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COMMITTEE V.3  
**MATERIALS AND FABRICATION  
TECHNOLOGY**

**COMMITTEE MANDATE**

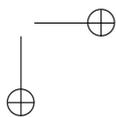
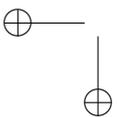
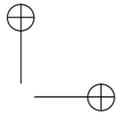
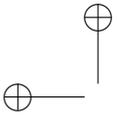
The committee shall give an overview regarding new developments in the field of ship and offshore materials and fabrication techniques with focus on trends which are highly relevant for practical application in the industry in the recent and coming years. Particular emphasis will be given to the impact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

**COMMITTEE MEMBERS**

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Jose Gordo  
Jang H. Lee  
Liangbi Li  
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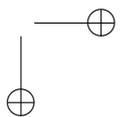
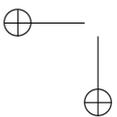
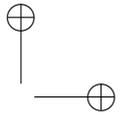
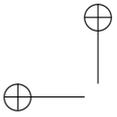
**KEYWORDS**

Welding of extreme thick plates, thickness effect, corrosion protection, composite material application, standard comparison, design for production and manufacturing, linking design and production.



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## 1 INTRODUCTION

After years of growth the global economic crisis has deeply affected the shipping industry. There are however clear signs of recovery in the last year. The shipbuilding industry has realised that, due to the crisis, new innovative designs and design and production methods are necessary to decrease operational costs, production costs and emissions, whilst meeting the changing rules and regulations. In this report ISSC committee V.3 discusses recent development in materials and fabrication technology. Chapter 2 focusses on worldwide trends in materials and fabrication methods. Developments in fabrication technologies, such as welding and corrosion protection are dealt with in Chapter 3. Applications of composite materials are increasing. Some main areas of applications and research in those areas are described in Chapter 4. A comparison of current worldwide standards is made in Chapter 5. Chapter 6 gives an overview of current developments in the linking of design and production in computer applications, thus increasing the efficiency of ship building.

## 2 NEW TRENDS IN MATERIAL AND FABRICATION METHODS

### 2.1 World

After five years of extraordinary growth, the global shipbuilding industry has experienced a sharp turn-around of trend. From the second half of 2008, the global economic crisis has deeply affected this industry worldwide enduring an unparalleled collapse of demand for new ships, the situation of most shipbuilding yards is expected to remain difficult for some time as the order books continue to deplete affecting the entire value chain in shipbuilding, Clarksons (2010).

Nevertheless, there are clear signs that the recovery has started. Growing cargo volumes, improved earnings for ship-owners and also the slow increase of new order volumes are welcome and encouraging news, CESA (2010).

The strategic nature of the shipbuilding industry encouraged many countries to develop domestic capabilities to build ships without necessarily taking into consideration

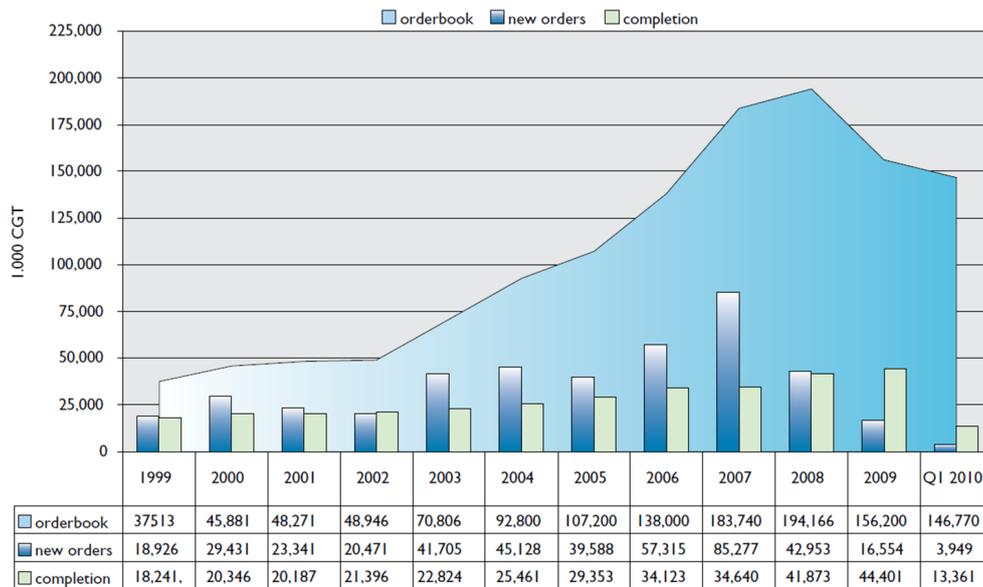


Figure 1: World Commercial Shipbuilding Activity – CESA (2010)

the developments in the world market. The most prominent example is South Korea, and more recently, the Republic of China which in 2009 accounted for 28% of the world production (compared to Korea 32% and Japan 21%).

The low ordering level in 2009 combined with higher deliveries brought the world order book down by 21% (see Fig. 1). Despite a large total order book, many yard's workloads are shrinking rapidly. New orders in 2009 totalled 16.5 million CGT which equals roughly 1/3 of the completions. Ordering has slightly improved during the first quarter of 2010. However, a much higher activity is needed to balance the rate of deliveries. The global merchant fleet today is relatively young; the average age of the container ship fleet is 10 years. The need for replacement due to age in this specific segment will, therefore, contribute less to the new building requirement in the coming years.

In an effort to maintain as much capacity as possible, sectoral programmes are implemented by several governments around the globe to maintain the national shipbuilding industry. Many market observers strongly criticise these moves as obstacles to the necessary market correction, which will prolong the current imbalance of supply and demand (see Fig. 2). The current crisis prompts the need to consider and adopt new designs to reduce the operational costs and lower emissions. Leading shipping companies recognise that low emission operations save costs, open quality sensitive markets and will be the key driver to profitability in the future. The innovations in the shipbuilding sector have the potential to greatly reduce the operating costs as the sector has already developed and demonstrated significant advances in green technologies.

The trend of ship production in different parts of the world is described in the following sub-sections. 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, etc. In this context, the European shipbuilding industry focuses on higher end sectors such as cruise ships and naval vessels. Production technologies with regard to thin plate thicknesses are therefore important. The Asian shipbuilding industry focuses on cargo ships, attaching importance to productivity in mass production in large shipyards.

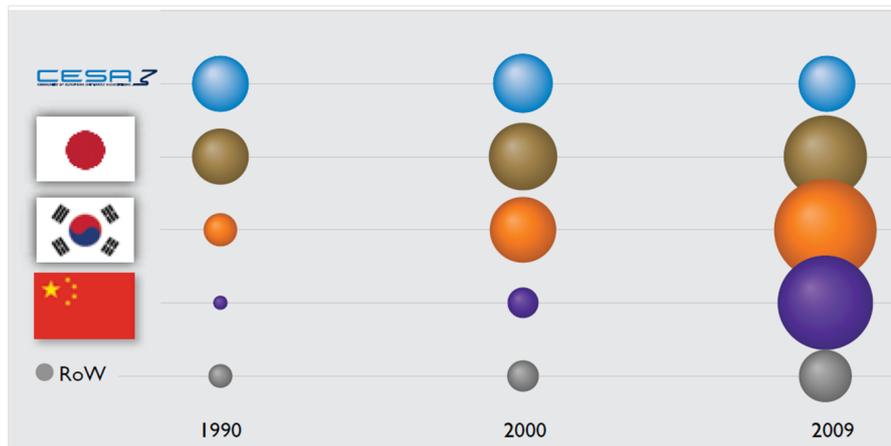


Figure 2: Massive capacities built up cause huge imbalance between capacity and demand (Production shown in CGT) – CESA (2010). The colors are related to the areas given by the flags. RoW stand for the Rest of the World.

## 2.2 Asia

### 2.2.1 Japan

After the economic crisis in 2008, the worldwide shipbuilding industry is operating in an increasingly competitive environment, and Japan is no exception, although Japanese shipyards produced more than 20 000 000 GT, a record high, in the year 2010. Under these rapidly changing circumstances, it is increasingly important to reduce shipbuilding costs by increasing productivity. In addition, the ship production process is affected by various international regulations to enhance safety and to protect the environment, requiring overall optimization of the production process. In response to these changes, Japanese shipyards are trying to make their production line more cost efficient and optimized, making use of advanced information technology, robotics, and so on. In this context, many achievements have been reported recently.

The application of laser arc hybrid welding usually requires considerable investment, and has not been widely introduced except for European yards building cruise ships made of thin steel plates. Koga *et al.* (2010) and Terada *et al.* (2010) extended this application to cargo vessels such as tankers, container ships, LNG and LPG carriers. By developing a simple welding carriage system and dispensing with large gantry crane equipments, the application of laser arc hybrid welding became practicable for various kinds of vessels. Currently the application is limited to butt welding of plates of less than or equal to 13 mm thickness, but its extension to fillet welding is also expected. This will result in considerable reduction in welding distortion, which, in combination with the application of laser cutting, 3D laser measurement, simulation of welding distortion and appropriate lifting plans for erection blocks, will lead to greater accuracy in the ship production process Yamamoto and Choshi (2010).

Miyazaki *et al.* (2009) has successfully applied the hydrogen gas cutting method, reducing the time required for cutting, preheating and piercing.

Line heating of steel plate to fabricate curved shell plating is one of the processes which is most labour intensive and difficult to learn, requiring a training period of more than 10 years. Automation of this process was reported by the committee in 2006, Borzecki *et al.* (2006). Based on this technology, Tango *et al.* (2011) has reported the application of an advanced fully automatic system, which was enabled through automatic evaluation of the distortion results, automatic corrective heating, automatic plate turn over and advanced robotics.

### 2.2.2 Korea

Since 2003, South Korea has become the world's top shipbuilding nation, but was surpassed by China in 2009 and 2010. Korean shipyards are making efforts to regain their world lead position. Tankers (17 million DWT), bulk carriers (16 million DWT) and container-ships (10 million DWT) still make up the largest share of deliveries, BRS (2010), but South Korea is focussing more on high-priced vessels and offshore facilities. Industry watchers consider that Korea is responding to the growing demand for technically-advanced ships with increased added value, such as drilling vessels and floating oil production facilities in response to the rapidly increasing oil prices. Whilst increasing their competitiveness in areas of offshore plants and high-value, specialized vessels, the companies are also investing heavily in alternative energy (e.g. Hyundai Heavy wind facility plant operation). Korean dockyards have been working to develop environmentally friendly shipbuilding technologies and 'green' vessels as the green wave reaches the global shipbuilding industry. Some Korean shipbuilders have

already developed hybrid ships that significantly cut carbon emissions and improve fuel efficiency. e.g. STX GD (Green Dream Project), ECO-Ship (STX Europe).

Hyundai Heavy Industry Co. Ltd. has established a method to control global bending distortion caused by the fabrication process for hatch-covers in a container ship. Lee *et al.* (2010b) measured the transitional behaviour of global bending distortion in the deck of a hatch-cover during fabrication by three dimensional measurement instruments. Ha and Yang (2010) have developed a modelling methodology by which global deformation after multi-pass welding can be analysed at the shell element level in one simulation.

In the field of welding automation, HHI (Hyundai Heavy Industry Co., Ltd.) and DSME (Daewoo Ship Building and Marine Engineering Co., Ltd.) announced the development of a corner-piece welding robot for LNG Carriers and a welding carriage with high deposit rate, respectively. Kim *et al.* (2010a) (HHI) has developed a Gas tungsten arc welding (GTA) robot system. They have verified the system and its performance through field testing on actual work pieces.

The welding position employed at the erection stage is usually the flat and vertical position. Application of submerged arc welding (SAW) and electrogas welding (EGW) for these positions makes it possible to achieve enhanced productivity and high quality. However, owing to their large size and weight it is difficult to apply these techniques in short and narrow regions. To overcome this problem, Kim *et al.* (2010c) (DSME) has developed a compact, lightweight, 4-axis welding carriage which perform 3D weaving. Next to the developments in line heating systems mentioned in the Japan section, curved plates can also be manufactured using cold-forming techniques with a die system. However, the total number of curved plates with the same geometry is usually very small for ship structures. Therefore traditional fixed target surface machines are impractical. Paik *et al.* (2010) describe the concept of a changeable die system. In the publication the prediction of the spring-back characteristics of curved metal plates after cold-forming is discussed by means of the elastic-plastic large deformation finite element method. The algorithm provides accurate predictions of the spring-back deformation when compared to tests.

Hwang *et al.* (2010) and STX shipyard also have suggested a MPPF (multi-point press forming) that have a single side multipoint dieless tool for cold forming. They developed an integrated system for thick plate forming performed by the single side MPPF. To determine the piston strokes in multi-point forming from a set of scattered data points, the compensated position of each piston point was calculate by an integrated displacement compensation method which combines ICP (Iterative Closest Point) algorithm, DA (displacement adjustment), and FEA. DA was used to automatically calculate the spring-back compensation necessary for all hull plates. The DA method is incorporated into a commercial FE code through a batch-run interface to repeat the iterative compensation by the integrated system.

### 2.2.3 China

The Chinese shipbuilding has undergone significant expansion since 2000. Its orderbook has increased from 10.6 million to 185 million DWT. Bulk carriers made up the largest proportion of yearly deliveries (41 million DWT), followed by tankers (15 million DWT) and container ships (4 million DWT), BRS (2010). Recently, China's shipbuilding has prospered in the building of supertankers, container vessels and engineering ships. In addition, there are new developments in China's equipment manufacture for ocean engineering.

But there are still some problems for shipbuilding in China. Firstly, shipbuilding costs are rising steadily. Labour costs have increased month by month, and according to most shipbuilding enterprises, the wages for workmen in China's shipbuilding industry at coastal areas by the end of December rose at a mean rate of 15% compared with the beginning of the year. Secondly, the price of ship steel in 2010 has risen month by month, which increases the procurement costs of shipbuilding enterprises. Thirdly, international shipbuilding rules and regulations are renewed and updated more frequently, requiring China's shipbuilding enterprises to develop new hull forms and modern shipbuilding methods in order to comply.

### 2.3 *Europe*

European yards have been careful in their business development and have largely refrained from massive capacity expansions. The pursuit of numerous opportunities in specialised markets, which could be exploited through innovative solutions, have played a focal role for many years. With this approach, European yards have been able to double their turnover since 2005, whilst keeping the output in tonnage-terms stable. Thus, it is becoming more apparent that the focus on niche markets has placed the European yards as leaders in the building of complex hardware for a wide range of specialised maritime activities such as dredging, fishing, cruising and leisure, supply and support for harvesting offshore energies, research, environmental preservation, pollution control, etc. Despite this specialisation, the European yards continue to lose market share in shipbuilding production, CESA (2010).

The EU is confronted with twin challenges: sustainable growth and scarce natural resources. The maritime industries are pioneering the development of new markets with high growth potential, like wind and wave energy, food from the seas, pollution control, clean and safe transport of passengers and goods, deep-sea mining for minerals, etc. EU shipyards are now conducting research, development and innovation in order to adjust to the changed business environment and benefit from growth markets.

### 2.4 *America*

#### 2.4.1 *Brazil*

According to Lloyd's Register, in 1980 Brazil was the world's 2nd largest shipbuilding nation behind Japan. However, the industry collapsed in the following decades due to local economic factors such as hyperinflation, high interest rates and the ending of state subsidies. By 1999, no ships over 100 tons were being built and the industry had shrunk to only 2000 workers nationwide, Paschoa (2010).

However, an amazing revival has occurred in the last decade in response to large deep-water offshore oil and gas discoveries. For political reasons, the Brazilian Government, through its state-sponsored oil company Petrobras and its shipping subsidiary Transpetro, have used these oil discoveries as a vehicle for job creation. Wherever possible the Brazilian government has required as many of the requisite vessels and oil rigs to be built within the country. This has resulted in a shipbuilding boom. Today, the industry has a national workforce of over 45 000 with approximately 80 booked orders for a variety of ships and rigs, França (2009) and Paschoa (2010). New developments in risers and anchorage systems are currently two important research topics, Andueza and Estefen (2011) and Rossi and Fernandes (2011).

### 3 FABRICATION TECHNOLOGY

#### 3.1 Welding Thick Steel

Recently, various requirements for the use of thick steel plate in a number of industrial fields, including the shipbuilding industry, have been identified. Especially with the continual increases in marine transportation volumes on a global scale, the steel of container ships and LNG carriers has become thicker and thicker with the increased size of ships (An *et al.*, 2010), see Fig. 3. In the previous report, the introduction of YP460 steel plates (high tensile steel plates with the specified yield point of  $460 \text{ N/mm}^2$ ) to reduce the maximum plate thickness was introduced. High-tensile strength steel has also been selected to meet the required structural strength in the joints of thick plates, Kim *et al.* (2010c), Funatsu *et al.* (2010), Kaneko *et al.* (2010).

However, the application of extremely thick steel plates raises additional issues, such as brittle fracture and fatigue strength, which still need to be addressed.

##### 3.1.1 Welding of Extreme Thick Plates

Focusing on safety-related issues of extremely thick steel plate applied to large container ships, a national joint research project was organised by the Japan Ship Technology Research Association (JSTRA), and many research activities were carried out between 2007 and 2009, Sumi *et al.* (2010). This project tasked its 3 working groups with the following studies:

- Working group 1: Study of the arrest design of brittle crack propagation
- Working group 2: Study of prevention of brittle crack initiation
- Working group 3: Study of NDT technology for welding joints of extremely thick plates

In the activities of Working group 1, which are summarized by Yamaguchi *et al.* (2010), a new test method for brittle crack arrest toughness was established Kawabata *et al.* (2010), and a number of large-scale structural component model tests were carried out to simulate crack propagation and arrest from the hatch side coaming into the upper deck plating. In addition, the effects of structural discontinuities, in terms of welds Handa *et al.* (2010), full-scale structural component tests and ultra-wide duplex Esso tests were carried out, which confirmed the  $K_{ca}$  criterion of  $6000 \text{ N/mm}^{3/2}$ , Inoue *et al.* (2010). In addition, to ensure that the brittle crack does not propagate straight along the butt joint throughout the hull section, a butt shift of  $300 \text{ mm}$  in general is

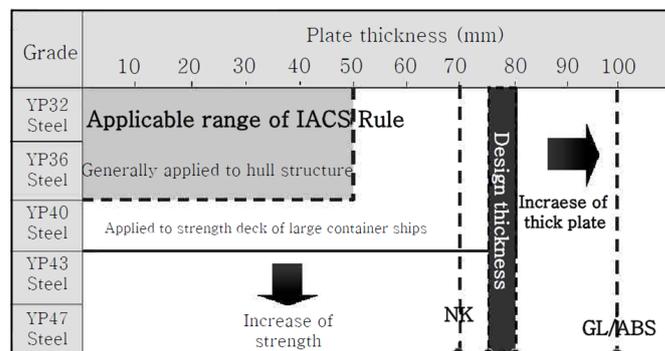


Figure 3: Recent history of thicker and stronger steel plates for large container ships  
 – An *et al.* (2010)

Table 1: Recommendation to prevent brittle fracture accidents

	New ships	Existing ships
During new construction	Full length UT with allowable defect length of 25mm $K_{Ic} \geq 3000 N/mm^{3/2}$	Not applicable
After delivery	Full length UT every 10 years  Visual inspection as far as practicable within the interval of not greater than 3 years	Full length UT after 10 years from delivery and subsequent every 5 years  Visual inspection as far as practicable within the interval of not greater than 3 years

recommended between the hatch side coaming and the upper deck structure, based on the numerical simulations conducted under various conditions (Yoshinari and Aihara, 2009). All these findings were summarized in the Class NK “Guidelines on Brittle Crack Arrest Design” (Nippon Kaiji Kyokai 2009) as a guideline to ensure brittle crack arrestability for large container ships.

The brittle crack arrestability of ultra-thick plates has been also studied by An *et al.* (2010). In their study, crack arrest tests were conducted in order to investigate the crack arrestability of thick plates for shipbuilding steels, where test plate thicknesses were between 50 mm and 80 mm.

Working group 2 studied the prevention of brittle crack initiation. Fatigue crack growth from an embedded initial defect in the butt joint of the hatch side coaming was analysed. The critical crack size to prevent brittle fracture was identified for the purposes of determining allowable initial defect sizes for large container ships in combination with the results of Working group 3, which focused on the study of NDT technologies for welded joints of extremely thick plates. Several UT techniques were tested for accuracy by six Japanese shipyards, using test specimens with internal artificial defects.

All these results were summarized in the recommendation to prevent brittle fracture accidents, published by Association (2009). The recommendation proposes the control of the size of embedded defects in weld joints by UT, not only during new construction, but also after delivery, and also the control of the quality of weld joints to ensure that they exhibit sufficient brittle fracture toughness. Tab. 1 shows the recommendation for some typical trading patterns and conditions.

Shin *et al.* (2010) suggested a predictive equation for the prediction of the transverse residual stress at the thick FCA butt weldment of large container vessels. They used restraint degree, the yield strength of the base metal, the thickness of the weldment and welding heat input as the variables for the predictive equation. Restraint degree at the thick weldment of a container ship under different weld sequences was calculated by FEA in their study. On the basis of these results, an H-type specimen was designed to reproduce the level of restraint at the actual weldment of a container ship. Based on the FEA result, they proposed predictive equations for the mean value and the distortion of transverse residual stress at each location of the weldment using 3-D FEA and a multiple-regression method. The predictive equations were verified by comparison with those measured by XRD in the actual weldment of the container ship.

Lee *et al.* (2010c) suggest a finite element analysis (FEA) model to predict the residual stress in welded parts joined by FCA welding with more than 20 layers of weldment. The characteristics of residual stresses in FCW welds of high tensile strength steels

whose yield stresses were between 400 MPa and 500 MPa, respectively was investigated by both FEA and measurement. Three-dimensional thermal elastic-plastic analyses were conducted to investigate the welding residual stresses. EH40 and API2W-50 plates of 80 mm thickness were used as the base materials and a double 'V' butt joint configuration was used to join the plates. The joint for the specimen was welded with 28 layers. The residual stress was measured by X-Ray diffraction after the specimen was polished by chemical etching. The residual stress obtained by the FEA was also compared with that of experiment. Their study describes the 3-dimensional finite element model required to predict the welding residual stress in extremely thick plates of EH40 and API2W-50 joined by FCAW and discusses the comparison between the experimental results and numerical predictions of residual stress.

### 3.1.2 Thickness Effect to Fatigue Strength

Another problem associated with the application of extremely thick steel plate is fatigue strength. It is well known that increasing plate thickness causes a decrease in fatigue strength. Phenomena such as an expected larger stress concentration in the weld toe for thicker plates with identical weld profiles, larger stress gradients in thickness direction compared to thin plates especially in bending, possible larger residual stresses and increased probability of crack initiation due to larger areas of high stress can be causes for this decrease in fatigue strength. Some phenomena are already included in established fatigue rules and standards, such as DNV (2010), Hobbacher (1996) and IACS (International Association of Classification Societies) (2008). However, there are still some points which require further study, such as the thickness effects in extremely thick steel plate, thickness effects in actual ship structure details *etc.*

Polezhayeva and Badger (2009) studied the effect of plate thickness on fatigue strength through fatigue tests for the combinations of plate thicknesses 22 mm and 66 mm, in bending and tensile load, and for base material and butt welded joints. The authors proposed a thickness exponent of  $z = 0.1$  for base material and  $z = 0.2$  for butt welds, which is consistent with the IIW recommendations, Hobbacher (1996). On the other hand, some Japanese studies revealed far less of an effect of plate thickness in cases where the subject location for the fatigue strength assessment was just above a longitudinal supporting member, such as in the case of longitudinal stiffeners. Nakamura and Yamamoto (2007) carried out analytic research on stress concentrations in the welded joints of longitudinal stiffeners and web stiffeners, and concluded that the thickness effect is negligible. Fukuoka and Mochizuki (2010) carried out several fatigue tests and stress analyses, and also pointed out that the thickness effect for weld joints on I-section beams is much smaller than that of established rules and standards, and proposed new correction exponents. Im and Chang (2009) also investigated the fatigue strength of ultra-thick plates. Three types of joint, referred to as AW (As-Welded), UP (Ultra Peening) and TG (Toe Grinding), were cut from API 2W Grade 50 steel.

It is considered that the correction exponent included in the rules and standards are based on the results of small fatigue test specimen and not actual ship structural details. In addition, the mechanism for this effect is not yet clearly identified. Many factors are considered to influence the thickness effect, such as stress concentration factor, stress gradient in the thickness direction, residual stress due to welds and increased probability of crack initiation due to the larger area of high stress. Further study is considered to be necessary to reveal how each factor contributes to the thickness effect, and to establish reasonable and reliable thickness effect correction methods applicable to actual ship structural details.

### 3.1.3 Improvement of Fatigue Strength

In the committee's previous report, a new steel was introduced, called FCA (Fatigue Crack Arrester) steel, which shows improved fatigue initiation life as well as improved crack growth life in welded structures. To maximise the benefit to be obtained from this steel, a new design S-N curve for welded cruciform joints made with FCA steel has been proposed, Konda *et al.* (2010). In this study, 66 small scale fatigue tests with FCA steel in association with 18 tests with conventional steel were conducted, supplemented by some large scale tests of relevant ship details. The proposed S-N curve has significantly longer life for the high cycle region of the S-N curve. As a result, the authors say that FCA steel is especially beneficial for details subjected to typical stress ranges from wave loading, leading to 3 times longer fatigue life, calculated for a typical long term stress range distribution.

Hara *et al.* applied FCA steel in the connecting areas between a cargo tank cover and the upper deck in the midship region of a 153 000  $m^3$  Moss type LNG carrier, and showed that FCA steel can be used without any scantling increase to relax or cancel the scope of weld toe grinding or to improve fatigue life, Hara *et al.* (2010). Takaoka (2010) presented examples of fatigue strength assessments from the application of FCA to crude oil carriers and bulk carriers. In this study, the fatigue life increased by 1.8 – 2.8 times on average.

In the previous report, the use of UIT (ultrasonic impact treatment) was reported as a very practical and effective method to enhance fatigue strength at welds. Takaoka (2010) studied the effective application of this method to ship structures, and found that its effectiveness is enhanced when UIT is carried out at locations under a tensile overall stress. They pointed out that such conditions occur when UIT is carried out on the weld joints on the upper deck of container and LNG carriers after launching. In addition, UIT is considered to be effective on accumulated fatigue damage, when it is carried out on aged vessels. IHI Marine United Inc. carried out UIT on an actual aged vessel and demonstrated its positive rehabilitation effect, Tango *et al.* (2011).

Due to the increase in the size of container ships and LNG carriers, and the use of higher strength and thicker steels, fatigue strength is becoming more of a concern. New developments such as FCA steel and UIT will help to improve the fatigue strength. However, in order to be able to fully take advantage of these developments, they need to be approved and included in rules and regulations.

### 3.2 Welding Aluminium

Aluminium is the material of choice for many ships and craft because of low weight, ease of fabrication and reasonable costs. However, welding of aluminium requires more joint preparation and cleanliness than is generally required for steel. Furthermore the need for shielding gas and the somewhat slower welding speeds make the process more expensive. Aluminium is more prone to distortion during welding than steel. A relatively new welding technique used for aluminium is Friction Stir Welding. It has found rapid application in the fabrication of structural panels. SSC-456 (2009) shows a comparison of the mechanical properties of friction stir welded and fusion welded aluminium plates. It was found that for a but-weld connection the tensile properties for friction stir welding were equal or better than for fusion welding. Also initial imperfections were smaller. For the compressive strength performance in the welded area friction stir welding is less good due to the occurrence of delaminations in the welded region, this could be resolved using a lap weld instead of a but weld.

When delaminations are prevented the ultimate compressive strength performance of the friction stir welding procedure is superior to fusion welding.

### 3.3 Corrosion Protection Techniques

Since 2008, research related to corrosion in ships and protection against corrosion has continued worldwide. Most of the efforts have been concentrated in three geographical regions, Australasia, North America, and Europe.

Most of the studies have focused in one of the following areas, a) corrosion behaviour, b) corrosion protection, and c) corrosion analysis. A summary of the developments will be presented in the following according to these three groupings.

#### 3.3.1 Corrosion Behaviour

In terms of corrosion behaviour, studies in the last few years have included aluminium structures; differences between erosion-corrosion and corrosion; alternate alloys for the corrosion environment; elastomeric materials for bearings; anti-corrosive coatings; thermal spray coatings and direct metal deposition.

The specific strength of aluminium ships is higher than that of steel ships. Aluminium ships can travel at high speeds, have increased load capacities, increase ease of recycling, and have high anti-corrosion properties. For those reasons, the corrosion and mechanical properties of aluminium ships are continuously being developed. Kim *et al.* (2010b) reported on a number of electrochemical experiments undertaken to determine the optimum corrosion protection potential conditions for MIG welding to enhance protection for 5083-H116 (Al-Mg alloy) in natural seawater. For protection against stress corrosion cracking and hydrogen embrittlement in 5083-H116 aluminium alloys, the optimum corrosion protection range was reported as -1.2 to -0.7 V for the base metal and welds.

Zhao *et al.* (2008) studied the difference between synergistic erosion-corrosion and corrosion using a rotating disk apparatus and immersing mild steel specimens in a 0.05 wt. % SiC suspension. Techniques used in their study included scanning electron microscope (SEM), positron annihilation lifetime spectra (PALS) and X-ray photo-electron spectroscopy (XPS). The PALS results showed that both the size and number of vacancy defects depend on the cavitation and immersion time. Yet the size and number of vacancy clusters induced by cavitation erosion was much larger than that induced by corrosion damage alone. Reactions involving core level valence band electrons appeared to have led to greater oxidation of mild steel during cavitation erosion which was not observed in corrosion alone.

In an attempt to identify new materials for ship applications, titanium and super-austenitic stainless steels (SASS) were examined for marine diesel exhaust scrubbers operating with seawater as the used reactant that collects and neutralizes the sulphur dioxide of the exhaust gas. Aragon *et al.* (2009) conducted a series of corrosion resistance tests on welded samples of titanium and super-austenitic stainless steel alloys to evaluate their capacity in these applications. The authors concluded that super-austenitic alloys gave acceptable resistance characteristics in both parent metal and welded/HAZ areas, as long as there was no crevice in the test specimens. They also showed that high grade SASS (PRE > 40, Mo content > 6%) could be a possible material provided that strict welding conditions are ensured and that the design of the scrubber be able to avoid any crevice configuration. Titanium samples were able to sustain the harshest corrosive conditions, including crevice geometry areas.

Elastomeric compounds, due to their favourable properties like sufficient hardness, toughness and natural resistance to abrasion and corrosion, are commonly used as bearing materials for the propeller shaft system of Indian Coast Guard Ships. They can be subject to unequal and non-uniform wear. Hirani and Verma (2009) analysed a sea-water lubricated journal bearing, investigating the actual geometric clearances of new and worn bearings recorded by the ship maintenance team and their effects, and duplicated in tests the operational data (load, speed and operating hours). Unplanned excessive radial clearance reduced the load capacity of the bearings and resulted in rapid and uneven wear. As such, bearing life can be enhanced by proper selection of radial clearance for the bearings.

### 3.3.2 Corrosion Protection

In terms of corrosion protection, recent studies have included cathodic protection, use of organic coatings, effects of surface preparation on epoxy coating performance effectiveness, effects of flash rust on the protective properties of organic coatings and active dehumidification during ship lay-ups.

To prevent salt-induced premature coating failure, International Maritime Organization (IMO) has adopted a Performance Standard for Protective Coatings (PSPC) specifying  $50 \text{ mg/m}^2$  or less as the allowable NaCl limit for primary and secondary surface preparation for ship water ballast tank. Lee *et al.* (2010a) evaluated coating performance of epoxy coatings and established allowable soluble salt criteria, especially NaCl, in terms of adhesion strength and blistering resistance tests in immersion, condensation and cathodic protection environments. The authors recommended that the blistering resistance to soluble salt for each coating system be included in coating performance tests to verify and approve coating systems for IMO PSPC.

Since the implementation of the PSPC requirement in 2008, large numbers of vessels have already been delivered. Due to the preparation of hardware and software to fulfil the PSPC requirements, it seems that the shipbuilding industry is managing the stringent requirements effectively, although new facilities for blasting, painting and stock as well as increased labour time and enhanced quality management were necessary with the associated increases in cost, Seo (2010).

Based on actual experience, future revisions of the PSPC requirement have been proposed by the industry, e.g. replacing the requirement on surface roughness of “30 – 75  $\mu\text{m}$ ” by “Medium” as defined in ISO8503-1/2, Lin (2010).

Amongst the many stringent requirements of PSPC, surface treatment using blasting is one of the most demanding factors, necessitating investment to the facilities as well as potentially creating a poor working environment and increasing industrial waste. As a promising alternative to this blasting, Yamagami (2010) established a new air mixed high-pressure water blasting technology, called Konki-Jet, which was demonstrated to fulfil the PSPC requirements.

Kim *et al.* (2008) examined the effect of the flash rust and surface roughness on the coating performance by evaluating adhesion forces and delamination areas through pull-off tests, visual inspection and electrochemical test. The rust layer on the substrate reduced the adhesion and accelerated the disbondment of epoxy coatings, but flash rust area ratios below 20 to 30 percent hardly affected the adhesion and performance of coatings. Anticorrosive pigments were observed to improve the barrier effect and protective performance of coatings. Brown (2010) proposed that dehumidifying systems should be used to control moisture on board and protect the ship from

corrosion during lay-ups. Dedicated dehumidification equipment is fundamental and effective in bringing air in the enclosed areas of the ship, such as ballast tanks, storage tanks, and control rooms, to a relative humidity not exceeding 50%. According to Brown, desiccant type dehumidifiers are the most effective and efficient equipment for controlling moisture in large areas such as container ships.

Sorensen *et al.* (2009) prepared an extensive state-of-the-art review of the use of marine and protective coatings for anti-corrosive purposes. International and national legislation aimed at reducing the emission of volatile organic compounds (VOCs) have caused significant changes in the anti-corrosive coating industry. Meeting environmental regulations and reducing production costs remain a key challenge and a major driving force for new developments in anti-corrosive coatings. The authors pointed out that the next generation of high-performance anti-corrosive coatings face many challenges, and that the incomplete understanding of the physical and chemical mechanisms responsible for the failure of anti-corrosive coatings during service represents hindrances towards further progress. Thorough understanding and quantification of the degradation mechanisms by mathematical models may provide a useful tool in the development of new coating products and development of binders and pigments that may be capable of providing excellent protection against corrosion. Novel ideas which require further investigation and maturing include self-healing coatings.

Papavinasam *et al.* (2008) published an extensive review of the state-of-the-art of thermal spray coatings for corrosion protection. Thermal-spray coatings can be used in marine structures including offshore pipelines without external cathodic protection (CP). Al, Zn and ZnAl coatings protect steel by acting both as barrier coatings and as sacrificial anodes at local defects where corrosion could occur. Well-bonded, relatively dense, sealed coatings have the ability to provide effective long term corrosion protection (10-20 years), with minimum periodic maintenance. Practical examples of thermal-spray coatings can be found in Europe and in North America for corrosion protection of steel in urban, industrial, and marine environments, e.g over 40 bridges in Britain and the mile-long Pierre-Laporte suspension bridge near Quebec City.

In an attempt to deposit a corrosion resistant coating on a C71500 (70Cu-30Ni) alloy for marine applications, Direct Metal Deposition (DMD) technology using a CO<sub>2</sub> laser was developed. Bhattacharya *et al.* (2011) reported that a Cu-30Ni alloy (with a similar composition to the substrate) was successfully laser deposited on a rolled C71500 plate substrate. The Cu-30Ni clad specimen showed higher ultimate tensile strength but lower yield strength and percentage elongation than the C71500 substrate. The corrosion resistance of a DMD Cu-30Ni clad specimen was found to be lower than the C71500 substrate, but was found to improve in the case of the DMD Cu-30Ni clad/C71500 substrate specimen. The higher corrosion rate of the DMD Cu-30Ni clad specimens was attributed to the presence of porosity in the clad layers.

### 3.3.3 Corrosion Analysis

In terms of corrosion analysis, recent studies included several different approaches. The most relevant trend appears to be the development of models that are operational based, taking into consideration long term operations with cumulative damage and operational environment (region of navigation, sea water, temperature, etc.). Corrosion behaviour according to time-varying ultimate strength and strain rate has been investigated. Reliability of structural performance was examined under structural health monitoring. Advanced techniques such as the non contact EMAT measurement of aluminium alloy has proven to be a viable technique for characterising cor-

rosion and sensitisation. Finally, electrochemical impedance spectroscopy (EIS) also demonstrated good results in monitoring damage to organic coatings.

Guo *et al.* (2008) presented a semi-probabilistic approach to assess the time-varying ultimate strength of the deck plate of an aging tanker considering corrosion wastage. The authors proposed a non-linear corrosion model for deriving the time-varying probability density function of corrosion wastage of the deck plates. The model was validated using data from a total of nine sample tankers, designed in the 1970s, 1980s and 1990s. The results demonstrated that this procedure can be easily applied to assist the risk-based inspection.

When sensitized, 5XXX grade aluminum alloys are more susceptible to inter-granular corrosion (IGC) and inter-granular stress-corrosion cracking (IGSCC). The formation and growth of beta phase ( $Mg_2Al_3$ ) along the grain boundaries is responsible for the susceptibility of these alloys. Conventionally, the degree of sensitization (DoS) is quantified by the ASTM G67 Nitric Acid Mass Loss Test, which is destructive and time consuming. Li *et al.* (2011) experimented with an electromagnetic acoustic transducer (EMAT) to measure the DoS in AA5083 aluminium alloy samples sensitized at  $100^\circ C$  with processing times varying from 7 days to 30 days. Correlations between DoS and shear wave velocity, as well as shear wave attenuation allowed for easy DoS characterization in AA5XXX aluminium alloys. The authors successfully used EMAT ultrasonic measurements to discriminate low ( $5\text{ mg/cm}^2$ ), medium ( $30\text{ mg/cm}^2$ ), and high ( $60\text{ mg/cm}^2$ ) levels of DoS for planar samples with accuracy about 90 %.

Melchers and Paik (2009) conducted laboratory experiments subject to pre-existing rusts to high levels of tensile strain to examine the effect of tensile strain on the rate of marine corrosion of steel plates. They exposed the steel to a natural marine environment, including the atmospheric and tidal zones. It can be concluded that low levels of tensile strains applied to previously corroded steel specimens have a relatively minor influence on the loss of adherent rusts from the surface of the metal and practically negligible effect on steel mass loss due to marine immersion corrosion. On the other hand, high levels of strain, approaching the yield strain of the steel, produced observable losses of adherent rusts and observable cracking of the adherent rust layer. Short-term marine immersion exposure tests of samples under these conditions experienced increases in mass loss due to corrosion by some 10-15 %.

Okasha *et al.* (2010) presented in their paper an approach for integrating the data obtained from structural health monitoring (SHM) in the life-cycle performance assessment of ship structures under uncertainty. Lifecycle performance of the ship structure is quantified in terms of the reliability with respect to first and ultimate failure and system redundancy. Structural Health Monitoring data obtained by testing a scaled model of a Joint High-speed Sealift Ship representing the worst operational conditions of sea state 7.35 knot speed and head seas were used to update its life-cycle reliability and redundancy. The results obtained showed that the dynamic load effects can be significant in rough operational conditions.

Regarding specific environmental effects on corrosion and corrosion wastage of ship structures, Guedes Soares *et al.* (2009) developed a new corrosion wastage model based on a reference non-linear time-dependent corrosion model by including the effects of different environmental factors such as relative humidity, chlorides and temperature. The inclusion of these factors that are especially relevant to the rates of corrosion in marine environment allows for more accurate predictions of the expected corrosion levels and better planning of the corrosion inspections along the life of the ships. The

paper proposed equations that serve as guide to ship owners and Classification Societies about which variables need to be monitored to allow more accurate predictions of corrosion wastage in marine atmosphere. The authors highlight that it is necessary to put in place monitoring programs to produce and collect the required data for validation of the proposed model in the long-term.

Combining the Support Vector Regression (SVR) approach with the Particle Swarm Optimization (PSO) method, Wen *et al.* (2009) established a model for prediction of the corrosion rate of steel under five different seawater environment factors, including temperature, dissolved oxygen, salinity, pH value and oxidation-reduction potential. The major objective of the paper was to compare between this method and back-propagation neural network (BPNN). The results illustrate that the predicted errors of SVR models are smaller than those of BPNN models for the identical training and test dataset, and the generalization ability of the SVR model is also superior to that of the BPNN model. The SVR does exhibit more limited extrapolation ability than the other methods.

Yan *et al.* (2009) used electrochemical impedance spectroscopy (EIS) combined with open circuit potential measurements and scanning electron microscopy (SEM) to characterise the corrosion process and products of two commonly used ship coatings, epoxy aluminium coating and chloride rubber iron red coating, and their composite coatings. These systems were immersed in 3.5 % NaCl solution. The authors demonstrated using potential-time measurement that the free corrosion potential of these three coatings with immersion time are more positive than that of metal substrate. The results also showed that the growth of the electrochemical area of the anode and corrosion takes place continuously. EIS results showed that corrosive species can penetrate into coatings and reach the coating/substrate interface rather quickly, causing the coatings to lose their shielding role and initiate the start of electrochemical corrosion. The penetration of the corrosive media also caused damage to the coatings by destroying the intermolecular cross linkage and rendering the coatings coarse, porous and brittle. Composite coatings exhibited synergistic behaviour between the two coatings offering better protection performance, demonstrating the effect of  $1 + 1 > 2$  according to the authors. The authors also concluded that electrochemical tests along with surface analysis are adequate tools for studying the corrosive behaviour of organic coatings-substrate systems and for assessing their performance in corrosion environments.

#### 4 COMPOSITE MATERIALS AND THEIR PRACTICAL APPLICATION

In recent years the application of composite lightweight materials has increased, both in the application of full composite ships and in a combination of composite parts with steel hulls. Composites have several advantages such as a light weight, large freedom of shape and corrosion resistance, which make them very suitable for application in maritime environments. Examples of the use of composites are e.g.:

- The hybrid high speed vessel midfoil (Navantek ltd)
- The ship hull of the patrol boats KNM Skjld of the Royal Norwegian Navy
- Mine counter measure vehicles (MCMV lansort Class) of the Royal Swedish Navy
- Visby corvettes (Royal Swedish Navy)
- Superstructure of the la Fayette class frigate (French Navy)
- Advanced enclosed mast/sensor (US Navy)

As can be seen from this list, most applications are in military ships. Commercial ship application is still lagging behind. Especially for the combination of composites and

metals, research on the connection between the two is being conducted (§4.1), as well as research on connections within the composites itself.

The main technical drivers for the application of composites are corrosion resistance, Bergen and Needham (2009), reduced costs and weight saving and magnetic signature, Faraday (2008). The reduced costs can only be seen when through life costs are taken into account. Initial front costs for composite materials are higher. Since most owners/operators are still front cost driven, this is not an advantage that is generally considered. The main advantage of weight saving that is normally seen is the increased stability or payload increase. Fuel saving due to weight reduction is normally stated as less important.

The major drawback for the application of composites is the SOLAS fire regulations. A lot of research is being conducted on how to provide and prove equivalent safety for fire (§4.2). Another large application of composites is in the repair of steel structures, mostly to increase the fatigue life. Details on research in this area will be discussed in §4.3. Now that the use of composites is increasing, attention is also starting to focus on optimisation of the design (§4.4)

#### 4.1 Connections

From earlier studies it was seen that the connection between metal parts and composites can be a problem due to stiffness differences. Both experimental work and modelling techniques have been considered, Kabche *et al.* (2007); Boyd *et al.* (2008). Next to studying the behaviour of certain designs, also optimization of the joint design is a major research subject. The effect of variations in core thickness, laminate thickness, materials, overlaps and adhesives is also being studied, not only for metal-composite connections, but also for full composite connections, Song *et al.* (2008); Bella *et al.* (2010). In Boyd *et al.* (2008) a genetic algorithm, based on natural selection and genetics, is used for the optimisation of the connection of a composite superstructure to a steel hull used in the La Fayette frigate. Based on several criteria on strength, stiffness and weight the best performing designs are interlinked to create a new family of designs. Several optimisation rounds are conducted.

Detection of damage in the joints can be difficult. Palaniappan *et al.* (2008) discussed the use of fibre Bragg grating optical techniques to detect disbonds in composite bonded constructions. Cracks in the bond are detected by strain changes in the sensors. Noise levels are still a problem in this technique.

#### 4.2 Fire Safety

The main concern for using composites in large load-bearing structures has to do with the fire performance. The Solas regulations are mainly based on metals. Other materials can be used providing equivalent safety is demonstrated. A lot of research has been going on the fire safety of composites. In contrast to metals a lot of processes play a role in the fire behaviour. A combination of thermal, chemical, physical and failure processes occur, with interactions between these processes. A good overview of the work done so far on the modelling of all these processes is given in Mouritz *et al.* (2009). The authors report on the recent modelling techniques and on the limitations of the models. Often the thermal analyses is decoupled from the fire/composite interaction, which is a simplification, since the composite material degenerates in the fire and, for example, the gases that are released in this process can ignite, thereby influencing the fire behaviour. A lot of research is focused on none-reactive (e.g. glass fibre) composites. Very little research has been conducted up to now on reactive fibre

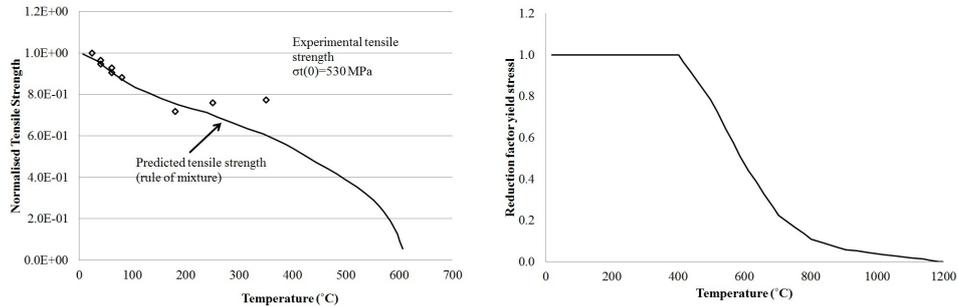


Figure 4: Strength decrease at elevated temperatures, left composite laminate, right steel Grade S275 (EN 1993 1-2) – Feih *et al.* (2007)

response. A lot of progress is reported on the modelling of the change in mechanical behaviour of composites under compressive loading subjected to a one-sided fire, Asaro *et al.* (2009). Gu *et al.* (2009) provide design diagrams and a quantitative methodology for fire protection design. In Asaro *et al.* (2009) it is shown that for moderate load levels the rate of degradation largely influences the panel response and not the temperature. For high load levels (close to normal failure loads) the temperature of the fire is the dominating factor.

Much less research has been conducted on composites in tensile loading conditions. This is because the softening behaviour in that case is far more difficult to model. However Feih *et al.* (2007) does address that issue. Thermo-mechanical models are described in this paper which predict time to failure in polymer laminates loaded in tension or compression subjected to one-sided fire. The mechanical models are based on the two-layer approach, in which part of the composite is not influenced by the fire (the virgin layer) and part (the charred layer) does have degenerate mechanical properties due to the fire interaction (see Figure 4). Limited verification with experiments is presented. It was concluded that compressive loading leads to earlier failure than tensile loading, and time to failure decreases with increased heat flux or mechanical loading.

#### 4.3 Composite Patch Repair

Normally when a crack is detected in a metal structure it is repaired via welding or replacement of part of the structure. However, when hot-works are not allowed, welding is not an option. Also replacement can be a time consuming, costly option, since not all spare parts are available in-situ. Repair of corroded or cracked parts by composite patches is a good alternative. Composite patches are corrosion resistant; they prevent crack growth, can work as crack arresters, lower the stress concentrations and extend the life time of the structure. Furthermore the lightweight composite patches do not add much additional weight. Applications so far are mainly in aircraft. The application in bridges and other civil engineering structures is increasing. Maritime applications are still limited, although the advantages in offshore applications are becoming clear. A new FP7 EU project is started in January 2010 on composite patch repair for marine and civil engineering infrastructure applications ([www.co-patch.com](http://www.co-patch.com)). Much research has been done on the fatigue behaviour of cracked steel plates, repaired by one-sided composite patches, Xiong and Shenoi (2008); Tsouvalis *et al.* (2009); McGeorge *et al.* (2009). It is seen that the patches can effectively slow down crack growth and extend the specimen life time. McGeorge *et al.* (2009) describes a recommended practice for patch repairs on floating offshore units. Xiong and Shenoi (2008) combine the research

on effects on the fatigue life of cracked metals with investigation of the static strength of the repaired specimen. No significant effect on the static strength was found with different patches. A large influence of patch thickness and material was seen in the fatigue life results.

#### 4.4 Optimisation of Composite Design

Now that the use of composites is increasing, people are also looking into optimizing the design. This can take the form of optimization of certain parameters of composite structures, such as the use of shear keys to improve the shear behaviour of sandwich materials Mitra (2010). Other authors however, describe optimisation techniques to improve the overall behaviour of a structure, based on a combined optimisation of strength, stiffness and weight, Eamon and Rais-Rohani (2009).

Sriramula and Chryssanthopoulos (2009) address the uncertainties that are often result from fabrication and production of FRP composites. A deterministic approach often leads to severe over dimensioning, thereby diminishing the advantages of composites. The paper gives an overview of stochastic models, mostly with some validation, at both micro, meso and macro level.

Since the use of composites is still only limited and relatively recent, not much real time data is available yet on the expected life time in extreme service conditions. Miyano *et al.* (2008) present a new method based on temperature/time superposition for testing of composite responses. Tests are performed at a higher temperature at a higher loading rate to obtain long term prediction of the materials behaviour.

#### 4.5 Recycling and Scrapping of Composite Materials

Patel (2010) forecasts that in 2040, 380 000 tons of fibre reinforced composites have to be disposed of each year. Recycling the material will be necessary to cope with this amount of disposal, both from an environmental point of view as well as from an economical point of view due to material scarcity. Due to the economical impact, more effort is being put into recycling of carbon fibre composites even though glass fibre composites production volumes are much larger.

Both mechanical, thermal and chemical recycling have been studied in the last few years. Pickering (2006) gives an overview of some of the methods investigated for thermoset composites (see Fig. 5). Thermoplastic composites can be reshaped again by heating and are not discussed here.

Most methods result in fibre shortening and a degradation of properties. Values of 60% reduction in tensile and interface strengths have been found by Palmer (2009)

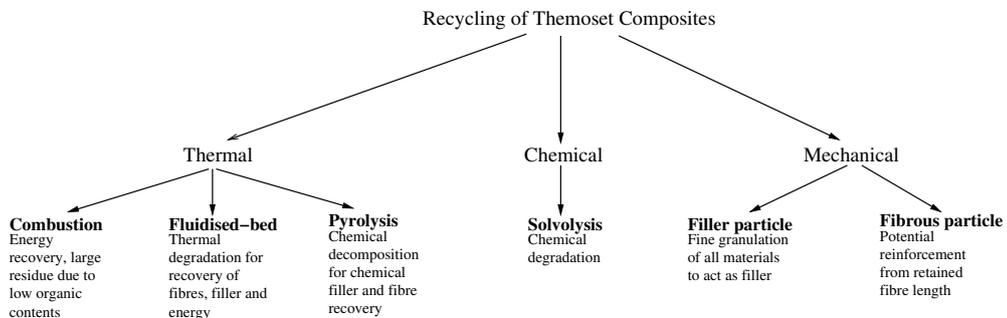


Figure 5: Recycling methods for thermoset composites – Pickering (2006)

for glass fibres, Job (2010) states values varying from 20-30 % for the fibre strength and 50% of the bonding strength for glass fibre composites. Carbon fibres show less decrease in strength, retaining up to 90% of the original properties. Nottingham university Piñero-Hernanza *et al.* (2008) has succeeded in recovering long carbon fibres with limited degradation (85-99 % of original properties) by chemical recycling using sub-critical and supercritical alcohols.

#### **4.6 Metal Sandwich Materials**

The main application of metallic/hybrid sandwich materials in ship structure is still in the production of different superstructure parts (vehicle decks, short deck panels, balcony, stairways, hatch cover, etc.) mainly exposed to local loading, Zanic *et al.* (2009); Kortenoeven *et al.* (2008). Inclusion of sandwich panels as the part of global hull girder bending carrying structure is under investigation, Romanoff *et al.* (2010).

Roland *et al.* (2006) present an overview of EU research projects dedicated to lightweight structures, their manufacturing and integration into the ship structure and summarise available solutions and trends. Feraris *et al.* (2006) give a brief review regarding the opportunities for the use of lightweight metallic structures in large high speed vessels. State of the art production technology and the possibilities offered by the new generation of High Strength Low Alloy steels and aluminium alloys have been discussed. Bohlmann (2006) presented experiences of using extra high tensile steel HT69 related to the design, construction and fabrication of large high speed craft. Reinert and Sobotka (2006) presented experiences in the development of all metallic I-core sandwich panels dedicated for inland waterway cruise ships.

The improvement of the strength-stiffness-weight characteristics of sandwich panels is continuously in progress. Structural optimisation of laser welded sandwich panels with adhesively bonded cores is presented by Kolster and Wennhage (2009), while Barkanov (2006) presented a methodology for optimal design of large vehicle decks and stair modules made of laser welded sandwich. Improvement of the shear properties of web core sandwich panel structures using different filling material is presented by Romanoff *et al.* (2009).

Thin steel sandwich panels need to be joined to one another and to conventional structures. The main focus in recent research has been on design and testing of appropriate joint shapes with respect to technological limits and strength requirements, Polic *et al.* (2011). Frank *et al.* (2011) investigated the influence of different laser welded T-joints geometries on fatigue strength.

## **5 STANDARDS**

### **5.1 Standards Comparison**

Okumoto *et al.* (2009) points out that fatigue cracks are influenced by structural stress concentration, construction tolerances, alignment, welding bead shape, as well as the exerted stress range and residual stress. In an actual ship structure, some construction deviation such as thin horse distortion and misalignment is inevitable. Such construction deviations are controlled under construction standards such as JSQS, and it is considered that strength is warranted by the feedback from actual structural damage of ships in service.

Although a long history of shipbuilding proves that this system has worked, simple standards such as JSQS do not accurately take into account the influence of design variations such as a wider application of higher tensile strength steel leading to increased

nominal stress, or different structural configurations. By quantitatively evaluating the influence of construction tolerances, the quality in terms of fatigue strength can be enhanced.

Actually, such design is required to some extent in the field of gas carriers. Comprehensive application of such design methodology can be found in Adhia *et al.* (1997).

On the other hand, some requirements of construction standards do not seem necessary in terms of strength, and have arisen as a result of empirical as-built records or aesthetic reasons. The unclear origin of such requirements causes confusion when applied to novel designs.

Comparison of standards was conducted in this committee in the 1997 term. After 15 years, a similar comparison was attempted. Results of the comparison of some typical attributes are summarized in Tab. 2. As a whole, no significant changes are observed. However, the following discussion points are raised with respect to the following items.

#### 5.1.1 Distance Between Welds

IACS etc. allows no restriction on the distance between butt and fillet welds or scallops if it is not a strength member, whereas VSM does not. Taking account advances in materials and welding methods, this restriction is considered to be unnecessary even for strength members. Research into the effect of lapped welds on the material strength, including fracture toughness, is expected to reasonably abolish this requirement, or at least result in its application only to certain material chemical compositions.

#### 5.1.2 Fairness of Frames

Required tolerances with regard to fairness of frames are stipulated in several construction standards, based on actual experiences of ship construction. However, as to the distortion of primary supporting members, it is not clear which requirements should be applicable. Especially, as to ferryboats and car carrier decks, whose girders usually have a long span, support small loads, and therefore have small scantlings and relatively large initial deformation, the requirements are critical for their efficient construction.

From this viewpoint, the newest revision of JSQS (JASNAOE, 2010) has introduced tentative requirements for the distortion of car deck transverses as Appendix-1. Somewhat relaxed requirements are stipulated for vertical distortion of deck transverse (standard range of  $3L/1000$  to tolerance limits of  $4L/1000$ ), lateral distortion of deck transverse (standard range of  $3 + 2L/1000$ , max 12 to tolerance limits of  $6 + 2L/1000$ , max 15), and distortion of web plate (tolerance limits of  $t$ ). According to its technical background, it is confirmed through detailed structural analysis that even under the maximum distortion of tolerance limit, structural strength is not deteriorated and the distortion will not increase after delivery. These tentative requirements will be re-evaluated at the next revision of JSQS.

Table 2: Standards comparison – Part 1

Attribute	IACS	JSQS	CSBC	VSM	IRCN
Alignment					
Butt welds	Strength members: Limit: $a \leq 0.15t$ , $max = 4\text{ mm}$ ; Other members: Limit: $a \leq 0.2t$ , $max = 4\text{ mm}$	Strength members: Limit: $a \leq 0.15t$ , $max = 3\text{ mm}$ ; Other members: Limit: $a \leq 0.2t$ , $max = 3\text{ mm}$	Skin plates and longitudinal members: Limit: $a \leq 0.15t$ , $max = 3\text{ mm}$ ; Bulkhead plates and interior members: Limit: $a \leq 0.2t$ , $max = 3\text{ mm}$	Class. level B: Limit: $a \leq 0.1t$ , $max = 3\text{ mm}$ ; Class. level C: Limit: $a \leq 0.15t$ , $max = 4\text{ mm}$ ; Class. level D: Limit: $a \leq 0.25t$ , $max = 5\text{ mm}$	Plating: Limit: $a \leq 0.15t$ , $max = 4\text{ mm}$ ; Flanges: Limit: $a \leq 0.2t$ , $max = 4\text{ mm}$
Cruciform fillet welds	Strength member and higher stress member: Limit: $a \leq t/3$ ; Other members: Limit: $a \leq t/2$ when the thickness of shlef plate ( $t_3$ ) is smaller, $t_3$ should be substituted.	Strength member: Limit: $a \leq t/3$ ; Others: Standard: $a \leq t/3$ ; Limit: $a \leq t/2$	Longitudinal members within $0.6L$ and principal transverse supporting members: Limit: $a \leq t/3$ ; Others: Limit: $a \leq t/2$	Limit: $a \leq t/2$ when the thickness of shelf plate ( $t_3$ ) is greater, $t_3$ may be substituted.	Limit: $a \leq t/3$ where $t$ is the thicker of the two
Distance between welds					
Between butt welds on one plane	For cut-outs: Standard: $d \geq 30\text{ mm}$ ; For margin plates: Standard: $d \geq 300\text{ mm}$ , Limit: $d \geq 150\text{ mm}$	Limit: $d \geq 30\text{ mm}$	Limit: $d \geq 30\text{ mm}$	Limit: $d \geq 50\text{ mm} + 4t$	Not specified
Between butt welds on two crossing plane	No restriction	No restriction	No restriction	No restriction (optional for satisfactory welding)	Not specified
Between butt weld and fillet weld	Strength member: Limit: $d \geq 10\text{ mm}$ ; Others: no restriction	Main structure: Limit: $d \geq 10\text{ mm}$ ; Others: no restriction	Main structure: Limit: $d \geq 10\text{ mm}$ ; Others: no restriction	For fillet weld first: Limit: $d \geq 30\text{ mm} + 2t$ ; For butt weld first: Limit: $d \geq 10\text{ mm}$	Not specified
Scallops over weld seams	Strength member: Limit: $d \geq 5\text{ mm}$ ; Others: no restriction	Main structure: Limit: $d \geq 5\text{ mm}$ ; Others: no restriction	Limit: $d \geq 5\text{ mm}$	Limit: $d \geq 10\text{ mm}$	Not specified

Table 3: Standards comparison – Part 2

Attribute	IACS	JSQS	CSBC	VSM	IRCN
Weld Gap					
Single vee butt	Standard: $G \leq 3 \text{ mm}$ , Limit: $G \leq 5 \text{ mm}$ ; For $5 \text{ mm} < G \leq 1.5t$ , $max = 25 \text{ mm}$ , weld up gap; For $G > 25 \text{ mm}$ or $1.5t$ whichever is smaller, partial renew	Standard: $G \leq 3.5 \text{ mm}$ , Limit: $G \leq 5 \text{ mm}$ ; For $5 \text{ mm} < G \leq 16 \text{ mm}$ , weld up gap; For $16 \text{ mm} < G \leq 25 \text{ mm}$ , weld up with edge preparation or partial renew; For $G > 25 \text{ mm}$ , partial renew	Limit: $G \leq 5 \text{ mm}$ ; For $5 \text{ mm} < G \leq 25 \text{ mm}$ , weld up gap; For $G > 25 \text{ mm}$ , partial renew	For $JWPS < G \leq t$ , $max = 30 \text{ mm}$ , weld up gap	For $JWPS < G \leq 25 \text{ mm}$ , weld up gap; For $G > 25 \text{ mm}$ , partial renew
Butt weld insert plate size	Limit: $w \geq 300 \text{ mm}$	Limit: $w \geq 300 \text{ mm}$	Limit: $w \geq 300 \text{ mm}$	not specified	Limit: $w \geq 100 \text{ mm}$ or $10t$
Fillet weld	Standard: $G \leq 2 \text{ mm}$ , Limit: $G \leq 3 \text{ mm}$	Standard: $G \leq 2 \text{ mm}$ , Limit: $G \leq 3 \text{ mm}$	Limit: $G \leq 2 \text{ mm}$	Class. level B: Limit weld throat: $G \leq 0.5 \text{ mm} + 0.1x$ , $max = 2 \text{ mm}$ ; Class. level C: Limit weld throat: $G \leq 0.5 \text{ mm} + 0.2x$ , $max = 3 \text{ mm}$ ; Class. level D: Limit weld throat: $G \leq 0.5 \text{ mm} + 0.3x$ , $max = 4 \text{ mm}$	Limit: $G \leq 3 \text{ mm}$
Fillet weld correction	For $3 \text{ mm} < G \leq 5 \text{ mm}$ , increase leg length by $(G - 2) \text{ mm}$ ; For $5 \text{ mm} < G \leq 16 \text{ mm}$ or $1.5t$ , weld up; For $G > 16 \text{ mm}$ or $1.5t$ , partial renew	For $3 \text{ mm} < G \leq 5 \text{ mm}$ , increase leg length by $(G - 2) \text{ mm}$ ; For $5 \text{ mm} < G \leq 16 \text{ mm}$ , weld up or liner treatment; For $G > 16 \text{ mm}$ , partial renew	For $2 \text{ mm} < G \leq 5 \text{ mm}$ , increase leg length by $(G - 2) \text{ mm}$ ; For $5 \text{ mm} < G \leq 16 \text{ mm}$ , weld up or liner treatment; For $16 \text{ mm} < G \leq 25 \text{ mm}$ , weld up; For $G > 25 \text{ mm}$ , partial renew	For $G \leq 5 \text{ mm}$ , increase leg length by $(G - 1) \text{ mm}$ ; For $G > 5 \text{ mm}$ , weld up or liner treatment; For $G \gg t$ , partial renew	For $3 \text{ mm} < G \leq 5 \text{ mm}$ , increase throat by $G/2$ ; For $5 \text{ mm} < G \leq 25 \text{ mm}$ (main item) or $30 \text{ mm}$ (secondary item), weld up; For $G \geq 15 \text{ mm}$ (main item) or $20 \text{ mm}$ (secondary item), partial renew
Fillet weld insert plate size	Limit: $w \geq 300 \text{ mm}$	Limit: $w \geq 300 \text{ mm}$	Limit: $w \geq 300 \text{ mm}$	Standard: $w \geq 300 \text{ mm}$ , Limit: $w \geq 150 \text{ mm}$	Limit: $w \geq 10 \text{ mm}$ , $min = 10t$

Table 4: Standards comparison – Part 3

Attribute	IACS	JSQS	CSBC	VSM	IRCN
Fairness of frames					
Shell plate	Parallel part: Standard: $2L/1000$ , Limit: $3L/1000$ ; Fore and aft part: Standard: $3L/1000$ , Limit: $4L/1000$	Parallel part: Standard: $2L/1000$ , Limit: $3L/1000$ ; Fore and aft part: Standard: $3L/1000$ , Limit: $4L/1000$	Parallel part: Limit: $3L/1000$ ; Fore and aft part: Limit: $4L/1000$	Limit: $0.2\sqrt{L}$	Not specified
Deck plate	Standard: $3L/1000$ , Limit: $4L/1000$	Standard: $3L/1000$ , Limit: $4L/1000$	Limit: $4L/1000$	Limit: $0.2\sqrt{L}$	Not specified
Inner bottom	Standard: $3L/1000$ , Limit: $4L/1000$	Standard: $3L/1000$ , Limit: $4L/1000$	Limit: $4L/1000$	Limit: $0.2\sqrt{L} + 3$	Not specified
Bulkhead	Limit: $5L/1000$	Standard: $4L/1000$ , Limit: $5L/1000$	Limit: $5L/1000$	Limit: $0.2\sqrt{L} + 3$	Not specified
Accommodation	Standard: $5L/1000$ , Limit: $6L/1000$	Deck: Standard: $3L/1000$ , Limit: $4L/1000$ ; Outside wall: Standard: $2L/1000$ , Limit: $3L/1000$	Not specified	Limit: $0.2\sqrt{L}$	Not specified
Others	Standard: $5L/1000$ , Limit: $6L/1000$	Standard: $5L/1000$ , Limit: $6L/1000$	Limit: $6L/1000$	Limit: $0.2\sqrt{L} + 3$	Not specified
Accuracy of dimensions					
Deviation of rudder from shaft C.L	Standard: $4\text{ mm}$ ; Limit: $8\text{ mm}$	Standard: $4\text{ mm}$ ; Limit: $8\text{ mm}$	Limit: $8\text{ mm}$	Not specified	Not specified

### 5.1.3 Deviation of Rudder from Shaft Centreline

IACS, JSQS and CSBC require 8 mm deviation at maximum. But it seems that even if this maximum deviation is exceeded, no functions are deteriorated, and that it comes from rather actual as-built records. Actually, according to the technical background of JSQS (JASNAOE, 2010), this 8 mm limit was derived according to the histogram of as-built records of 48 ships. Considering that the original JSQS was published in 1964, the ships surveyed to determine this requirement might be built before 1960's. Ship's size and rudder types are totally different nowadays and the validity of this requirement is questionable. The background of the same requirement of IACS Rec.47 is not known. This kind of requirements causes confusion among surveyors and shipyards. Such requirements should be reconsidered, and may be better to be left to each shipyard's practice.

### 5.2 Effect on Structural Performances

Pretheesh *et al.* (2010) studied the effect of distortion on the buckling strength of stiffened panels through a parametric non-linear finite element analysis under an axial loading condition, and proposed a new strength parameter to represent buckling strength which takes into account the inelastic post-buckling behaviour of the structure.

## 6 LINKING DESIGN AND PRODUCTION IN COMPUTER APPLICATIONS FOR INCREASED EFFICIENCY

Throughout the engineering disciplines, many "Design for X" processes have been developed in order to correct the inadequacies of the designs during the ship design stages. DFX is the process of pro-actively designing products to optimise all the functions throughout the life of the product. This has been called "Design for X" where X is whatever the specific focus happens to be. So "Design for X paradigm" covers many areas such as Design for Production, Design for Manufacturing, Design for Assembly, Design to Cost, Design for Simplicity, Design for Maintenance, Design for environment, Design for Safety, Design for Life Cycle Cost, Design for Robustness, Design for Six Sigma, etc., Olcer *et al.* (2004); Papanikolaou *et al.* (2009).

The future challenge will be the multi objective optimisation of the ship and offshore structures (lean manufacturing, costs, safety, environment, etc.) to obtain a good synergy at a given time (see the report of the design method committee). Rapidly changing parameters such as the steel market prices make this optimisation in total time-frame design-build ship difficult.

### 6.1 Design for Production and Design for Manufacturing (DFP)

For most ships, productibility has become a major design attribute. If a ship cannot be manufactured or assembled efficiently, it is not properly designed. Any adjustment required after the design stage will result in a penalty of extra time or cost. Deficiencies in the design of a ship will influence the succeeding stages of production Larkins (2010); Olcer *et al.* (2004); Ou-Yang and Lin (1997); Papanikolaou *et al.* (2009); Storch *et al.* (2000); Bruce *et al.* (2006). There are two main principles for DFP for ships, namely:

1. all designs should drive for simplicity, and
2. all designs should be the most suitable given the shipyard facilities.

DFP in the context of shipbuilding can be understood as the following collection of principles and recommendations Larkins (2010); Caprace and Rigo (2010); Fanguy *et al.* (2008); Miroyannis (2006); Rodriguez Toro *et al.* (2004):

- Apply the ease of manufacturing: Designing for easy construction of parts, material processing and product assembly is a primary design consideration. Particularly if labour costs are a big percentage of the cost, problems in fabrication, processing and assembly can generate enormous costs, cause production delays, and demand the time of precious resources.
  - Avoid using thin plate to avoid distortions, reworking and straightening
  - Do not plan hull curvature into the structure (hull plating)
  - Eliminate cruiser sterns and cambered transoms
  - Maximize use of flat panels, straight frames, and reduce plate curvature
  - Simplify bow and stern shape by removing unnecessary curvature
  - Run strakes in the same direction as primary framing
  - Design for maximum use of high productivity tools such as automatic welding
  - Design bilge strakes with the same thickness as bottom plates
  - Make port side and starboard unit similar (symmetry)
  - Allow for large deck space to facilitate outfitting
  - Minimize lifting and handling of parts because it is labour intensive and non-value added
  - Minimize and optimize welding because it is the largest contributor to the total cost
  - Reduce the structural complexity
- Standardise as much as possible: Standardisation, as a means of reducing complexity and component variants, actually boosts the manufacturability of the product itself. It also increases the chances of automated assembly as it presents a repeated mode of assembly.
  - Minimise the number of parts
  - Standardise the parts to minimize the number of unique parts
  - Standardise the material and scantling types
- Use modularity wherever possible: Modular design Modular design or “modularity in design” is an approach that subdivides a ship into smaller parts (modules) that can be independently created. Besides reduction in cost (due to reduced customisation and learning time) and flexibility in design, modularity offers other benefits such as the reduction of lead time during production.
  - Design to facilitate assembly and erection with structural units, machinery units, and piping units

Several computer applications and prototypes that are using these principles are listed in the following section.

## 6.2 Computer Applications

Computer Integrated Manufacturing, CIM, systems for shipbuilding support the increase of productivity during the production stage by linking the design system with the production support system, Caprace and Rigo (2010). Many advanced CIM systems used in shipbuilding incorporate advanced production support systems. Such systems lead to improvements in the quality of production planning and scheduling, consequently enabling improved production flow. The systems also enable the introduction of automated facilities/robots by electronic data of the design information, Storch *et al.* (2000). The CIM software technology takes into account:

- Computer aided design (CAD)
- Computer aided manufacturing (CAM)

- Product data management (PDM)
- Enterprise resource planning (ERP)
- Computer aided process planning (CAPP)s
- Discrete Event Simulation (DES)

#### 6.2.1 *Difficulties to Link Design and Production*

One of the major problems in the shipbuilding process today is the lack of interoperability between data systems and software applications. Ship data is complex and stored throughout multiple applications that do not automatically interface with each other. The data must then be manually integrated by gathering information from multiple sources and verifying individual results (Briggs *et al.*, 2005). Enterprise Resource Planning (ERP) systems have been developed for shipbuilding and are currently playing a major role in optimising resources in a shipyard's supply chain, value chain and information chain. These systems also link the necessary ship data to help decision makers retrieve information and make educated management decisions, Zhang and Liang (2006).

In order to overcome these issues, some authors are recently proposing solutions to improve the design and interoperability of production software.

A first example is provided by Borasch (2010). He proposed a digital method for outfitting called DigiMaus in order to link different IT-tools, design and construction applications such as CAD, ERP, project management software and visualization systems. This new tool has demonstrated a reduction of man-hours for prototypes or the first vessel in a series. One of the main functionalities is that the tool can show all outfitting components assigned to one selected production activity in only one GUI (steel, pipes, HVAC, engine, electricity, etc.). Moreover it is possible to check the current assembly state of the visualised area.

Similarly, Boesche (2010) developed a 3D-CAD catalogue to integrate 3D-Models of equipment directly into almost all used 3D-CAD Systems, in native format. Therefore shipyards are able to speed up their design for production earlier in the design process avoiding unscheduled problem during the production (interferences, bad accessibility, low maintainability, etc.).

Because many different participants and systems are involved in the very dynamic process with high modification rates, there is always a constant risk of errors being introduced in the different CIM software's. Koch (2010) recently developed a prototype to validate the engineering design and the production data based on data retrieval and rule-based analysis. This methodology has been shown to reduce the risk of costly errors often uncovered very late in the production process. Moreover, this rule based approach has the advantage of protecting customer know-how and provides a high degree of flexibility and sophistication.

#### 6.2.2 *Linking CAD/CAM to Production*

The benefits of fully adopting CAD/CAM technologies have been proven in other industries as well as at smaller levels in the shipbuilding process. Three-dimensional (3D) modelling has been proven as the next necessary step in shipbuilding. One complete model can be developed and used by all designers and additions or modifications can be completed more effectively. Using the unified model, multiple optimisations can be completed prior to production. Benefits of using CAD/CAM technologies include the following Okumoto *et al.* (2006):

- Decreasing lead time: The time period from purchase order to delivery can be reduced.
- Effective production without backtracking: Trial and error work can be eliminated and manufacturing efficiency can increase. Labour cost is 30 % to 40 % of the total ship cost, but this can be reduced with effective production methods.
- Decreasing material cost: Material cost is 50 % to 60 % of the total ship cost. Simulations can be used to effectively optimize the model and reduce material costs.
- Non-skilled production: Skilled work can be replaced by systematisation and automation using information technology.

Most simulations have just been implemented in the design stage, mainly due to the complexity and experience required for ship production. There are major benefits in using simulation and early assessment in the ship production stage, as well as throughout the design. Simulations could be used to analyse and evaluate the production process, plan and assist with production, train workers, in skills such as welding, and confirm the safety of work operations. Implementation of applying CAD to ship production has been slow in the shipbuilding industry mainly due to the large cost associated with developing the models. Capabilities of computers and the cost reduction of CAD programs have made this technology very attractive for the shipbuilding industry, Okumoto *et al.* (2006); Okumoto (2009).

An example of making the design and production stages of shipbuilding more effective is the generation of real-time production indicators for the designers. Caprace (2010) proposed a fuzzy metric to assess the producibility of the straightening process during detailed design. Straightening is the process by which the welding distortions are reduced in order to improve the structure flatness for aesthetic or service reasons. This metric has been used in CAD software to compare the relative costs of different design alternatives of stiffened deck structures.

The same authors, Caprace and Rigo (2010), have more recently proposed a real time complexity indicator for practical ship design. The aim of this application, running on a CAD/CAM software, is to provide recommendations to designers in order to improve the design quality. In this approach the complexity indicators are made up of different components such as the shape complexity, the assembly complexity and the material complexity. Each of these components is computed with data coming from the 3D CAD model. Then they are gathered in only one indicator after calibration with real production data.

### 6.2.3 Optimization of Schedule, Flow and Resources

Shipbuilding production usually is a complicated process that requires a lot of individual planning due to its one-of-a-kind nature. Traditionally the planning activity is mostly an empirical procedure, but with the introduction of computerised systems such as linear programming, concurrent engineering, the critical path method (CPM), program evaluation and review techniques (PERT), Discrete Event Simulation (DES) and ERP systems particularly the administrative aspects have been covered increasingly well in an automated or semi-automated way, Das and Tejpal (2008).

Following the full-scale use of CAD systems a trend has developed towards using simulation systems that can model the physical and dynamic behaviour of products being designed. At the same time, various approaches have been made to apply simulation techniques to production planning and factory design problems. Many of

these systems focus on the generic description of processes or, more specifically, on logistics, manufacturing processes, or material flows through factories or warehouses.

Creating a simulation model based on generic process descriptions and properties takes a considerable effort and includes a wide range of potential configurations. This is acceptable for factory design and layout simulations for example, where the cost of creating the model accounts only for a small part of the total investment and where the involvement of trained experts can be easily afforded. However, when it comes to reflecting actual shipyard configurations and processes on a day to day basis (including capturing changes over time) this effort has been found to be quite high for production planners and engineers. Few shipyards in Europe and Korea (Steinhauer, 2010, 2011; Shin *et al.*, 2009) are able to afford specialists focusing on these tasks.

However, this issue can be addressed through the use of simplified scheduling models coupled with optimisation, Biman and Navin (2008); Moyst and Das (2008); Yamato *et al.* (2009); Wang *et al.* (2009); Dong *et al.* (2009). Some of these authors are using simple PERT methodology while others are coupling linear programming with an optimisation algorithm in order to solve the scheduling problem. A similar approach has been developed by Lödding *et al.* (2010) and Koch (2011) in order to simplify the creation of the production simulation models based on a rule based decision making module. Obviously these kinds of simplified methodologies are less expensive to implement and to maintain than complex DES models. It is especially convenient for small and medium size shipyards.

Outfitting and more specifically piping seem to have a renewed interest among researchers in recent years, probably because the assembly work of the pipe unit is currently carried out by experienced, skilled workers, using complicated two dimensional drawings. Wei and Nienhuis (2009); Li *et al.* (2009) developed an automatic schedule generation with the expectation of helping to reduce the on-site coordination and installation effort and increase the level of pre-outfitting, which reduces cost and lead-time. Both of the developments have been based on the Theory of Constraints (TOC).

Another major problem for tasks related to planning is the lack of precise product information required to execute reasonably reliable production simulation runs at early project stages. Trying to forecast production of a future project at an early point in time poses a problem due to unavailable or unstable design information. Therefore Steinhauer (2010) proposed a generic model for simulation data. This data model will cover the required data for production simulation in shipbuilding and it will be usable for other companies from maritime industries or related branches. The goal is to increase efficiency at shipyards already using simulation and to help other shipyards introducing simulation technology even if the required data is not available completely.

Beside these difficulties, the DES keeps the interest of many researchers around the world. Two categories of simulations can be defined:

- The layout planning related to shipyards under planning (Greenfield) or construction and shipyards that are making retrofitting or extension of existing workshops, Shin *et al.* (2009).
- Production planning related to shipyards in operation, Reyes *et al.* (2009); Pires *et al.* (2010); Pires and da Silva (2010).

To make the most use of the simulation, coupling the overall simulation of the steel construction stages with the outfitting simulation is expected to be far more effective

in improving the planning quality as well reducing the effort required in production planning and control. In 2006 SIMoFIT (Simulation of Outfitting in Shipbuilding and Civil Engineering, [www.simofit.com](http://www.simofit.com)) was founded as an interbranch cooperation between shipbuilding and civil engineering, Steinhauer (2007). Outfitting processes in the shipbuilding and the building industry bear a high resemblance to each other. The planners have to answer the same questions: how to find a practicable schedule with sufficiently utilised equipment and employees satisfying principal guidelines. In the inter-branch team of SIMoFIT methods for outfitting simulation are further developed and used in various fields.

Both the limited space available in shipyards and the growth in the size of blocks and sections force the shipyards to optimise the block splitting and the lock erection processes. Asok and Kazuhiro (2009) and Karottu *et al.* (2009) proposed systems for block splitting optimisation based on graph theory and respectively on a fuzzy logic and genetic algorithm. Similarly, Roh and Lee (2009) developed the block division method for dividing the structure into blocks using the relationships between the structural parts. A generation method for production material information is then developed that includes calculating the weights associated with each block. Finally, a simulation method for block erection is developed.

Complementary approaches have been developed by Seo *et al.* (2007) who focused on a process planning system using case-based reasoning (CBR) and theory of constraints (TOC) for block assembly in shipbuilding. Then Cha and Roh (2010) combined discrete event and discrete time simulation framework to support the block erection process in shipbuilding.

Further steps to production simulation would be the realisation of the virtual shipyard by the use of both production simulation and virtual reality. Nedess *et al.* (2009) and Lödning *et al.* (2010) presented virtual reality models for the shipbuilding industry ensuring a focus on better processes, increases in productivity and reduction in throughput time. These prototypes further support the finding and verification of assembly sequences by providing necessary information, e.g. about the next part to assemble. Also an automatic model preparation for collision control is procured.

## 7 CONCLUSIONS AND RECOMMENDATIONS

According to the increase in ship size of container ships and LNG carriers, thicker plating and new high tensile steels are becoming more widely utilised, causing more concern about fatigue strength. With regard to the thickness effect on fatigue strength, the mechanism is not yet clearly identified, and further study is considered to be necessary to establish reasonable and reliable thickness effect correction methods applicable to actual ship structural details. New developments to improve fatigue strength such as FCA steel and UIT have demonstrated their effectiveness through published papers. Rules and regulations should incorporate these new technologies.

Most of the research in the last years on the application of composite materials relates to fire resistance and recycling and scrapping. Composite patch repair is being increasingly used in many fields of application where hot works are not acceptable. With the increase in the use of composite materials, the demand for optimised composite design is also increasing.

It is obvious that DFP is critical to achieving a globally competitive shipbuilding business but the real question is how to apply DFP. The days of simplistic applications of DFP principles, such as minimisation of unique parts, are gone due to the scale

and complexity of the modern global shipbuilding business. The correct combination of shipbuilding technology, business process improvement, ERP technology, production simulation and advanced material technology, such as virtual reality will be the delimiters for future shipyards.

After 15 years, a comparison of construction quality standards has been conducted and no significant changes were observed as a whole. However, to promote more rational and effective quality control, research activities directed towards more strength oriented standards are recommended, as well as a study to remove the current standards, which have their origin in as-built records of very old ships, and to leave these requirements to the more rational practice of each shipyard.

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