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COMMITTEE V.3
MATERIALS AND FABRICATION TECHNOLOGY

COMMITTEE MANDATE

The committee shall give an overview about new developments in the field of ship and offshore materials and fabrication techniques with focus on trends which are highly relevant for practical applications in the industry in the recent and coming years. Particular emphasis shall be given to the impact of welding and corrosion protection techniques on structural performance, on the development of lighter structures and on computer and IT technologies and tools, which are meant to link design and production tools and to support efficient production.

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KEYWORDS

Welding, Residual Stresses, Distortions, Corrosion Resistant Steel, YP460 Steel, Lightweight Materials, Corrosion Protection, Coating, Cost Estimation, Accuracy Management, Simulation Based Production

CONTENTS

1. INTRODUCTION

Due to the expansion of worldwide seaborne trade in the last several years, world shipbuilding market enjoyed a steady upward trend until 2008. Many shipyards are trying to produce more ships and offshore structures with their limited facilities and investments. At the same time, we are experiencing rapid changes of circumstances:

- IMO is more and more dedicated to ship structural and coating rules, reflecting increased demand for safer shipping.
- Environmental issues such as global warming are of more and more concern. Less emission of GHG from shipbuilding and shipping process is required.
- Long term trend of prices of raw materials is rising. Lighter structure or new materials may be necessary to be sought.
- In some countries, aging of the workforce is prominent. Ship production need to change so that young workers can easily contribute.

All these changes affect how we should build ships and offshore structures, and many research works are being carried out to meet these demands. This report of SC-V.3 presents a review of recent research and development activities about materials and hull fabrication technology.

Chapter 2 reviews general situations of the research works, focusing on trend of market situation and main trends in different parts of the world. Chapter 3 investigates the impact of welding – the most important joining technique – towards the structural performance. Chapter 4 describes latest development of new materials and lightweighting in shipbuilding, focusing on new steel materials, composites and hybrid structures, their properties, fabrication, assembly and practical application. Chapter 5 focuses on effective means to cope with the stricter corrosion protection rules in terms of materials, coating systems and application. Chapter 6 summarizes recent developments in computer applications in terms of cost estimation, accuracy management and simulation based design. Chapter 7 gives conclusions and recommendations derived from each chapter.

2. NEW TRENDS IN MATERIALS AND FABRICATION METHODS

Worldwide shipbuilding industry experienced strong period since 2003 to 2008, recording new orders of 85.3 million CGT, completion of 34.6 million CGT and orderbooks of 177.7 million CGT in 2007 (CESA 2008). Figure 1 gives a historical overview of worldwide shipbuilding production in terms of gross tonnage (SAJ 2008), and figure 2 shows shipbuilding turnover in the last decade (CESA 2008). It is observed that:

- Expansion in production is very rapid especially during the last decade.
- This rapid expansion was mainly covered by Korea in the last decade and by China especially in the last few years.
- Although European share in production is small in terms of gross tonnage, it was one of the region with the highest turnover.

As pointed out in the previous report, shipyard production technologies are heavily influenced by the types of ships being built, size of shipyards, geographical aspect and so on. In this context, European shipbuilding industry focuses on more high end segment such as cruise ships and naval vessels. Production technologies with regard to thin plate thicknesses are comparatively important. Asian shipbuilding industry focuses on cargo ships, attaching importance to productivity in mass production in large shipyards.

Trend of ship production in different parts of the world is described from the following sub-section.

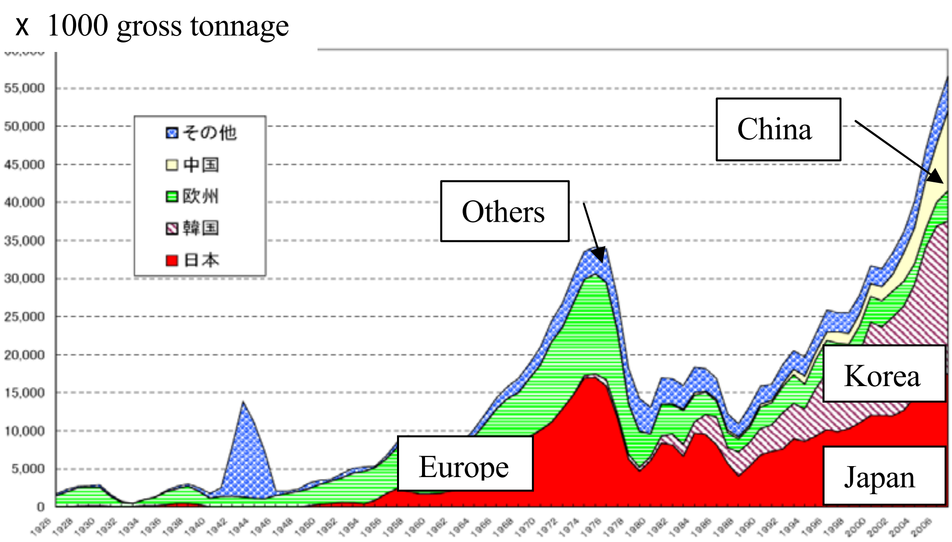


Figure 1: Historical overview of worldwide shipbuilding production (SAJ 2008)

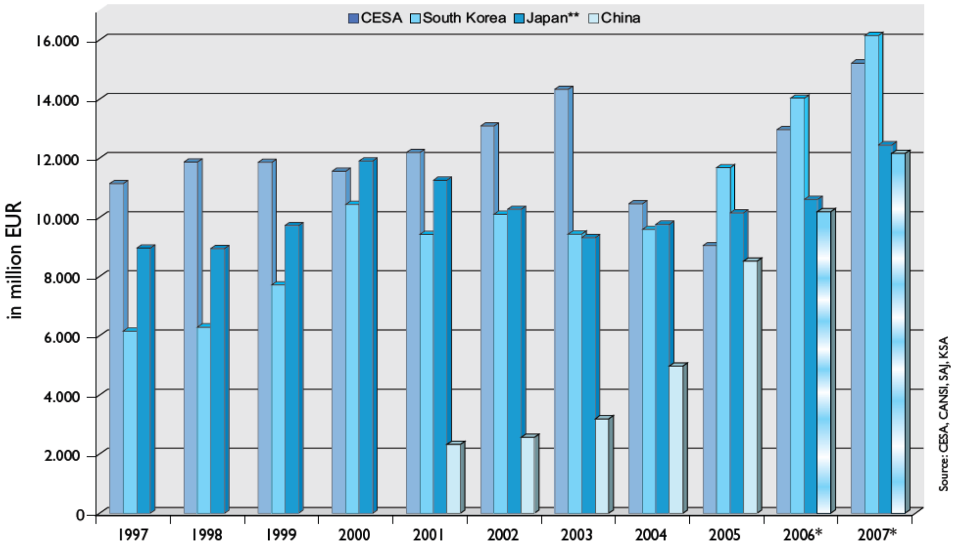


Figure 2: Development of shipbuilding turnover by regions (CESA 2008)

2.1 Asia

2.1.1 Japan

In the previous report of this committee, it was pointed out that the skills of shipbuilding workers might be lost rapidly as the workers get older and retire. Figure 3 shows age profile of the workforce of Japanese shipbuilding industry, which was investigated in 2003 (http://www.mlit.go.jp/maritime/senpaku). We can see that almost half of the workforce was older than 50. Because very large amount of workers reached their retirement age in 2007, this problem was called the “2007 Problem.” The year 2007 has already passed, and it seems that the Japanese shipbuilding industry is somehow overcoming the problem.

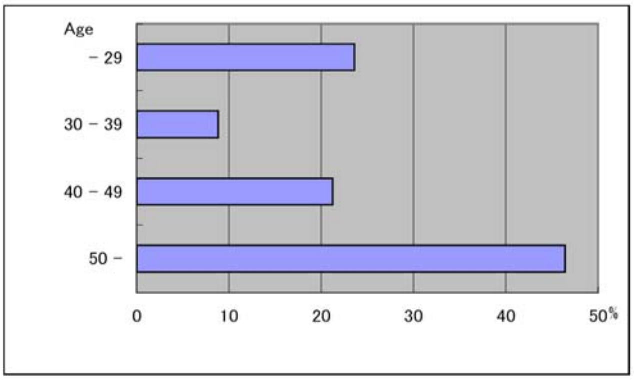


Figure 3: Age profile of Japanese shipbuilding industry

To cope with the problem, the industry took actions from three different aspects.

- Just to transfer knowledge and skills to the successors;
- To help unskilled workers to accomplish difficult jobs with the help of information technology;
- To replace the skilled workers with automation;

One method to transfer skills to young workers is introduced in Tamai *et al*. (2006), as the "Master of Skills" systems. Because Japanese shipbuilding industry lacks the middle-aged workforce due to the long recession period, it was considered that the ordinary OJT (On the Job Training) process was not sufficient, and that full-time teachers should be assigned to transfer their skills to young workers through one-to-one coaching. For example, 9 masters of skills were appointed for the term of half a year in a shipyard, from various fields such as welding, lugging, fitting, machinery, painting. Those masters were perfectly free from the jobs in the lines, and concentrated to teaching and recording of the training.

Information technology is another approach to transfer skills. Hiekata *et al*. (2005A, 2005B, 2006, 2007) developed knowledge transfer system, which can be applied effectively to acquire knowledge of elder experts. The characteristics of each job were revealed through questionnaire and structured interviews, and the job process is analysed and represented by workflow and related documents, where tacit knowledge of some tasks can be turned to explicitly documented knowledge. This system was applied to actual shipbuilding design process in Japanese several shipyards as a case study, and proved to be useful. Another approach to utilize information technology is the simulation of production processes, which will be discussed in 6.3 of this report.

Automation is also important to replace the skilled workers. Welding is one of the most important jobs in shipyards, and the ratio of the mechanized welding in Japanese shipyards is 42% in average, and 64% in the most advanced shipyard (Miyazaki 2008). Further development of mechanized welding calls for a breakthrough. Miyazaki (2008) showed some challenges such as mechanized welding inside the double hull structure in the assembly stage, and mechanized butt welding of longitudinals inside the double hull structure in the erection stage. These can be realized through development of small-sized robots which can move through manholes, root gap adaptive control, etc.

Other than this, automation and optimization of production engineering was attempted in various fields. Okumoto *et al*. (2005D) optimized the block allocation on the assembly area using simulated annealing method. Wibisono *et al*. (2007) optimized block division planning using genetic algorithm and product model. Universal Shipbuilding Corporation (2008) developed a high performance NC Printing Machine, which enables fast printing irrespective of the number of characters and lines to be printed. Information of hull and machinery outfitting can be printed as well as hull structure assembly information, and overall efficiency was substantially enhanced.

2.1.2 Korea

In 2006 Korean shipbuilding companies got new orders of 19,585,000 CGT, which was the highest number since 2000. Moreover in the first half of 2007 Korean shipbuilders have received 51.3% more orders than that of a year ago. Strong demand for new vessels was expected to continue for the next few years at least, due to expanding world-wide seaborne trade, especially between China and USA, and increasing need of new ships to adapt new International Maritime Organization's requirements.

Amidst a boom in orders, Korean shipbuilders are expanding their facilities and striving to improve production technology to meet delivery time. Important issues to increase the production capability are, for example, limited production space and lack of skilled worker.

Hyundai Heavy Industries has successfully built a large LPG cargo without using dry dock "called on-ground building method" for the first time in the world. Daewoo Shipbuilding & Marine Engineering has built Bulk and LPG carriers with "on-ground building and launching barge" mixed production method. Hanjin Heavy Industries has delivered 8400 TEU container ship, whose length was over the length of dry dock, by using "DAM Production Technology". By this technology two parts of a ship could be erected on the sea after launching from the dock. Samsung Heavy Industries has been developed "tera-block" method that allows the company to assemble a vessel from just two large ship blocks. All these construction methods were developed to cope with limited dry dock space and increase turnover of the dry dock.

Information Technology, which is one of global competitive technologies in Korea, was introduced to utilize the production area more efficiently. Chang (2006) has reported a using of a wireless internet environment and PDA system to exchange real time information data between the workers. Shin (2006) has presented a prototype of block tracking system for pre-erection area using of PDA and GPS to chase the location of each block and to exchange the pre-erection work order. Simulation based production scheduling and Product Data Management are also important, which will be dealt within section 6.3 in more detail.

As Japanese shipyard, the Korean shipbuilding companies faces with an increase of aging worker, a shortage of skilled workers and the worker's health problem. To overcome this problem a robot welding and painting system were introduced (Ryu *et al* 2006, Kim *et al* 2007). Robot welding system has been successfully applied in most big Korean shipyard, however, the paint system has only used in restricted job due to its harsh production environment.

To control welding distortion and predict the deformation in each production stage are also vital research theme in Korean shipyard. Because the geometric inaccuracy caused by welding distortion hinders the application of automation and mechanization in production stage and the distortion needs addition corrective work. A desire for Korean shipbuilder to tap into the value-added market especially that of passenger ships including cruise vessels, where steel plates are mainly thin thickness, is another factor to support research works for welding distortion. Many research works have been carried out in Korea, some of which will be discussed in section 6.2.

In addition to shipbuilding market most of big shipbuilding companies have great interest on offshore drill platform business. Because rising fuel prices in world-wide are prompting more exploration of deep sea oil reserves and raising demand for offshore platforms drill. Korean firms have got all global drill ship projects and many semi-drill rigs in 2007. To produce these offshore structures more effectively, well-known production and welding technology in shipbuilding should be applicable (Han *et al*. 2005, Lee *et al* 2007).

2.1.3 China

As described in the introduction of this section, the boom of Chinese shipbuilding industry is prominent in the last few years. Under the governmental policy to build ships which carry Chinese goods in China, Chinese shipyards are rapidly accumulating shipbuilding technology, and enhancing productivity. According to the governmental plan, shipbuilding capability will be 17 million DWT in 2010, and 22 million DWT in 2015. However, it is also said that including the shipyard that are being built or planned to be built, the capability may reach 40 million DWT. This is raising serious concern about the gap between demand and supply in the future.

2.2 Europe

After four consecutive years of increasing new orders, the order book of European shipbuilding has reached about 16 million CGT at the end of 2007. The major market sectors of European shipbuilding remain to be passenger vessels (with a slightly increasing share) and container vessels. However, the segment of other none-cargo vessels, such as offshore support vessels, grew fastest and reached more than 17% at the end of 2007, compared to about 14% in 2006 and only 7% in 2005 (See figure 4).

With the aim to maintain and increase the global market position of European shipbuilders in particular for high value added complex vessels, built to a large extend according to specific customer needs, the European shipbuilding industry supported by the European Commission and the member states have launched in 2003 the "LeaderSHIP 2015" initiative, which is since then continuously monitored and further developed. LeaderSHIP 2015 comprises the following strategic objectives:

- Establishing a Level Playing Field in World Shipbuilding
- Improving Research, Development and Innovation Investment
- Developing Advanced Financing and Guarantee Schemes
- Promoting Safer and More Environment-Friendly Ships
- A European Approach to Naval Shipbuilding Needs

- Protection of Intellectual Property Rights (IPR)
- Securing the Access to a Skilled Workforce
- Building a Sustainable Industry Structure

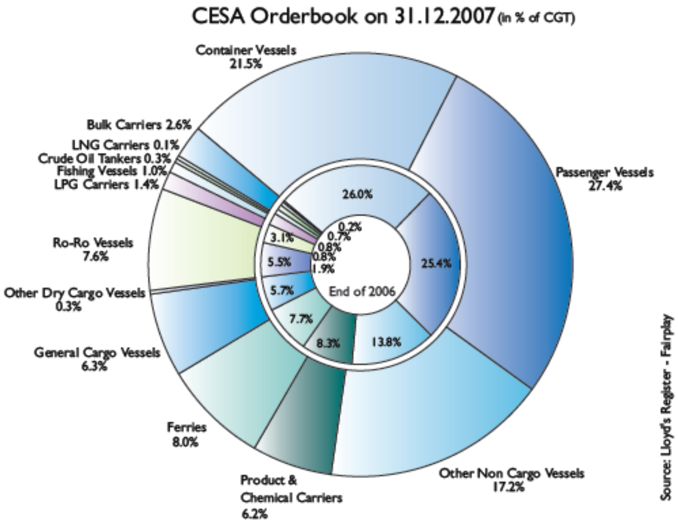


Fig. 4: Orderbook of European shipbuilders by ship types (CESA2008)

This initiative has a significant impact on research, development and innovation in the European maritime sector. Task forces follow the main lines of activity within LeaderShip 2015, resulting e.g. in the introduction of an innovation aid scheme in many of the EU member states as well as an increase in research funding both on European and national level. The European initiative was translated into national programmes in the member states, such as the High Tech Initiative in Germany, with the maritime cluster forming one of 18 strategic fields.

European maritime research has been fostered by a significant increase of research funds for the maritime sector within the 7th European Framework Programme for Research, Development and Innovation (http://cordis.europa.eu/fp7) as well as by the foundation of the European Technology Platform WATERBORNE (http://www.waterborne-tp.org). European Technology Platforms are meant as coordination platforms between the industry and research communities, the European Commission and the member states. With this goal, WATERBORNE has defined a "VISION 2020" for the Maritime Industry as well as a Strategic Research Agenda, defining the strategic development also in the field of production and new materials.

With this background, the following key research areas related to ship production can be seen in Europe:

- Increased <u>work sharing in the shipbuilding production chain</u>, including shipyards and subcontractors call for integrated IT-solutions for design and manufacturing, modular product concepts and new process chains for a more efficient work sharing.

- Various strategies are followed to achieve this goal, reaching from increased outsourcing and the creating of manufacturing centres to in-sourcing of strategic services and production areas. New business models can also help to make investment of innovative – but expensive – high-tech equipment more economically feasible for the comparatively small European shipyards.
- Similar as in other countries, European shipbuilding is increasingly suffering from a shortage of skilled workforce. In order to maintain know-how within the shipyards and to ensure that the specific skills of elderly personnel are kept, Knowledge Management is an increasingly important topic both for design and production. Research reaches from the development of knowledge data bases (Bal 2007) to dedicated work flows and IT tools to "learn from experience" and the increased use of simulation both in design and production.
- Life cycle cost assessment is becoming increasingly important to make the customer aware of the life cycle benefits of innovative solutions. An integrated view requires dedicated methods to compare production and operational cost, safety and environmental aspects as well as tools for life cycle optimization in the different design and production phases of a ship.
- Thin sheet material processing remains to be an ongoing research issue for European shipyards, with innovative laser systems being increasingly applied. A strategic line of research is the more flexible use of laser systems either through mobility or laser networks to increase economic feasibility.
- After extensive applications and research in the naval field, composite and other lightweight materials increasingly find their way into commercial shipbuilding. Further research is however required to make joining and outfitting of lightweight structures more efficient, to find the optimum material mix and to solve problems related to safety and operational requirements

These tendencies will be described in more detail in the following chapters of this report.

2.3 America

2.3.1 USA

As in the past two decades, U.S. shipbuilding activities mainly concentrated in the naval arena with some commercial participation. Since 2000, the commercial sector launched 20 ships of a variety of size and capacities, from 12,900 to 193,000 metric ton DWT, from container ships to crude and chemical carriers. There are still another 28 ships in the different stages of fabrication and completion (ShipbuildingHistory.com 2008). In comparison to other regions in the world, mainly Far East, this number remains low.

To strengthen the U.S. naval shipbuilding, the National Shipbuilding Research Program (NSRP) currently funds programs in both ship construction and repair technology, from procedure qualification to personnel training, from robotic welding to production planning, from coatings to design, and from materials to distortion (NSRP 2008A, NSRP 2008B).

While structural steels are still the material of choice for ship hulls and other major components, material choices have shifted to higher strength grades. DH36 and EH36 are more used these days. In the U.S. naval sector, weight reduction, improved performance, fuel economy, and increased marine corrosion resistance are still the major drivers for incorporating other materials into the ship design and fabrication. Aluminum and titanium alloys have been gradually incorporated as fabrication and properties issues are resolved. Several aluminum-copper (e.g. AA 2519, AA6061-T6) and aluminum-magnesium (5456-H116, 5083-H116, and 5086-H116) alloys have been used in shipbuilding (Czyryca *et al* 2006). These materials are being considered for topside structure, piping, armor, doors, hulls, and other stiffened structures. These materials are non-magnetic, can be fabricated by current shipyard practices and can potentially offer 60% weight savings over steel.

Main technical issues to be resolved before greater implementation of aluminum alloys in ship structures include weld quality since these alloys are more difficult to weld relative to steel and that shipyards typically have limited experience in these alloys. In terms of mechanical properties, aluminum alloys generally exhibit lower fatigue strength when compared to steel. As-welded fatigue properties can be as low as 6 to 7 ksi (Czyryca *et al* 2006). Regarding design, it is known that the undermatched HAZ near welds in aluminum structures may accumulate plastic strains much faster than the rest of the structure, and may have a significant impact on limit-state calculations (Collette 2007). Literature search has demonstrated little knowledge and success in limit-state design for aluminum structures, requiring the development of practical limit-state models for aluminum welds.

Aluminum alloys also display high fatigue crack growth rate, as much as three times faster than in steel specimens when subjected to the same stress intensity (Czyryca *et al* 2006). Aluminum alloys are anodic to most other materials used in construction and therefore, susceptible to localized galvanic corrosion. They are also sensitive to stress corrosion cracking. Other concerns involve marine fouling since aluminum alloys cannot be coated with conventional Cu-based antifouling coatings.

In summary, the U.S. shipbuilding industry should address the greater adoption of aluminum alloys by focusing research and development work in the areas of design, fabrication, operation, and maintenance (Sielski 2007). Significant challenges remain in successful joining of aluminum to steel, residual stresses and distortion mitigation, fatigue design and analysis, fire protection, minimization of vibration and slam loads.

Different from aluminum, titanium offers excellent strength-to-weight ratio when compared to steel, high fracture toughness and stress corrosion cracking resistance. It is nonmagnetic and exhibits excellent fire and shock resistance. Titanium alloys also show excellent compatibility with composites. Titanium is technically the best engineering material for seawater service. It has been successfully used for years in shipboard heat exchangers, pumps, piping, and other components. The use of CP-Ti, Ti-3-2-5, Ti-5111, and Ti-6-4-ELI has been reported in the seawater cooling and service systems, and ship structure (Czyryca *et al* 2006). One of the major disadvantages is the high up-front costs (both material & fabrication). Another intrinsic property that has limited the use of titanium is welding fabrication is its reactivity. Significant process development work must be conducted to implement this technology for broader use of titanium and titanium alloys in shipbuilding.

Another group of materials that has received much attention of shipbuilders and researchers is the composite materials, which provide excellent opportunities in weight reduction and reduction of radar signature. Current applications lie mainly on topside structures. However, joining composite materials to the steel structure still represents a challenge (Graham *et al* 2006). The concept of hybrid composite-to-metal joint appears to demonstrate potential. Better joint efficiency and tailored stiffness must be accomplished to further enhance the chances of application of composites on ship structures.

2.3.2 Brazil

Brazilian shipbuilding industry, the main representative of this industry in Latin America, has been very active during the 70s and 80s. Afterwards it has experimented a deep decline. The main preserved construction niche was devoted to supply boats for offshore operations. More recently, due to a political decision from the federal government, most of the orders for offshore platforms and large ocean ships have been placed in the national shipyards. This policy generated some industrial initiatives with the establishment of new shipyards and the recovery of others which had provided considerable output in the past decades.

Recent concluded floating structures included the new generation of semi-submersible platforms and FPSOs. For the period 2008-2015, the demand already established is for 51 tankers, 8 gas ships, 5 containerships, 4 semi-submersible platforms and 5 FPSOs (Portos e Navios, 2008). In addition, the new oil and gas discoveries offshore Brazil in deepwater sub-salt reservoirs will demand the construction of 28 drilling units due to start operation in the next decade.

In order to follow this significant demand for ship and offshore constructions a new research program has been established to cover activities related to design, safety and fabrication. The associated research projects have been conducted by the main universities and research centers traditionally involved with the Brazilian shipbuilding activities. The research program supported by the Ministry of Science and Technology aims at contributing to provide international competitiveness to the shipbuilding industry in the beginning of its recovery period. Aspects related to shipbuilding processes, in particular simulations for layout and workflow, have been emphasized in combination with recommendations for both distortions and residual stresses control during fabrication in order to increase productivity and improve the structural strength.

3. WELDING AND ITS IMPACT ON STRUCTURAL PERFORMANCE

3.1 New Trends in Welding Techniques

Traditional panel production lines were developed in the last few decades. At present they are comprising various alternatives (e.g. one side/two side welding; Series Arc process/Fluxocord-Mikro-Injection process) for different customer requirements (Gaede, 2005).

Production technologies for thin plated panels however have been somewhat neglected. Only recently research work was carried out in this field (Hoops 2006). Welding of panels with thicknesses of about 3 to 7 mm is prone to buckling and shrinkage. Solutions were obtained by systematic modification of the relevant parameters (e.g. heat input, welding material, welding position, preloading of the structure). The modifications resulted in a significant reduction of distortions, cutting down the time spent for rework. Butt welding in vertical position with three passes including further modifications (e.g. reduced heat input) formed a suitable solution. Fillet welding of panel stiffeners was supported by a preloading device to counteract welding distortions. To further reduce distortions also structural modifications (arrangement of deck longitudinal near section seam) were carried out (Hoops 2006).

Out of the 18 existing traditional welding techniques only MIG, TIG and SAW will continue to dominate in the near future (Langdon 2004). Considering the attained technological level in the framework of traditional panel line equipment no major future innovations are expected. Carlson (1996) stated that “it has been obvious for quite some time that the traditional welding processes in general are pressed to the limits, given by nature of the processes themselves”.

An entirely new trend emerged in welding with the gradual introduction of Laser techniques (Carlson, 1996, Kristensen 1996, Roland 1996). In this stage of development leading West-European shipyards started with the implementation of Laser-technology in prefabrication. The mile stones of this development, commencing at about 1995, are given below (Roland 2006A, Langdon 2004):

- Production plant for sandwich panels
- Flexible manufacturing cell for subassemblies-cutting, welding and marking
- Laser facility for butt welds up to 16 m
- Laser cutting and welding plant for subassemblies of marine and fast cruise ships

- Preassembly hall with 4 Laser systems for butt and fillet welding of stiffened panels up to 20 m x 20 m

In this framework a German shipyard for example commenced Laser application in 1997. Since 2001 Laser welding was implemented in a production line. All flat stiffened panels (up to 12 m x 4 m) are manufactured there within a 3-shift-system to cover the shipyards demand for panels. Typical plate thickness e.g. for superstructures of naval vessels processed on this production line are 3 mm – 4 mm (Keil 2007).

Due to the restrictions of the mainly applied CO2-Lasers (bound to simple straight line processes because the beam is directed by mirrors) and the YAG-Lasers (considerable less capacity) a new type, the fibre Laser, attracted a lot of interest.

At present an extension of the Laser application takes place based on the rapid development of the fibre Laser because of its outstanding advantages namely, beam quality, capacity, efficiency, reliability and compactness (Grupp 2006). No other Laser type has experienced a faster development in material processing than the fibre Laser. In 2004 the first 10 kW-fibre-Laser worldwide was put into service (Sumpf 2005A). Only two years later the availability of 20 kW-fibre-Lasers is reported (Schmid 2006). This indicates the rapid development of Lasers in this field.

The research was focussed on the development and testing of tools and methods for Laser-processing in difficult accessible regions of block- and hull-erection and in outfitting. Moreover solutions were developed for prefabrication (Sumpf 2005A, Jasnau 2007A, Mobiles Laserbe… 2006, Roland *et al* 2006B).

Mobile tools and equipment developed in the framework of these researches pave the way for application of Laser processing also in production areas, where stationary equipment, due to the size of the objects to be processed, could not be applied so far. The developed system mainly consists of (Jasnau 2006, Mobiles Laserbea … 2006):

- A transportable base station with Laser source (Pethan 2006)
- The base station can be connected by a Laser light cable with mobile Laser processing units working at a distance of up to 50 m from the base station.

The very compact base station is part of a highly flexible system adjustable to varying production conditions. The mobile base station consists of Laser source, storage cabinet and chiller and has the dimensions of 4,6m x 2m x 2,2m.

Mechanised Laser processing units have been developed for three typical application areas in shipbuilding:

- Welding of long linear fillet welds with tractor systems,
- tack welding with a mechanical system,

- manual guided welding/cutting for outfitting

Mobile applications with fibre Lasers

Because of the mobility of the Laser source and the application of Laser light cable it is nowadays possible to bring the tool to the work piece, i.e. to the erection site (Jasnau 2006, Sumpf 2005B).

Peremptory demands for mobile cutting and welding are:

1. A mobile Laser source and
2. processing heads for cutting or welding and guiding systems being capable to secure the advantages of Laser application under the conditions of an erection site.

The flexibility of such systems is clearly increased by their integration in mobile units, such as containers or pallets. In general three levels of mobile Laser systems can be distinguished:

- Manual guided systems. The feed motion is carried out manually
- Mechanized systems are equipped with a feed drive, so that only a manual positioning and guiding of the tool by the worker is required
- Automated systems. They work without a direct engagement of the worker and maintain various functions (e.g. feed drive) during the working process.

In a number of cases mobile solutions have been developed and implemented. Mechanized tools lead to a high quality and reproducibility of the products.

Mobile Laser GMA hybrid welding (Jasnau 2007B, Pethan 2006, Sumpf 2005B)

Hybrid welding processes are “State of the Art” and also in connection with fibre Lasers applicable. The adjustment to particular boundary conditions is well possible.

In the framework of the researches one major task was the tractor guided Laser-GMA-hybrid welding of long straight seams with the following aims, defined by the participating shipyards (Pethan 2006):

- Welding of T-joints and T-bars,
- welding of butt seams in panel production and
- welding of butt seams in sandwich structures.

Based on these demands a tractor-prototype was developed and built.
Selected results of the following experimental investigations with the Laser-GMA-hybrid welding are given below:

- Remarkable increase of welding quality and productivity
- less rework due to the decrease of thermal distortions
- plasma cut plates with root gaps < 1mm weldable with Laser-GMA-hybrid welding
- butt welds up to 10 mm plate thickness in one run of weld is possible (10-kW-Laser)
- welding of T-joints in one run (10-kW-Laser) (Sumpf 2005B)

The results of the researches form the technological base for the application of mobile Lasers in shipbuilding.

3.2 Methods for Estimating Deformations (Shrinkage, Distortions, Implication on Buckling)

The welding process has a significant influence on the fabrication factors associated with distortion and residual stress of steel stiffened panels representatives of ship and offshore structures. Leggatt (2008) explains the residual stresses in welded structures, i.e. how the different factors affect the magnitude, directionality and distribution of residual stresses in welded joints and structures. These fabrication factors may, if not properly controlled, have a significant detrimental effect on the buckling behaviour of the panels. In addition, the work spent to repair excessive distortions which cause delays during the edification phase of the construction implies in a serious problem for the shipyards and their competitiveness. Therefore, one of the critical points in consideration for the improvement of the shipbuilding processes is the dimensional control associated with both distortion and residual stress. New technologies have been incorporated to nondestructive measurements in order to provide reliable and accurate measurements of these fabrication factors. The possibility of incorporating these data into finite element structural modeling of the panels means a step forward to better understand their effects on the structure ultimate strength.

3.2.1 Experimental Methods to Measure Residual Stress in Welded Pieces

3.2.1.1 Destructive methods

The experimental methods to measure the residual stress can be split in mechanical (destructive) and physical (non-destructive) approaches. Mechanical methods of residual stress determination rely on detecting deformation (strain) or distortion in the test specimen that arises following some cutting of material removal. The most well known of such techniques is hole drilling (deep hole drilling, incremental centre hole drilling). The strain change is detected by specially designed devices like strain rosette (gauge). The results of a hole drilling method are interpreted using elastic numerical models.

The influence of the repair welds on the residual stress distribution in plates are considered by Brown *et al*. (2006). Deep hole drilling technique is used to validate numerical modeling of the constrained letter box repair of thick section plate. Lee *et al*. (2006) adopts the application of the electro discharge machining (EDM) hole-drilling method to the measurement of residual stress in AISI D2 cold work tool steel, AISI H13 hot work tool steel, and AISI 1045 medium carbon steel. A calibration procedure based on the thermal conductivity of the material is conducted to compensate for the additional compressive stress induced in the work piece by the EDM hole-drilling operation. The SEM, TEM, and nano indentation techniques are then used to examine the microstructure and hardness of the white layer resolidified on the EDMed surface. The experimental results reveal that combination of the hole-drilling strain-gage method (ASTM standard E837) with an EDM drilling process provides an effective means for determining the residual stress in materials with high hardness and good wear resistance.

3.2.1.2 Non-destructive methods

Physical methods of residual stress evaluation rely on the determination of some parameters of the system that is known to correlate with residual stress. The most well-known of the physical methods of stress determination is the X-ray diffraction. Neutron and synchrotron X-ray diffraction have been employed for residual stress evaluation, Price *et al*. (2008), Withers *et al*. (2008), Pearce *et al*. (2008), Ganguly *et al*. (2008). These methods are outstanding in their non-destructive abilities to obtain residual stress within the surface and interior of the components. It is well known that special care is needed in dealing with welds (alloys) where one can expect a change in stress-free lattice spacing due to composition and/or microstructural variations. Experimental measurements have already shown that this value changes with position near weldments. However, some researchers reported that for some alloys there is little or no difference between the heat affected zone (HAZ) and base (pattern) metal in spatial resolution of strain measurements. Paradowska *et al*. (2006) reported on results of strain measurements of the weld produced by flux-cored arc welding (FCAW) process in low carbon steel. It should be noted the use of a new technique called “activation technique”, based on radioactive decay of a nucleus for relative estimation of the residual stress in welded specimens, Roy *et al*. (2007).

Bouchard (2008) discussed the uncertainties associated with residual measurement techniques. The causes of these uncertainties are associated with the weldments – residual stress may vary from weldment to weldment made from the same materials, from the same design, using the same weld procedure. The residual stress measurement procedures, including interpretation (processing) of the measured results are also considered as an additional source of uncertainties.

3.2.2 Numerical Simulation of the Effect of Welding

Janosch (2008) gives an overview of the International Institute of Welding activity on residual stress and distortion predictions in welded structures. It has been concluded that significant progress has been achieved to improve the modeling approaches and to optimize experimental technologies to calculate and measure accurately the residual stress distribution and distortion in welded assemblies.

The numerical simulation and prediction of the residual stress and distortion for multi-pass welding is still a challenge. Three-dimensional computations of residual stresses and distortions induced by this kind of processes, using the finite element method, demands very refined meshes in order to correctly describe the properties and stress gradients in the HAZ along the path of the heat source. To model these strong nonlinearities very high computational times and memory requirements are needed. Camilleri *et al*. (2007) compare different modeling strategies for finite element analysis of welded stiffened panels to determine both longitudinal residual stress and out-of-plane distortion. Some finite element models employing different simplifications are compared with an analytical model and experimental data. In the analytical model, the calculated temperature field during welding is used to calculate longitudinal and transverse contraction strains which in turn are used in a single-step elastic mechanical analysis. The latter method is found to give good estimations of the welding distortions, though perhaps not the residual stress field.

Nishikawa *et al*. (2007) present an iterative substructure method where two models are solved in parallel, one weakly non-linear model of the whole problem and one small local strongly non-linear model of the area around the heat source, this small model follows the movement of the heat source. The models are coupled by the displacement field along the boundary for the small model.

The numerical simulation of the residual stress in friction stir weld (FSW), solid state joining process, is presented by Rajesh *et al*. (2007). During the process, no bulk material melting occurs and material is joined by locally introducing frictional heat and plastic deformation. The thermo elasto-plastic model is solved using FEM. This kind of welding is used especially for joining aluminum alloys. Richards *et al*. (2008) present results for the numerical simulation using FEM technique for friction stir weld under global mechanical tensioning conditions. Analysis of the residual stress for friction stir welds in AA2050 (Al-Li-Cu-Mg alloy), performed by Pouget and Reynolds (2008), show that the stress profiles are in agreement with other published results of FSW residual stress and weld residual stress in general. Some results about residual stress distribution in plates joined by FSW is reported by Tan *et al*. (2007).

A simplified method is proposed by Sun and Wan (2007) for the simulation of the welding process and the welding residual stress prediction. The method adopts the line heat source instead of a point heat source by introducing a time ratio of heating and cooling during the welding process, so that the 3D problems are transformed into 2D, with consequent decrease of the computational time.

3.2.3 Effects of Welding on Distortions and Buckling

The welding process will create varying distortion in welded hull structures. This will affect the assembly process and may also enhance the risk for buckling. A full three-dimensional non-linear thermo-mechanical finite element analysis may be employed but for more complex geometries prohibited by long computational times. Several approaches have been proposed, where the local yielding with resulting plastic strains in the weld zone is approximately handled, see Camilleri *et al*. (2007) above. Jung (2007) presents an alternative method where the plastic strains generated by the welding, often called inherent strains, is used as a load in an elastic finite element analysis using shell elements to predict weld distortion in ship panels. Park *et al*. (2007) present an attempt to simulate welding deformations produced during the manufacture of large steel structures using a commercial FE-software and an equivalent load method considering constraint degrees.

Welding distortion during the assembly process is affected not only by local shrinkage due to rapid heating and cooling, but also by root gap and misalignment between parts to be welded. Deng *et al*. (2007) propose an elastic finite element method to predict welding distortion during the assembly process caused by both local shrinkage and root gap. Initially, thermal elastic-plastic finite element analyses are performed to estimate inherent deformations for typical welding joints. Then, the proposed elastic analysis is conducted to predict welding distortion for large welding structures. The influence of initial gap on welding distortion is also investigated. Experimental results have been correlated with the numerical simulations confirming the effectiveness of the proposed elastic method.

Michaleris *et al*. (2006) compare several different methods to predict the buckling distortion of welded stiffened panels. Models compared are 2D and 3D models, small deformation and large deformation models, and a method where the plastic strain generated by the welding is calculated in a 2D analysis and used as a load in a 3D finite element analysis. It is seen that the more advanced 3D large deformation analysis is needed to capture the angular and buckling distortion and also the magnitude of the residual stress and distortion found in parallel experiments.

Bhide *et al*. (2006) compare the longitudinal residual stress and angular distortion in steel plates welded with different methods. Plates welded with the friction stir welding method were found to have buckling distortion while the gas metal arc and arc welded plates were found to have angular and bowing distortions.

3.2.4 Effects of Distortions on the Structural Strength

Structural failure of Suezmax tanker due to extreme bending moment is analyzed (Estefen T.P. *et al*., 2007A). The paper describes both numerical and experimental structural simulations. Small scale panels representative of the double hull tanker bottom under axial compressive loading are analyzed in order to perform correlation studies to adjust the numerical model for further use in full scale structures. Numerical analyses for a model representative of a Suezmax tanker compartment between robust transverse frames is submitted to sagging and hogging loading conditions to evaluate the influence of geometric initial imperfections on both moment-curvature relationship and panels buckling behavior. The same methodology was previously employed to analyze the influence of different geometric imperfection distributions on the ultimate strength of columns of the new generation of semi-submersible platforms (Estefen T.P. *et al*., 2007B).

Measurements of distortions (geometric imperfections) and residual stresses during ship construction can provide data to be input in the numerical model in order to estimate the ultimate strength under realistic fabrication factors. Critical regions could then be identified which will contribute to indicate the areas to be given especial attention during construction of new units of the same series as well as to better planning in-service inspections.

3.3 Fabrication Techniques to Enhance Fatigue Strength

A welded structure is susceptible to growth of cracks initated at the weld during cyclic loading, i e fatigue. Sonsino (2008A) discusses the influence of the loading mode, residual stress and local weld geometry on the structural durability, i e the fatigue life. This increased risk for fatigue damage is considered in codes for the design of welded structures issued by for example classification societies. Hobbacher (2008) presents a revised version of the IIW (International Institute of Welding) recommendations for fatigue design of welded components. In the current revision of the Design codes, guidelines for multi-axial loading of the weld have been modified, see also Sonsino (2008B) where current methods for multi-axially loaded welded joints are reviewed.

The revision also includes updated recommendations for the use of improvement techniques for welds. These methods can be divided into methods to improve the weld profile, like grinding and remelting, and methods to improve the residual stress situation, like peening (hammer, needle, shot, brush-peening or ultrasonic treatment) , overloading, and (for thick-walled structures) thermal stress relief. Among them, ultrasonic impact treatment (UIT) is considered to be effective due to its good features in terms of workability, simplicity in use and quality control, good reproducibility of results. Nose *et al*. (2007) investigated the effect of UIT using cruciform welded joint, and confirmed that the fatigue life was extended to more than 3 times as shown in Figure 5. In this study, the authors made estimation of the factors contributing to the improvement of fatigue life; i.e. compressive residual stress 55%, stress concentration improvement by shape control 35%, improvement of microstructure 10%. UIT was actually applied to a very large ore carrier to substantially improve fatigue performance (Mitsui Engineering & Shipbuilding 2008).

Maddox *et al*. (2008) report a similar improvement in fatigue life (a factor of 4) for longitudinal fillet weld joints subject to a UIT treatment. Tests with the joints loaded with a mean stress corresponding to the dead weight of a complete structure yielded similar results for the fatigue life.

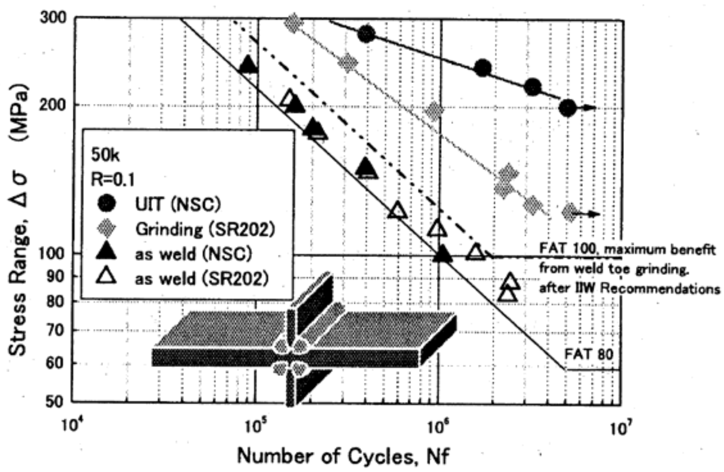


Figure 5: Effect of UIT on fatigue life in cruciform welded joint (Nose *et al.* 2007)

Introducing new welding methods, giving a higher weld quality, may also increase the fatigue durability. Barsoum and Samuelsson (2006) have compared the fatigue strength for non-load carrying cruciform welded joints using a hybrid Nd: YAG laser /MAG and conventional MAG welding methods. Local weld geometries were measured and residual stresses were calculated using nonlinear finite element analysis as described above and measured using the X-Ray technique. A low stress concentration factor at the weld toe, fewer weld defects and low residual stresses are key factors improving the fatigue strength. It is found that detected weld defects were spatter with resulting cold laps. The laser welded joints showed lower residual stresses at the weld toe but no noticeable increased fatigue life as compared to the MAG method. Both methods give fatigue strengths higher than the IIW recommendations (Hobbacher, 2008). Cho *et al.* (2007) study the laser hybrid welding process and report an improved weld toe geometry for fillet welds. A proper application of the laser heat input induced molten metal resulted in larger weld toe angles which decreased the stress concentration and increased the fatigue life. Caccese *et al.* (2006) also report improved fatigue life for cruciform fillet welds when welded with laser hybrid methods, mainly due to an improved weld toe geometry.

Barsoum and Jonsson (2008) carried out defect assessments and fatigue testing on specimens welded with robotic and manual welding using flux cored (FCAW) and metal cored (MCAW) filler materials. The specimens welded with flux core weld wires showed the best fatigue strength, small defects and low residual stresses. Introducing shot peening improved the fatigue strength due to compressive stresses induced. Scatter in the fatigue results were due to the defects along the weld toe, mainly spatter induced cold laps.

The use of LTTW (low transformation temperature welding) for fillet welds would introduce compressive residual stresses due to a volume expansion at the martensitic transformation at low temperatures, and thus an increased fatigue strength. This beneficial effect has been reported by Darcis *et al*. (2008) for cruciform welded joints.

Effects of imperfections on the fatigue strength of longitudinally stiffened welded decks of a container ship were studied numerically by Chakarov *et al*. (2008). Imperfection studied were thickness change misalignment, angular imperfection, rotation of a transverse weld and residual deformations caused by dropping an object on deck. The fatigue damage was assessed based on FE-calculated stress concentration factors used for the hot spot stress approach.

4. NEW MATERIALS AND LIGHTWEIGHT STRUCTURES

The total global consumption of lightweight materials will continue to increase according to the extensive lightweight materials in transportation report published in May 2007 (BCC Research, Figure 6). High strength steel accounts for the largest percentage of total tons of lightweight materials consumed, followed by aluminium and plastics. In value terms, plastics with their relatively high unit process are the largest market segment. Aluminium and high strength steel are the second and third largest product segments. Shipbuilding is the second largest consumer of lightweight materials, next to motor vehicles.

Main reason for the application of lightweight structural arrangements in ships are:

- Greater payload for a given size or weight of vessel
- Higher speeds
- Reduction of fuel consumption and environmental emissions or a given payload and distance travelled
- Improvement of stability
- Sometimes reduced space requirements due to more compact solutions

In this chapter developments in new materials are summarized. Also attention is paid to application of these materials.

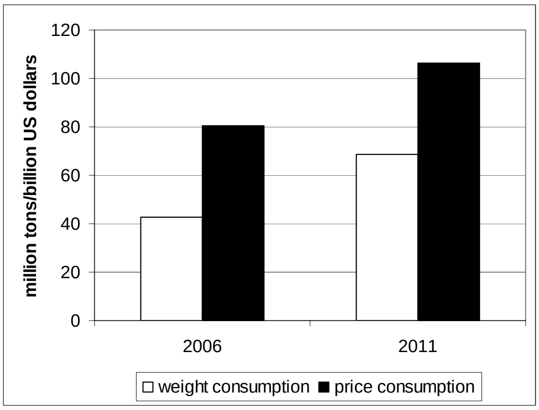


Figure 6: Expected growth lightweight materials in transport sector

4.1 New Steel Materials

Ordinary ship hulls are made of steel, and requirements to the materials of better quality is the strong driving force of the development of new steel materials. Table 1 summarizes the recent achievements as to new steel materials. Corrosion resistant steel will be discussed in 5.6 of this report.

Table 1
New steel materials

	Demand	Application
Corrosion resistant steel	To enhance safety, increase life-cycle value	Upper deck and inner bottom plate of tankers
Fatigue crack arrester steel	To enhance safety, increase life-cycle value	Structural member vulnerable to fatigue damage
YP460 steel	To enhance safety, realize lighter weight	Hatch side coaming of large container ship

4.1.1 Fatigue Crack Arrester Steel

Quite a large portion of structural damages of ships is caused by fatigue, and it is very important to prevent fatigue damage. Ship’s hull is composed of complex welded structures, and fatigue cracks often initiate at those welded zone with high stress concentration. Therefore, it is important to enhance fatigue strength in the welded structures as well as in the base metal. To achieve this, a steel, called FCA (Fatigue Crack Arrester) steel, that can delay fatigue crack propagation has been developed (Sakano *et al*. 2005A, 2005B, Katsumoto *et al*. 2005).

The developed steel has a microstructure of quite fine ferrite and bainite dual phase, which leads to high resistance to fatigue crack growth. In addition, cyclic softening property of bainite structure decelerates crack propagation. With regard to the welded structure, better fatigue strength was obtained thanks to the fact that the hardness distribution around the weld toe is uniform, and that the HAZ has higher fatigue crack initiation life.

4.1.2 YP460

Due to the rapid increase of worldwide container trade, container ships are becoming larger and larger. Accordingly, plate thickness around upper deck and hatch side coaming is expected to be thicker and thicker, and this extra-thick plate brings many concerns such as fracture toughness, brittle crack arrestability, as well as productivity in welding and applicablity of large heat input welding. YP390 steel plates (high tensile steel plates with the specified yield point of 390N/mm2) have been usually applied for more than 20 years, but the thickness is becoming 80mm or even more in recent years as shown in Figure 7. As a solution for these concerns and to enhance overall safety of large container ships, YP460 steel plates (high tensile steel plates with the specified yield point of 460N/mm2) were developed (Hirota *et al*. 2007, Yamaguchi *et al*. 2006, Ichimiya *et al*. 2007, Kaneko *et al*. 2008). Such higher tensile strength steel is also beneficial to reduce hull steel weight, fuel oil consumption, thus leads to less load to the environment.

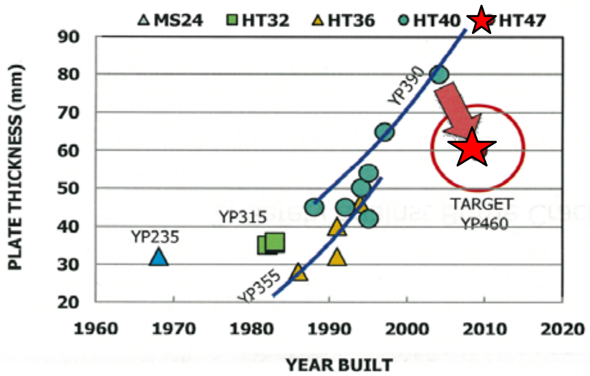


Figure 7: Specified yield point and plate thickness around hatch side coaming

It is known that a brittle crack generally diverts from the welded joint into a base plate, and EH steel plates can work as a crack arrester. However, Inoue *et al*. (2006) showed that a brittle crack ran along a welded joint and penetrated the test plate in case that the thicknesses were larger than or equal to 65mm and the applied stress was higher than 200MPa, through several large-scale crack arrest tests. Then, it was considered that it is important to keep the thickness within a reasonable range using YP460 steel, and that steel plates with high crack arrestability should be arranged at appropriate locations of the hull structure. Ishikawa *et al*. (2007) pointed out that the fracture toughness is strongly dependent on the matching of hardness in the welded joints of heavy thickness plates by comparing the fracture toughness Kc obtained by center-notched wide-plate tensile test (deep notch test), and that calculated from the results of Charpy V-notch test.

Another approach to prevent brittle crack penetration was proposed by Handa *et al*. (2007) and Kiji *et al*. (2008). In general, hatch side coaming is welded to upper deck plate by fillet or penetration welding with un-welded root face. A series of the ESSO tests of Tee joint was carried out, and it was found that the brittle crack was arrested more easily when the un-welded root face was longer. Brittle crack arrestability of un-welded root face was confirmed through large-scale crack arrest test and FEM analysis. In actual container ships, the lowermost part of the vertical weld line of hatch side coaming butt joints is directly welded into upper deck plates, and there is no un-welded face at this point. To cope with this problem, Tamura *et al*. (2007, 2008) proposed to insert a thin plate under the hatch coaming butt joint to prevent welding to melt into the upper deck plates.

4.2 Lightweight Materials

Several new materials are being developed to meet the requirements of better quality, lightweight, improved maintenance and performance of present day ship building.

Typically four groups of new materials can be identified, new steel materials already dealt with in Chapter 4.1, composite materials, lightweight metals and hybrid metal/composite materials.

4.2.1 Composites

The main advantages of using composites in ship building is the reduced maintenance, lower repair costs, weight, limited fatigue cracking, good strength and stiffness to weight ratio, improved styling and absence of corrosion. Disadvantages are the higher raw material costs, the fire behaviour of most composites, large scale manufacturing and joints. Table 2 gives a summary of the differences between steel and composites construction (Noury et. al. 2002).

Table 2
Summary differences steel and composites

Property	Steel construction	Composite construction
Weight	High	Allows significant reduction in structural weight
Corrosion	Rusts in marine environment resulting in high maintenance cost	Very durable in marine environment, little maintenance
Combustibility	Non-combustible, will not contribute to fire or generate toxic fumes	Combustible, surface must be protected in fire hazard areas
Thermal conductivity	High, must be insulated to prevent fire propagation and to control infrared signature	Low, inherent insulation more than sufficient
Electrical conductivity	High, inherently provides electromagnetic shielding	Low, must embed conductive layer is electromagnetic shielding is needed

As stated one of the main issues with composites is the fire safety. Since 2002 a SOLAS amendment allows for other materials than steel, providing that equivalent safety can be shown. Up till now this mend that with composites and aluminium normally more fire insulation is needed, which counteracts the weight saving from using composites. New lightweight insulation materials are being developed and successfully tested in fire tests (Shipping world shipbuilder, 2007).

Due to the only relatively recent use of many composites little is yet known on the structural behaviour and durability of these materials. The degradation of composite materials is normally time, temperature, moisture and strain rate dependent. Long term testing will be needed to accurately capture the degradation behaviour. Yasushi Miyano *et al* (2007) developed an accelerated testing methodology for the long term durability of polymer composites. A lot of effort is put in identifying and simulating the failure behaviour of composites due to all types of loading (Schuecker 2006A and 2006B, Pahr 2004 and 2006, Wimmer 2006, Rivallant 2006, Bisagni 2008, Fritzsche 2008, Zarei, 2008, Hayman 2007).

The bonding of composites is still a main issue. Within the BONDSHIP project (Bondship 2005) in the network of excellence MARSTRUCT general requirements are stated to ensure the reliability and safety of load carrying bonded joints in ships. Attention is focussed on long term behaviour, joint design, production and influence of environmental conditions. NDT techniques and its limitations are also investigated. Herszberg *et al*. (2005) describe an optical sensor system to monitor debonding in situ. DNV developed a standard on the failure of composite components. Other research (Dharmawan *et al* 2004, Toftegaard 2005) mainly focuses on full composite joint testing or on failure predictions (Pitarresi *et al* 2007).

4.2.2 Lightweight Metals

Developments can be seen using lightweight metals, such as aluminium, titanium and all metal sandwiches. In this paragraph the main developments will be discussed.

Today many vehicles, including ships, use aluminium and its alloys (Haustov 2005). Traditional areas of aluminium alloys in shipbuilding are hull constructions of high-speed ships and superstructures. Aluminium and magnesium alloys (type 1561) is widely used in high-speed ship construction (Krizhevich et. al. 2005). Another lightweight metal for ship applications is titanium. Titanium is generally accepted as the best engineering material for seawater service and has been successfully used for years in shipboard heat exchangers, pumps, piping, and other components. The use of CP-Ti, Ti-3-2-5, Ti-5111, and Ti-6-4-ELI has recently been reported in the seawater cooling and service systems, and ship structure (Czyryca and Wells 2006). The major disadvantages lies in the high up-front costs (both material & fabrication). Another intrinsic property that has limited the use of titanium is welding fabrication is its reactivity with oxygen and nitrogen. Significant process development work must be conducted to implement this technology for broader use of titanium and titanium alloys in shipbuilding. A third development is the use of full metal sandwiches, i.e. metal platings combined with metal stiffeners as a core material is described in Romanoff (2007). Both steels and lightweight metals as aluminium are used in this development.

4.2.3 Hybrid Materials

Most hybrid materials consist of metal skins combined with a composite core. In these materials the properties of metals and composites are combined to obtain a lighter, better insulation, improved crashworthiness with increased local strength. Also due to the metal outer facings the attachment of other metal parts in the structure might become easier. However, due to the normally relatively thin outer facings, special welding or bonding techniques may be needed when joining other hybrid or metal parts to the structure. Several different combinations of materials are considered, austenitic/sandwich combinations (key-to-steel 2006), steel facings combined with vinylester or polyester matrix (Bermejo *et al*l 2008), metal plates combined with metal fibre composite (US patent 6764772 2004) or steel or aluminium skins combined with metal or plastic core (kortenoeven 2007). Within the SAND CORe project (SAND.CORe 2005) several hybrid sandwiches were discussed. Test data of hybrid panels in fatigue testing is given together with guidelines for design and analyses of hybrid sandwiches.

4.3 Structural Lightweight by Design

An increasing demand for lighter ships is seen. Reasons for lighter ships can vary between increased speed demands, fuel saving or cargo carrying capacity. Several methods to decrease the ships weight are seen:

- Construction of part of the vessel in lightweight materials, e.g decks, superstructures
- Combining steels and lightweight materials in hybrid structural systems, e.g. steel backbones combined with composite hull panels
- Optimized design methods for lightweight material

4.3.1 Lightweight Material Ship Parts

Main application of lightweight material in part of the ship is the use of a lightweight superstructure or decks. Within the LASS project (LASS 2006 and Ahuja, G. and Ulfvarson A. 2006) 5 demonstrator applications were chosen in which a 30% reduction of weight and a 25% decrease in costs had to be accomplished by a lightweight design. All solutions in this project indeed focus on replacing either decks, superstructure of the complete structure with lightweight aluminium or composite alternatives. However, also a combination of a steel midship combined with a lightweight bow and stern is considered (Marsch 2004, Coa and Genestedt 2004), especially when lightweight is required but the hull girder stiffness cannot be provided with a complete lightweight design. Main problem still existing is the joining of the lightweight material part to the metal ship. Most of today's research focuses on the design and testing of these joints (Coa and Genestedt 2003, Caccesse *et al* 2007A, Coa and Genestedt 2004). Several types of joints are considered in the testing, bolted, bonded, co-infused and combinations of bolted-bonded joints. When properly designed failure will not occur in the joint, but in either the lightweight or the metal part. A comparison of hybrid joint test beams and full composite sandwich beams did show that the failure load of the hybrid beam was about 90% of the full composite beam (Coa and Genestedt 2004).

4.3.2 Hybrid Structural Systems

The implementation of composite materials in conjunction with metals into hybrid structural systems is currently being developed in several key applications such as ships, aircraft, building, automobiles and other transportation vehicles. Next to weight saving, also cost saving, maintenance and performance improvement are advantage. For ship application thought is given to the combination of a metal backbone with a composite outer shell. The metal frame simplifies the connection of other systems, e.g. the propulsion system to the hull. When using a bolted connection between the composite plates and the metal backbone also maintenance will be simplified. The MACH project (modular advanced composite hull forms, MACH 2002) aims at developing watertight, hybrid, composite/metal structural joint concepts for naval ship hull application. Main problem again with these hybrid structural systems is the joining of the composite and metal components of the system (Caccese, Kabche and Berube 2007B and Coa, Genestedt and Maroun 2006).

4.3.3 New Design Methods for Lightweight Materials

Existing design methods and tools were developed with metal structures as the main application. Therefore, the design of lightweight structures will not be optimized when these methods are used. For particular applications the combination of analyses and testing leads to an optimized design (Brown and Zureick 2001). However, for more general application of lightweight materials in ship structure new design tools and methods are being developed. Moraes *et al* (2007) developed an optimization tool for the preliminary design of high speed catamarans. The tool includes hull arrangement, costs, weight, resistance and wave behaviour. In the SAND.CORe project (SAND.CORe 2005), the state of the art in application of sandwich structures in the European transport sector is made available. Guidelines are given on the manufacturing, design and analysis of both all metal, hybrid and full composite sandwiches and joints. A new project on lightweight sandwich structures for vehicles and vessels (DE-LIGHT transport 2006) is started aiming at developing a generic design approach for evaluation and optimization of a wide range of materials. One notable change in the way construction materials are used is the tendency to move much of the basic preparation work on materials away from the shipyard and into specialist providers (Pike 2007, SPS and other sandwich or multi material panel concepts).

5. NEW METHODS OF CORROSION PROTECTION

In 2001 the Federal Highway Administration (FHWA) in the US published the results of a two year study to determine the cost to the US economy as a result of corrosion (Koch *et al*, 2001). One of the 26 sectors investigated in the study was the shipping industry. In this sector, the cost of corrosion was estimated at between \$2.7 billion dollars every year (Johnson, 2001). This cost was reported in three areas: the cost associated with new ship construction (\$1.1 billion), with maintenance and repairs (\$0.8 billion) and with corrosion-related downtime (\$0.8 billion).

Corrosion is therefore a significant cost to the shipping and offshore industry both at the construction phase and also through the operating life of the vessel or structure. Therefore economic factors play an important role in the selection and application of anticorrosive protection. However, as well as optimum performance and cost for a coating system, environmental, safety and regulatory requirements have to be considered when specifying an anticorrosion system (Azevedo, 2006). Following such accidents as the Exxon Valdez, the Erica and the Prestige, the industry has seen a step change in the regulatory requirements for the coating of ballast and cargo tanks.

5.1 Critical Survey of Rules and Regulations

The first regulation to be introduced regarding the use and applications of coatings was IMO Resolution A798 (1994) followed by SOLAS amendment II-1/3.2 (1998). The TSCF (Tanker Structures Cooperative Forum) produced guidelines for Ballast Tank Coating Systems and Surface Preparation in 2002 (TSCF, 2002) which interpreted the above SOLAS regulation. It is predominantly on these guidelines that IMO based their performance standard and in December 2006, the Maritime Safety Committee (MSC) and IMO adopted resolution IMO PSPC Resolution MSC.215(82) which defines the Performance Standards for Protective Coatings (PSPC) for dedicated seawater ballast tanks in all new ships and also for double-side skin spaces of bulk carriers (IMO PSPC, 2006). This resolution will be mandated by amendments to the SOLAS regulations II-1/3-2 due to be implemented on the 1st July 2008 and will apply to all ships over 500 GRT (Gross Registered Tonnage).

The rationale for the development of a mandatory performance standard was the premise that corrosion of ballast tanks due to premature coating failure is most effectively addressed by ensuring that the coating is applied correctly at the newbuild stage as repairing a damaged coating is difficult and not always successful (Hoppe, 2006). The performance standard sets a target useful coating life of 15 years from initial application, over which time the coating has to remain in a ‘good’ condition as defined by IMO resolution A.744(18) i.e. minor spot rusting. The standard therefore sets out the basic requirements of the coating necessary to achieve this target as; design of the coating system, primary surface preparation, secondary surface preparation and miscellaneous requirements relating to ventilation, environmental conditions, testing and repair.

5.2 Improving Coating Edge Retention

One of the locations at which it is critical to ensure adequate coating coverage and adhesion is at corners, edges and weld seams as these areas often have insufficient coating coverage and are susceptible to mechanical damage. The role of the coating is to provide a physical barrier to prevent contact of the corrosive environment with the ship surface and also to prevent the flow of the corrosion current by acting as an electrical insulator. Therefore, the effectiveness of the coating is reliant on maintaining an adequate and optimum thickness; the greater the thickness, the larger the barrier to the diffusion of corrosive species and the greater the electrical resistance across the paint film. However, if the coating thickness becomes too large then internal stresses can cause cracking and a decrease in performance.

5.2.1 Edge Preparation and Stripe Coating

Edges, in particular, often have reduced coating thickness as surface tension effects pull the coating away from the edge during application. Therefore, to improve the adhesion of coating in these areas, the secondary surface preparation (SSP) stage in the coating requirements states that:

> *"the steel surface shall be prepared so that the coating selected can achieve……..adequate adhesion by removing sharp edges, grinding weld beads and removing weld spatter and any other surface contaminant. Edges shall be treated to a rounded radius of minimum 2mm or subjected to three pass grinding or at least equivalent process before painting" (IMO PSPC, 2006)*

This procedure is mandatory as it is considered that coating retention is better on a rounder edge. However, as well as defining the edge profile to increase the coating thickness at the edges, the IMO PSPC also dictates that:

> *"there shall be a minimum of two stripe coats and two spray coats, except that the second stripe coat, by way of welded seams only, may be reduced in scope where it is proven that the NDFT can be met by the coats applied, in order to avoid unnecessary overthickness. Stripe coats shall be applied by brush or roller." (IMO PSPC, 2006)*

A stripe coat is an additional coat of paint which is applied to edges or welds to increase the dry film thickness (DFT) in these vulnerable areas. The advantages of the stripe coat are that it can fill small voids and irregularities in the surface of the steel, therefore increasing the thickness of subsequent coats, and also, if it is allowed to dry to the point of tackiness, can help adhesion of the next coat of paint to the edge (Cavallo, 2001).

Recent published work is challenging the level of edge preparation and stripe coating required by the IMO PSPC. Seo *et al* (2007) conducted a study to compare the edge retention rate[1] of a two-layer epoxy coating on four different edge preparation profiles; as flame cut, 2mm radius edge (2R), 3-pass grinding (2C) and 1-pass grinding (1C). Each of the profiles was grit blast to a SA 2½ prior to coating. Under these conditions, they concluded that 1 pass grinding and disk papering for burr removal, with a two coat stripe coating provided adequate coating thickness at the edges. Indeed excessive edge preparation and multiple stripe coating produced coatings that were too thick and susceptible to cracking. Yun *et al* (2005) conclude that the optimal coating thickness to ensure adequate edge coverage is a DFT between 300 and 400µm. At this level of coating thickness, the edge coverage for 1C grinding with grit blasting to SA 2½ is almost exactly the same as that for 2C, 2R or 3R (3mm radius edge) and therefore there is little advantage to be gained by the increased amount of labor required to prepare the edge. In addition, they reported that, for the coating system studied, when the coating thickness exceeded 250µm, there was no increase in the ERR upto the maximum film

[1] Edge retention is measured through the ERR (Edge Retention Ratio) parameter which is given by ERR=edge DFT/flat surface DFT where DFT is the Dry Film Thickness. A good edge retentive coating should attain an ERR greater than 0.7 (Azevedo, 2006).

thickness tested of 500μm. Note that the IMO PSPC specifies a nominal DFT (NDFT) of 320μm.
Obviously a large amount of labor is required to prepare all of the edges by mechanical grinding and stripe coating, therefore alternative solutions are being sought to maintain the integrity of the coating on the edge whilst decreasing the labor costs.

5.2.2 Enhanced Coating Systems

A potential solution to the problem of retention of the coating on edges is to develop a coating with improved edge retention properties.

One approach is to use a coating with a higher solid coating which, theory suggests, will have a reduced tendency to flow away from the edge. This thesis was tested by Chung *et al* (2003) who evaluated the edge retention properties of two coatings having 60% and 80% SVR (Solid Volume Ratio) on plates prepared to different levels of edge roundness. However, the results indicated that the paint with 60% SVR had a better coverage rate than the 80% SVR paint and had achieved an ERR of 1.0 at the 1mm radius edge profile (1R). This trend for a lower SVR paint to have higher edge retention was also reported by Yun *et al* (2005). Further investigation by Chung *et al* (2003) indicated that the enhanced performance of the 60% SVR paint could be attributed to a property defined as the surface tension differential. As the paint dries, solvent is released preferentially from the edge, raising the surface tension locally and creating a differential in surface tension between the edge and the plate and thinning around the edge. The lower the surface tension differential, the better the edge retention.

If the release of solvent is creating a surface tension differential, then one solution proposed by de Paiva and Martins (2000) is to use a solvent-free epoxy coating. Of the latest publications in this area, Azevedo (2006) describes a solvent-free epoxy system with improved edge retentive properties. One of the benefits of this system, as stated in the paper, is that the ERR is greater than 0.7 when applied to an edge prepared by 1C grinding. As a result, use of this system, although more expensive than a solvent based, modified epoxy system, could reduce the time and cost of edge-preparation, if 1C grinding was allowed to IMO PSPC. Dallons (2008) advocates the use of solvent free coatings from materials such as the cashew nut, on the basis of improved edge retentive properties, but also due to the environmental benefits in terms of lower VOC (Volatile Organic Compound) emissions and the use of a renewable resource.

Osawa *et al* (2007) recently published the results of initial testing of a ferromagnetic pigment (FMP) paint system designed to increase the thickness of the paint on the edges. The principle is that, if a magnetic flux is applied to a plate, the density of the flux field is greater at the edges than on the flat surfaces, therefore under the influence of a magnetic field, any ferromagnetic pigment will be drawn to the edges increasing the coating thickness. In the tests, the FMP paint system was compared against a modified epoxy resin system for different types of edge geometry. The results indicated that the FMP system provided better coverage than the epoxy system with the edge retention behavior improving with decreasing edge bevel angle. Although this paint system could be used to reduce the amount of mechanical grinding required prior to coating application, its use is restricted because a magnetic field has to be applied to the ship hull during application which is a problem in itself, but can also attract other fine ferrous material to the surface which may enter the coating film and enhance corrosion.

5.3 Coating Developments to Attain DFT Requirements

As mentioned previously, applying the optimum thickness of coating is critical to maintaining coating performance. The IMO PSPC specifies that the DFT should be guaranteed to be 320μm. Shipyards and coating manufacturers are therefore challenged with developing products and inspection techniques that ensure that this specification can be met. Several coatings are now becoming available which aid the applicator and inspector in the achievement of the required DFT (SW&S, 2007).

Inspection of the coating is aided by adding pigments that are sensitive to certain wavelengths of light to the paint used for the first coat but not to that used for the second coat. If the coating is inspected both between coatings and after the second coat under an appropriate light source (e.g. ultraviolet) then variations in DFT, holidays and contamination in the coating can be identified. This system would also aid maintenance of the coating as any damage to the topcoat, when viewed under the light source, will reveal the active first coat and identify areas for maintenance. Nippon Paint has also announced the development of a self indicating paint (SW&S, 2007) which changes color when the required coating thickness has been achieved without the need for inspection under special lighting conditions. It is considered that the adoption of this sort of paint may remove the requirement for two coats by attaining the required coating thickness in one application.

5.4 Developments in Corrosion Resistant Steels

Pitting corrosion of the inner bottom plating of cargo oil tankers has been highlighted as a particular area of concern in the shipping industry. For example, several thousand corrosion pits have been observed in a VLCC with a reported maximum pit depth as high as 10mm after only 2.5 years between dry-docks (Sakakita *et al* 2007). This not only results in large costs in hull maintenance and repair for the ship owner, but also poses a threat to both the ship and environmental safety. In response, corrosion resistant steels have been developed by Japanese major steel makers (Imai *et al*, 2007A, 2007B; Inohara *et al*, 2007A, 2007B; Kashima *et al*, 2007; Sakakita *et al*, 2007).

In these studies, the mechanisms of pitting corrosion were investigated. The inner bottom plating of a COT is covered with an oil coating, which performs the same function as paint in terms of corrosion resistance. However, this oil coating is deteriorated by exposure to water and physical damage during COW (cargo oil washing). Thus, localized corrosion occurs at the defective areas in the oil coating. The corrosion rate in these areas is enhanced as the environment has been found to be strongly acidic, containing a high concentration of chloride ions. It was also found that, at the corrosion pits left unrepaired at the dry-dock, corrosion does not progress any further. The reason is that the pits are covered by thicker oil coat when the ship loads new crude oil at the first voyage after the drydock (Imai *et al* 2007A).

An understanding of the mechanism enabled a corrosion test to be developed that simulated the conditions in the crude oil tank in order that the pitting resistance of the new corrosion resistant steels could be tested. The results indicated that the pit growth rate of the newly developed steels ranged between 20% and 65%. This means that, at the 2.5 year inspection interval, the maximum depth of the pits may be less than 4mm, the level at which repair is required. In combination with the fact that the pit growth appears to be arrested after every dry-dock, the repair of pitting corrosion may become unnecessary throughout the service life of the ship. This mechanism is schematically illustrated in Figure 8. One of the newly developed corrosion resistant steels was actually applied to a VLCC, and at the first drydock after 2 years and 3 months, no localized corrosion requiring repair was observed (Imai *et al* 2007B).

It has also been reported that these corrosion resistant steels are effective in reducing the general corrosion around the upper deck plating of cargo oil tanks. As a new SOLAS regulation to make PSPC for cargo oil tanks mandatory is under discussion in IMO, corrosion resistant steel is considered to be an effective and rational alternative to coating.

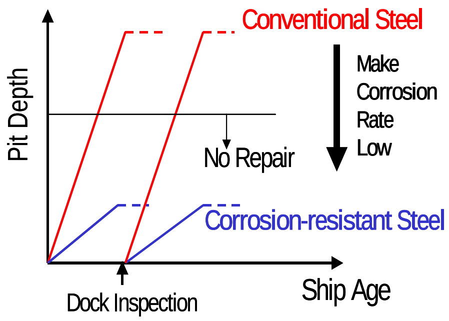


Figure 8: Repair free schematics for COTs built with corrosion-resistant steel

5.5 *Modeling of Degradation*

5.5.1 Modeling of Degradation and Use in Reliability Assessments

The majority of ship structures are fabricated using plain, low carbon mild steel (carbon content <0.2%) and it is an undisputed fact that unprotected mild steel will corrode in a salt water environment. It is therefore a regulatory requirement, as described previously, to protect the ship hull plating and ballast tank surfaces from the effects of salt water. However, in addition to salt water attack, the steel surface is also susceptible to corrosion attack in the cargo tanks and holds from the cargo, when loaded, and also from the atmosphere, if there is sufficient water, when unloaded. A categorization of the marine corrosion environments that are applicable to marine and offshore structures is provided by Melchers (2003A), extending from immersion into marine, brackish or fresh water, mixed zone such as splash zone or tidal zone, to atmospheric corrosive zone.

The ability to model the corrosion reaction and therefore to predict the rate of degradation is important, not only for answering the immediate question at the regular inspection of 'how long will it last?', but also to be able to answer this question during reliability assessments, both at the design stage and for existing structures. The role of the corrosion model in a reliability assessment is illustrated in Figure 9. The intersection of the loading and resistance curves in this figure defines the probability of failure of the structure. As corrosion proceeds the loading on the structure increases and the probability of failure increases. The corrosion model dictates the rate at which the loading curve changes.

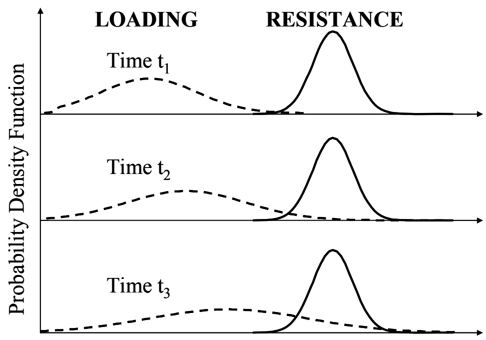


Figure 9: Effect of corrosion rate model in reliability assessments

Melchers (2007A) has correctly concluded that in order to successfully model corrosion in the marine environment, a fundamental understanding of the acting corrosion mechanisms is required; including general corrosion, resulting in uniform loss of metal across the section, and localized corrosion, such as pitting, crevice and galvanic corrosion. A summary of the main types of corrosion relevant to ships and offshore structures is detailed by Melchers (2003A). Each of these types of corrosion will proceed at a different rate due to the different mechanisms involved and therefore should be considered separately in any model.

It is therefore imperative in the development of a successful corrosion model, that the type of corrosion that is being modeled is understood, and that the environmental conditions that have resulted in that corrosion are well defined.

From the literature it is possible to define two main types of corrosion model; those that try to model the fundamental corrosion processes and those that are a statistical fit to datasets of thickness measurements. Developing a theoretical corrosion model is not a straightforward task because the rate of corrosion is influenced by a large number of often interacting variables such as the corrosion environment, temperature, exposure time, level of humidity, salinity levels, amount of dissolved oxygen, water velocity, type of corrosion protection system employed and type of cargo carried, amongst others. This type of information is invariably not available.

Therefore, in lieu of being able to develop a fundamental understanding of the corrosion process therefore, many approaches attempt to model corrosion wastage using the thickness measurements obtained during the classification survey inspections. The problem with taking this approach is that the data sets of measurements are often derived from different types of ships operating under differing service conditions and information about other parameters and environmental effects that influence the corrosion rate, such as temperature, salinity etc. are not available or included in the data. In addition, the errors in the measurements have to be taken into consideration, including the inherent accuracy of the measurement device and also the location at which the measurement is being taken. Inaccuracies in the results will be inevitable if the readings are not taken in exactly the same position at each survey. The consequence is that there is a large amount of scatter in the data which reduces the accuracy of the resultant models (Melchers, 2003A; Gardiner and Melchers, 2003). Another caution to be issued regarding the use of empirical corrosion models is that they should not be used to predict corrosion rates for situations beyond the characteristics of the data on which they were developed (Paik *et al* 2003, 2004).

5.5.2 Modeling of Immersion Corrosion

The theoretical models are based on oxidation theory and predict that as the layer of oxide builds on the surface of the steel, the corrosion rate decreases. The empirical constants used in these models are then calibrated to field data, although this has resulted in large degrees of scatter.

Over a period of ten years, Melchers has been developing a phenomenological probabilistic corrosion model to describe the immersion corrosion of mild steel in salt water. This model is presented most recently in Melchers (2007A). The model (represented in Figure10) exhibits four consecutive phases; initial corrosion (controlled by the availability of oxygen at the corroding surface from the sea water), oxygen diffusion control (controlled by the rate of oxygen diffusion through the corrosion products and marine growth on the surface), food supply to the microbe colony and finally anaerobic activity. The model has been applied to the prediction of internal corrosion in naval vessel ballast tanks (Gudze and Melchers, 2007), however it is recognized by Melchers and others (Qin and Cui, 2003), that further work is required, particularly in the understanding of the importance of environmental variables, to be able to apply this model more widely.

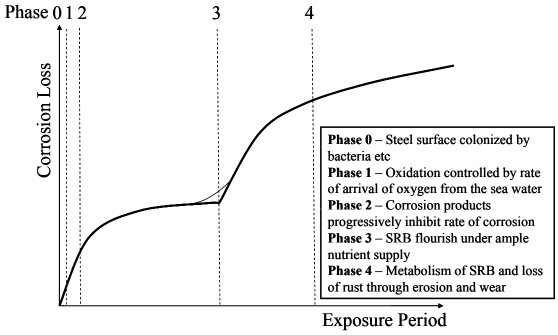


Figure 10: Corrosion loss model for immersion corrosion of steel in natural sea water (Melchers, 2007A)

One of the elements not included in the above model is the time dependent coating and cathodic protection (CP) degradation as this process was not considered to be well understood from a fundamental point of view. However, other researchers have attempted to model the breakdown of the corrosion protection system. In the model proposed by Guedes Soares and Gorbatov (1999), corrosion is assumed to progress in three phases (Figure 11). In the first phase no corrosion occurs as the corrosion protection systems (coating and CP) are assumed to be protecting the system. As soon as these systems fail, then corrosion proceeds non-linearly with the corrosion rate decreasing with time due to the build up of oxide corrosion products, which protect the steel until eventually the corrosion rate is reduced to zero in phase three. Melchers (2007A) argues that this assumption that corrosion will stop with time is not observed on actual structures. Indeed, if this was the case, then it would be possible to manage corrosion on a marine structure by increasing the wall thickness to the level beyond which no further corrosion will occur. The above model has been adapted to take account of the influence of environmental factors (Guedes Soares *et al*, 2005).

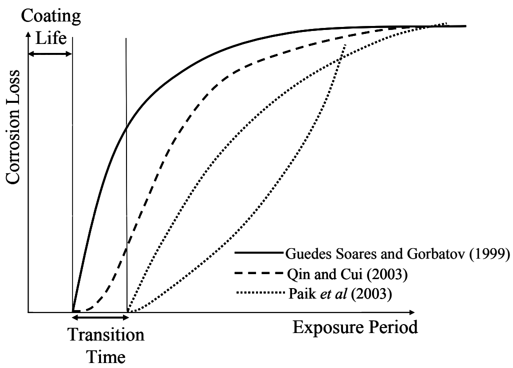


Figure 11: Schematic representation of models due to Guedes Soares and Gorbatov (1999), Paik *et al* (2003) and Qin and Cui (2003)

Paik *et al* (2003) also propose a three phase model for the modeling of both localized corrosion (as defined in Table 2) and general corrosion. As for the previous model, phase one describes the breakdown of the protective coating using the log-normal distribution described by Yamomoto and Ikegami (1998). However, in this model, corrosion is not assumed to occur as soon as the corrosion protection breaks down and therefore phase two describes a 'transition time', which is assumed to be exponentially distributed (Yamomoto and Ikegami, 1998). In the third phase, corrosion progresses with time according to either a convex or concave model; the convex shape indicates that the corrosion rate is decreasing with time due to the build up of a stable corrosion product on the steel surface under static loading conditions; the convex shape indicates that the corrosion rate is increasing with time, which could occur under conditions of dynamic loading when the corrosion product is continually ruptured exposing fresh metallic surface to the environment. This phenomenon has been reported in oil tanker structures (TSCF, 1992). The general equation for the model described above is given by Eqn (1)

$$t_r = C_1 T_e^{C_2} \tag{1}$$

Where t_r is the depth of corrosion wastage (mm), T_e is the time of exposure under the corrosion environment which is calculated from the age of the vessel, the life of the coating and the duration of the transition time and C_1 and C_2 are corrosion coefficients. These coefficients will be different for different locations and environments within a vessel and are determined by statistical analysis of corrosion thickness measurements. In their work on single and double hulled oil tankers, FSO_s and $FPSO_s$, Paik *et al* (2003) define 34 areas in the vessel and determine different values for C_1 and C_2 for each location, including ballast areas. Using these individual models, the authors were able to determine illustrative design corrosion margins for each of the structural areas defined (assuming a coating life of 7.5 years). It is admitted in their paper that the datasets for some of the locations are sparse, making the results less statistically significant and it is anticipated that this model will be updated as more corrosion inspection data becomes available. The model described above has also been used for the prediction of corrosion rates in seawater ballast tanks (Paik *et al*, 2004). Seawater ballast tank corrosion is a special case of immersion corrosion as the temperature within the ballast tank could be higher than in open sea and also the effects of ballasting and de-ballasting may accelerate the corrosion process due to wet-dry cycles on the steel surface. In this work a total of 1937 measurements were taken from seawater ballast tanks and the appropriate values of C_1 and C_2 determined.

The immersion corrosion model due to Qin and Cui (2003) is also a three phase model for general immersion corrosion. However, in contrast to the models of Guedes Soares and Gorbatov (1999) and Paik *et al* (2003), it is assumed that the corrosion protection system will deteriorate gradually and that pitting corrosion may occur at isolated areas where protection of the coating system and CP system is lost. The time for pitting corrosion to occur is defined as Tst. General corrosion then proceeds when the corrosion protection system fails. Therefore the three phases are no corrosion;

accelerating corrosion rate as pits initiate and grow and decelerating corrosion rate due to the action of the protective oxide and biofilm. As with the model of Guedes Soares and Gorbatov (1999) however, this model predicts that the corrosion rate will approach zero at long exposure times. Qin and Cui (2003) present results of comparison of their model with that of Guedes Soares and Gorbatov (1999) and Paik *et al* (2003) using an assumed database of corrosion measurements. A fairer comparison would be to use a database of actual measurements.

5.5.3 Modeling of Atmospheric Corrosion

In the marine environment there are essentially two types of atmospheric corrosion that can occur; open air atmospheric corrosion and enclosed space atmospheric corrosion.

The rate of open air atmospheric corrosion in a marine environment is influenced by the time of wetness, the relative humidity, sulfur dioxide pollution, sea salt deposition, solar radiation, precipitation and air temperature. Historically, atmospheric corrosion has been modeled using a power law relationship of the form:

$$C = At^n \tag{2}$$

Where C is the corrosion loss after t years and A and n are constants dependent on the material and climate type. Generally the constants are determined by an empirical fit to experimental data (e.g. Feliu (1993)). Melchers (2007B) has sought to apply the multi-phase model developed for immersion corrosion and described by Figure (Melchers 2007A) to data from tidal, splash-zone and near-shore atmospheric locations. Melchers concludes that the data does indicate consistency with this type of model, which casts doubt on the applicability of the power law model of Equation (2) to describe atmospheric marine corrosion, particularly for the prediction of long-term corrosion loss from short-term data. It also leads to the interesting conclusion that marine atmospheric corrosion occurs in similar phases to marine immersion corrosion with a transition from aerobic to anaerobic control.

Enclosed space atmospheric corrosion occurs in areas of the ship where moisture in the air can be adsorbed onto the surface and cause corrosion, e.g. in unloaded cargo holds and ballast tanks or in void spaces. Gardiner and Melchers (2001) have developed a simple semi-empirical model based on three key parameters from the list above, which are relevant in an enclosed space; time of wetness, salt deposition and temperature to describe this form of corrosion. In contrast to open air, where exposure is on a continuous basis, enclosed space corrosion is intermittent in nature and therefore the model is applied on a per voyage basis. There is scope for developing this model further and, as there is a high variability in the parameters characterizing the corrosion, a probabilistic model may be more appropriate.

5.5.4 Modeling of Splash Zone Corrosion

Although there is some collated data reported in the literature (Melchers, 2003A) there are no phenomenological or empirical corrosion models specifically developed to model splash zone corrosion. However, as described in Section 5.5.3., Melchers (2007B) has applied his multi-phase model to limited data from splash zones.

5.5.5 Comments on Corrosion Modeling

The above literature review has highlighted some key points that should be considered when using corrosion rate models to conduct reliability based assessments and design methods. Although statistical models are widely used, it is imperative that the limitations of the model and the data set for which they were derived are understood to prevent their use outside of their range of applicability. It is also important to understand that, even for a certain type of vessel or corrosion location, operational and legislative changes could render the model unreliable. For example, Melchers (2003A) points out that the requirement to coat ballast tanks may render models that have been derived for previous uncoated ballast tanks inapplicable. The final point to remember is that the accuracy of the measurements directly affects the resultant accuracy of the model and the quantification of errors is extremely important.

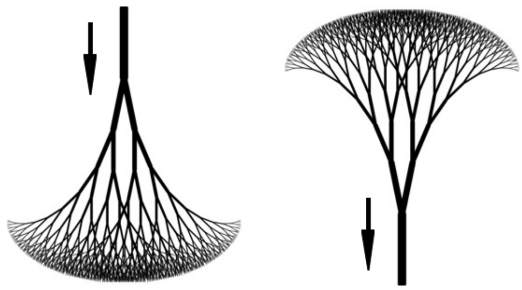
6. COMPUTER APPLICATIONS TO LINK DESIGN AND PRODUCTION TOOLS AND TO SUPPORT EFFICIENT PRODUCTION

6.1 Methods and Tools for Cost Estimation

To succeed commercially, the shipyards must be able to accurately assess costs. Cost assessment is necessary for the bid process, for change orders, and for trade-off studies. Numerous cost assessment approaches exist. They are based on extrapolations from previously-built ships, detailed parameters, and integrated physics-based analyses. The option for the production cost assessment differs with the level of required information to run the analysis (input data). The less information is needed, the earlier a method can be employed in the design process. The more information is used, the finer differences between design alternatives can be analysed Bertram *et al* (2005).

The methods for estimating production cost are classified into:

- Top-Down (macro, cost-down or historical) approaches (empirical, statistical and close form equations, etc.), see Figure 12 (a)
- Bottom-Up (micro, cost-up or engineering analysis) approaches (direct rational assessment), see Figure 12 (b)



(a) Top-down (b) Bottom-up

Figure 12: Top-down and bottom-up methodology

6.1.1 Top-Down approaches

The top-down approach determines the production cost from global parameters such as the ship type and main dimensions, weight of the hull, the block coefficient, ship area, complexity, etc. The relations between cost and global parameters are found by evaluation of previous ships. Thus, the top-down approach is only applicable if the new design is similar to these previous ships. In addition, the cost estimation factors will reflect the past practices and experience. However, this cost evaluation method is appropriate for the early design stage when the data available are small (see ISSC committee IV.2)

6.1.2 Bottom-Up approaches

The traditional cost assessment approaches using system-based, weight-driven cost models are not always sensitive to changes in production processes and advanced manufacturing techniques. Thus the need exists for a cost model which can better relate to design and construction product and process issues, to enable a more conscious cost decision making and at the end more affordable ships Ennis *et al* (1998).

The alternative bottom-up approach breaks down the project into elements of work and builds up a cost estimate in a detailed engineering analysis. Moe *et al* (1968), Rigo (2001), Southern (1980), and Winkle (1986) developed simplified cost models based on direct calculation using quantities and unitary cost to assess the global production cost. Welding position, accessibility, etc can be considered using additional corrections.

The bottom-up approach requires more effort and more detailed information than the top-down approach. One of the main advantage of the bottom-up approach is to take into account the differences in design details and are thus suitable for scantling and shape optimizations Bole (2006 and 2007), Caprace (2006). Changing the local hull geometry influences the number of frames and may require bending, change the amount of plate bending, and the degree of weld automation which depends on the curvature of the weld joints.

All these effects are reflected by an appropriate decomposition of the total work process into its individual components. At present, this approach is not available in most shipyards. The main reason is probably that the required historical databases are not available. It is then necessary to develop an appropriate approach, and collect the data required to use this approach.

An advanced optimization application in this field is the work performed by ANAST[2] for the optimisation of ship structures using the LBR-5 system Rigo *et al* (2005) and Toderan *et al* (2007). To our knowledge, LBR5 is the only system that has been applied in shipyard work at an industrial level.

The Smart Product Model (SPM) of Proteus Engineering, Ross *et al* (2002 and 2004), is crafted in such a way that at all times during the design of a vessel it will provide the best cost estimates for the available information. The system estimates ship production costs in a Ship Work Breakdown Structure (SWBS) hierarchy for three independent levels of details:

- for concept design, the cost estimate will be based on whole-vessel technical and parametric relationships derived from approximately about 20 data items (e.g., length, beam, displacement, installed power).
- for preliminary design, system information becomes available, and the cost estimate is based on about 125 data items.
- for the contract design, the cost estimate is based on hundreds or even thousands of data items. As the design progresses, more and more of the technical and cost information migrates from statistical parameters to physics-based, and the accuracy of the cost estimate improves.

Mitsubishi Heavy Industries (MHI) developed a system interfaced to its structural design CAD system, Sasaki *et al* (2001, 2002 and 2003). Production planning information estimation functions and levelling functions were added to a commercially available line simulation system. Application of the system to an actual vessel resulted in the reduction of the 2~3 week time period conventionally required for consideration to just one day. The process planning system with 3-D visualization function enables the designer to semi-automatically define the hull block assembly sequence and to calculate the evaluation value (cost, time, weight, etc.) for each process design candidate, Figure 13. The cost estimation function in the CAPP (computer aided process planning) system of Mitsubishi multiplies weld length (for each weld class) by a factor K reflecting the work difficulty (e.g. 1 for downward, 2 for upward, 1.5 for horizontal).

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[2] University of Liege - Naval Architecture and Transport System Analysis

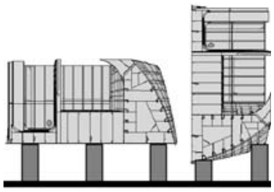

Figure 13: Application of bottom-up approach comparing shell-base production (left) and deckbase production approach (right); analysis gave 3% cost advantage for deck-base approach

6.1.3 Life cycle approaches

In order to improve the design of products and reduce design changes, cost, and time to market, life cycle engineering has emerged as an effective approach to address these issues in today's competitive global market. As over 70 % of the total life cycle cost of a product is committed at the early design stage, Eyres (2001), designers can substantially reduce the life cycle cost of products by giving due consideration to the life cycle implications of their design decisions.

People are always concerned about product cost, which encompasses the entire product life from conception to disposal. Manufacturers usually consider only how to reduce the cost of materials acquisition, production, and logistics. In order to survive in the competitive market environment, manufacturers now have to consider reducing the cost of the entire life cycle of a product, called the life cycle cost, Seo *et al* (2002).

Landamore *et al* (2007), Gratsos *et al* (2007) has recently implemented methods for the investigation of economic and environmental costs within a marine system. The life cycle cost assessment approach is a promising future holistic methodology in order to maintain the effectiveness of ships during their overall life.

6.2 Accuracy Management

Ship's hull is joined and constructed by welding many pieces cut out by gas, plasma or laser cutting. Thus, thermal input and following distortion is inevitable. Due to this distortion, it may become necessary to carry out cumbersome corrective works or to trim the intersections of members, causing worse quality and less productivity. Therefore, control of hull structure accuracy is important. There are many approaches and techniques to control accuracy, and major items are listed in Table 3.

<u>Transient thermal tensioning</u>

Conrardy *et al*. (2006) developed a number of thin-steel welding distortion control techniques, and performed a series of tests to evaluate them and optimize production processes. Among them, transient thermal tensioning was investigated for reduction of buckling distortion during thin-panel longitudinal stiffener welding. Transient thermal tensioning applies moving local heat sources along the plate to induce zones of local tension. It moves together with the welding torches. This tension cancels the compression induced by the welding, and prevent buckling distortion.

Line heating

Another in-process control of welding distortion is proposed using line heating from the reverse side. Mochizuki *et al*. (2007) developed in-process control method using reverse-side TIG heating at a fixed distance ahead of MIG welding, applied to an aluminum alloy T-joint. The effect to reduce the distortion was verified by experiment and three-dimensional thermal elastic-plastic finite element analysis. It was found that this mechanism is a result of two main effects: one is that TIG heating on the reverse side produces the opposite angular distortion, and the other is the preheating effect.

Jang *et al*. (2006) developed an analysis method to predict the reduction of welding distortion of stiffened plates by conventional line heating, which has been carried out with the trial and error method by skilled workers based on their experiences and intuitions. Experimental methods to estimate the heat input of gas flame and to measure deformations of a unit fillet welded structure by heating were developed. The deformation of stiffened plates by line heating was predicted based on inherent strain.
Turner *et al*. (2006) developed a portable automated plate straightener to remove the welding distortion from the decks. This utilized induction head instead of acetylene torches in combination with measurement of plate distortion, and it is expected that costly and time consuming process of plate straightening is alleviated.

Table 3
Techniques for accuracy control

		Merit	Demerit
To enhance accuracy of cutting			
Laser cutting		Accurate, easy to automate, slight fume	Slow speed, thickness limit, expensive
Water-jet cutting			Very slow, only thin plate
Plasma cutting	Adaptive control by measuring cutting width		
	Double sides cutting by 2 torches		
	Cutting sequence, bridges		
Residual stress controlled steel		Less cutting distortion, less dispersion of welding distorsion	Material cost
To reduce or control welding distortion			
Minimize heat input	Laser welding	Small distortion	Premature, expensive

	Control of heat input by automation of welding		Capital investment
Add restraint	Welding pass sequence	Less distortion	Tight control
	Mechanical restraint	Less distortion	Cost
Corrective action	Mechanical correction	Less distortion	Additional work required
	Line heating (post-welding)	Less distortion	Costly, time consuming work required
	Line heating (in-process)	Less distortion	Investment
	Line heating (induction head)	Less distortion	Investment
Active mitigation of residual stress	VWT (Vibratory Weld Conditioning)	Less distortion	Investment
	Thermal Tensioning	Less buckling, no additional work	Investment
Cancel distortion beforehand	Elongation for compensation	Cancel distortion	
	Pre-bend	Cancel distortion	Capital investment, not flexible
	Application of FEM simulation of weld distortion (See 3.2 of this report)	Flexible	Premature, computing time and cost
New materials	Low-transformation temperature welding wire	Less distortion	Expensive
3D measurement			
Edge finish using 3D measurement results		Accurate	Subsequent finishing work
Design Modifications			
Structural modification	Add panel breakers	Less buckling	Increased weight and piece number
	Reduce stiffener spacing	Less buckling	Increased weight and piece number
	Increase plate thickness	Less buckling	Increased weight
	Reduce cutouts	Less buckling	Increased weight
Reduce welding leg length		Less distortion	Higher stress

Vibratory weld conditioning

Vibratory weld conditioning (VWC) is a new welding technology, which uses the welding thermal field and vibratory dynamic stresses to refine grains and decrease the residual stresses during the solidification processes (Xu *et al*, 2007). The main purpose is to refine the grains, relieve the residual stress, reduce welding deformation and improve the properties of the welded joint. The effect of the VWC was considered in multi-pass girth-butt welded pipes. Through comparison between VWC and normal submerged arc welding it was showed that VWC can reduce the residual hoop stress at the outer surface by approximately 30%, and radial distortion by 50%. However, VWC has only a slight effect on the axial distortion and residual stress at the outer surface. The study of the effects of VWC was extended for cylinders with different thickness welded by Qinghua *et al*. (2008) for submerged arc welding (SAW). The experiments showed that the vibration applied during welding generally reduces the residual deformation and stresses. The blind hole drilling method was used to determine the residual stresses.

Low-transformation temperature welding wire

In recent years, new methods to reduce welding distortion by the effect of the properties of material have been proposed. As a steel material, residual stress controlled steel has been developed, which is effective to reduce dispersion of welding distortion or bending by line heating, as well as to reduce cutting distortion. As a welding material, low-transformation temperature welding wire was developed. The martensitic transformation temperature of this welding material is under the mechanical melting temperature, and the transformation expansion cancels the heat shrink. Inose *et al*. (2005) clarified optimum transformation temperature to reduce angular distortion of T-joint, and showed that the angular distortion decreased to about 80% by using the newly developed welding wire.

3D measurement

A full-scale 3D measurement is a new and progressing technology for shipbuilding. Okumoto *et al*. (2006B) applied a laser scanner to make the three dimensional model of a bellmouth from the clay model. Furthermore, they also applied it to measure the edge of hull structure block to simulate joint connection between blocks, and many problems to be solved were identified, such as accuracy of the measurement, environment for the measurement, and so on.

Other techniques

Kim(2006) introduced a control method of welding distortion for thin panel block structure using mechanical tensioning. Han(2007) reported an analysis method and straightening parameters for longitudinal welding distortion in welded T-section built-up beams. Even many research papers were presented to predict welding distortion, most of them, however, were applicable only in simple structure.

6.3 Simulation Based Production

Shipbuilding market has grown rapidly in these years, and shipyards worldwide are coping with increased and more complex products using their limited spaces, facilities and workforces. Simulation of production process enables pre-estimation and virtual testing of different production planning scenarios, leading to the best solution. Another driving force of simulation based production is the aging of the workforce. Because of the huge production in 1960-70's and the following long recession period, shipbuilding workforces are generally in their fifties, and lack the brackets of forties and thirties. Therefore, shipbuilding in the near future must depend on very young workers who

have insufficient experiences. Digital mock-up and simulation technology can help unskilled workers to accomplish their jobs correctly.
In some European shipyards, simulation is already well established as the main tool for supporting decisions in production and planning, and the production area where simulation is applied is spreading from the machining center, the steel part manufacturing, the subassembly line, to the block assembly station (Bernaert *et al*. 2005, Hertel *et al*. 2005, Kaarsemaker *et al*. 2006, Steinhauer *et al*. 2005, 2006, Bentin *et al*. 2008). Further step would be realization of the virtual shipyard including outfitting as well as overall steel construction stages. In Korea, simulation based production scheduling is growing up, which can contribute improve production scheduling and planning works and evaluate various production scenarios (Lee *et al*. 2005, Kim *et al*. 2007, Lee *et al* 2005).

To make most use of the simulation, coupling optimization with simulation is expected to be far more effective to improve the planning quality as well as to reduce the efforts in production planning and control (Bair *et al*. 2005, Nedeß *et al*. 2006). Hamburg University of Technology and Flensburger Schiffbau-Gesellschaft initiated the research project SIMGO (simulation-based optimization for the production planning in shipbuilding), which will be funded by the German Federal Ministry of Education and Research. The research objective is the coupling of meta-heuristic optimization algorithms, such as genetic algorithms or Monte-Carlo-Method, with a production simulation model.

The limited space available in shipyards and the growth in the size of blocks and sections force the planners to optimise the utilization of the available surface within the workshops and storage areas. In order to solve this problem Okumoto *et al*. (2005D), Caprace *et al*. (2008), Lee *et al*. (2005) optimised block allocation on the assembly area with different optimisation techniques like simulated annealing, heuristic methods or CST (Constraints Satisfaction Technique).

The three dimensional CAD systems and product models are widely utilized in ship design in recent years. Utilization of such product models for the purpose of production simulation is effective, because various attributes such as weight, center of gravity, size and geometry, welding length, assembly sequences, and so on can be derived from the product model. Okumoto *et al*. (2005A, 2006A) showed some actual successful applications in a Japanese shipyard, such as erection of a complex hull block, carriage of equipments, scaffolding planning, walk-through simulation in engine room and installation of a rudder and a contra-rotating propeller. It is shown that such simulation of jobs using product models are effective for jobs in which many parties must cooperate to handle structures or equipment of complex shape. Kim *et al*. (2007) also developed an affordable but complete digital mock-up (DMU) system, which can be utilized for various simulations in production stage. This system aims at particularly small and midsized shipyards that do not have their own technology.

The assembly work of pipe unit is currently carried out by skilled workers, guided by complicated two dimensional drawings, and with their long experiences. Okumoto *et al*. (2005B) developed a pipe unit assembly simulation system to improve work efficiency, especially for less experienced workers. Using this system, work time necessary to observe drawings and to move around the shop to measure dimensions, confirm the drawings, etc. decreased, and the ratio of the direct work time for fitting work increased drastically from 17% to 39%.

A wearable computer is composed of a portable computer, a controller and an HMD (head mount display), and enables workers to move and work with simultaneous access to the full product model database. Using this system, workers can confirm necessary data as well as the results of the production simulation on site without moving back to the offices to check the drawings. Okumoto *et al*. (2005B) applied wearable computer to the management of pipes in a stock yard, and although many benefits are expected, found a problem that the workers get fatigued by viewing the HMD. Sasaki *et al*. (2005) applied wearable computer to work measurement system replacing traditional stopwatch method. Ahlers (2005) discussed wearable computer as well as mobile information and sensing networks in the field of ship production.

RFID (Radio Frequency Identification) is a promising device, which will be a main component to realize a digital factory. Okumoto *et al*. (2005C) applied it for the management of pipes to handle a huge number of pipes correctly. Nagano *et al*. (2007) applied RFID to detect the locations of workers in a subassembly line, and examined the reliability of data collection.

One example of successful replacement of skilled workers is automatic nesting. Nagashima *et al*. (2005) developed a new automatic nesting algorithm, named “FINEST” based on piece movement through stochastic process. Through nesting examples of actual ship data, it is demonstrated that both reduced man-hour and good scrap ratio are achieved at the same time. This algorithm was further expanded to plate size determination (Nagashima *et al*. 2006). Much more improved scrap ratio was obtained by applying FINEST at the stage of plate purchase order determination.

7. CONCLUSIONS AND RECOMMENDATIONS

A state of the art review of the recent research and development on materials and fabrication technology has been carried out. Findings and recommendations for further research are summarized as follows:

Welding has been and will continue to be the most important joining technique for shipbuilding. Residual stress and distortion associated with welding are the key issues to be overcome. Laser welding is one of the most important developments, and at present actual application is extending based on the rapid development of the fibre laser. Mobile laser equipment is the key for further extension of laser application.

Welding distortion hinders automation and mechanization of shipbuilding, and also requires additional corrective work, causing worse quality and less productivity. Vast literature exists in terms of residual stress measurement, numerical simulation of welding and its effect on distortion, and effects of distortion on the structural strength. From practical point of view, accuracy management is important, and it should be dealt with in terms of not only the reduction and control of welding distortion, but also the accuracy of cutting, 3D measurement and design modifications to reduce distortions.

Most of the ship structural failure is fatigue, and most of the fatigue damage is found at the welding. Among many techniques to enhance fatigue strength at the welding, laser hybrid method is expected to prominent because of less residual stress and good weld toe geometry. UIT (ultrasonic impact treatment) is a very practical and effective method to enhance fatigue strength at welds. From material side, new fatigue crack arrester steel is reported to give better fatigue strength even at the welding. It is encouraged that more research is conducted to collect sufficient background data, and the rules incorporate appropriate fatigue code to allow benefits by applying these new technologies.

There exists an increasing demand for lighter ships. This can be reached either by use of lighter materials (composites, light metals or hybrids) or lightweight design. High tensile steel with the specified yield point of 460N/mm2 (YP460) was developed and successfully applied to heavy thick plates in way of the upper flange of large container ships. To apply further higher strength or thicker steel plates, fatigue strength and brittle fracture are the issues to be overcome. Bonding of lightweight materials is still an issue. Also the connection of lightweight structural parts to conventional ship parts remains an area of further study.

As IMO adopted PSPC Resolution which defines the Performance Standards for Protective Coatings in 2006, its impact on productivity is of major concern among the industry. The goal of corrosion protection is to achieve safety by controlling thickness diminution. It is considered that there are many ways to achieve this goal, and many alternatives to the IMO PSPC and novel ideas are being researched. Some examples can be seen in enhanced coating systems to alleviate edge preparation and stripe coating, and development of corrosion resistant steels.

Simulation based production is already widely applied in many shipyards. Further step would be rationalization of the virtual shipyard including outfitting as well as overall steel construction stages, coupling optimization with simulation, and wider application of visible tools and on-site computing such as wearable computers and RFID. To optimize ship production process, it is important to accurately estimate construction cost. Many activities are being carried out to estimate cost accurately, but application of simulation and product model for cost estimation is still an area of further study.

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