.35	-12.37	-16.34	5.31
Cost of edge grinding	0	0	0	0	0
Cost of coating process labour	0	5.11	-12.73	-16.76	5.05

Optimised with Stiffen Spacing Less 1000mm

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Total surface area	1917.3	2205.4	2002.6	2077.5
Total non visible area	836.4	939.3	954.8	837.8
Total arc length	16008.0	23999.5	26300.3	16202.5
Total free edge length	4120.4	4120.4	4120.4	4120.4
Total weld length	5013.6	5301.6	5013.6	5235.9
Total area below working distance	84.1	119.0	130.0	84.0
Absolute complexity	27979.8	36177.1	38521.7	28173.4
Complexity including weighting	4663.4	6029.6	6420.4	4695.7
Relative complexity	37.2	57.8	42.1	52.2
Weight	217.5	203.0	203.6	216.3
Production costs				
Cost of steelwork materials	5724.6	5593.2	5594.3	5715.5
Cost of fabrication consumables	2120.5	2120.5	2120.5	2120.5
Work load for steel work	2739.8	2739.8	2739.8	2739.8
Cost of labour for steelwork	5479.6	5479.6	5479.6	5479.6
Weight objective function	240.0	240.8	241.8	239.7
Cost of coating materials	3365.7	3469.3	3495.7	3362.4
Cost of coating labour	23473.9	27205.0	28596.6	23489.3
Cost of surface preparation materials	613.5	632.4	637.2	612.9
Cost of surface preparation labour	4345.5	5026.2	5273.7	4347.2
Cost of edge grinding	2060.2	2060.2	2060.2	2060.2
Steelwork costs	13324.8	13193.4	13194.5	13315.6
Coating Costs	33858.8	38393.1	40063.4	33872.0
Total costs	47183.6	51586.5	53257.9	47187.6

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Cost Savings %				
Steelwork cost reduction	2.1	3.1	3.1	2.2
Coating cost reduction	14.82	1.26	-2.96	14.78
Total cost reduction	11.23	1.74	-1.45	11.22

Cost of steelwork materials	-0.92	1.41	1.39	-0.76
Cost of fabrication consumables	5.49	5.49	5.49	5.49
Work load for steel work	3.96	3.96	3.96	3.96
Cost of labour for steelwork	3.96	3.96	3.96	3.96
Weight	-2.19	4.77	4.48	-1.64
Cost of coating materials	5.65	2.49	1.72	5.75
Cost of coating labour	16.64	0.65	-4.25	16.57
Cost of surface preparation materials	5.65	2.49	1.72	5.75
Cost of surface preparation labour	15.07	-0.52	-5.19	15.02
Cost of edge grinding	11.30	11.30	11.30	11.30
Cost of coating process labour	16.40	0.46	-4.40	16.33

Optimised with Stiffen Spacing Less 1010 mm

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Total surface area	1895.9	2181.1	1978.3	2056.1
Total non visible area	816.3	915.3	930.7	817.6
Total arc length	15682.6	23482.1	25782.9	15877.2
Total free edge length	4026.8	4026.8	4026.8	4026.8
Total weld length	4920.0	5208.0	4920.0	5142.3
Total area below working distance	82.1	116.0	127.0	82.0
Absolute complexity	27423.7	35421.1	37765.6	27617.3
Complexity including weighting	4570.7	5903.6	6294.4	4603.0
Relative complexity	36.8	57.4	41.7	51.8
Weight	215.9	201.9	202.5	214.7
Production costs				
Cost of steelwork materials	5713.8	5585.7	5586.8	5704.7
Cost of fabrication consumables	2097.1	2097.1	2097.1	2097.1
Work load for steel work	2717.9	2717.9	2717.9	2717.9
Cost of labour for steelwork	5435.8	5435.8	5435.8	5435.8
Weight objective function	238.3	239.2	240.2	238.1
Cost of coating materials	3333.1	3432.3	3458.6	3329.8
Cost of coating labour	22788.0	26366.7	27758.4	22803.4
Cost of surface preparation materials	607.6	625.7	630.5	607.0
Cost of surface preparation labour	4233.4	4885.9	5133.4	4235.1
Cost of edge grinding	2013.4	2013.4	2013.4	2013.4
Steelwork costs	13246.8	13118.6	13119.7	13237.6
Coating Costs	32975.4	37324.0	38994.2	32988.6
Total costs	46222.2	50442.6	52113.9	46226.2

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Cost Savings %				
Steelwork cost reduction	2.7	3.7	3.7	2.8
Coating cost reduction	17.9	4.2	-0.3	17.9
Total cost reduction	13.5	4.0	0.7	13.5
Cost of steelwork materials	-0.7	1.5	1.5	-0.6
Cost of fabrication consumables	6.7	6.7	6.7	6.7
Work load for steel work	4.8	4.8	4.8	4.8
Cost of labour for steelwork	4.8	4.8	4.8	4.8
Weight	-1.5	5.3	5.0	-0.9
Cost of coating materials	6.7	3.6	2.8	6.8
Cost of coating labour	20.2	3.8	-1.4	20.1
Cost of surface preparation materials	6.7	3.6	2.8	6.8
Cost of surface preparation labour	18.1	2.3	-2.6	18.1
Cost of edge grinding	13.9	13.9	13.9	13.9
Cost of coating process labour	19.8	3.6	-1.6	19.8

Optimised with Stiffen Spacing Less 1100 mm

	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Total surface area	1817.3	2094.2	1891.6	1977.5
Total non visible area	742.2	831.0	847.1	743.5
Total arc length	14025.1	20948.9	23453.4	14219.7
Total free edge length	3592.0	3592.0	3592.0	3592.0
Total weld length	4485.2	4773.2	4485.2	4707.5
Total area below working distance	73.4	103.3	115.1	73.3
Absolute complexity	24735.1	31834.4	34384.3	24928.7
Complexity including weighting	4122.6	5305.8	5730.8	4154.9
Relative complexity	31.6	51.3	35.7	46.6
Weight	212.3	199.1	199.6	211.1
Production costs				
Cost of steelwork materials	5697.6	5573.1	5573.5	5688.4
Cost of fabrication consumables	1988.4	1988.4	1988.4	1988.4
Work load for steel work	2616.5	2616.5	2616.5	2616.5
Cost of labour for steelwork	5233.0	5233.0	5233.0	5233.0
Weight objective function	236.6	237.8	239.4	236.3
Cost of coating materials	3213.4	3300.0	3326.5	3210.1
Cost of coating labour	19454.8	22273.4	23677.1	19470.2
Cost of surface preparation materials	585.7	601.5	606.4	585.1
Cost of surface preparation labour	3690.8	4208.7	4459.4	3692.5

Cost of edge grinding	1796.0	1796.0	1796.0	1796.0
Steelwork costs	12919.0	12794.5	12794.9	12909.8
Coating Costs	28740.7	32179.6	33865.4	28753.9
Total costs	41659.7	44974.1	46660.3	41663.7
	Min complexity	Min Weight	Min Steel work cost	Min Coating Cost
Cost Savings %				
Steelwork cost reduction	6.06	7.09	7.09	6.13
Coating cost reduction	37.15	22.49	16.40	37.09
Total cost reduction	27.51	18.11	13.84	27.50
Cost of steelwork materials	-0.31	1.92	1.91	-0.15
Cost of fabrication consumables	14.05	14.05	14.05	14.05
Work load for steel work	9.95	9.95	9.95	9.95
Cost of labour for steelwork	9.95	9.95	9.95	9.95
Weight	0.72	7.41	7.14	1.30
Cost of coating materials	11.87	8.93	8.06	11.98
Cost of coating labour	42.68	24.63	17.24	42.57
Cost of surface preparation materials	11.87	8.93	8.06	11.98
Cost of surface preparation labour	36.96	20.11	13.35	36.89
Cost of edge grinding	31.10	31.10	31.10	31.10
Cost of coating process labour	41.77	23.91	16.62	41.67