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VOLUME 2

COMMITTEE V.3

MATERIALS AND FABRICATION TECHNOLOGY

COMMITTEE MANDATE

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

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KEYWORDS

Lightweight, composites, bonding, welding, residual stress, distortions, line heating, fatigue, productivity, corrosion, discrete event simulation, virtual and augmented reality.

CONTENTS

1. INTRODUCTION

Due to the past crises, the shipbuilding and offshore industry has realised that new innovative designs and design and production methods are necessary to decrease operational costs, production costs and emissions, while meeting the changing rules and regulations. This ISSC-V.3 report is discussing recent development in materials and fabrication technology applied to ship and offshore structures.

Chapter 2 focuses on worldwide trends in materials and fabrication methods. Developments in metallic and non-metallic structural materials are dealt in Chapter 3. Advances in fabrication and joining technologies such as welding are increasing. Some main areas of applications and research in those areas are described in Chapter 4. Innovative development about corrosion protection systems are presented in Chapter 5 while Chapter 6 give an overview about the application of production simulation and virtual reality to improve the production management of ship and offshore structures.

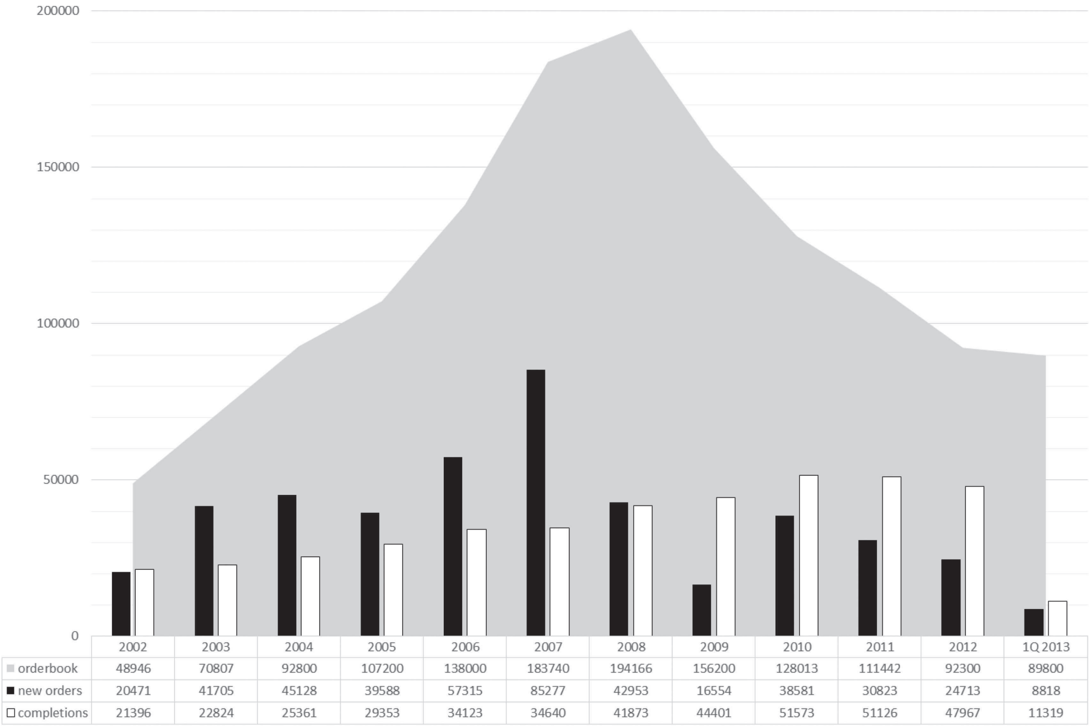
The ISSC-V.3 technical committee has performed a benchmark to define a Best Practice Guideline to use Computational Welding Mechanics tools (CWM) in shipbuilding and offshore industry. To achieve this objective various experimental welding tests have been performed in order to give a reference point. Both the residual welding distortions and residual stresses have been compared between numerical simulations and welding experiments for a common "T" welded assembly used in the shipbuilding industry. However, it has been decided to publish the results of this study in a separate document. Nevertheless, Chapter 7 of this report presents the state of the art as well as the experimental test case that has been analysed.

2. GENERAL TRENDS

2.1 *Developments in the Maritime Markets and their impact on the Trends in Fabrication and Materials Technologies*

With the exception of a decline in 2009 seaborne trade has seen a steady growth at around 4-6% per annum which is expected to last until 2016, (Hamers, 2013). In addition, the demand for passenger ships and ferries remains stable at a lower level than before the crisis. New markets related to the exploitations of the oceans (offshore oil and gas, offshore renewable energies and marine resources) develop continuously and call for new ships and marine structures.

Despite of slightly positive developments in market volumes, remaining transport over capacities have led to historically low order intake for global shipbuilding at around 16 million CGT annually, which is about 35% below the global capacity – Figure 1.



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	1Q 2013
▨ orderbook	48946	70807	92800	107200	138000	183740	194166	156200	128013	111442	92300	89800
■ new orders	20471	41705	45128	39588	57315	85277	42953	16554	38581	30823	24713	8818
☐ completions	21396	22824	25361	29353	34123	34640	41873	44401	51573	51126	47967	11319

Figure 1. World Commercial Shipbuilding Activity in Compensated Gross Tonnage (CGT). Source: SEA Europe, based on IHS Fairplay database

However, this situation does not equally affect all market segments, (Hamers, 2013). In particular, the following trends provide new market chances for the future:

- The sharp increase of bunker costs (about 3 times increase since 2008) as well as upcoming environmental legislation forces ship owners to increase energy efficiency and reduce the environmental foot print of their ships – this leads to an increased demand for new "green" ships as well as to an increased market volume for retrofitting;
- Fierce competition on the transport market requires the reduction of operational costs of ships taking the entire life cycle into consideration. This as well as the development of new market segments has increased the demand for specialized vessels with a comparatively high degree of outfitting, which accounted for 75% of the total investments made in 2012 – Figure 2;
- The two previous trends also lead to increased demolition rates, with a market volume increasing by 3.5 times since 2008. This again results in decreased average age of the tonnage scrapped.

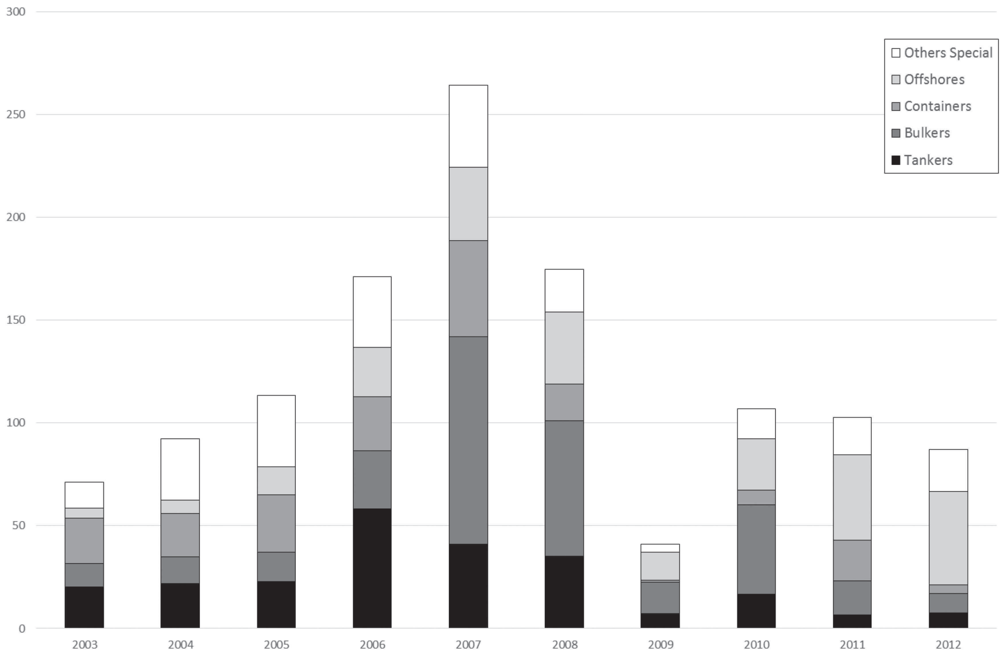


Figure 2. Global Investment in New buildings Market by Vessel Types. Source: SEA Europe, based on Clarkson database

In the frame of those global trends, the shift of shipbuilding capacities away from Europe and the US towards Asia and South America has continued during the last years. However, this does not equally apply to all market segments and a clear specialization can be observed in particular in high value added niche markets, see Figure 3.

Type of ships	China	Korea	Japan	Europe	Brasil	USA
Crude oil tanker	●●	●●	●		●	
Bulk carriers	●●	●	●●			
Product & chemical tankers	●	●●				●
LNG and LPG carriers	●	●●	●			
Container vessels	●●	●●	●			
RoRo and other cargo	●●	●●	●	●		●
Cruise, Pax and ferries			●	●●		
Mega Yachts				●●		
Offshore vessels	●●	●●		●	●●	●
Naval vessels	●			●●		●●

Figure 3. Simplified visualization of market foci in key regions of the world maritime industry, where • means moderate and "••" means important. Source: Center of Maritime Technology based on world order book end of 2013 from Clarkson

The following paragraphs discuss some specific market strategies and related research and development trends in the key maritime regions of the world. The discussion focuses on selected research areas with particular relevance to materials and fabrication and related structural reliability. Next sections intend to explain why different areas are putting the focus of their work on different subjects.

2.1.1 Korea

Korea has traditionally produced various types of ships and offshore structures, such as oil tankers, bulk carriers, cargo carriers, container ships and LNG carriers. With the increasing demand for liquefied natural gas (LNG), the construction of advanced LNG carriers and floating LNG production vessels has become an important market segment. Recently, the shipbuilding industry in Korea is accounting for some 80% of the international order backlog for LNG carriers, and is expecting a further increase of this market.

This market focus has triggered a number of research initiatives in the field of innovative steel materials and insulation materials for extremely low temperatures. Major shipyards in Korea have carried out research related to low nickel and high manganese steels to apply for the new LNG tanks, in a joint venture with POSCO and Nippon Steel & Sumitomo Metal Corporation (NSSMC).

2.1.2 Japan

The total order book (order intake) of Japanese shipyards (reported by Japan Ship Export Association) in 2013 comprised around 26.4 million GT, including primarily bulk carriers (56.9%), LNG tankers (8.1%) car carriers (4.6%) and container ship (3.4%). While this is a downward trend, as compared to the previous years, the weakening of the Japanese Yen and the anticipation of an upturn in the market resulted in a significant increase in orders during the second half of 2013, bringing the total order book (order intake) close to 13 million GT, from 9-10 million GT during the last couple of years. However, as the total annual new build capacity in Japan is approximately 16 million GT, there is still excess capacity.

In these days, over 80% of all new build contracts are for bulk carriers. However, it is considered that the future of Japanese shipbuilding does not lie in the mass production of bulkers, but in high-value tonnage and new advanced-design vessels capable of meeting environmental and fuel efficiency requirements. Many Japanese yards have recently revealed new fuel efficient and environmentally friendly designs, claiming a reduction in fuel consumption of more than 30% compared to traditional designs delivered only a few years ago.

Japanese yards are being encouraged to move into building more technically advanced and specialized offshore units. Kawasaki Heavy Industries (KHI) and Japan Marine United (JMU) have established themselves in Brazil by acquiring significant shares in yards focusing on the local Brazilian offshore market, and orders of specialized tonnage from foreign owners are increasing in Japanese yards.

2.1.3 China

According to China Association of the National Shipbuilding Industry (Cansi, 2014), China maintained the leading position in global shipbuilding in 2013, in terms of deliveries (41.4% of total GT), order intake (47.9%) and total order book (45%). After a decline in 2012, new orders have been increased in 2013, but the economic benefit of shipbuilding in China still continues to decrease. Shipbuilding enterprises face difficulties in delivery of vessel and financing. According to statistics, the whole shipbuilding industry realized profit 25.2 billion Yuan in 2013, a drop by 13.1 percent.

From January to August 2014 the hand-held orders in China increased by 34.1%. Incoming new orders continued to grow as well as the export of ships and main business income of shipbuilding. Nonetheless, the price of new ships fell under the influence of slow-down of global economy and low order shipping market. Moreover, the economic efficiency of key shipbuilding yards was on decline, and the market prospects in China remain stringent.

In response to that, measures to deal with the current shipbuilding situation were introduced. New ships will be developed along energy saving and environmental protection, and the government will give support for research and development of new ships and new ocean engineering equipment.

2.1.4 Europe

European shipbuilders have concentrated their RDI efforts to maintain and strengthen their position in high value added niche markets, such as cruise and passenger vessels, mega yachts and naval ships. Europe has a strong network of ship equipment suppliers, which are serving global markets. The close interaction between ship owners, shipyards and equipment suppliers provides the basis for the development of new customer specific ship generations and a holistic assessment of life cycle cost efficiency and environmental impact, which has become an integral part of most RDI activities. The need to increase payload to weight ratio leads to the development on lighter structures, made of traditional and innovative materials. Using the developments in material sciences, the use of smart and adaptive materials and structures to improve the ability of ships to adapt to a wide range of operational scenarios is a new trend observed during the last years. To improve cost efficiency in ship production, multi-material joining techniques as well as improved planning, resource management and logistics in outfitting along the supply chain have remained another focus of research.

Many small and medium sized European shipyards have successfully engaged in the growing market for repair, retrofit and conversion of ships, e.g. with energy saving devices. This has triggered research in reverse engineering, design for recycling and retrofit and the organization of retrofit processes.

The political decision to move towards renewable energies such as offshore wind calls for new materials and efficient processes for the pre-fabrication, erection, maintenance, repair and retrofit and for dismantling of structures and ships for offshore wind parks. First research projects related to that have been started.

Increased transport demands within European and with neighbouring regions in line with the political pressure towards environmentally friendly means of transport has started to initiate some research on innovative inland ship concepts and retrofit solutions for existing ships, although the focus of ongoing research in this sector is currently more on traffic management, energy efficient and environmentally friendly fuels and propulsion.

2.1.5 Brazil

The Brazilian shipbuilding industry is formed by three groups of shipyards, complemented by a huge number of small and sometimes improvised facilities engaged in construction of small crafts.

The first group includes a few shipyards, constructed in the 1970s, capable to build ships up to Panamax size. These companies are mainly build oceangoing ships to coastal operation (most of them ordered by the Brazilian state owned oil company – Petrobras); offshore supply vessels and some minor offshore works;

The second group corresponds to a number of yards dedicated to the offshore supply (OSV) market – green field plants or existing old fashioned facilities. Most of the OSV new buildings are ordered by private owners that have long term time charter with Petrobras;

The shipyards in the two first groups use conventional processes and show low productivity levels. The engineering content in their products and processes is relatively low. The shipyards usually subcontract both ship design and detailing drawings. There are a very small number of engineers in those companies and the engagement in research and development to introduce innovative processes and solutions is very limited.

The third group is composed by the yards engaged in offshore construction. This sector stands for a very large share of the ship and offshore construction market in Brazil in terms of value.

The five principal shipyards belong to this group are Keppel Fels Brazil, Estaleiro Atlantico Sul, Jurong, Enseada and Ecovix. All of them are owned by foreign companies or have long term cooperation with Japanese shipbuilders which are supposed to support the Brazilian shipyards through consultancy services, providing software, procedures and standards, training people and undertaking technical and managerial duties.

The order books of the main five shipyards consist of ships (tankers, FPSO, drill ships) and rigs owned by Petrobras or its subsidiaries.

The main shipyards have large production capacity and are planned to operate at a higher technological level than the usual in Brazilian industry, employing e.g. pre-erection of mega-blocks and intensive pre-outfitting. However, the four new facilities are facing some difficulties due to the lack of technological and managerial capability and scarcity of qualified workforce.

2.2 Ongoing research programmes on fabrication and materials

2.2.1 Korea

In Korea, R&D funds related to naval architecture and ocean engineering are mostly handled by the Ministry of Trade, Industry and Energy (Motie, 2014), (Keit, 2014) and the National Research Foundation (NRF), (Nrf, 2014). These institutes are responsible for planning long term strategy and to develop projects that best reflect the strategy and enable R&D to be conducted efficiently.

MOTIE has supported the following research programs associated with maritime transportation system:

- Development of materials and drilling steel pipe for shale gas production (2014 – ongoing; approximately 2.81 million US$);

- Development of core technology for a LNG ship-to-ship bunkering shuttle (2013 – ongoing; 0.7 million US$ per year);
- Development of manufacturing technique for high manganese hot-rolled steel and pipe parts for LNG storage and flow line (2013 – ongoing; 1.4 million US$ per year);
- Development of technologies for platform supply vessels under polar environments (2012 – ongoing; 0.8 million US$ annually);
- Since 2013, the development and assessment of fatigue and fracture performance of new high manganese steel is under investigation by HHI, SHI, DSME and POSCO (funded by MOTIE with 1.4 million US$).

The Global Core Research Centre for Ships and Offshore Plants (GCRC-SOP) at Pusan National University, funded by NRF, carries out research in the field of ships and offshore plants in extreme environment such as in deep sea, Polar Regions, or extremely low temperature. R&D funding of material related research by NRF has increased from 24.6 million US$ to 58.8 million US$ between 2007 and 2011.

2.2.2 Japan

The Japan Ship Technology Research Association (JSTRA) carries out two large projects subsidized by Nippon Foundation related to manufacturing technologies:

- Formation of strategic base for laser-arc hybrid welding technology in marine industry and development of innovative welding technique. In this project, a Center of Excellence (COE) of laser-arc hybrid welding was established in Kyusyu University. New welding techniques such as one-side full penetration welding are studied.
- Development of monitoring system for advanced construction management. Integration methods of monitoring data to generate virtual job shop are being studied.

JSTRA also conducts “Application of powered exoskeleton for shipbuilding work” and “Development of alternative anticorrosion techniques for PSPC/WBT coating system”. In the later project, inorganic zinc-rich coating system and corrosion resistant steel for WBT are studied by ClassNK.

2.2.3 China

The National Natural Science Foundation (Nsfc, 2014) will support some research programmes for ship and ocean engineering in China. Some recent projects focus on the following topics:

- Prediction and control of wrinkling of rolling sectional material of ship under forming
- Approach for multi-axial fatigue life assessment of welded structures based on critical plane theory
- Design research of pre-deformation of composite propeller
- Method and mechanism to welding deformation and crack resistance of marine thick plate with adaptive control of laser shock under welding process
- Research of accumulative damage and total life coupling fatigue and corrosion
- Interaction between fatigue crack growth and redistribution of welding residual stress of FPSO structure.

2.2.4 Europe

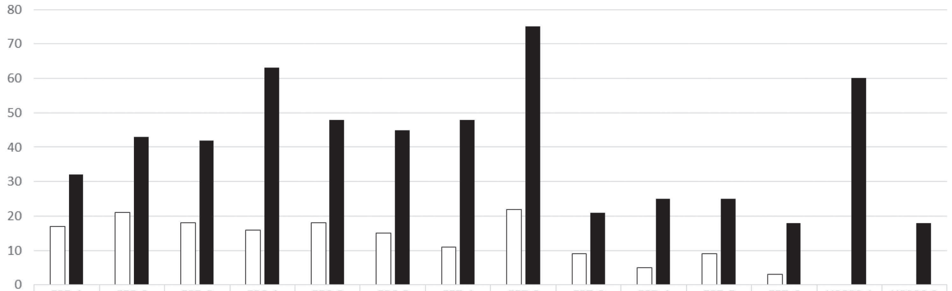
The main source of R&D funding, at European level, are the Research and Development Framework Programmes (FP) of the European Commission. Research projects related to ship production and materials have been primarily funded under the Priority Sustainable Surface Transport since 1998 with more widespread options to cover maritime aspects jointly with other sectors in the areas of key enabling technologies, such as ICT or materials.

The new European research and innovation funding scheme HORIZON 2020 has started in 2013 and will last for seven years. In addition to research projects, the framework includes instruments which foster innovation at higher Technology Readiness Levels (TRL) and specific funding instruments for small and medium enterprises, aiming to promote the market uptake of research result. While global challenges, like climate change and emission reduction have been dominating strategic goals in the previous programme, HORIZON 2020 clearly adds industrial competitiveness as a strategic goal of European research policy.

Since FP7 (2010) research topics related to offshore operations have been partly funded under a joint initiative The Oceans of Tomorrow. The funding available is increasing in this initiative and the follow-up priority Blue Growth, but most of the budget is used for marine sciences rather than maritime technologies.

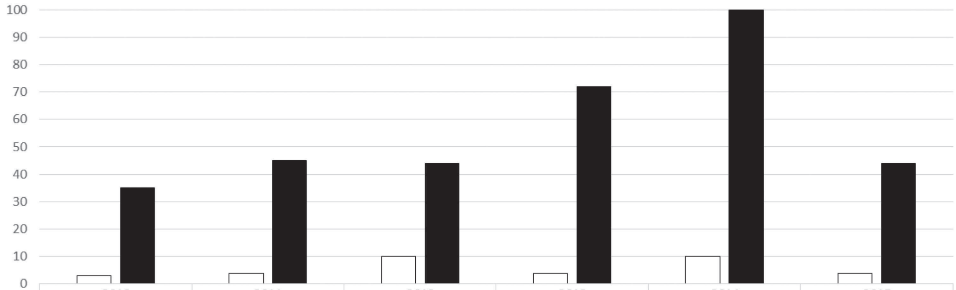
Studies financed through the EU framework programmes Marpos (2011) and Mesa (2013) have analysed the topics of research co-financed by the FPs as well as the amount of funding for maritime research, see Figure 4.

Estimates have shown that this corresponds to about 900 researchers financed annually. This comes in addition to national R&D programmes, which can be either generic or specifically dedicated to maritime technologies and reach the same order of magnitude as European funding in some member states, (Martec, 2014).



	FP5-1	FP5-2	FP5-3	FP6-1	FP6-2	FP6-3	FP7-1	FP7-2	FP7-3	FP7-4	FP7-5	FP7-6	H2020-1	H2020-2
☐ Number of projects	17	21	18	16	18	15	11	22	9	5	9	3		
■ Funding in million of Euros	32	43	42	63	48	45	48	75	21	25	25	18	60	18

(a) – Number of projects and funding from FP5 to H2020 regarding EU research “transport” topic



	2010	2011	2012	2013	2014	2015
☐ Number of topics	3	4	10	4	10	4
■ Funding in million of Euros	35	45	44	72	100	44

(b) – Number of topics and funding for “Oceans of Tomorrow” (FP7) and “Blue Growth” (H2020)

Figure 4. Research Funding under European Framework Programmes for Maritime Research

Parts of the national research funds are used for trans-national projects among a limited number of participants. Considering additional regional development funds for R&D infrastructure and networks across industry sectors and private investments, the strong involvement of the European maritime industry in research and development becomes evident, although this engagement is not equally spread across companies, sectors or regions.

All in all, long term strategic research and development without any doubt has produced significant results in the field of production technologies and materials in the maritime sector, the introduction of low distortion laser welding, sophisticated planning and logistics for highly complex outfitting intensive ships or the application of advanced design methods being only some example for that.

More importantly perhaps is the intense R&D network between European companies, research centres and academia which has developed during the projects but stretches far beyond research into rule making and commercial activities. This network increasingly also involves smaller and medium sized companies and less developed regions of the European Union and is probably unique in the world at least in the maritime industry.

2.2.5 Brazil

The Brazilian shipbuilding industry has never had much R&D involvement and at present seems to rely on technology transfer from abroad. However, some research institutions in Brazil have recognized expertise in the field of naval architecture and ocean engineering:

- The Graduate School of Engineering of Rio de Janeiro Federal University – COPPE/UFRJ,
- Polytechnic School of São Paulo University, Institute for Technological Research – IPT,
- Petrobras Research Centre – CENPES.

There are also some other universities developing research activities in related fields. On the other hand, a recent project, initiated by a group of scientific, professional and entrepreneurial associations, aims at creating a research institution dedicated to shipbuilding technologies. The creation of this institute was not accomplished until now, but has sound prospects of being created in the short term.

The main research programmes on Materials and Fabrication of Ships and Offshore Structures are developed at COPPE/UFRJ, and have been funded by Petrobras and Ministry of Science and Technology (Shipbuilding and Water Transportation Research Fund):

- Shipbuilding Processes Simulation and Optimization and
- Distortion and Residual Stress Evaluation in Ship Construction

The main source of R&D funds related to shipbuilding in Brazil is the Shipbuilding and Water Transportation Research Fund, managed by the Ministry of Science and Technology. This Fund has invested a significant amount of money in R&D projects proposed by research institutions, in the last decade. Nevertheless, due to the lack of engagement of the shipbuilding or engineering companies, there is no relevant log of projects on the field of materials and fabrication of ships and offshore structures.

2.2.6 USA

Research & Development expenditures in US are the highest per capita in the world, but represents only 2.8% of the GDP. Majority of the support comes from the industry at 308 billion US$ while the federal government provides approx. $ 36 billion. The industrial support translates to an average of 3.5% of revenues, (Battelle, 2014).

Sectors to receive particular attention are technology platforms like robotics, high-performance computing, social media, software, cost-effective energy sources and nano-biotechnology.

US expects to spend approx. 12.5 billion US$ on aerospace, defence and security sectors, while the energy sector will receive 7.3 billion US$ – a significant part of this funding is related to materials engineering. R&D on chemistry and advanced materials will be supported at 12.2 billion US$.

In relation to the maritime sector, the American Bureau of Shipping (ABS) and the National Science Foundation (NSF) fund fundamental research in several areas that involve materials and fabrication technologies pertaining to ship structures. The prominent research programs are being conducted through two main programs at NSF:

- Materials Processing & Manufacturing
  - Deformation Mechanics and Microstructure Evolution during Micro Forming of Metals;
  - Towards Room Temperature Formability in Magnesium Alloys;
  - Damage Tolerant 3D Periodic Interpenetrating Phase Composites with Enhanced Mechanical Performance - Design, Fabrication, Analysis and Testing;
  - Structure-Property-Processing Correlations in Ice template Materials;
  - Fundamentals of Bonding in Kinetic Consolidation Processes;
  - Fundamental Studies on Ultrasonic Vibration Assisted Laser Surface Modification;
  - Friction Stir Process for Joining Dissimilar Metals;
  - Enhance the Formability of Advanced Steels and Aluminium Alloys;
  - Characterization, Design and Modelling of Shape Memory Composites;
  - Mechanical Behaviour, Quasi-Static and Dynamic Crushing of Cellular Materials;
  - High Fidelity Numerical Investigations of Tailored Magnetic Fields for Defect Reduction in Continuous Casting of Steel;
  - Novel Manufacturing of Bio-inspired Metal Matrix Composites by Semisolid Forming-Joining.
- Structural Materials & Mechanics
  - Design and Development of Fire-Resistant Ferritic Steels for Structural Applications;
  - Enhancing the Life Cycle of Plastic Pipes Through Nano-reinforcement;
  - Ultra-High Performance Fibre Reinforced Concrete Structures;
  - Advanced Interpenetrating Networks for Structural Applications.

In addition, ABS has established many research programs for marine and offshore structures in collaboration with several international groups.

3. STRUCTURAL MATERIALS

3.1 Metallic materials

The lightweight metals in shipbuilding industry, such as aluminium allows and titanium, have been traditional used for hull constructions of high speed vessel, superstructures and outfitting. Due to increase demand for evaluation of total life cycle costs of the ship, compare to just acquisition costs, the new opportunity for increased usage of lightweight metals have been investigated. Low temperature applications, such as LNG storage, were already studied in the 70s, however recently attention focused into fatigue behaviour and fracture toughness at low temperatures as well as the use of new materials.

3.1.1 Aluminium alloys

The review of the benefits and cost impact of aluminium alloys for naval ship structure is given in Lamb et al. (2011). The traditionally excepted operational and performance advantages/disadvantages of aluminium are given in Table 1:

Table 1. Operational and performance advantages/disadvantage of aluminium (Lamb et al., 2011)

Advantages	Disadvantages
High strength- to-weight ratio	Higher raw material cost versus steel
Density one-third that of steel	Lower stiffness (one-third that of steel)
Excellent corrosion resistance in marine environments	Lower melting temperature than steel requiring additional insulation for fire protection
Weldability	Less industry experience with aluminium
Ease of forming, bending, and machining	Shortage of trained aluminium welders
Availability and diversity of functional semi-finished products	Smaller number of shipyards that have facilities for production with aluminium
Similarity of structural details and building approaches	Limited number of shipyards with facilities and experience to repair aluminium ships.
High recycling value	
Environmental compatibility	
Nonmagnetic	

The paper by Lamb et al. (2011) presents a comparative analysis of the acquisition cost of aluminium and steel ship equivalent designs. The life-cycle cost advantage of aluminium ships are presented, as well as advances in aluminium materials, design approaches, and manufacturing methods that are improving the cost and reliability of these ships. This paper illustrates that even though the cost of the equivalent aluminium ship structure is 40% more than the steel structure, the equivalent aluminium naval ship can be built within just 7.5% of the acquisition price of the steel ship. This is possible because of the cascading benefits of the aluminium ship’s significantly lighter weight. Advances in aluminium technology (material and fabrication) and new facilities in the shipyards for aluminium production are further improving the acquisition cost of aluminium ship. From a total life cycle cost perspective, aluminium ships enjoy a clear advantage over steel ships. Based on the findings presented in the paper, it is suggested that the US Navy should consider broadening its use of aluminium ships. As also stated in the paper, the materials section, close and constant collaboration between material supplier and customer is essential to materials and systems breakthroughs. By understanding the Navy’s and industries’ design and system performance requirements, the next generation of marine alloys and advanced aluminium designs can be developed.

As maritime industry increased their use and constructions of high speed vessel made of aluminium a practical reference of key design consideration is needed for rational design of those vessels. The (SSC-464, 2012) project ”Design and Detailing for High Speed Aluminium Vessels Design Guide and Training” provides a good overview of aluminium alloys and manufacturing and construction techniques that should be considered during the vessel design and construction processes. Specifically the guide describes the wrought and cast alloy and temper designation systems; the rolling, casting, extruding, and machining processes, riveting, bolting, welding and adhesives as joining techniques; general and high speed loading; the ultimate strength; and fatigue, fracture, fire and corrosion as specific considerations for aluminium vessels. Guidelines as these enable the extended use of aluminium in the maritime sector.

3.1.2 Titanium

As stated in the past ISSC-V.3 reports (2003, 2006, 2009) titanium is the best engineering material for marine environment, but its application is still limited mainly to pumps, piping and sea-water-cooled heat exchangers and other specific parts mainly in Navy vessels. Mountford Jr. and Scaturro (2010) estimated that 3000 to 4000 tons of titanium tubing and pipe are being used on offshore oil platforms in fire-main, service water, and other systems solving seawater corrosion and erosion problems. Structural application of titanium is still limited to specific structural parts in navy vessel (masts, radar structure, cargo, compartment and emergency doors, torpedo bay doors, vertical launch systems, etc.). They presented main attributes, benefits, use and application of titanium in the marine market. All of the explained attributes and benefits suggest strong reasons for evaluating the design and greater use of titanium in systems for eliminating problems associated with seawater and marine environments, to improve efficiencies, to increase payloads and survivability, to reduce weight, maintenance, labour, and fuel consumption, and to improve survivability and finally to decrease life-cycle costs. Dong et al. (2013b) investigated titanium and its alloys as ship hull materials for reducing life-cycle cost in high-speed sea transportation. Besides the increased interest for its application significant challenges remain in structural design and production. This is in large part due to the fact that titanium and its alloys represent a drastic change in material behaviour from traditional ship hull materials such as steel or even aluminium alloys. On one hand, their high strength to weight ratio can offer a significant weight reduction in hull design. On the other, some of the today's ship design rules, such as proportionality requirements for structural forms, prevent structural designers from taking a full advantage of this class of new ship hull materials. Additionally, a better understanding of some of the material characteristics and their impact on manufacturability in ship construction becomes important in order to devise effective build strategies from piece part fabrication to structural assembly. In this paper, some of the design and production challenges are highlighted based on a comprehensive investigation into the manufacturability and structural performance of a titanium mid-ship section. A math-based approach using advanced computational structural modelling and process simulation is described for addressing some of these challenges. Solutions for mitigating some of the design and construction concerns uniquely associated with titanium ship hull have been presented along with experimental validation results ranging from process development to fabrication trials on a series of selected component examples. These examples include a quantitative evaluation of weld sizing requirements for achieving static and fatigue strength requirements and panel welding distortion control. Finally, implications of author’s findings on building titanium ship hulls in today's shipyard environment and future areas of research and development have been discussed. It is advocated that welding-fabricated structural forms can now be viewed as a viable alternative to expensive extrusions which have been shown to be cost-prohibitive for ship hull applications.

3.1.3 Metal foam

Metal foam cores in metal sandwiches provide a light alternative to solid steel. It minimizes weight, while maximizing stiffness. Next to that also the damping and energy dissipation increases. Smith et al (Smith 2012) provide a good overview of the state of the art of steel foam materials. Although the paper focuses on applications in civil engineering, several applications are named that can also be beneficial to the maritime industry, e.g. the use of metal foams for crash applications or in floor and wall systems. The paper provides an overview of manufacturing techniques including pros and cons. The mechanical properties of the material are lower than of normal steel of course, with e.g. young modulus, depending on the manufacturing technique about 1/1000th to 1/20th of standard steel. Some of the materials do have a compressive strength that is in the same order of magnitude of solid steel. Standards are being developed, e.g. Japanese and ISO for the testing of these materials. The article concludes with an overview of analyses models. Jasion et al. (2012) and Szyniszewski et al. (2012) both provide analytical formulation for the determination of the buckling strength of these types of materials. Jasion focuses on the critical loads in beams and circular plates with aluminium facings and aluminium foam core. Due to the use of metal foam, shear effects in the core cannot be disregarded. When including these shear loads in the analytical model, Jasion finds analytical results that are within 6% of the finite element analyses and experiments. Szyniszewski provides a design method for the in plane compressive strength of steel sandwich panels with steel facings and a steel foam core. The formulation show that foaming the middle 30% of a solid steel plate leads to optimal strength gains for slender plates, which can be in excess of 200% of the strength of a solid steel sheet with the same mass (Figure 5).

Different aluminium sandwich structures have been further developed and evaluated in Crupi et al., (2013). The aim of this paper was the comparison of static and low-velocity impact response of two aluminium sandwich typologies: foam and honeycomb sandwiches. Quasi-static indentation tests showed

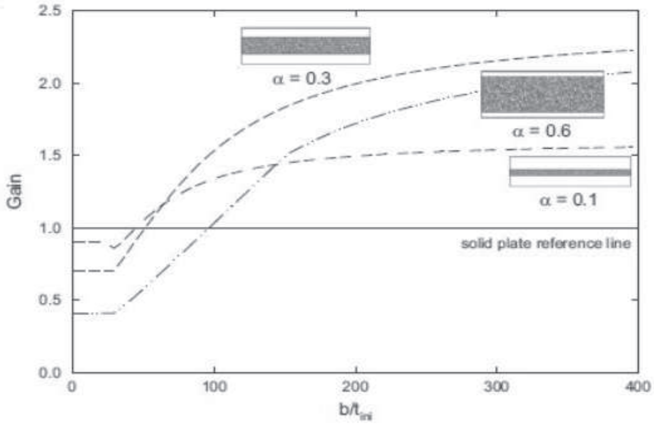


Figure 5. Strength normalised to solid plate of the same weight as function of the initial width to thickness ratio

that the indentation resistance depends on the nose geometry and is strongly influenced by the cell diameter and by the skin – core adhesion for the honeycomb and aluminium foam sandwich panels, respectively. The static bending tests, performed at different support span distances on sandwich panels with the same nominal size, produced two different collapse modes (mode I more bending like and mode II a more shear like failure mode) and simplified theoretical models, using plastic hinge representations, were applied to explain the observed collapse modes (Figure 6). The results with these theoretical models were in good agreement with the experiments. The capacity of energy dissipation under bending loading is affected by the collapse mechanism and also by the face-core bonding and the cell size for aluminium foam sandwiches (AFS) and honeycomb panels, respectively. A series of low-velocity impact tests showed that the aluminium honeycomb sandwiches fail due to the buckling of the cells and is strongly influenced by the cell size, whereas the aluminium foam sandwiches collapsed for the foam crushing and their energy absorbing capacity depends by the foam quality. The experiments clearly show that aluminium sandwiches are lightweight and can provide good energy dissipation properties. From the literature studied it can be concluded that metal foamed materials could be considered as a lightweight alternative for solid metal parts.

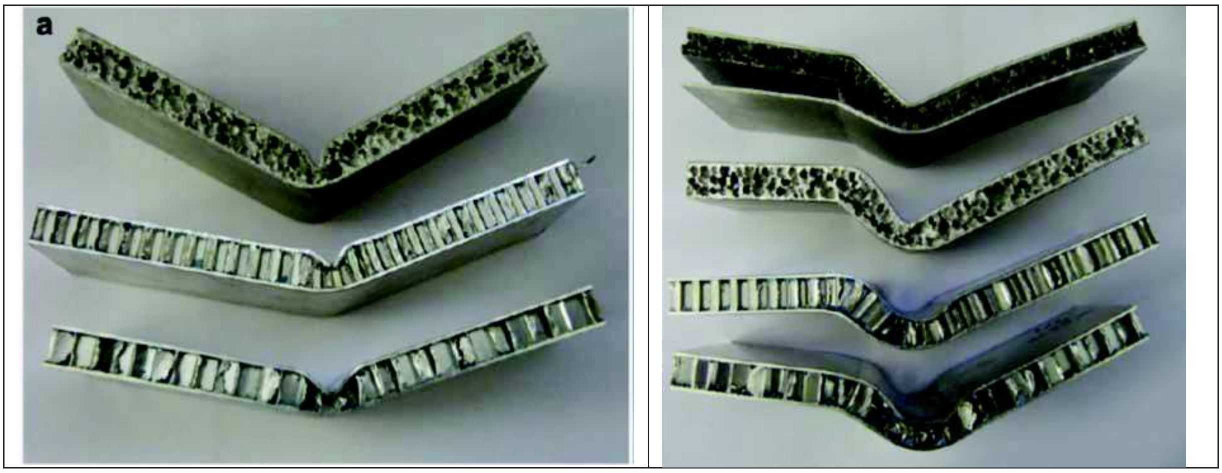


Figure 6. Collapse modes of investigated honeycomb and aluminium foam sandwiches obtained by static bending tests (Crupi et al., 2013)

3.1.4 Application of metals in low temperatures

Recently, the demand for liquefied natural gas (LNG) continues to increase due to the rise of environmental issues and the significant increase in crude oil price. In addition, the strict air emissions legislation by International Maritime Organization (IMO) and other local air quality controls led to the attention of vessel owners toward the use of LNG as a fuel. These events have resulted in increasing construction of LNG storage tanks such as LNGC (Liquefied Natural Gas Carrier), LNG FPSO (Liquefied Natural Gas Floating Production Storage and Offloading), FLNG (Floating Liquefied Natural Gas) and LNG bunkering system. Then, the construction of vessels and storage tanks leads to an increased demand for materials with specified low temperature properties.

A number of materials are available that are engineered specifically for service at a temperature of -163°C and lower. Initial studies and measurements of low temperature material properties already date from the 70's. However, past research did not include test results of fatigue and brittle fracture resistance at cryogenic environment. The weldability and the ease of fabrication are also important factors for selecting the optimum material. In Korea, extensive studies have been performed to evaluate the fatigue performance for various welded joints and the fracture toughness in weld metal and Heat Affect Zone (HAZ) at cryogenic temperature. In particular, there have been few JIP (Joint Industry Project) to evaluate cryogenic material properties. This paragraph provides a brief overview of JIP for fatigue and fracture performance assessments of low temperature materials.

The LNG storage tanks are exposed to cryogenic temperatures as low as -163°C, and low temperature alloys are required because their cryogenic mechanical properties exhibit superior performance such as, high strength, ductility and toughness at low temperatures. In this regard, 9% nickel alloy steel, stainless steel, Invar alloy and aluminium are commonly employed for low temperature applications as they possess good weldability and toughness in addition to the benefit of relatively low cost of construction. Recently, low nickel alloy steels and high manganese steel have been developed in order to replace existing commonly used low temperature materials due to its cost effectiveness. The most common low temperature materials and the newly developed materials are as followings:

- 9% nickel alloy steel
- Stainless steel (SUS 304L, SUS 316L)
- Invar alloy
- Aluminium alloy (Al 5083)
- Low nickel alloy steels (7%, 5%, 3.5% nickel steels)
- High manganese steel

3.1.4.1 Low nickel alloy steel

One of the most common materials for LNG storage systems has been 9% nickel alloy steel over the last 50 years because it provides excellent mechanical properties at cryogenic temperatures. It has been used mainly for the inner shell of LNG storage tanks as a ferritic cryogenic material. Brittle fracture properties, which are closely related to the safety of structures, of 9% nickel alloy steel have been extensively investigated by many researches. In recent years, the increase of nickel price led to the development of low nickel alloy steels to cope with the risk of sudden increase of the 9% nickel steel price. In this respect, low nickel alloy steel has been developed for replacing 9% nickel alloy steel with the motivation of cost effectiveness. Hyundai Heavy Industry (HHI), Pusan National University (PNU) and Nippon Steel & Sumitomo Metal Corporation (NSSMC) (2009) studied material properties of 9% nickel steel for the application of IMO Type-B LNG Cargo Containment System (CCS). They performed FCGR (Fatigue Crack Growth Rate), fatigue and fracture toughness tests for 9% nickel steel. In 2006, Korea Gas Corporation (KOGAS) built the largest above-ground LNG storage tank with a gross capacity of 200,000m3 at Tongyoung and Pyeongtaek LNG receiving terminals in South Korea. The LNG storage tank was made of 9% nickel alloy steel inner tank, pre-stressed concrete outer tank, suspended ceiling deck, secondary bottom and corner protection system, and bottom heating system. Furuya et al. (2011) investigated material properties and fracture toughness of 6% nickel alloy steel. As the fracture performance evaluation including of ESSO test and the wide plate tensile test, it was demonstrated that 6% Ni steel has good characteristics regarding brittle fracture initiation and propagation in base metal plates and welded joints. In addition, ethane has the boiling point at temperature of -87°C, shipyards have a considerable interest for employing 3.5% nickel alloy steel in replace of 9% nickel steel or stainless steel in order to reduce the cost of weld materials. In this respect, HHI and PNU are planning to examine the tensile strength, fatigue and fracture performance of 3.5% nickel alloy steel.

3.1.4.2 Aluminium and stainless steel

Kim et al. (2014) performed an experimental study on the fatigue performance of cryogenic metallic materials for IMO Type-B tank. This study was supported by DSME, HHI, SHI, ABS, DNV, Lloyd and POSCO group. In particular, the project investigated tensile property, fatigue performance and fracture toughness assessment of three materials SUS 304L, 9% nickel steel and Al 5083. These materials are being considered as possible material candidates for IMO Type-B LNG carriers. In order to ensure the structural reliability of IMO Type-B tank, it is very important to evaluate the material properties at cryogenic environment. Al 5083 is considered to be the most suitable material for IMO type B LNG tank compared to SUS304 and 9% Ni steel. This is because the material characteristics of the Al 5083 at cryogenic temperatures turned out to be comparable to other materials. SUS304 is also considered to be a good choice once the potential problem of relatively lower CTOD value is overcome by suitable design.

3.1.4.3 High manganese alloy steel

Many industries are considering the use of high manganese alloy steel that can replace the commonly employed low temperature materials because of the high cost of nickel alloy. In this regard, the material properties and fatigue strength assessments of high manganese alloy steel are carried out by Lee et al. (2014b). The fatigue strength of the high manganese alloy steel at room temperature is examined and appears to be as good as other low temperature materials. However, the fatigue strength at cryogenic temperature is slightly less than that of other materials. POSCO and KAIST (2014) have developed a high manganese steel grid-pattern LNG storage tank that can dramatically increase the storage capacity of LNG tanks. This new technology employing high manganese steel can enhance the storage capacity up to 20,000 cubic meters from the existing 1,000 cubic meters. High manganese steel can be welded better than stainless steel, making it easier to manufacture storage tanks.

3.1.4.4 Invar alloy

Invar alloy (Fe-Ni 36%) possesses low thermal expansion, moderately high strength and good toughness at low temperature. These properties and good weldability are usefully employed in the many cryogenic applications. In particular, Invar alloy is widely used in the primary and secondary barriers of membrane type (No. 96 type) of LNGC. No. 96 type LNG tank is designed with two identical metal membranes forming two independent thin plates of Invar alloy in order to minimize the possibility of LNG leakage in the second barrier. Han et al. (1994) investigated fatigue strength of overlap welded joint for Invar alloy. This study performed fatigue test for Invar/Invar overlap welded joint and Invar/stainless steel overlap welded joint. Oh et al. (2014) studied fatigue performance of various Invar weld joint such as raised edge specimen and overlap welded joint specimen. In addition, this research proposed the fatigue design curve of Invar alloy based on the effective notch stress approach.

3.2 Non-metallic materials

After a long use of composites in the sporting and leisure ships and an increased application in navy vessels according to Hellbratt (2008) the time is now ready for light weight composite materials to enter the merchant shipbuilding. A study was done in which the life cycle costs of a 127 m long ferry were assessed. The ferry was designed in steel, aluminium and composite. A full life cycle cost assessment was performed to show the assets of composites. The life cycle cost analysis included the effects of weight savings of aluminium and composites, manufacturing costs, maintenance and operational costs including disposal. The analysis substantiates that although composites are more expensive in production, the life cycle costs are considerably lower than the metal alternatives. In this particular case the composite ferry became less expensive than the steel version after only 2 years of operation. A breakeven point with aluminium was reached after 10 years of operations. The authors emphasize that although most advantages will be seen in high speed vessels, also slower vessels can benefit from the use of composite materials for example via lower weight superstructures, masts etc. Selvaraju and Ilaiyavel (2011) comment on the benefits of composites due to the ability of combination of functional requirements with these types of materials. They see an increased application of composites in the navy due to among others the low weight, corrosion resistance and low signature value and noise dampening. Also in the commercial and leisure market the effect of low weight and noise and vibration damping is an important asset in the increased application.

Since composites tend to be more expensive in production it is necessary to look at life cycle costs. In the Through life project (Throughlife, 2014) several applications were considered. The results from the life cycle cost calculations show that after around 4.5 years the best performing sun deck design alternative starts to have less life cycle costs than a reference steel design. A car deck design in composite was more profitable from the beginning.

In offshore the corrosion resistance and low weight are the main reason for increased use in low pressure pipes, tanks, cable ladders, gratings and trays. Edvardsson (2013) showed in a presentation within E-lass EU project (Elass, 2014) the already existing application of FRP gratings, piping, pressure vessels etc. Some investigations are going on in the use of composites for propellers. The better fatigue characteristics and theoretically better cavitation performance combined with the possibility of directional property optimisation make composites suitable for propeller application.

Due to the increased application in the maritime sector the effect of sea water exposure on composites is an area of increased interest. Recycling remains a topic of interest as well as the assessment of composite structures and repairs using composites. The latter is studied for example in the Co-Patch EU project (Co-patch, 2010).

Next to the more conventional fibre materials such as glass and carbon an interest is seen in the use of natural fibres such as hemp, flax and bamboo. These fibres are abundantly available, from a renewable resource and bio-degradable. However, the hydrophilic nature of these fibres and the larger spreading in mechanical properties are areas to be investigated. In general fire remains an issue in non-metallic materials. Therefore fire retardant composites are of interest. The increased attention for LNG has led to an interest in the use of composites in cryogenic application.

3.2.1 Fire resistant materials

Fire issues remain an important research area for composite materials. To comply with the Solas regulations research into flame retardant materials is ongoing. Next to Solas the high speed code is the only other code that allows for the use of composite (combustible) materials via prescriptive rules. The inland waterway codes for now, as far as the authors know, do not permit the use of combustible materials. However, some work is going on in that area to adapt the HSC for this purpose. Next to that different national regulations exist. It would be beneficial to have regulations for inland and short sea shipping in Europe, to open up this market for lightweight materials.

In September 2012 the EU FP7 Nanocore project was started (Nanocore, 2011). The aim of this project is the development of a new flame retardant system for use in PVC-based polymeric foams for sandwich core materials with low fire, smoke and toxicity (FST) values and enhanced mechanical properties. This goal will be reached by insertion of nanoparticles modified with a phosphorous fire retardant. Kandola and Krishnan (2014) studied the reduction of flammability of unsaturated polyester (UP) resin by blending it with less combustible in char-forming resins such as phenol-formaldehyde, melamine-formaldehyde and furans. Fire retardant fibre reinforced composites can be made using 3 different methods. Adding an outer protective material or the application of fire retardant paints of coatings are passive protections. They have no effect on the combustibility of the fibre reinforced material. The latter can be done by chemical of physical modification of the basic resin material. Most of the systems used in the latter approach either lead to the release of toxic gases or could decrease the mechanical properties of the resin. The authors of the paper are studying several alternatives to identify the best candidates for blending with UP. Several tests have been performed on co-cures unsaturated polyester with a char forming resin, such as phenolic, melamine-formaldehyde or furan. The thermal stability of all three options was higher than that of the UP. Depending on the test chosen to quantify the different aspects of a materials fire performance, the alternatives rank in a different order. However, overall it was concluded that the phenolic resin and its blend with PU shows the highest fire safety ranking. In FP7 the project FIRE-RESIST was started. Information on this project can be found in a presentation given by Paajanen and Hakkarainen at the September 2013 kick-off meeting of e-lass (Paajanen and Hakkarainen, 2013). In the project 5 different types of fire retardant measures are assessed, e.g. multi-micro-layered structural composites, hybrid thermoset composites and particle-doped polymer fibres for fire-retarded commingled composites. In the BESST, Breakthrough in European Ship and Shipbuilding Technology) project (BESST, 2013) among others full scale flash-over fire tests were performed on the demonstrator developed in the EU DE-Light project.

3.2.2 Bio-composites

Due to the increased environmental awareness of costumers and governments and rising prices of petroleum based products, the demand for natural bio-composites increases. In 2010 the global natural fibre market share was 2.1 Billion US Dollar, growing to 3.8 Billion Dollar in 2016 according to Brief (2011). Most of its growth is seen in the automotive and construction industry. According to Lucintel, the maritime industry, specifically the leisure boat industry, is only a small part of the total composites market, although much of this market (68%) is already composite materials based. Also Cicala et al. (2010) state that most application of bio-composites was in automotive applications. According to them this was because the bio-composites were mostly in the shape of short random fibre reinforced parts that were used for non-structural applications, such as car roofs, covers and door panels. The studies that were done on long fibre structural reinforced members were mainly based on housing applications. Fernberg (2014) gave a presentation at the final Throughlife workshop in Papenburg, providing an overview on bio-based composites in which fibres, resins, mechanical properties and costs are discussed. He also concludes that application is mainly in small products although he does mention some 6 and 7 m sailing boats made from bio composites. According to Jose et al. (2012) bio-composites can be divided into 2 groups, the bio-fibres embedded in petroleum based plastics such as PE or PP and bio fibres embedded in bio-plastic (PLA). The full green composites, so natural fibres embedded in a bio-plastic, are fully degradable and sustainable. They may be used effectively in short life cycle mass production consumer goods. Lucintel further divides the natural fibres into two main groups, wood and non-wood fibres. The Figure 7 shows the subdivision made by Lucintel.

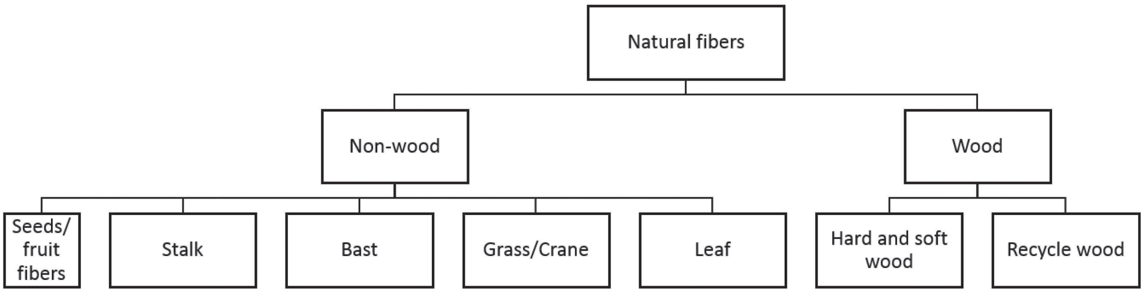


Figure 7. Subdivision of natural fibres according to (Brief, 2011)

Jose et al. (2012) discusses the main properties of several common synthetic and natural fibres. Although the density of both groups is normally in the same order of magnitude, the tensile strength and Young's modulus are normally one order or more smaller for natural fibres. This is confirmed by data given by Westman et al. (2010) and Cicala et al. (2010). Typical strength values for natural fibres such as hemp, sisal, banana, flax, etc. are in the range of 300-700 MPa, whereas glass and carbon fibres normally show values between 2000-4500 MPa. Also for the Young's modulus the same trend is seen. Typical values for glass are in the order of 80 GPa and for carbon even in the 230 GPa, while the natural fibres, according to polymer composites volume 1, shows values of 10-30 GPa. From a strength point of view, banana and sisal fibres are the best options. According to Jose et al. (2012) and Cicala et al. (2010), fibres will show an increasing strength with increasing cellulose content and decreasing spiral angle with respect to the fibre axis.

One of the main issues with respect to natural fibres is the hydrophilic nature of most of these materials. This means that the fibres will absorb water from the air leading to degradation in the fibre properties, but also to difficult and weak bonding between fibres and matrix. To limit these effects, treatment of the fibres is needed. Several processes can be used for this, such as cold plasma chemistry, oxidative and non-oxidative chemical treatment, acytilation and alkali treatment, (Jose et al., 2012), (Westman et al., 2010), (Cicala et al., 2010). The effect of chemical treatments on the natural fibres is twofold. While most chemical treatments lead to a decrease in the fibre strength due to the delignification and degradation of cellulosic chains during the treatment (Cicala et al., 2010), polymer composites shows an increase of tensile strength of a sisal/PP composites after immersion in water, see Figure 8. This is probably due to the better bonding between fibre and matrix after chemical treatment.

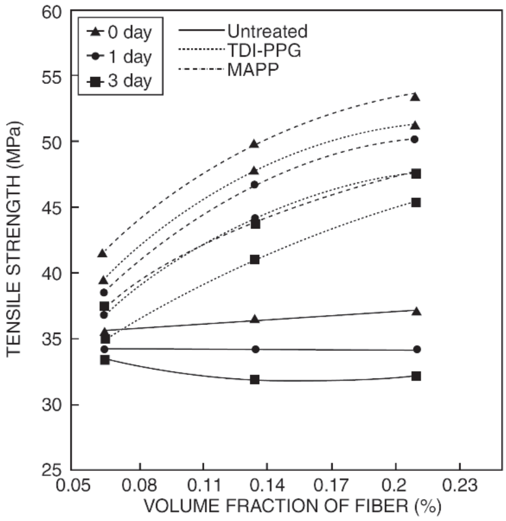


Figure 8. Effect of chemical treatment on the tensile strength of sisal/PP composites after immersion in water, Fibre loading 2s0%, temperature 20 degrees C (Jose et al., 2012)

A study on chopped Kenaf fibre mats impregnated by a vinyl ester resin was carried out by Westman et al. (2010). There was no specific treatment of the fibre mats. Specimens were tested in tensile and flexural tests and immersed in water for 24 hours to assess the water uptake. The Kenaf fibres absorbed approximately 10-12% of water, while a standard glass fibre specimen only absorbed around 0.2%. Without significant water absorption the specific strength of the Kenaf specimens was close to half of that for the glass fibre specimens both in tensile and in flexural tests. The glass specimens showed a decrease of roughly 10-15% in the tensile and flexural strength after 24 hours soaking in water, while the Kenaf specimens only had 50% (tensile) or 33% (flexural) of their specific strength left. The initial difference in specific modulus was less, but the drop in specific modulus after immersion in water of the Kenaf specimen was again considerable (50-67% for tensile and flexural tested specimens respectively). The authors expect that fibre treatment can reduce the water absorption and as such decrease the material degradation after immersion. It can be concluded that although natural fibres provide an environmentally friendly and cheap alternative to synthetic fibres. The lower mechanical properties, the larger spreading in material properties and the susceptibility of the materials to sea water will probably be restricted to small, non structural parts unless these issues are successfully countered.

3.2.3 *Influence of sea water on non-metallic materials*

The studies on the influence of sea water on composites focus on the effect of the all or single sided exposure to sea water of both static, fatigue and dynamic properties. Siriruk and Penumadu (2014) studied a carbon vinyl either composite in air, fully immersed and exposed to sea water on one side. They noticed a severe degradation of the fatigue life in exposed conditions. According to the authors the effect is due to the growth of voids between fibres and matrix due to the contact with sea water, which leads to an early fatigue failure. When fully immersed a reduction of fatigue life of 85% was seen, for one sided exposure 50% decrease was found. Poodts et al. (2013) tested glass fibre reinforced plastic also for the effect of sea water on fatigue. They compared fully immersed specimens with specimens in air. A saturation of the specimen in water was seen after 22 weeks. No clear difference was found for the submerged and dry samples in fatigue testing. Comparing the two studies it seems that the choice of materials has a large effect on the sea water degradation influence on fatigue. Also vibrational tests done by Poodts et al. (2013) showed no differences. For a static 3 point bending test a small decrease was seen in the quasi static strength in the first month of exposure, after this time the results remained constant. Korach et al. (2014) not only studied the effect of sea water exposure but also of humidity and UV radiation. For their research they exposed carbon fibre reinforced vinyl ester coupons to different conditions. The first group was tested in a test chamber subjected to certain UV, temperature and humidity conditions. In these test chambers an elevated temperature was maintained. The second group of coupons was tested in dark containers, fully submerged in fresh, sea or salt water. A final group was placed in a tidal pool, either just above the water surface, in the tidal zone or fully submerged. A three point bending test has been performed on the specimen to see the influence of the different exposure conditions over time (6 months and 1 year of exposure). The various types of exposure do not have a significant effect on the flexural modulus. However, the flexural strength does show a decrease up to 18% for both indoor immersion and outdoor exposure. It should be noted that there is little difference between immersions in fresh or salt water. The decrease in flexural strength is attributed to the degradation of the matrix fibre interface and the formation of micro-cracks on the coupon surface, which was also stated by Siriruk as the reason for the fatigue characteristics degradation on this type of material. A decrease in the energy release rate is seen in the tidal pool and indoor immersed specimens. Most degradation in this respect was seen for the coupon exposed to 25% of sea air and 75% immersed in the tidal pool. Xu et al. (2012) emphasise the need to do exposure studies only for one sided exposed specimens. Although they cannot make a clear comparison with other authors due to a difference in test conditions, they find an impact strength reduction of only 10% after 29 months of exposure of an E-glass/vinyl ester composite, whereas other authors show values of 30 up to even 70% for all-sided exposed panels. After 10 months the authors see a saturation setting in. The reducing effect of one sided exposure found by Xu et al. (2012) is in line with the results seen by Siriruk and Penumadu (2014).

3.2.4 *Recycling and disposal*

In the previous ISSC report attention was paid to the different recycling techniques and residual properties of recycled materials. Petrovic et al. (2012) looked at the tensile strength and tensile modulus of 20 mm short fibre reinforced glass epoxy material. The recycling was done using a chemical solvent to remove the epoxy. Nearly 6% of the glass fibres were also lost in this process. From the remaining recycled fibres and from new fibres similar tensile test specimens were made. The recycled samples showed a mean Young’s modulus and strength that was approximately 14% lower. This is due to the decreased bonding of fibres and matrix due to the solvents, which damage the fibre surface layer.

Before recycling is opportune, the composite vessel or structure has to be scrapped first. Hellbratt (2008) describes in his article the scrapping of a 54 m long Danish standard flex 300 patrol ships.

The scrapping took place in a floating dock in 7 days. Total costs of the operation were less than 0.1 million euro. In this example, the complete composite scrap was burned for the energetic value.

3.2.5 Application of non metallic materials at low temperatures

Due to the broad range of materials and material combinations composites are a good material for combining different functionality. As stated in section 3.1.4, industry is looking into alternative materials for low temperature applications. Fibre reinforced composites could be one of these alternatives. Yu et al. (2012) studied the effect of fibre addition to the insulation material and adhesive layers in a LNG containment system to delay or avoid crack forming. Normal insulation materials for LNG containment systems will crack when the primary containment barrier fails. This will lead to exposure of the second barrier to LNG and failure of that barrier. Within the paper an experimental and numerical study is described into the effect of adding short glass fibres in both the insulation material and the adhesive layer between the secondary containment system and the insulation material. From tests it was seen that if the adhesive layer was reinforced with a volume fraction of more than 15.4% of glass fabric, the failure strain of the second barrier, made of aluminium, was a factor 4 higher than for a non reinforced situation. This was due to the spreading of plastic deformation.

3.3 Hybrid materials

Combining metals and composites in ship design leads to an optimised solution with the potential to reduce manufacturing costs associated with complex bows and sterns, while leading to a lower weight and better non-magnetic properties. In his paper, Barsoum (2003) discusses different types of hybrid combinations of metal and composite (GFRP) and advantages both in normal operations and in naval applications are discussed. The paper gives references to some research done in the area of hybrid joints, slamming and deck buckling.

The ADAM4EVE EU project (Adam4eve, 2014) focuses on the development and assessment of applications of adaptive and smart materials (or combinations) and structures to enable ships to react more flexible to the changing operational and environmental conditions. The use of smart and intelligent materials will also offer new functionality.

In 2011 the EU FP7 project MOSAIC was started (Mosaic, 2011). The main aim of this project is to investigate if high strength low allowed steels could be used in specific structural details and to see if composites could be used as a replacement for steel in parts of the ship, such as the superstructure, transverse bulkheads etc. The main reasons for the project partners to look into these replacements are improved structural response, reduced corrosion, reduced maintenance and operational costs and weight reduction.

The US navy is building two ships with a composite superstructures and hangers, the DDG1000 and DDG1001 for weight saving reasons. However, according to the US navy possible weight savings elsewhere in the ship were possible, so the third sister ship DDG1002 will be build, for a lower price, completely in steel again (Cavas, 2013).

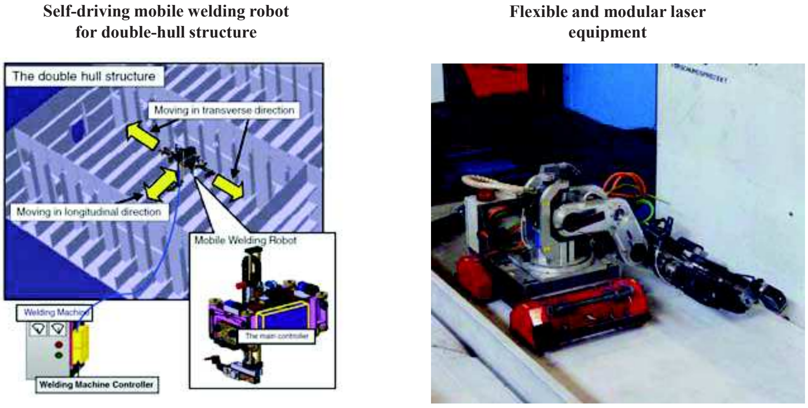
The Oshima shipbuilding Co. together with DNV has developed an open hatch bulk carrier for the future. The concept is equipped with large composite hatch covers consisting of single skin glass-reinforced plastic and a sandwich construction (Noury, 2014). All these applications show that it is a good development to combine the best of different types of materials to reach the most optimum design.

4. JOINING AND FABRICATION TECHNOLOGY

4.1 Advances in joining technology

4.1.1 Welding automation and recent developments in joining technologies

With the development of microelectronics and power electronics technologies, various advanced control methods have been successfully implemented to the arc welding systems with superior dynamic performance. This enables to enhance quality, productivity, and usability in the automatic welding system for the heavy industry field. The sampling time for the control of the automation welding system has been significantly reduced from 10 ms to 1 ms with the application of high performance microprocessor. In addition, the external interfaces of the conventional system including CC-Link, Profibus and DeviceNet have been replaced by the high speed interface method such as Ethercat. It leads the development of the automatic welding system requiring high accuracy position control of welding pool such as TIG welding process. Recently, various studies have also been performed to develop the lightweight automatic welding system with a universal robot, which can be applied to welding in narrow spaces during shipbuilding; see e.g. (Ku et al., 2010), (Sanders et al., 2012) and (BESST, 2013). Some examples are shown in Figure 9. The technologies including an intuitive user interface and high performance teaching pendent are replacing off-line teaching system, based on PC, and have accelerated the usability of the automatic welding system as well. The recent application topics in the arc welding machines have been mainly focused on the reduction of the energy consumption and the improvement of the welding quality by using high-speed inverter control technology. Unlike the conventional welding machines (SCR type and low-speed inverter type), high-speed advanced inverter technology also facilitates the light weight and compact design of the welding machine. It provides also a speed regulation up to ten times higher compared to the conventional inverter technology. A shipbuilding company has launched “Hybrid welding power source”, which changes the polarity DCEN (Direct Current Electrode Negative) to DCEP (Direct Current Electrode Positive) and vice versa by electric circuit. It means that GTAW and FCAW process together are applicable in a single power source. Furthermore, prototype Ethernet port integrated power source is on testing to monitor the welding parameters and machine error messages. In the future, the supervisor will be able to check the welding conditions in real time regardless of working sites.


Self-driving mobile welding robot for double-hull structure

Flexible and modular laser equipment

Figure 9. Examples of recently developed automated welding robots, (Ku et al., 2010) and (BESST, 2013)

4.1.2 Underwater welding

The offshore platforms and pipelines require continuous operation and, thus, reliable underwater welding on-situ. The underwater welding is applied also for ships, when ship is repaid afloat. During the last three decades, underwater welding has been developed as a solid fabrication and repair technology; see e.g. (Reynolds, 2010). At the same time, inspection has developed to ensure the quality of underwater welds. A comprehensive review of the field was provided by the international workshop on the underwater welding and inspection technology (Liu et al., 2010). Traditional arc and hyperbaric welding have been improved and new techniques such as friction processes have been further developed. Richardson et al. (2010) summarised the development in dry hyperbaric welding. In past years, the focus has been primarily on the development of remotely controlled welding for the deep water technologies. The gas metal arc and flux cored arc processes have received considerable attention over the past years, since they can produce stable welds at depths to 2.5 km without any pressure dependent process limitation. In addition, welding experiment with solid and metal cored wires has proven their robustness on a range of materials including low and high alloy steels. During last decades, the friction welding was also successfully applied for underwater environment; see (Couch, 2010), (Gibson et al., 2010), (Cui et al., 2014b) and (Cui et al., 2014a). Benefit of friction stud welding is that it is a solid phase process and, thus, the absence of a liquid weld pool avoids potential problems with hydrogen absorption. In addition, there is no change in welding parameters and weld chemistry with increased water depth. However, the process is presently limited to the welding of studs and small hot tapping fittings. Friction stir welding avoid this limitation, (Liu et al., 2011) and (Zhao et al., 2015). Fitness for service assessment and inspection of underwater welds were discussed in Dong (2010), Terán et al. (2014), Dong et al. (2012), Jia et al. (2013), Cridland (2010), Perez (2010), Goldberg and Marshall (2010), Al-Abbas (2010) and Olson et al. (2010). In fitness for service assessment, the main challenges are weld quality definition considering various defects, fracture mechanics based stress intensity solutions for complex joint configurations, the long-term load modelling and residual stress distributions that can be significantly different from air welds. Holdsworth and Reynolds (2010) provided a comprehensive review about the standards for underwater welding. During the recent years, the standards have been further developed. However, further development is required to make them better to support the variety of industries that apply underwater welding and inspection.

4.1.3 Frictions stir welding of steel

Friction stir welding (FSW) process was invented in 1991 (Thomas et al., 1991), and it is nowadays widely used for lightweight metals such as aluminium in deck structures for ships (Shah &Tosunoglu, 2012). During the last decade, a significant effort has been made on the development of cost effective and durable tools for harder alloys such as steels; see e.g. (McPherson et al., 2013) and (Cam, 2011). Until recently, the transfer of FSW capability into the steel application has been very limited due to the relatively poor performance and high cost of the tools required (Azevedo et al., 2014). This situation is changing with FSW tools that are capable of producing industrially useful lengths of welds in steel, (Miyazawa et al., 2012), (Cater, 2013) and (Toumpis et al., 2014). The lower heat input associated with FSW should produce less metallurgical change in the HAZ, smaller distortion and residual stresses in comparison to fusion welding processes, see e.g. (McPherson et al., 2013) and (Mahoney et al., 2010). Furthermore, the problems with hydrogen cracking in steels as well as welding fumes would be eliminated (Gomes et al., 2012). Most of the studies on FSW of steels reported that FSW achieves grain refinement in the stir zone of the carbon steel similar to aluminium alloys, (Cam, 2011), (Lienert et al., 2003) and (Reynolds, 2010). Additionally, complex phase transformations also occurred in the FSW process. The microstructural evolution of steels during FSW is more complicated than that of aluminium alloys due to the occurrence of transformation, recrystallization, as well as grain growth at high temperature. The effect of the carbon content and the transformation on the mechanical properties and microstructures of the FSW carbon steel joints was investigated by Mahoney et al. (2010) and Fujii et al. (2006). They concluded that the microstructures and mechanical properties of the carbon steel joints are significantly affected by the welding conditions; the strength of the steel joints increases with a decreasing heat input. Unlike the FSW of aluminium alloys, the FSW of steels may require the use of a shielding gas mainly due to protect exposed portion of the tool from oxidation; see e.g. (Shah and Tosunoglu, 2012). New FSW tools based on iridium are almost unaffected by oxidation at elevated temperatures (Miyazawa et al., 2012). This may discard the need for shielding gas in future applications.

Tool design and life are major considerations in FSW, (Thompson et al., 2013), (Meilinger & Török, 2013), (Meilinger & Török, 2013) and (Rai et al., 2011). Rai et al. (2011) presented an insight on the several important aspects of FSW tools such as tool material selection, geometry and load bearing ability, mechanisms of tool degradation and process economics. The hybrid polycrystalline cubic boron nitride (pcBN)/W-Re tool families are currently amongst the best performing systems for FSW of steels, (Cater, 2013) and (Mahoney et al., 2010). Tool life may become a critical factor, although the process cost can be influenced by other factors. The typical failure mode for the current tools is for the shoulder to wear back at the junction of the shoulder and the probe, and for the probe then to break off. By using iridium (Ir) and rhenium (Re) the recrystallization temperature and high- temperature strength can be increased. Application of an Ir-10%Re welding tool to AISI 304 stainless steel was studied in Miyazawa et al. (2012).

Mechanical properties of FWS steel joint were studied e.g. by McPherson et al. (2013) and Azevedo et al. (2014). McPherson et al. (2013) investigated a series of 4, 6 and 8 mm DH36 steel welds, which were produced using optimum welding conditions. The mechanical properties of FSW joint were compared to SAW joint typical shipbuilding production process route. Overall, the performance of the FSW material was superior to the SAW joints. Distortion and fatigue were particularly positive in the FSW joints. An 8 mm thick plate was also produced using two FSW passes, one from either side, and it was found to have superior toughness and fatigue performance compared to the single sided 8 mm FSW material. Good fatigue properties were reported also by Azevedo et al. (2014). They studied fatigue behaviour of FSW welded steel shipbuilding joints in the GL-36. The 4-mm-thick plates were welded with several different parameters, tools and pre-welding conditions. The results showed the feasibility of welding shipbuilding steel by FSW producing good quality welds. Micro-hardness results showed an increased tendency from the base material to the stirred zone and, thus, all tensile specimens broke outside the welded region, see

Figure 10. The fatigue test results showed significantly higher fatigue strength in comparison to FAT80 design curve, which is typically used for arc welded butt joints.

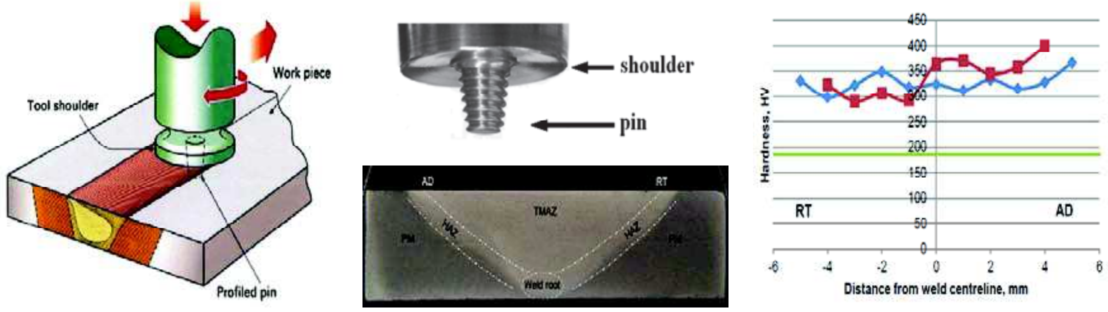


Figure 10. Examples of a FSW tool, welded steel joint and hardness distribution of weld, (Toumpis et al., 2014) and (Meilinger and Török, 2013)

4.2 Innovations in fabrication technology

4.2.1 Plate bending with line heating

Line heating has been used as a method for forming curved shell plate for more than half a century. Traditional flame heating is strongly related to the experience and know-how of a worker. During last two decades, significant effort has been made in order to automate the line heating method. Recently, the fully-automated plate bending system was implemented in practise; see Figure 11. This automated bending system ("IHIMU- α") consists of a heating plan creation program, robots to handle the heating, and plate turnover system (Tango et al., 2011). The system calculates heating plans by using the Finite Element Method and inherent strain theory. Saenz et al. (2011) studied the factors affecting inherent deformation during plate forming by line heating. They focused on the plate edge effect caused by fact that inherent deformation at plate edge does not behave similarly in the central region of the plate. Saenz *et al.* proposed two new methods for line heating to minimize the plate edge effect. Osawa et al. (2011) developed method for numerical estimation of inherent deformation induced by induction line heating. An electromagnetic-transient analysis of induction heating test was carried out and a transient conduction simulation process was proposed. The developed method was successfully validated with experiments. Since induction line heating can provide more controllable heat input in comparison to traditional flame heating, increasing interest has been shown to it during the last years; see e.g. (Lee, 2012). In addition, high-frequency induction heating can heat thick steel plates to a target temperature through the desired depth in short time. Lee (2012) studied the plate bending by multidisciplinary analyses. The new simulation program for induction heating was proposed to overcome the restriction of shape of coil, clearance between coil and plate, and consideration of the variance of parameters dependent on temperature. Lee and Hwang (2014) and Lee et al. (2013) utilized laboratory-scale high-frequency induction-based line heating to investigate the influence of heating patterns on the permanent deformation behaviour of an SS400 thick plate. They concluded that proper design of triangular heating pattern appeared to be the most important factor in determining the final shape of the thick plate. A numerical model to predict a 2-dimensional circular heat input for triangular heating was proposed in Bae et al. (2012). The parameter influencing on induction heating has been studied and discussed by Zhang et al. (2011) and Zhang et al. (2012). The prediction and evaluation of curved shapes after heating is one of the fundamental issues for automated plate bending system, (Seong et al., 2013) and (Nguyen et al., 2014). An approach to hull plate forming was developed by Seong et al. (2013). An inverse solution to three-dimensional plate forming was proposed. Bending angles and shrinkages were firstly achieved and they were converted to forming parameters through the database map, which represented the relationship between geometrical parameters and forming parameters. Experiments were performed for validation. The alternative approach for heat-path prediction was developed by Nguyen et al. (2014). They developed an artificial neural network system, where the vertical displacements and transverse shrinkage of the plate are used as inputs. The induction heating positions and parameters are the output of the models. The system utilised laminated plate theory and with Finite Element Method.

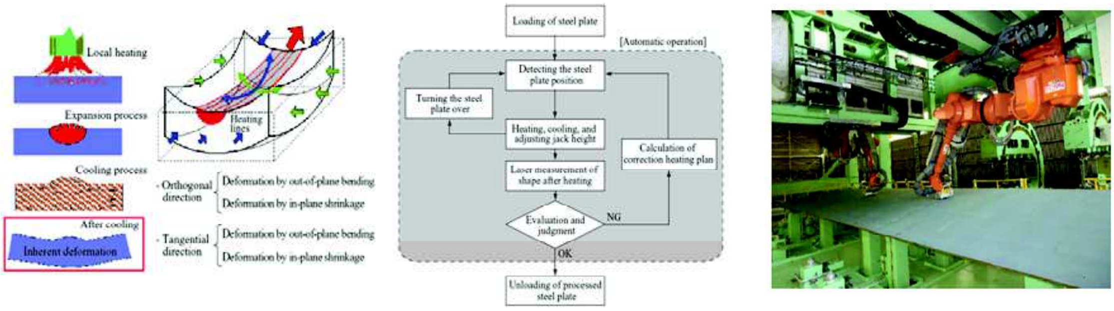


Figure 11. "IHIMU- α" automated steel plate bending system (Tango et al., 2011): deformation caused by local heating, automated process flow and robotic heating system.

4.2.2 Post-treatment of welded joints and plate edges

The utilisation of the high-strength steel materials in marine applications requires use of advanced production technology. If the traditional production technology is applied, it is assumed that the crack-like defect occurs. Then, the increased fatigue strength for high strength steel is lost due to increased notch sensitivity. Because of the higher notch sensitivity, the stress concentration factor is higher for high strength steel than that of normal strength steel (de Jesus et al., 2012). However, post-treatment of critical structural details such as welded joint or plate edge can remove surface defects and, thus, allow better utilisation of high strength steel. Remes et al. (2013) and Korhonen et al. (2013) investigated the influence of surface integrity on the fatigue strength of high-strength steel used in large marine structures e.g. the balcony openings of a cruise ship; see Figure 12. The investigation utilised large-scale specimens, which have yield strength of 355 MPa, 460 MPa, or 690 MPa. After plasma cutting, the specimens were treated by grinding or by grinding followed by sandblasting, i.e. using post-cutting treatments that are suitable for shipyard conditions. The fatigue strength was found to increase with increasing material strength for the grinded specimens. The slope of the S-N curve was influenced by both the material yield strength and the surface treatment condition. Based on the results it was concluded that a significant increase in fatigue strength can be achieved using manufacturing methods suitable for shipyard conditions. The increase in fatigue strength was determined to be due to the reduced surface roughness and compressive residual stresses. Sandblasting after grinding increases the surface roughness, but reduces the fatigue strength only slightly since sandblasting produces a favourable defect shape that has a larger notch radius when compared to grinding.

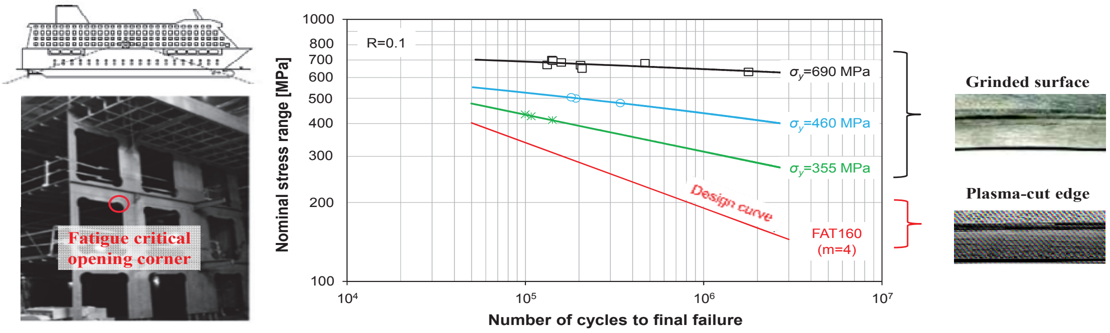
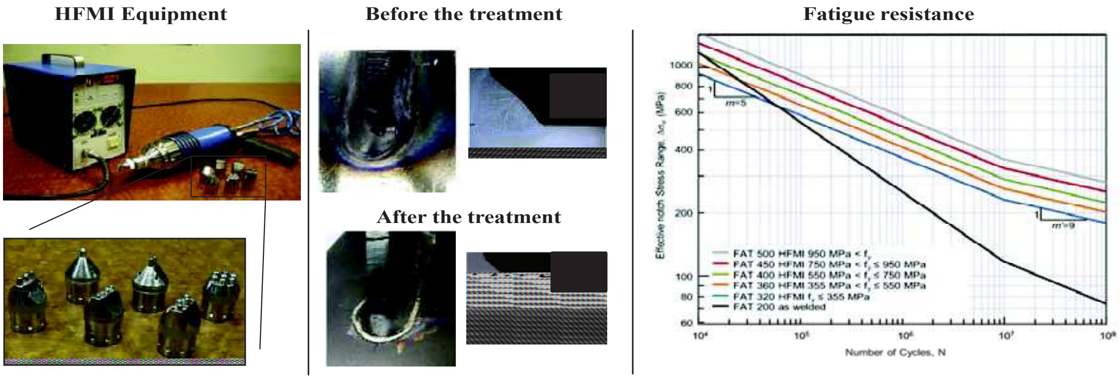


Figure 12. Influence of post-cut treatment and material yield strength on the fatigue strength. The reference design curve FAT 160 is given for comparison, (Remes et al., 2013).

Post treatment has also been known to have positive influence on fatigue strength of welded joints. However, the main challenge in their utilisation in practise has been the lack of the design recommendation. Recently, the utilization of post-weld treatment has been supported by several investigations. In particular, the high-frequency mechanical impact (HFMI) treatment is observed to be a reliable and effective method for post-weld treatment (Yildirim & Marquis, 2013). The benefits of the HFMI technique are low induced noise level and small tools, which produces a smooth rounding to weld fusion zone, compressive residual stresses and hardened surface layer at weld; see e.g. (Leitner et al., 2014), (Le Quilliec et al., 2013) and (Tai & Miki, 2014). Due to this, the fatigue crack initiation life is increased and the fatigue strength of welded joint has been significantly improved, (Leitner et al., 2014), (Tai & Miki, 2014), (Yildirim & Marquis, 2012), (Yildirim et al., 2013), (Yildirim & Marquis, 2013) and (Yildirim & Marquis, 2014). Based on the experimental and numerical investigations, design guideline is proposed for fatigue strength improvement depending on material yield strength; see Figure 13. In comparison to as-welded joint, the improvement achieved with HFMI varies between 60% and 150% depending on material yield strength (Marquis et al., 2013). The quality control issues have been investigated by Yekta et al. (2013) and the quality assurance guidelines is proposed by Marquis and Barsoum (2014). This proposal considers steel structures of plate thicknesses of 5 to 50 mm and for yield strengths ranging from 235 to 960MPa. Since the post-weld treatment is possible only for weld toe side, the advantages of the treatment can be fully realized if other potential failure modes such as weld root failure are avoided, (Marquis, 2010). The fatigue strength improvement is influenced also by preload and mean stress since the compressive stress is considered as one of the main reasons for fatigue improvement, (Marquis, 2010) and (Okawa et al., 2013). Consequently, Deguchi et al. (2012) proposed that the utilisation of HFMI treatment should be focused on the structural members for which extensive compressive load rarely occurs. To further develop guidelines for marine structures, the future research should be directed towards large-scale structures and variable amplitude loading with varying mean stress.

4.2.3 Hybrid structures and joints

Use of composite is alternative approach to improve the strength to weight ratio. Typically in marine structures, composite has been utilised for selected weight or strength critical areas or joints. Thus, these hybrid structures or joints consist of both traditional steel and composites; see e.g. (Kabchea et al., 2007). Composite has been successfully applied as repair path for corroded and damaged onshore pipelines and ship deck structures; see e.g. (Grabovac & Whittaker, 2009). To extend these repairs to offshore pipes such as risers, (Alexander & Ochoa, 2010) investigated the composite repair under tension, bending, internal and external pressure. Based on limit analysis and strain-based design, a new carbon–fibre composite repair system was introduced. The effectiveness of composites for underwater steel pipeline repairs is discussed also in Shamsuddoha et al. (2013). Composite-to-metal adhesively bonded lap joint joints were studied by Anyfantis and Tsouvalisn (2013). They concluded that the effect of the adhesive thickness and stiffness ratio is negligible compared to the effect of the overlap length to the stiffness and strength of the joints. Errouane et al. (2014) studied cracked aluminium plate and developed a numerical model for path design considering the patch height, width and thickness, as well as adhesive thickness. The results show that the stress concentration at the crack tip can be strongly reduced by using patch repairs. Fatigue behaviour of carbon fibre reinforced polymer plate was studied by Yu et al. (2013). Based on the experimental and theoretical investigations for different degrees of fatigue damage, significant fatigue life extension was observed for the strengthened cracked steel plates. Thus, the over-lamination of the welded joint provides an alternative solution to improve fatigue strength of the welded joints. Although the composite is most widely applied for repair path in marine application, the larger composite structures are coming to obtain more weight saving. For instance, Kabchea et al. (2007) studied bolted composite metal hybrid panel assembly, where deck plates were replaced by light weight solution. Furthermore, composite was recently used in superstructures of two navy ships, (Cavas, 2013). However, due to higher cost US Navy switched from composite back to steel in the next new buildings.


HFMI Equipment

Before the treatment

After the treatment

Fatigue resistance

Figure 13. An example of high frequency mechanical impact (HFMI) equipment, treated weld and the recommended fatigue resistance curves for HFMI treated welds in comparison to the curve for weld without treatment, (Yildirim and Marquis, 2014) and (Marquis et al., 2013)

4.3 *Influence of production quality on strength*

The good production quality and workmanship are the key issues for structural safety and also for successful utilisation of new materials. The latest developments on quality standards were discussed extensively in the previous ISSC Committee V3 report (Chapter 5). Thus, this report is aimed to summarise recent findings in the field of production quality and strength.

4.3.1 *Weld geometry and misalignments*

The joining and fabrication processes induce unfavourable defects, which can have significant effect on the strength of the structures. Thus, the quality of production would directly influence the strength. The most common joining technology in shipbuilding industry is welding. The variations in geometry, generated at the weld toe, create local stress concentrations. The mechanical behaviour of welded structures can be significantly affected by the effects of the employed joining process. Performing technological examinations for different materials and welding tasks is directly connected with the weld qualities and strengths produced depending on the type of joint and application, (Neubert & Kranz, 2013), (Fricke et al., 2012a) and (Fricke et al., 2012b). Different weld type and process could influence geometrical parametric of weld joint, and the stress concentration factors and fatigue lifetime could be different, (Ahmadi & Lotfollahi-Yaghin, 2012), (Pasqualini et al., 2013), (Ahmadi et al., 2013), (Fricke & Tchuindjang, 2013) and (Remes, 2013). Design of block joints in ship structures of permissible tolerances for axial and angular misalignment is particularly important for fatigue assessments. The partly large imperfections such as axial and angular misalignments were extensively recorded in order to obtain the characteristics of typical pre-deformations. For plate thickness below 5 mm, the production induced distortion increases and thus, it is recommended to extend the tolerance values in the production standards for angular distortion, (Eggert et al., 2012) and (Lillemae et al., 2012). The optimised weld processes are required to achieve low distortions and good weld profile, and thus, improvement in the fatigue strength, (Remes & Fricke, 2014). Stoschka et al. (2013) studied a relation between experimental fatigue life and the weld parameters. The experimental results showed that in case of high quality welds with negligible geometric notch factor, a small, but distinct influence of the filler metal on fatigue is observable.

4.3.2 Effect residual stress and distortions

Heating and the subsequent cooling also modify the material and mechanical properties in this specific area and introduce a residual stress field. Consequently, welded joints become critical areas regarding fatigue damage, and most fatigue cracks initiate at the weld toe. For fatigue strength of welded structure, the influence of welding residual stresses has to be considered. Pan et al. (2013) emphasizes the important role played by residual stresses in determining the failure location. For an accurate estimation of the fatigue performance of welded joints, not only the initial residual stress field but also its variation under load is decisive. The relaxation of residual stresses during fatigue loading, however, reduces this hazard to the structural health, (Baumgartner & Bruder, 2013). That is, before considering the influence of residual stresses in fatigue, the effect of fatigue on residual stresses should be understood, (Farajian, 2013). Heating and the subsequent cooling has also significant influence on material properties particularly in aluminium structures, where the material properties in the (HAZ) can be reduced even 50% in comparison to in base material strength, (Sensharma et al., 2010).

Most fabrication processes introduce distortions and affect the material properties. Shapes and magnitudes of the initial geometrical imperfections were observed to affect the ultimate load (Xu & Soares, 2012). The existence of a heat affected material showed no influence on the ultimate strength of the tested panels, (Paulo et al., 2013). Concerning the effect of the residual stresses on the collapse load of the plates, it can be concluded that this stress field leads to a decrease in the plate collapse load, when comparing with a stress free model, (Paulo et al., 2014). Gannon et al. (2012) researched the three-dimensional distribution of welding-induced residual stress and distortion, and the results showed the residual stresses reduced the ultimate strength of the stiffened plate by 11% with a consequent reduction in hull girder ultimate moment of 3.3%. Cerik and Cho (2013) investigated the effects of residual stress on the ultimate strength behaviour of stiffened cylinders, and it is shown that rather than cold bending stresses, especially yield level tension zone induced by welding has a significant effect on both strength and stiffness. The presence of residual stresses in between stringers causes considerable loss in axial stiffness of stiffened cylinders. It can be concluded that this fact should be taken into account.

4.3.3 Utilisation of high strength steel and thin plates

High strength steels has showed increasing interest in shipbuilding industry in order to reduce steel weight and increase energy efficiency. Nevertheless, the sensitivity to mechanical property degradation by hydrogen increases dramatically with strength. This phenomenon leads to hydrogen-assisted cold cracking. It was proved that this can be avoided by the established sufficient post-weld heat treatment, (Steppan et al., 2013) and (Stein & Kallage, 2008). In order to utilise high strength steel in fatigue loaded marine structures, a better surface integrity than that obtained with traditional production process is needed. The investigation shows that post-cutting treatments suitable for shipyard conditions can considerably increase the fatigue strength of high-strength steel used in opening corners of a large-scale structure. Sandblasting after grinding increases the surface roughness, but reduces the fatigue strength only slightly, (Remes et al., 2013) and (Korhonen et al., 2013). The fatigue strength improvement as a function of yield strength was observed also for post-weld treated joints in Yildirim and Marquis (2012). Furthermore, recent investigations showed that increased fatigue strength can be obtained for cut plate edges without treatment, when cutting quality is good, (Sperle, 2008) and (Laitinen et al., 2013).

New light-weight structures in shipbuilding aim at thinner plates in combination with welding processes characterized by low heat-input, i.e. laser and laser-hybrid welding. The distortions are an key issue particularly with thin plates with thickness of less than 5 mm, (Eggert et al., 2012), (Lillemae et al., 2012), (Lillemae et al., 2013) and (Fricke et al., 2013). For thin plates and slender ship structures, the secondary bending stress due to angular misalignment plays an important part and it can changes as the function of the applied tension load. Therefore, it is important to consider the plate straightening effect in structural stress analysis and fatigue strength assessment, (Lillemae et al., 2012). The lower heat-input of laser-based welding methods is able to produce joints with lower distortion, which increases fatigue strength noticeably in terms of nominal stress range, (Lillemae et al., 2012), (Fricke et al., 2013) and (Selle et al., 2013). The quality of the welds is also importance, when the fatigue strength of thin plate is considered. Thin plate structures are sensitive to welding-induced flaws such as undercut, (Remes & Fricke, 2014). However, with optimised welding parameters, these challenges can be avoided and similar fatigue strength properties can be obtained as those of thick plates, (Remes & Fricke, 2014), (Fricke et al., 2013) and (Selle et al., 2013).

4.4 Dimension and quality control

Dimension control is an important part of efficient and reliable production. Especially for thin and slender structures, the control of the production-induced deformation is one of the main challenges. Chen et al. (2011) introduced an approach for measuring weld-induced initial distortions. The approach utilises photogrammetry, which generates the displacement field from sets of digital images. The procedure was validated against direct measurements of the deflections of box girders and statistical analyses of the error between the measurements and photogrammetric evaluations were presented. Hiekata et al. (2011) developed a laser-based measuring system for the accuracy evaluation of a curved shell plate. In this system, the point cloud data of a curved shell plate was measured by a laser scanner, and the displacement errors between the measured data and design data expressed with NURBS are compared to provide feedback for quality control. The production process has significant influence on the amount of deformation. Consequently, reliable methods for prediction of deformation and shrinkage are essential for dimensional control. Effect of welding sequence on residual stress and distortion in flat-bar stiffened plates were investigated by Gannon et al. (2010). The simulation considered thermal and structural analyses using an element birth and death technique to model the addition of weld metal to the work piece. A smaller distortions and residual stresses were observed to welding sequence, where welding was started from the middle. In addition, it has been shown that distortions predicted by the finite element model agree well with experiments. Camilleri et al. (2010) studied the influence of different tack welding fabrication procedures on the deformations. The length of the tacks, number of tacks, and position of tacks with respect to the seam weld were altered, and their sensitivity was investigated. It was concluded that tacking the plate at fewer, but longer tack welds led to less deformation. Initial clamping during tack welding had also significant effect on the final distortion. Reduction of welding distortion for a hatch forming production was studied in Wang et al. (2013b). It was shown that optimised assembly process and welding sequences can reduce distortion significantly. Weld shrinkage predictions can be predicted using semi-analytical regressions models or finite element (FE) analysis. The regression model is based on experimental and simulated data (Wang et al., 2013a), while finite element simulation is done using linear-elastic or plastic analysis, (Wang et al., 2013b), (Kim et al., 2012) and (Yang et al., 2011). (Yang et al., 2013) and (Yang et al., 2014) developed a regression-based model for overall distortion prediction. The input data of model is panel design parameters including parameters such as material type, plate thickness, stiffener shape, spacing, and length, and overall panel dimensions. In addition, fabrication details such as the welding process, weld sizes, welding parameters, and the use of fixtures can be considered. Accurate prediction of distortions, however, requires the utilisation of finite element method. Wang et al. (2013a) applied elastic FE analysis based on the inherent deformation theory. The inherent deformations of different types of welded joints included were evaluated beforehand using thermal elastic plastic FE analysis. Kim et al. (2012) developed equivalent load method based on inherent strain for welding distortion analysis of hull blocks. The equivalent load was determined by integrating inherent strain components, which were calculated in HAZ using the highest temperature and the degree of restraint. Then, welding distortion was calculated by elastic analysis. Yang et al. (2011) also introduced two-step distortion modelling methods for large welded structures to reduce the computation time. To improve overall quality management in shipyard, Buksa et al. (2013) introduced quality improvement system considering all stages of the production process in a shipyard. They utilized a differentiation-based approach to quality management, and by taking targeted corrective and proactive actions into account they identified points of the manufacturing process, in which errors are likely to occur. Improvement for planning and scheduling of retrofitting for old ship were discussed by Krause et al. (2014).

5. CORROSION PROTECTION

5.1 Protection rules

Germanischer Lloyd AG, Hamburg, has established some guidelines and rules for corrosion protection in 2010, (GL, 2010). These Guidelines contain technical fundamentals on corrosion and the rules applying to corrosion protection on ships, structural parts, components and structures under maritime environmental and application conditions.

Under the condition that the corresponding boundary conditions are observed, they can also be applied to other systems, structural parts and components. These Guidelines are intended to supplement the GL Rules for Hull Structures (I-1-1), Section 35 and the GL Rules for Coating of Ballast Water Tanks (VI-10-1) and for Corrosion Protection of Crude Oil Cargo Tanks (VI-10-3) which are limited to only those aspects which are imperative from the classificatory point of view and which shall always be complied with for the construction of ships with GL Class. National or international provisions and rules are to be observed in addition.

Similarly, NORSOK has developed standards and guidelines for ship structure corrosion issues, such as Petroleum and natural gas industries - Floating offshore structures - Part 1: Monohulls, semi-submersibles and spars (ISO 19904-1:2006), Petroleum and natural gas industries -- Arctic offshore structures (ISO 19906: 2010), Common Structural Rules for Double Hull Oil Tankers with Length 150 metres and above - DNV Rules for Classification of Ships (DNV Ship Rules Part 8 Chapter 1:201207), Assessment of structural integrity for existing offshore load-bearing structures. Edition 1 (NORSOK N-006) , Design of Offshore Steel Structures, General (LRFD Method) - DNV Offshore Standards (DNV-OS-C101:201104), Concrete LNG Terminal Structures and Containment Systems - DNV Offshore Standards (DNV-OS-C503:201010), (Norsok, 2014).

5.2 Coating and paints

5.2.1 Epoxy-based coating systems

Ingle et al. (2011) examined the databases that track the corrosion/coating failure conditions in specific tanks of US Navy vessels since the late 1990's. They reported that the legacy solvent-based coating failures includes higher levels of coating loss as a function of time as compared that the ultra-high-solids (UHS) coatings. It was also shown that the 11 year UHS data did not contraindicate the US Navy's goals for a 20 year life span from seawater ballast tank coatings. Baere et al. (2013) compared the conventional construction method of ship's ballast tanks, grade A steel and protected with a standard epoxy coating backed up with sacrificial zinc anodes with some feasible alternatives. The considered alternatives are: (i) an increase of the scantlings, (ii) application of the novel and more durable TSCF25 coating (iii), the use of corrosion resistant steel or (iv) a standard PSPC15 coating combined with lifetime lasting aluminium sacrificial anodes. They concluded that the durable coating and the use of lifetime lasting aluminium anodes are bound to improve the actual basic tank concept. Corrosion resistant steel becomes attractive depending upon the evolution of the international steel market.

5.2.2 Zinc-rich paints

Shi et al. (2009) studied the corrosion behaviour of an epoxy zinc-rich paint on interface-contaminated carbon manganese-silicon steel. They found that the corrosion resistance of the contaminated paint was significantly influenced by diffusion of zinc corrosion products during the initial stage of immersion, and diffusion of iron corrosion products at the end of immersion. Three transmission line models were applied to account for the corrosion process of the uncontaminated and contaminated zinc-rich paints.

Gergely et al. (2014) developed zinc-rich hybrid paint coatings using nano-size particles composed of alumina hydrate modified with polystyrene-sulfonate (PSS) doped polypyrrole (PPy) and either purifiedor functionalised multi-walled carbon nanotubes (MWCNTs). They demonstrated the improved barrier and galvanic function of the hybrids over traditional zinc-rich paints (ZRPs) by examining performance metrics.

Hao et al. (2013) studied the inhibitive properties of epoxy coatings containing different volume fractions of zinc phosphate. They showed that zinc phosphate could improve the protection ability of epoxy coatings and its best volume fraction was 30%. They also showed that the presence of zinc phosphate can form an inhibiting film which was composed of the phosphating film of $FePO4$, $Fe2O3$, and FeO, as well as the shielding film of zinc phosphate on the steel surface.

Kowalczyk and Spychaj (2014) investigated the corrosion protection of a steel substrate using zinc-rich epoxy–alkyd paints (ZRPs) modified with ionic liquids (HMIMPF6 or BMPyrrTFSI). They found that the pyrrolidinium IL significantly reduces the corrosion rates of steel and zinc but the ZRPs with HMIMPF6 offered better cathodic protection of steel than unmodified ZRP and ZRPs with BMPyrrTFSI.

Schaefer and Miszczyk (2013) investigated the influence of nanosized particles on electrochemical action of standard zinc-rich paints by means of SEM as well as potential and impedance measurements. Samples with different concentration of nanoparticulate zinc (0%, 5%, 10% and 40%) were tested, and they found that addition of 5–10 % nanoparticulates extended the galvanic action of the coating.

5.2.3 Thermal spraying and deposition

Hausbrand et al. (2012) developed the thin silica coatings (15–60 nm) by applying a flame assisted chemical vapor deposition (CVD) process. These coatings showed good corrosion properties in cyclic humidity testing (bare) and salt spray testing (painted). It was found that the corrosion started at pin-holes and proceeded then further under galvanic coupling with the surrounding regions, and the corrosion rate was reduced by a factor 10 or more with respect to uncoated steel.

5.2.4 *Antifouling (AF) coatings*

Acevedo et al. (2013) investigated the antifouling activity of organic extracts from some epibiont-free Colombian Caribbean Sea sponges and a sea-cucumber. Extracts were incorporated into hard stable gels and into soluble matrix antifouling paints. They demonstrated that the greatest antifouling activity was contained in extracts of A. Tabulata and Holoturia Glaberrima.

Bellotti et al. (2012) explored the possible application of a natural and abundant product, such as tara tannin (TT), in the preparation of antifouling (AF) coatings. They found that the AF performance of “tara” tannin derivative was better than that of “quebracho” tannin, and the use of the fruit pods of the TT avoided the cutting down of the trees as it occurs in the case of “quebracho” trees.

Chambers et al. (2014) investigated a combination of the antifouling compound (a natural product extract) and the delivery system (control depletion polymer) by using surface engineering techniques and analysis. They examined the effect of incorporated natural product on the matrix, and potential issues in a working environment, in some form of binder on a substrate in the ocean, were discussed. Flemming et al. (1998) have evaluated a system for fouling and biofouling in marine systems.

5.2.5 *Self Healing Coatings*

Within the European project THROUGHLIFE, (Throughlife, 2014) self healing model coatings have been developed, (Scharf et al., 2013) and (Molter et al., 2014) and tested at lab scale as well as in a ballast water tank of a ferry with good success. The tests showed good effects of the embedded micro capsules on corrosion life time at about 10% higher cost compared to standard coatings, see Figure 14. Discussions to turn the research results into commercial products are ongoing as well as long term tests.

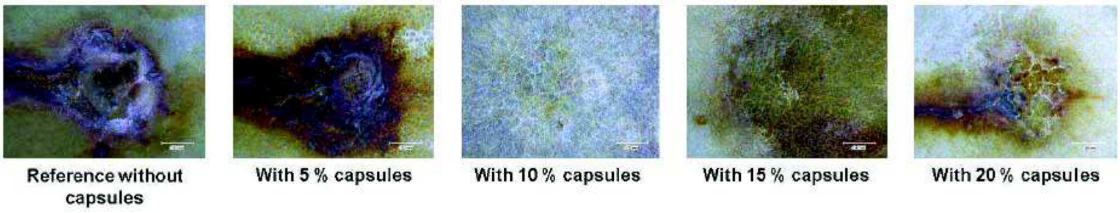

Reference without capsules
With 5 % capsules
With 10 % capsules
With 15 % capsules
With 20 % capsules

Figure 14. Damages in the model coatings caused by the Erichsen cupping after 1000 hours of salt spray test (source: Fraunhofer IFAM), (Throughlife, 2011)

5.2.6 *Intelligent Coatings*

The European project ADAM4EVE (Adam4eve, 2014) is developing and testing coatings which change their colour and reflection properties in dependence of the temperature. Those coatings can be applied to steel surfaces or windows to reduce the energy demand for air conditioning of reefer or cruise ships, (Lackieren, 2014). The project is ongoing and practical tests on board of ships are foreseen at a later stage.

5.2.7 *Ice-breaker Coatings*

Ice strengthening on the other hand is found much more commonly in ships designed for Arctic or Antarctic work. There is no actual universal definition of what needs to be done to a ship to be "officially ice strengthened" and it can be applied to all manner of ships, whether supply ships, tankers, container ships, warships etc. Commonly ice-strengthened ships can cope with continuous one year old ice about 50cm - 100cm thick. Breaking ice by any ship is not a case of forcing the ice aside, but by the ship riding up and over the ice in front of it, with the weight of the ship then breaking the ice, this may be a continuous process or can result in a lot of back-and-forth in particular thick places, (Coolantarctica, 2014).

These ships are heavy for their size, to make them more effective at breaking through ice when they are pushed up above it by their engines. Hull made from special steels designed for optimum strength at low temperatures Air bubbling systems to assist ice-breaking. Air is forced under pressure from 2m or so below the water line where ice is met, helping to break it and move it out of the way. Extra thick steel is used at the bow, the stern and at the waterline. An "ice horn" is used to protect the rudder and propeller when in reverse, and an "ice knife" in front to protect it when in forwards motion.

Rounded keels and a lack of stabilizing fins means that progress is quicker and smoother through ice and that there aren't any parts to be ripped off. A further discomfort comes from breaking through continuous thick ice with constant vibration, noise and jarring against the ice. The hard coatings used to protect the knife is described, (International, 2014).

These coatings have been used on ice breakers for many years. Such coatings require specific film properties and application conditions to achieve their unique anti ice abrasion characteristics. Class societies recognise these unique properties and give allowances to reduce steel scantling thickness if these coatings are used. The reduction of steel weight is a key driver in the design of offshore structures by engineers.

These low friction coatings are able to retain their smooth surfaces even when moving through heavy ice up to 2m. This is demonstrated by in field measurements. The very best of coatings have a track record going back 35 years.

Ice abrasion resistant coatings are now a key requirement for the hulls of polar class drill ships. The Stena DrillMAX ICE currently under construction in SHI Korea makes use of such a coating. With an upgrade to Polar Class 4 for its classification it will be able to operate in 1st year ice up to 2m thick.

Some yards are not keen to apply special ice abrasion resistant coatings as specialist equipment is needed. However, for an industry that prides itself on using the most appropriate and state of the art technology this is a poor excuse to allow yards to select inappropriate coatings. Achieving the maximum performance from ice abrasion coatings has already been reviewed, (Park et al., 2006). The review reinforces that true ice abrasion resistant coatings have very quick hard dry times and require hot twin feed airless spray application.

5.3 Cathodic protection

Surkein et al. (2009) presented a review of offshore vessel and fixed structure CP (cathodic protection) design, contrasting the effectiveness of impressed current and sacrificial anode designs for the hull. They concluded that a galvanic anode is superior to ICCP (impressed current cathodic protection) for stationary FPSs except in cases where an FPS is relatively small or has a fairly short design life.

Sun et al. (2013) studied the corrosion behaviour and working performance of Al–Zn–In–Mg–Ti sacrificial anode in simulated deep water environment. They found that the corrosion of Al–Zn–In–Mg–Ti was accelerated by the cathodic process, and the efficiency dropped dramatically in deep water, and at least 22% more Al–Zn–In–Mg–Ti anode should be required in deep water environment.

5.4 Corrosion resistant steels

This specification covers structural steel plates, shapes, bars, and rivets for use in ship construction. Materials under this specification can be categorized as ordinary strength and higher strength. Plates in all thicknesses shall be normalized or thermo-mechanical control processed while shapes and bars in all thicknesses shall be heat treated and rolled. Heat analysis of ordinary strength structural steel shall be used to determine the required chemical composition for carbon, manganese, phosphorus, sulphur, nickel, chromium, molybdenum, silicon, and copper. Same analysis shall be used to higher strength structural steel to determine the required chemical composition for carbon, manganese, phosphorus, sulphur, silicon, vanadium, aluminium, titanium, nickel, chromium, molybdenum, silicon, copper, nickel, and niobium. Materials shall conform to the required metallurgical structure which shall be evaluated by determining the average grain size. Mechanical properties such as elongation and toughness shall be evaluated using tension test and Charpy V-notch impact test.

The ASTM Spec. covers the requirements of ship steel forms as below, (ASTM-A131/A131M-14, 2014):

- 1.1 This specification covers structural steel plates, shapes, bars, and rivets intended primarily for use in ship construction.
- 1.2 Material under this specification is available in the following categories:
- 1.2.1 Ordinary Strength—Grades A, B, D, and E with a specified minimum yield point of 34 ksi [235 MPa], and
- 1.2.2 Higher Strength—Grades AH, DH, EH, and FH with a specified minimum yield point of 46 ksi [315 MPa], 51 ksi [350 MPa], or 57 ksi [390 MPa].
- 1.3 Shapes and bars are normally available as Grades A, AH32, and AH36. Other grades may be furnished by agreement between the purchaser and the manufacturer.
- 1.4 The maximum thickness of products furnished under this specification is 4 in. [100 mm] for plates and 2 in. [50 mm] for shapes and bars.
- 1.5 When the steel is to be welded, it is presupposed that a welding procedure suitable for the grade of steel and intended use or service will be utilized. See Appendix X3 of Specification A6/A6M for information on weldability.
- 1.6 The values stated in either inch-pound units or SI units are to be regarded separately as the standard.

Shiotani et al. (2012) have presented a new development for superior corrosion resistant steel for ballast tank application. First, the actual environment at the upper deck in a ballast tank of a bulk carrier was measured. The upper deck environment was characterized by cyclic repetition of water evaporation and condensation accompanied with daily temperature increases and decreases. The corrosion resistance of steels was evaluated by the cyclic corrosion test with salt spray using conditions found from the environmental measurement results. The degradation area of coating films at a scratch in the developed steel was about 70% that in the conventional steel. The fine rust particles which formed under the coating film on the developed steel were considered to contribute to its excellent corrosion resistance. The mechanical properties of the developed steel, such as tensile properties and Charpy impact properties satisfied the KE36 specification. The effect of corrosion on the structural reliability of steel offshore structures has also been recently evaluated by NKK as a guideline, (Melchers, 2005).

5.5 Corrosion Monitoring

To reduce labour cost and increase the quality of edge preparation prior to coating, German research projects developed technologies for thermal edge rounding by means of laser of plasma sources. This method was pre-approved by DNV of structural shipbuilding steels, (Jasnau et al., 2011). Within this project, various edge geometries and preparation technologies have been systematically investigated. Results showed that there is no statistical evidence that a preparation of edges with a 2mm radius will improve corrosion protection of the edges compared to alternative edge geometries, (Heinemann & Roland, 2011).

5.6 Non destructive testing

Non-destructive testing (NDT), also referred to as NDE (non-destructive evaluation/examination) and NDI (non-destructive inspection), is a family of specialized technical inspection methods that provide information about the condition of materials and components without destroying them, (DNV, 2014).

Weld Surface Appearance Welding in hull construction is to comply with the requirements of Section 2-4-1 “Hull Construction” of the ABS Rules for Materials and Welding (Part 2) and IACS Recommendation No. 47 “Shipbuilding and Repair Quality Standard”. Methods used for preparing and cleaning welds and non-destructive test procedures are to be to the satisfaction of the Surveyor.

5.6.1 Visual Inspection of Welds:

Welds are to be visually inspected to the satisfaction of the Surveyor. Visual inspection acceptance criteria are contained in Section 8 of the Guide, (ABS, 2011).

Visual inspections of welds may begin immediately after the completed welds have cooled to ambient temperature. However, delayed cracking is a concern for extra high strength steels, 415 N/mm2 (42 kgf/mm2, 60,000 psi) yield strength or greater. When welding these high-strength steels, the final visual inspection shall be performed not less than 48 hours after completion of the weld and removal of preheat. Refer to 1/1.5 below for requirements for delayed cracking inspection.

5.6.2 Inspection for Delayed (Hydrogen Induced) Cracking

Non-destructive testing of weldments in steels of 415 N/mm2 (42kgf/mm2, 60,000 psi) yield strength or greater is to be conducted at a suitable interval after welds have been completed and cooled to ambient temperature.

- Minimum 48 hours of interval time for steels of 415 MPa (42 kgf/mm^2, 60,000 psi) yield strength or greater but less than 620 MPa (63 kgf/mm^2, 90,000 psi) yield strength.
- Minimum 72 hours of interval time for steel greater than or equal to 620 MPa (63 kgf/mm^2, 90,000 psi) yield strength.

At the discretion of the Surveyor, a longer interval and/or additional random inspection at a later period may be required. The 72 hour interval may be reduced to 48 hours for radiography testing (RT) or ultrasonic testing (UT) inspection, provided a complete visual and random MT or PT inspection to the satisfaction of the Surveyor is conducted 72 hours after welds have been completed and cooled to ambient temperature.

When delayed cracking is encountered in production, previously completed welds are to be re-inspected for delayed cracking to the satisfaction of the Surveyor. At the discretion of the Surveyor, re-qualification of procedures or additional production control procedures may be required for being free of delayed cracking in that production welds.

5.6.3 Methods of Inspection

Inspection of welded joints is to be carried out by approved non-destructive test methods, such as visual inspection (VT), radiography (RT), ultrasonic (UT), magnetic particle (MT), liquid penetrant (PT), Thermal Imaging, etc.

A plan for non-destructive testing is to be submitted. Radiographic or ultrasonic inspection, or both, is to be used when the overall soundness of the weld cross section is to be evaluated Magnetic particle or liquid penetrant inspection or other approved method is to be used when investigating the outer surface of welds or may be used as a check of intermediate weld passes such as root passes and also to check back gouged joints prior to depositing subsequent passes.

Surface inspection of important tee or corner joints in critical locations, using an approved magnetic particle or liquid penetrant method, is to be conducted to the satisfaction of the Surveyor. Where a method (such as radiographic or ultrasonic) is selected as the primary non-destructive method of inspection, the acceptance standards of that method govern. However, if additional inspection by any method should indicate the presence of defects that could jeopardize the integrity of structure, removal and repair of such defects are to be to the satisfaction of the Surveyor. Welds that are inaccessible or difficult to inspect in service may be subjected to increase the levels of non-destructive inspection.

The extent and locations of inspection and selection of inspection method(s) are to be in accordance with (ABS, 2011):

- The applicable ABS Rules;
- The material and welding procedures used;
- The quality control procedures involved;
- The results of the visual inspection, and
- The discretion of the Surveyor;

5.6.4 Under film corrosion detection

Osawa et al. (2014) have studied the effectiveness of fluorescent ferric ion indicator for under film corrosion detection of coated steel panels in water ballast tank. (1S)-3'-(diethylamino)-N,N-diethyl-3-oxo-3',9a'-dihydro-3H-spiro[isobenzofuran-1,9'-xanthen]-6'-amine oxide “RhoNox-1”, has been chosen as Fe2+ indicator.

Under film corrosion sensing semi-transparent modified epoxy films, which contains RhoNox-1, are prepared in the process. SS400 steel test panels are blasted and the prepared semi-transparent Fe2+ sensing paints are applied. Some panels are scribed after coating, and NaCl solution is dropped onto the steel surface before coating in other panels. These panels are subject to immersion tests in NaCl solution and cyclic corrosion tests by using artificial seawater. Changes in fluorescence are observed during these tests. The following behaviour is noted:

1) RhoNox-1 is not responsive to amine-based hardener, and "prematurely fluorescent” can be prevented; 2) RhoNox-1is functioning as an early detection indicator for steel corrosion; 3) Steel's anode reactions in underfilm corrosion that progressed during the cyclic corrosion tests had been detected clearly by using the developed Fe2+ sensing paint. 4) It is enough to apply 1wt% RhoNox-1 containing paint as a mist coat for non-destructive monitoring of anode reaction when semi-transparent paint used in this study is applied as a top coat.

6. MANUFACTURING SIMULATION

Nowadays the shipbuilding industry is facing a high competitive environment due to production overcapacity and competitors that are applying hostile low labour costs. Under these circumstances, the optimization of design, production and operation processes are vital to keep and increase their competitive power in global extent.

In recent years, engineering departments of shipyards and universities have been attempting to tackle this problem through the:

- improvement of the quotation and design steps in order to quickly provide an optimum solution in term of structure, production and cost,
- minimization of costs and production time through automation and improved schedules,
- Maximization of product quality.

To overcome this gap, strong emphasis has recently been placed on the development of Computer Integrated Manufacturing (CIM) systems to support the design and production of ships by linking the design system with the production support system. Indeed, progress in these fields has led to the improvement of quality and accuracy, which are two essential preliminaries for effective production.

Amongst CIM methodologies used in shipbuilding industry, recent developments about Discrete Event Simulation (DES), production optimization, Virtual Reality (VR) and Augmented Reality (AR) are presented in the next sections.

The main advantage of these CIM tools is that they allow anticipating possible problems in the production and operation phases. This can thus provide a virtual prototype without the costs of a physical model and available from an early design stage.

One of the major problems in the shipbuilding processes simulation and scheduling today is the lack of interoperability between data systems and software applications, (Lee et al., 2014a). 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. Lee et al. (2014a) states in his paper that it is tedious and the most time consuming part of that process.

However, Enterprise Resource Planning (ERP) systems have been developed for shipbuilding and are currently playing a major role in optimizing 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.

6.1 Discrete Event Simulation and production optimization

Discrete Event Simulation (DES) is a simulation which describes the target system with state variables, transition functions and time advance function. Its operation is carried out by changing its states with the response to event occurrence. Discrete Event Simulation (DES) only takes points in time (events) into consideration. Such events may, for example, be an element entering a station or leaving it, or moving on to another machine. Any movements in between have little interest for the simulation itself. What is important is that the entrance and the exit events are displayed correctly. When the element enters a material flow object, the software calculates the time until it exits that object. Finally, the simulation software makes a list of all the important events where each event is programmed and executed step by step. DES programs allow the mobilization of virtual plants or supply chain such as shipyards where product data contains all geometrical and methodical information about the ships and offshores structures while the simulation model includes all parameters describing the production facilities, resources (machines, humans, etc.) and processes. One of the major advantages of the DES is that it is possible to integrate the operating rules of each workshop or transportation activity and simulate the complex interactions between the different actors (human and material resources, transportation, machinery and tools, etc.). The DES is particularly effective to tackle phenomena such as the surface management, transport management, flow management (identification of bottlenecks), management of failures and hazards that a simple analytic workload simulation cannot integrate.

Creating a DES 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 planning 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 (production planning) this effort has been found to be quite high for production planners and engineers. Major shipyards in Europe and Korea (Lee et al., 2014a) are able to afford specialists focusing on these tasks. Both, layout planning and production planning are presenting recent developments. Recent research activities about DES have been observed and detailed in the following sections.

6.1.1 Layout planning

A layout planning DES has been recently developed by Kim et al. (2013). A stochastic shipyard simulation has been introduced to evaluate the capacity of executing master production schedules in a shipyard as it simulates Integrated Hull and Outfitting Plan. The results highlighted the production problems such as capacity shortages and throughput of each resource. Then, the production capacity of each facility is evaluated. Similarly, Lee et al. (2014a) presented recently a simulation based manufacturing in order to check the feasibility of master production schedule of big shipyards. He advocates that this type of simulation avoid strategic errors at the upper stage of the planning and strongly reduce the risks of having bad surprises during the manufacturing of complex products.

Song et al. (2010) developed an interesting simulation approach to select the best shipyard layout alternative amongst 70th possible generated arrangements. Each arrangement represents a scenario which will be assessed in term of efficiency by simulation. Then the best alternative is selected based on key performance indicators such as working volume per day, work in progress, required space, etc.

6.1.2 Production planning

Goo et al. (2013) presented a layered ship production scheduling system based on DES. He introduced a Layered DES framework for simulation with mixed level of information for shipbuilding in order to better take into account the dissimilarities between the intermediate products in shipbuilding industry. The model is divided by level of details of usable information (layer) and it is designed to facilitate cross-linked information between different layers.

Ozkok and Helvacioglu (2013) presented a case study of a DES applied to the production of double bottom blocks. He compared various improvement strategies by production simulation and has demonstrated that simulation were able to largely improve the throughput of the shipyard workshops (about 100% for the best strategy). Thereafter a list of production recommendations is proposed to improve the productivity of the shipyard. Similarly, Chen et al. (2013) demonstrated the feasibility to use DES on block production line of a small shipyard size in order to promote the lean manufacturing. He demonstrated that simulation is able to provide a powerful decision tool in order to improve the planning by identifying bottlenecks, poor space utilization and resource utilization.

However the most promising developments regarding DES concern the coupling of simulation with optimisation algorithm. Tokola et al. (2013) recently introduced a DES model coupled to a local search heuristic optimization algorithm. The objective function is focus on minimizing the lead-time of the erection process of a suezmax tanker using various erection strategies such as aft-to-fore, bottom-up and pyramid. Then, simulation is used to study how much benefit can be obtained by the optimized sequencing in different capacity conditions.

Another issue that has shown a regain of interest during the past years is the scheduling and optimization of shipyard space allocation. Today, shipyards change their design method in order to increase the number of simultaneous tasks with the use of more structural blocks (modular construction strategy). The assembly of big elements requires a necessary available area within the fabrication workshop to perform the production. As the blocks become larger and heavier, production space in the shipyard becomes a constraint. Therefore it is important to properly use and optimise this space avoiding unnecessary moves that results in non-value-added costs. Cipriano and Barreto (2014) recently proposed a resource constrain project scheduler in order to solve that problem. However he deals with a limited number of production constraints, which hardly reflect the realistic production situation. Conversely, Caprace et al. (2013) developed a heuristic algorithm solver efficiently generate and compare multiple space allocation alternatives in a reduced time with the ultimate goal of maintaining the critical ship erection schedule. He shows on a real scheduling case (about 150 blocks during 1.5 year) that an improvement of 12% can be reached between a schedule obtained by the solver and a manual schedule made by an experienced planner.

6.1.3 Outfitting and customization

Outfitting, and more specifically, piping seem to have a renewed interest among researchers these past years probably because the assembly work of pipe unit is currently carried out by skilled workers, guided by complicated two dimensional drawings, and with their long experiences. This is also a high interest topic for offshore industry (offshore platforms, FPSOs, etc.) and naval industry (submarines) where outfitting cost is higher than in other segments.

Complexity of pre-outfitting and outfitting structures, delays in final design delivery and unpredictable events on shop floor trigger scheduling conflicts that arise because of compartment space shortages, resource constraints and unfeasible assembly sequences. The concept of 4D planning have been recently introduced by Bouvet (2013). 4D planning stands for 4-Dimension Planning and enables to display the progress of an assembly sequence step-by-step. It has been developed primarily to reduce the cost of rework during on-board outfitting. A large part of rework is due to unexpected lack of space in crowded compartment where outfitting work has already started. When a piece of equipment cannot be fitted because too many items are already installed, disassembly work is required and that will cause unexpected delays. This kind of rework can be avoided by getting equipment fitted right the first time, following a feasible sequence validated beforehand through 3D simulation.

In addition, Wei et al. (2010) and Wei and Nienhuis (2012) proposed two methodologies to generate automatic schedules for outfitting processes within shipbuilding and offshore industry. She concludes that further research and developments should be performed to obtain more practical and realistic outfitting schedules algorithms. Noda et al. (2013) recently proposed an improvement of the automatic scheduling system of outfitting process planning provided Wei et al. They introduce a new system which divides the pipes into several groups considering assembling order that skilled workers adopt. Then concluded that the work efficiency is improved comparing the existing solution without degrading the on-site assembling flexibility.

To improve the shipbuilding system efficiency in the presence of variation (unexpected delays), a two-stage strategic-level outfitting planning model has been developed by Dong et al. (2013a). The results of the model provide the optimal percentage of outfitting work that should be completed at each stage of the assembly process (on-board outfitting, pre-outfitting, etc.). A closed formed equation for system cycle time is provided by applying Kingman's equation from queuing theory. Using the closed form equation, the optimal percentage of total outfitting work processed at each stage can be calculated given any scenario.

A long-term scheduler module applied to the outfitting cabin installation for cruise ships have been recently developed by Sasaki et al. (2013). This simulation module focuses only on the bottleneck processes and uses a constrain-based scheduling system. Sasaki states that the developed approach was useful to find work improvement plan to shorten the lead time of the whole cruise ship project.

6.1.4 Logistic simulations

Discrete-event simulation has been used as an analysis tool to evaluate the new production system concepts and has also been used in the operation and planning of manufacturing facilities. However, an important aspect that could also be analysed with this method is the supply chain and intern logistic of shipyards.

Woo et al. (2010) developed a logistic based simulation to improve the decision-making system for ship blocks production of a big size shipyard. This system verifies if the resource allocation and planning for the block stock area, the transporter, transportation jigs, and roads that come with logistics flow of the yard are suitable for the established production planning. Both, logistic transport and storage areas are modelled using DES. The authors made a comparison between two logistics alternatives and concluded that production simulation as largely improving the productivity of the shipyard. They state that the simulation can be used for both long-term and short-term planning decisions. Similarly, Solano-Charris and Paternina-Arboleda (2013) made a sensitivity analysis on a DES model of the supply chain of a naval shipyard. This model supports the operations planning and the decisions on capacity in naval shipyards.

6.2 Virtual and Augmented Reality

Further step to production simulation through DES would be realization of the virtual shipyard by using of both virtual reality and augmented reality (von Lukas et al., 2014).

Virtual Reality (VR) is defined as an immersive and interactive computer simulation of real or imagined world that are 3 dimensional and calculated in real-time. Most current VR environments are primarily empirical experiences, displayed either on a computer screen or with special stereoscopic displays, and some applications include additional sensory information such as sound, smell, touch (haptic), etc.

The VR application applied to shipbuilding industry is not new, but it is more extended now thanks to the important improvements in software and hardware. From a user point of view, it is possible now to find a wide range of solutions to meet the most demanding requirements, to achieve measurable results, in terms of efficiency and costs, (Fernandez & Alonso, 2015) and (Alonso et al., 2014).

Maybe the engineering department of shipyards is where it is more current to use this kind of solutions. And production department is maybe where it should be extended because is where there are the most costly errors. They are not usually working with a VR solution but now it is clear that it is very useful to check the model in order to avoid interferences and collisions between parts, schedule and sequence errors and any inconsistencies. VR can also be use to improve the ergonomic aspect during construction and operation of the ships. At the end, the great impact in cost reduction is possible thanks to the early error detection, being much more expensive the modifications in manufacturing and production stages.

VR can also improve the assembly sequence planning by providing a tool to check the robustness of the schedule in terms of ergonomy and interferences. This is especially interesting for outfitting of complex marine structures where delays and re-planning are frequent. A prototype coupling VR to assembly sequence planning have been recently developed by Lodding et al. (2011). He shows that to simplify the use of VR in shipbuilding industry the data preparation effort should be greatly reduced in order to be profitable. These prototypes further supports 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.

Friedewald and Schleusener (2014) studied the coupling of Physics Engines (PE) to VR simulations in the research project Power-VR. Results show that there is an interest to use PE in VR to improve the quality of simulations in the case of suspended loads at sea. For instance the movement of a safety boat suspended to the davit before launching can be simulated considering the swell. Similarly, Ham et al. (2014) and Ha et al. (2014) developed a simulation of the motion of the erected block and floating bodies on the multibody system dynamics. Then, the calculated motion and wire rope tension are used for dynamic effect estimation. Various applications are presented such as, a block turnover simulation by gantry crane, a block turnover simulation by floating crane, a flare tower turnover simulation, a crane transportation simulation by two synchronised floating cranes, connexion between two floating structures at sea and a life raft launching simulation. In order to reduce the tedious time data preparation of this kind of simulations, Ku et al. (2014) developed a scenario management of multibody dynamic simulator. He presented a prototype with a test case on lifting blocks using cranes. Due to his modular behaviour this system drastically reduced the modelling time.

Augmented reality (AR) system combines the real world with virtual information and provides expanded and information-rich view of the environment to the user. Recent advances in technology, lower cost of otherwise expensive equipment and especially development of the smart handheld-device market have propelled the rapid development of the AR. Head Mounted Displays (HMDs) are probably the most promising because they provide the best immersive experience. HMDs are worn on the user's head and have a small display device in front of each eye presenting virtual objects or information over the view of the real world. As stated by Vasilijevic et al. (2011), many fields already benefit from AR technology and there is actually some developments in maritime industry such as in ship construction, electronic navigational aids, maintenance assistance, diving assistance, etc.

7. WELDING SIMULATION

7.1 Computation Welding Mechanics

The exponential growth in computer performance combined with equally rapid developments in numerical methods and geometric modelling have enabled Computational Weld Mechanics (CWM) to reach the stage where it can solve an increasing number of problems that interest the shipbuilding and offshore industries, (Goldak and Akhlaghi, 2006), (Lindgren, 2007) and (Babu, 2010).

In a scientific context Finite Element (FE) based on thermo-mechanical simulations to determine the temperature and stress fields present during welding have been performed for about forty years. The FE technology and the computer capacity (computations and storage) have developed significantly in the recent years, and now allow including detailed weld process parameters in the simulations.

Recently published CWM standards (AWS, 2013) indicates that CWM is in the progress to become an established and mature engineering process in the field of Residual Stresses and Distortion Predictions (RSDP) (Radaj, 2003). It also indicates that CWM analyses can be used as a fairly reliable tool at the assessment of Welding Procedure Specifications (WPS) and proposed weld process parameters at the manufacturing engineering stage. It has also been reported that CWM analyses has been used to optimise the effects of welding induced residual stresses (WRS) at the structural integrity design phase (Cox, 2011), (Goldberg and Marshall, 2010) and (Pahkamaa et al., 2012).

Finite Element Analyses (FEA) of arc weld processes is quasi-dynamic multi physical problems that generally require High Performance Computer (HPC) with Massively Parallel Processors (MPP).

To be accurate, welding simulation should consider carefully the use of realistic material properties and welding heat source, as described in the next sections.

7.2 Arc Welding Simulation Methodologies

Arc weld processes are characterised by transient thermal and dynamic material phenomena of the interacting weld and base material. During the weld metal's solidification and contraction process the weld melt pool's surrounding base material is first expanding and thereafter contracting.

7.2.1 Sequentially coupled thermos-mechanical models

Finite Element weld simulations are commonly executed by the use of sequentially coupled thermo-mechanical models, (Brickstad & Josefson, 1998), (Muránsky et al., 2012) and (Fu et al., 2014). It implies that first is the entire transient thermal simulation solved and secondly is the transient mechanical simulation solved by the use of the temperature field solution obtained from the thermal simulation, see Figure 15.

7.2.2 Thermo-mechanical staggered coupled

Thermo-mechanical staggered coupled may also be used. There the Finite Element weld simulations are executed as "Non-linear transient thermo-mechanical staggered coupled implicit FEA" (Lindgren, 2007). It implies that the transient thermal and mechanical simulations are solved parallel to each other. There the two FEA-processes provide essential input data to each other, see Figure 16. At the end of the process, transient temperatures, stresses, thermal strain, elastic strain and plastic strain are provided. It should be noted that a computational time reduction of about 85 % compared to ABAQUS for a fully 3D transient thermal TIG-bead on plate benchmark simulation has been reported (Lindström, 2013).

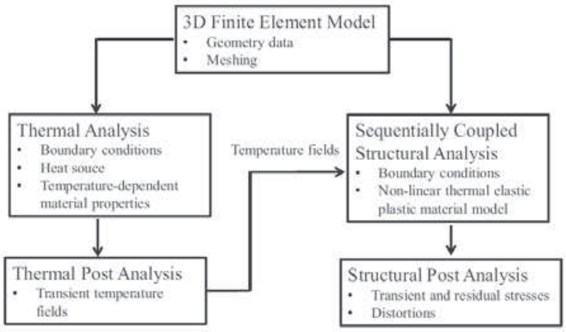


Figure 15. Schematic description of a sequentially coupled thermo-mechanical Finite Element weld simulation (Fu et al., 2014)

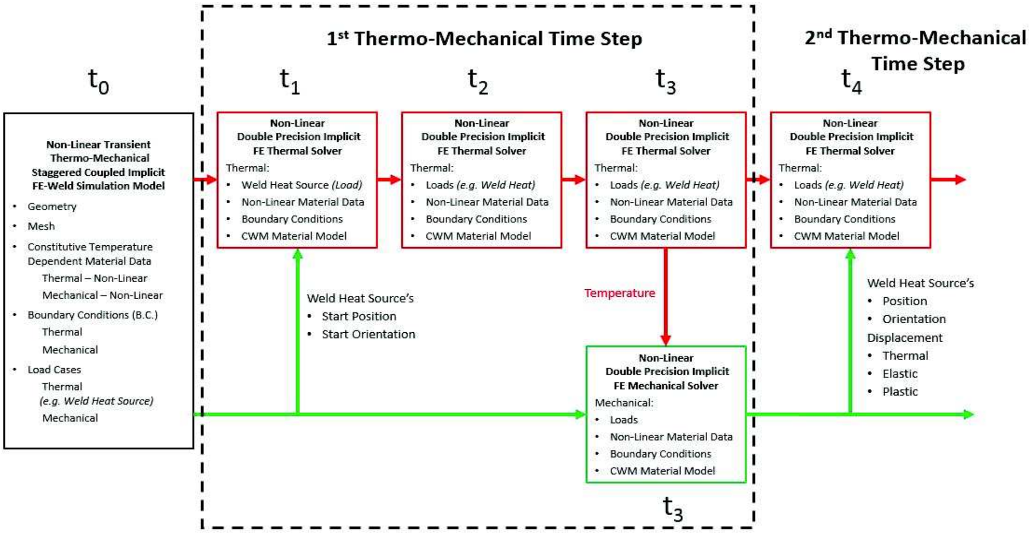


Figure 16. Schematic description of a staggered coupled thermo-mechanical Finite Element weld simulation (Lindström, 2015)

7.3 *Heat source models*

Because the welding process consists of a highly coupled thermal-mechanical processes, accurate simulation of the thermal transfer analysis in the welding process is an important pre-requisite to ensure reliability in numerical simulation. Over recent decades, several analytical models have been developed to determine an appropriate heat source model for estimating the temperature fields.

Rosenthal (1941) firstly developed the travelling instant point heat source model to research the temperature fields in welding process. Eagar and Tsai (1983) modified the Rosenthal's model including 2D Gaussian distributed heat source model.

More recently Josefson (1983), a square shaped 2D transient equivalent heat flux density function was used that 15 years later was (Brickstad & Josefson, 1998) modified to the shape of an triangle. This approach was adopted by TWI, after a modification by (Wei & He, 2010) and by DNV GL after additional modifications (Lindström, 2013).

In another approach formulated by Dong and Hong (2003) adopted by the Swedish Radiation Safety Authority (2009) (Zang et al., 2009a), (Zang et al., 2009b), (Mullins & Gunnars, 2009) and in continuous use by Dong et al. (2014) the 2D weld heat flux is applied in the form of a constant liquid weld metal temperature during the time it takes for the weld head to pass by the cross-section plane. However, this approach has been reported (Lindström, 2015) to result in a weld heat flux distribution with a fairly unrealistic shape. Figure 17 compare five different method to distribute the same amount of weld heat energy (Q = 6.86 MJ) as a 2D heat flux over time relative to the weld cross-section.

In order to obtain the temperature field as realistic as possible, some volumetric heat source model was developed. One of them has been considered as 3D continuous double ellipsoidal moving heat source model (Goldak et al., 1984). This model commonly denoted “Goldak weld heat source” is still a reference for numerous welding simulation code (Shapiro, 2003) and (Oddy et al., 1990).

Later, a number of numerical and analytical models were developed to predict temperature fields in welding process based on these heat source models. Gery et al. (2005) and Shanmugam et al. (2010) investigated the effects of welding parameters on the temperature distribution in a single butt welding and T-joints welds, respectively. Attarha and Sattari-Far (2011) investigated the temperature fields in thin welded plate through the experimental measurements and numerical simulations based on the double ellipsoidal heat source model. Winczek (2010) and Winczek (2011) proposed analytical solutions to model the temperature fields in a half-infinite body during welding process.

More recently Fu et al. (2015) presented a neural network model developed to predict the four double ellipsoidal weld heat source starting from the Voltage, Amperage and Speed of the welding machine. The main advantage of the process is a reduction of the computation time required to setup the parameters of equivalent heat flux of big simulation models.

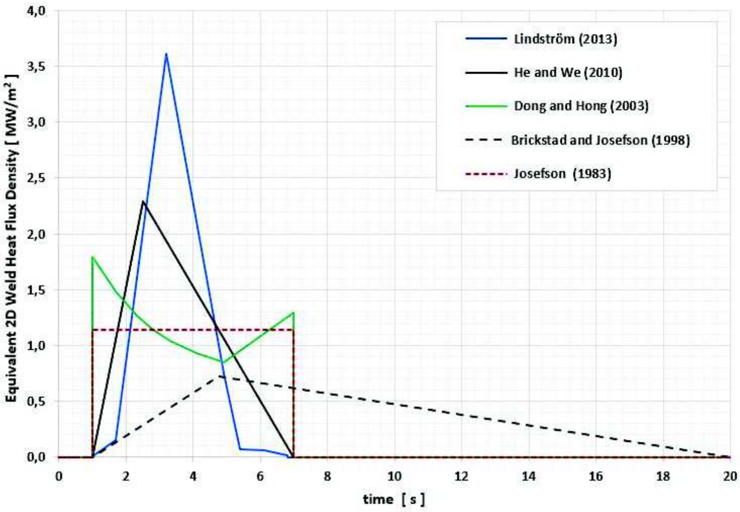


Figure 17. Diagram illustrating how five different methods are distributing the same amount of weld heat energy (Q = 6,86 MJ) as a 2D heat flux over time relative to the weld cross-section (Lindström, 2015)

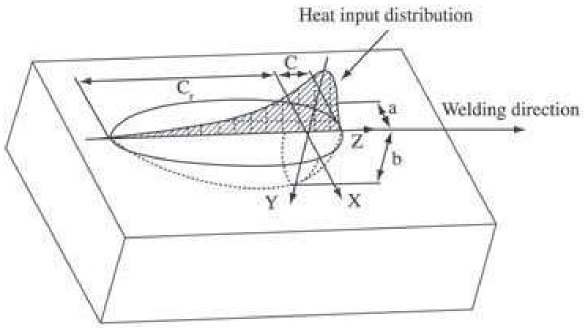


Figure 18. Illustration of the double ellipsoidal weld heat source model

7.4 *Material Models*

Arc welding technology has been continuously improved during the last decades becoming an established process for the manufacturing, maintenance, and repair of metal structures. Today, it is understood that the ultimate mechanical properties of a welded joint depends upon an intricate relationship between several contributing factors, see Figure 19.

Both the thermal and mechanical material model should be designed to be used for modelling of the base material, solidified weld material and weld pass material to be activated in a later sequence of the multi-pass weld simulation process. There the mechanical material model is a non-linear thermo-elastic-plastic model that can employ a mixed hardening with a range from 100% isotropic hardening to 100% linear kinematic hardening that allows residual stress release, triggered by temperature.

The residual stress release function (also known as annealing function) eliminates the material's prior accumulated hardening history. It implies that the base and weld material only can retain and/or build up residual stresses at temperatures below the residual stress release temperature.

Weld material should be present from the very first simulation sequence in the form of quiet material and are gradually activated during the time it takes for the thermal energy of the heat source to heat up the quiet weld filler material between its solidus (TS) and liquidus temperatures (TL).

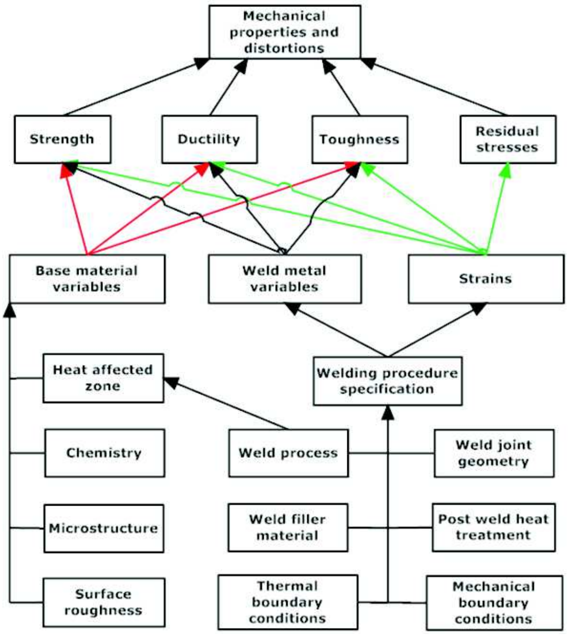


Figure 19. Flowchart of the intricate relation between the variables that affect the mechanical properties and distortion of a welded joint (Lindström, 2015)

The quiet materials represent volumes empty from metal i.e. vacuum or fluids (gas and liquid). A quiet material stress should never reach the yield point; therefore shall the Young's modulus (E) value be small enough to not influence the surroundings but still be large enough to avoid numerical problems.

The quiet thermal material's initiation temperature intervals are the solidus (TS) and liquidus temperature (TL). The quiet mechanical material's initiation temperature is intended to be set a couple of hundred Celsius degrees above the TS and TL. This to reflect that the liquid weld filler material is entering the weld melt pool in an overheated state (Lindström & Ulfvarson, 2003) and thereby facilitate the capture of thermo-mechanical contributions from the liquid, solidification and solid contraction (Campell, 2004), see Figure 20. Above TL is the thermal conductivity value (λ) 300 W/(m°C) and between TS and TL is λ = 150 W/(m°C) to mimic the heat and mass transfer of the weld melt pool (Belytschko et al., 2014).

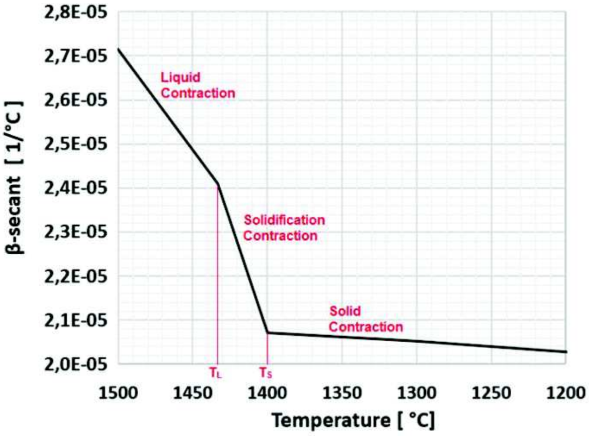


Figure 20. Illustration of the liquid, solidification and solid contraction in relation to TL and TS for an austenitic stainless steel of the type 316L, (Campell, 2004)

7.5 Thermal- and Mechanical Boundary Conditions

Simulation of weld processes there the object (weld model) is exposed to still standing air are the thermal boundary conditions of the surfaces described by an apparent thermal convection. Describing the total amount of heat transfer from the surfaces due to convection and radiation Equations 1 and 2, (Argyris et al., 1983). This approach is recommended by the Swedish Radiation Safety Authority (Zang et al., 2009a).

$$\alpha_h = 0.0668 \cdot T \qquad 20°C \le T \le 500°C \tag{1}$$

$$\alpha_h = 0.231 \cdot T - 82.1 \qquad T > 500°C \tag{2}$$

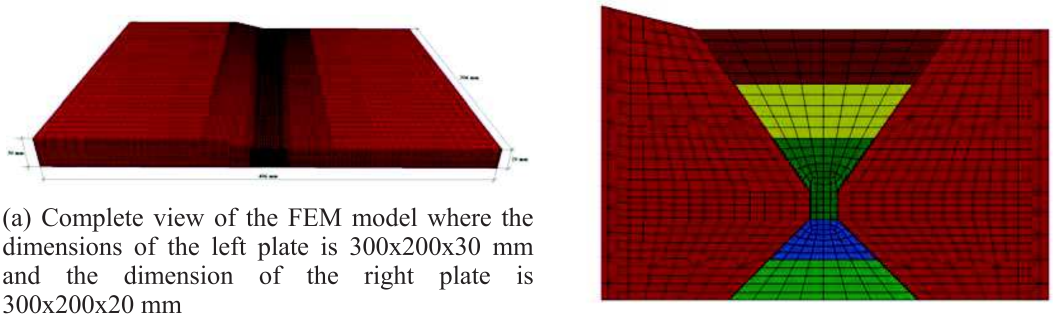
In the case a surface is exposed to a forced flow of fluid will the thermal boundary conditions be calculated by the use of the methodology presented in Lindström (2009).

Contacts between material surfaces are modelled as thermo-mechanical conditions by the use of a penalty based coupling approach, with a heat transfer conductance of 75 kW/(m^2°C) and a static friction coefficient of 0.15.

7.6 *Mesh size*

At thermo-mechanical FEA is elements of the 1st order type used in one and the same mesh for both the thermal- and mechanical simulations. There the polynomial describing the total strain field is one order lower than the polynomial of the thermal strain field. Anyhow, by the use of a very fine mesh (small mesh size) in areas with steep temperature gradients i.e. the Fusion Zone (FZ) and the Heat Affected Zone (HAZ) inconsistent stress and strain results are avoided (Oddy et al., 1990).

Element size in the way of the weld joint i.e. the weld metal and about 30 mm base material on each side of the weld metal shall have a very fine and preferably square shaped mesh. The element size should for the 1st order element type be about 0.3 – 0.5 mm. And the preferred element side length ratio is 1:1:1 and in worst case the element side length ratio of 1:2:3 may be used. At distance of about 50 mm from the fusion line or the regions of interest the element size can be rapidly increased. A typical mesh used at parametric 2D CWM analyses of a critical ship hull plate weld joint is presented in Figure 21.



(a) Complete view of the FEM model where the dimensions of the left plate is 300x200x30 mm and the dimension of the right plate is 300x200x20 mm

(b) Local view of the FEM model around the butt welded joint

Figure 21. 3D transient thermal butt weld model made up of 131716 solid elements and 140793 nodes (Lindström, 2013)

7.7 *Computational time and cost*

The computational cost of a CWM analysis depends on the total number of degrees of freedom (DOF), the transient time and the amount of physical processes that are simulated.

Lindström (2015) mentioned that the computational time for fully 3D CWM analysis constituting of 2142782 DOF (thermal and mechanical) costs about 8 000 CPUh whilst the 2D CWM analysis (5227 DOF) of the same problem constitutes of costs about 2 CPUh. On the other side can the cost of the fully 3D CWM analyses be reduced to 4 000 CPUh if the use of symmetry boundary conditions is feasible.

7.8 *Weld residual stress measurements*

Parallel to the development of the CWM technology there has been research activities related to the measurement of residual stresses in metallic materials. Residual stress measurement methods fall into one of the following two categories destructive or non-destructive. Some destructive methods are argued to be semi-destructive examples on that are the hole drilling and deep hole drilling method. It can be discussed if the stakeholder is prepared to take the risk to operate a structure with an Ø 10 mm hole drilled through a critical component. Overviews of the most commonly used residual stress measurement methods are presented in Schajer and Ruud (2013), Cheng and Finnie (2007) and Fitzpatrick and Lodini (2003).

Recently industrial standards demonstrates that the X-ray diffraction method is the most matured method followed by the hole drill and strain gauge method, and the slitting method (ASTM-E1426-98(2009)e1, 2009), (ASTM-E915-10, 2010), (ASTM-E2860-12, 2012), (ASTM-E1928-13, 2013), (ASTM-E837-13a, 2013).

7.9 Benchmark case

The ISSC-V.3 technical committee has performed a benchmark to define a Best Practice Guideline to use Computational Welding Mechanics tools (CWM) in shipbuilding and offshore industry. To achieve this objective various experimental welding tests have been performed in order to give a reference point. Both the residual welding distortions and residual stresses have been compared between numerical simulations and welding experiments for a common "T" welded assembly used in the shipbuilding industry. However, it has been decided to publish the results of this study in a separate document.

The experiments were performed using the low carbon grade DH36 ferric steel plate typically employed in shipbuilding industry. The geometric model of the T-joint weld is shown in Figure 22. The length of the T-joint is 500 mm, the width of the flange is 500 mm with a thickness of 9 mm, and the height of the web is 300 mm with a thickness of 9 mm.

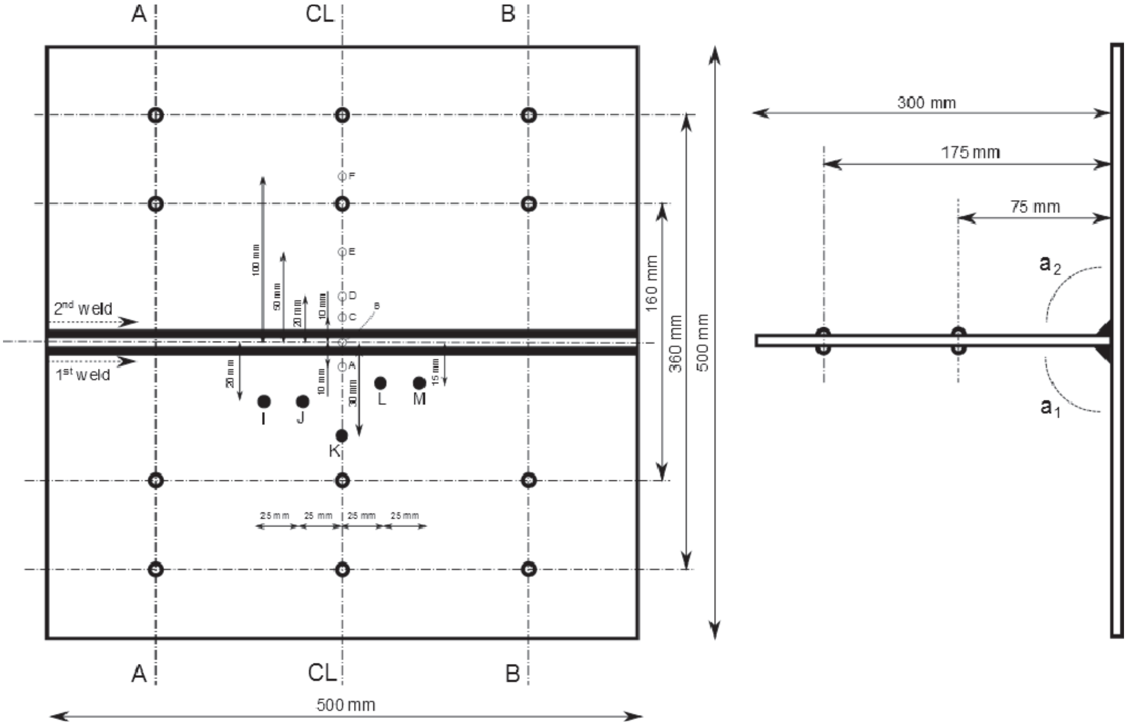


Figure 22. Welding experiment of a "T" joint assembly and position of thermocouples (I-M), residual stress measurements (A-F) and distortion measurements points (sections A-A, CL-CL and B-B)

Two mechanical boundary conditions have been analysed. The first one corresponds to free supported side edges while the second one correspond to clamped side edges.

The filler material corresponds to an AWS A5.20 E71T-1C/9C/-9C-J where the electrode diameter was 1.2 mm. The Flux Core Arc Welding (FCAW) single-side one pass welding procedure is employed with two different weld legs of respectively 5.5 mm and 7 mm. The second fillet weld is started when the temperature of specimen cools down to the ambient temperature. The welding conditions have been set-up respectively to 184 A, 28 V and 290 mm/m for 5.5 mm weld leg and 215 A, 28 V and 230 mm/min for the 7 mm weld leg.

Five thermocouples were mounted on the plate (at the half thickness) prior to the welding process and connects directly to the multi-channels data logging system. In this way, the temperature during the welding process at any specified time can be conveniently stored for later data processing and comparison with numerical results. The thermocouples (I to M) are at 20 mm, 20 mm, 30 mm, 15 mm and 15 mm from the welding seam and −50 mm, −25 mm, 0 mm, 25 mm and 50 mm from the centreline of the plates (CL), respectively. Thermocouples are located to the side of the first weld.

A portable Coordinate Measuring Machine (CMM) was employed to measure the deflection of the upper surface of the flange after welding. A list of target points have been defined along 3 planes (A-A, CL and B-B) −125 mm, 0 mm and 125 mm from the centreline of the plates, respectively. The coordinates of the target points are measured before and after weld. The deflection can be obtained by using the differences of the coordinates before and after the welding in vertical direction. The angle α can also be calculated by using the coordinates of the target points on the flange and web. The angular distortion is known as the difference of the angle α before and after weld.

Residual stresses are measured by X-ray diffraction 0.2 mm below the surface of the base plate at the center line on the opposite side of the welds. Five target points (A to F) have been defined at −10 mm, 0 mm, 10 mm, 20 mm, 50 mm and 100 mm from the weld seam. Point F corresponds to the side of the second weld.

The preliminary results of the benchmark show some discrepancies between the various simulation models (various simulation software's and methodologies) and the physical experiment. Biggest difficulty is probably the calibration of the equivalent heat flux source model that required high skilled experts and standards procedures elaboration. Moreover the CWM simulation is time consuming for both modelling and computing. Obtaining reliable material database for this kind of simulation is another big challenge. We consider that practical use of that methodology is still reserved for big companies and big research centres. Further research is still required to establish fully reliable procedures. However, we noted that some small software companies are really active in this domain and the gap will be soon filled.

8. CONCLUSIONS AND RECOMMENDATIONS

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

There exists an increasing demand for lighter ships. This can be reached either by use of lighter materials (composites, light metals or hybrids) or lightweight design. It has been demonstrated that even though the cost of the equivalent aluminium ship structure is 40% more than the steel structure, the equivalent aluminium naval ship can be built within just 7.5% of the acquisition price of the steel ship due to the cascading benefits of the lightweight material. Some recent publications showed a regain of interest to use titanium and its alloys for ship hull materials to reduce life-cycle cost in high-speed sea transportation. However some design and production challenges are still remaining to be viable. Metal foam cores in metal sandwiches provide a light alternative of solid steel for decks and bulkheads. It minimizes weight, while maximising stiffness but it is still immature for practical use.

The demand for liquefied natural gas (LNG and LNG FPSO) continues to increase due to the rise of environmental issues. A number of materials are available that are engineered specifically for service at a temperature of -163°C and lower. New researches present results of fatigue and brittle fracture resistance of welded assemblies at cryogenic environment. High nickel (9%) alloy steel is common for the inner shell of LNG storage tanks. However the increase of nickel price lead actually to the development of low nickel alloy steels for these structures.

After a long use of composites in the sporting and leisure ships and an increased application in navy vessels the time is now ready for light weight composite materials to enter the merchant shipbuilding. Since composites tend to be more expensive in production it is necessary to look at life cycle costs. Due to the increased application in the maritime sector the effect of sea water exposure on composites is an area of increased interest. Recycling remains a topic of interest as well as the assessment of composite structures and repairs using composites. Fire issues remain an important research area for composite materials. To comply with the Solas regulations research into flame retardant materials is ongoing. Due to the increased environmental awareness research on bio-composites has been started. Bonding of lightweight materials is still an issue. Also the connection of lightweight structural parts to conventional ship parts remains an area of further study.

Welding has been and will continue to be the most important joining technique for shipbuilding. Residual stress and distortion associated with welding are the key issues to be overcome. Recent publications highlight the development of automated guided robots able to weld in confined space such as double bottom of ships. The offshore platforms and pipelines require continuous operation and, thus, reliable underwater welding on-situ. Traditional arc and hyperbaric welding have been improved and new techniques such as friction processes have been further developed for underwater applications. Laser welding is still facing important developments, and at present actual application is extending based on the rapid development of the fibre laser. A prototype of mobile laser equipment has recently been developed. Huge progress has been performed in the development of Friction Stir Welding for industrial application of steel while it is traditionally used for Aluminium. New tools are now capable of producing industrially useful lengths of welds in steel.

Line heating has been used as a method for forming curved shell plate for more than half a century. However is strongly related to the experience and know-how of the workers. Recently, a fully-automated line heating plate bending system was implemented in practice. Post-treatment of critical structural details such as welded joint or plate edge can remove surface defects and, thus, allow better utilisation of high strength steel reducing appearance of fatigue cracks. New studies show the influence of surface integrity on the fatigue strength of high-strength steel used in large marine structures.

The good production quality and workmanship are the key issues for structural safety and also for successful utilisation of new materials. The joining and fabrication processes induce unfavourable defects, which can have significant effect on the strength of the structures. Thus, the quality of production would directly influence the strength. Different weld type and process could influence geometrical parametric of weld joint, and the stress concentration factors and fatigue lifetime could be different. Recent studies shows that optimised weld processes are able to achieve low distortions and good weld profile, and thus, improvement in the fatigue strength. Welding distortion hinders automation and mechanization of shipbuilding, and also requires additional corrective work, causing worse quality and less productivity. Vast literature exists in terms of residual stress measurement, numerical simulation of welding and its effect on distortion, and effects of distortion on the structural strength. Concerning the effect of the residual stresses on the collapse load of the plates, it can be concluded that this stress field leads to a decrease in the plate collapse load, when comparing with a stress free model. From practical point of view, accuracy management is important, and it should be dealt with in terms of not only the reduction and control of welding distortion, but also the accuracy of cutting, 3D measurement and design modifications to reduce distortions.

Corrosion remains one of the main challenges of the shipbuilding and offshore industry. The goal of corrosion protection is to achieve safety by controlling thickness diminution. It is considered that there are many ways to achieve this goal, and many alternatives to the IMO PSPC and novel ideas are being researched. Recent studies have been done for the development of zinc-rich paints sometime including nanoparticles. Extended galvanic action of the coating is generally observed. Self healing model coatings have been developed and tested at lab scale as well as in a ballast water tank of a ferry with good success. New developments for superior corrosion resistant steel for ballast tank application have been presented.

Simulation based production is already widely applied in many shipyards. Further step would be rationalization of the virtual shipyard including outfitting as well as overall steel construction stages, coupling optimization with simulation, and wider application of visible tools and on-site computing such as wearable computers, RFID and augmented reality systems.

The literature review on Computation Welding Mechanics Simulation shows that there are no existing standard procedures to construct this kind of complex models. Biggest difficulty is probably the calibration of the equivalent heat flux source model that required high skilled experts and standards procedures elaboration. Moreover the CWM simulations are time consuming for both modelling and computing.

A benchmark to define a Best Practice Guideline to use Computational Welding Mechanics tools (CWM) in shipbuilding and offshore industry have been realised. Results of the benchmark will be published in a separate document but presented during the congress.

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