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COMMITTEE V.5

SPECIAL CRAFT

COMMITTEE MANDATE

Concern for structural challenges of non-conventional, special surface craft, including uncertainties in established design methods and modelling techniques. Particular attention shall be given to mega yachts, naval craft, offshore service vessels and work boats, which can be characterized by particular materials and structural configurations (wide openings, large unsupported structures, unconventionally shaped superstructures, etc.) and/or are to sustain specific loading conditions (harsh environment, severe cyclic loads or extreme operational ones).

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KEYWORDS

Special Craft, Structures, Naval Craft, Offshore Operation Vessels, Yachts, Motor Yachts, Sailing Yachts, Polar Ship, Icebreaker, HSC Rules, Naval Standards, Special Hull Structures, Free-Fall Lifeboat, Heavy Lift Ship, SWATH, Wave-Piercing Catamaran, Moonpools, Helideck Design, Autonomous Vessel, Total Cost of Ownership, 3D Structural Printing

CONTENTS

1 INTRODUCTION TO SPECIAL CRAFT

The intent of this report is to highlight the wide range of vessels that operate around the world, as well as the unique structural variations and design aspects that grant them the privilege of being "Special." First of its kind, the ISSC 2018 Specialist Committee V.5 for Special Craft will attempt to cover the three major marine market sectors. The goal will be to highlight developments, published work and previous ISSC report writings over the last decade that warrant further discussion on these structural unique vessels. Previously, the Specialist Committee V.5 focused on Naval Vessel structural design developments. Although developments on this vessel type will be covered within the report, naval vessels will not be the focus of the report. The first Specialist Committee V.5 Special Craft report is broad in subject matter in order to cover a wide range of vessel types, developments over the last decade and focus on structural configurations that have been considered "special" by the V.5 Committee members in support of the current mandate. Recommendations are provided in Chapter 7 of this report which provide future V.5 Special Craft Committees suggested focus areas based on the vessel types. In order to allow future reports the ability to address more in-depth analyses of structural challenges and topics, current market trends are also included.

1.1 Definition of Special Craft and Types

For purposes of this report's discussion, Special Craft were chosen to be those vessels which perform a unique marine operational mission or function that requires the vessel to have a uniquely designed structural configuration. The structural arrangement and design is purpose-designed to consider a wide range of variables, including environment and loading scenarios. For thoroughness, the Committee members have chosen to cover all three of the marine market sectors: Military, Commercial and Pleasure. The definition of craft for the intents and purposes of this report is only pertaining to a surface vessel capable of self-propulsion. The implication that the definition of "craft" pertains to a small or high-speed vessel is not the intention within this report. All craft, including large full-displacement vessels as shown in Figure 1, were considered with regard to this Committee's mandate. Specialized hull forms and other structures that demand a detailed discussion are highlighted in Chapter 6.

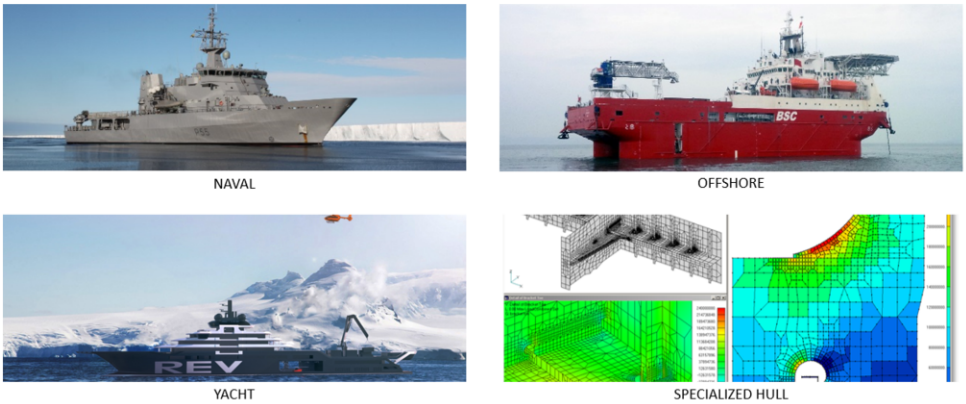

Figure 1: Markets and Specialized Hull Structures Addressed in Report

1.1.1 Market Analysis of Naval Craft

The previous three ISSC V.5 Specialist Committees have focused on Naval Vessel design specific to the Committee's report. Chapter 3 will address Naval Standards and the economic and structural design challenges involved in their utilization. This discussion is in part because the Official Discusser of the 2015 ISSC V.5 Report, Naval Ship Design, Jelle Keuning suggested a discussion in this area for Naval Ships is necessary. This Chapter will briefly discuss the cost variations in naval vessels which make them not only special in structural complexity, but in economic impact to government budgets.

The current trends within the naval vessel market show the world's Navies are racing to repair and replace their existing capabilities, as well as further expand on their fleet to allow for new capabilities. Countries are discovering the cost of new construction programs is not advancing towards cost effective as it is extremely expensive to maintain an outdated platform beyond its designed service life. Navies are finding new construction is necessary to keep the industrial base alive for future programs as well as the vessels design is technologically and economically viable to maintain. Based on data collected by Maritime Affairs (2015) and shown in Figure 2, there are a substantial number of vessels planned in the next 15 years.

Table 1. World Naval Market Forecast 2013–2032.

	In progress		Planned		Projected		Total	
Vessel Type	No. of Hulls	US$B	No. of Hulls	US$B	No. of Hulls	US$B	No. of Hulls	US$B
Aircraft carrier	9	49.8	2	4.0	2	3.0	**13**	**56.8**
Amphibious	129	29.5	204	33.9	33	3.4	**366**	**66.8**
Auxiliary	57	8.1	112	40.1	16	3.1	**185**	**51.3**
Corvette	51	7.1	43	13.1	23	5.8	**117**	**26.0**
Cruiser	2	2.6	6	3.6	-	-	**8**	**6.2**
Destroyer	55	55.3	90	113.8	3	2.9	**148**	**172.0**
FAC	147	5.5	45	3.5	34	2.8	**226**	**11.8**
Frigate	193	68.8	75	42.4	44	17.0	**312**	**128.2**
MCMV	28	4.5	71	6.4	28	2.6	**127**	**13.5**
OPV	121	12.5	139	16.7	31	3.1	**291**	**32.3**
Patrol craft	1121	9.7	482	7.5	157	1.6	**1760**	**18.8**
Submarine	154	142.3	142	100.7	27	11.5	**323**	**254.5**
Total	**2067**	**395.7**	**1411**	**385.7**	**398**	**56.8**	**3876**	**838.2**

Source: AMI International, "2013 Naval Market Forecast", September 6, 2013, www.amiinter.com (accessed January 25, 2015).

MARITIME AFFAIRS Vol. 11 No. 1 Summer 2015

Figure 2: Forecasted Naval Craft Builds (Market Affairs 2015)

1.1.2 Market Analysis of Offshore Operation Vessels

The Offshore Oil & Gas market is supported by highly specialized vessels designed to perform very specific missions. These Offshore Operations vessels are required to be unique in hull and structural design which lends them to the "special" category. Chapter 4 touches on a few types of these specialized craft, their function and recent literary work that addresses the structural aspect of their on-board equipment, hulls and function. Chapter 2 will focus on the Rules that are relevant to these offshore vessels. Chapter 6 will go more in depth on the structural design of the hulls and other appurtenance.

Prior to the rapid oil and then offshore decline in late 2014, market predictions showed a steady uptick in offshore new construction on both offshore support vessels and specialized merchant vessels. The market has struggled to keep the industrial workers employed and companies learned quickly that diversified portfolios were extremely important to maintain. Clarkson's Research (2016) showed Offshore Supply Vessels (OSVs) have recently shown a sharp decline in the global order book due to the declining oil prices as shown in Figure 3. As a result, clientele will eliminate new build risk by focusing on acquisitions of highly specialized and multi-purpose vessels in order to allow for maximum flexibility in asset usefulness when oil prices dip once again.

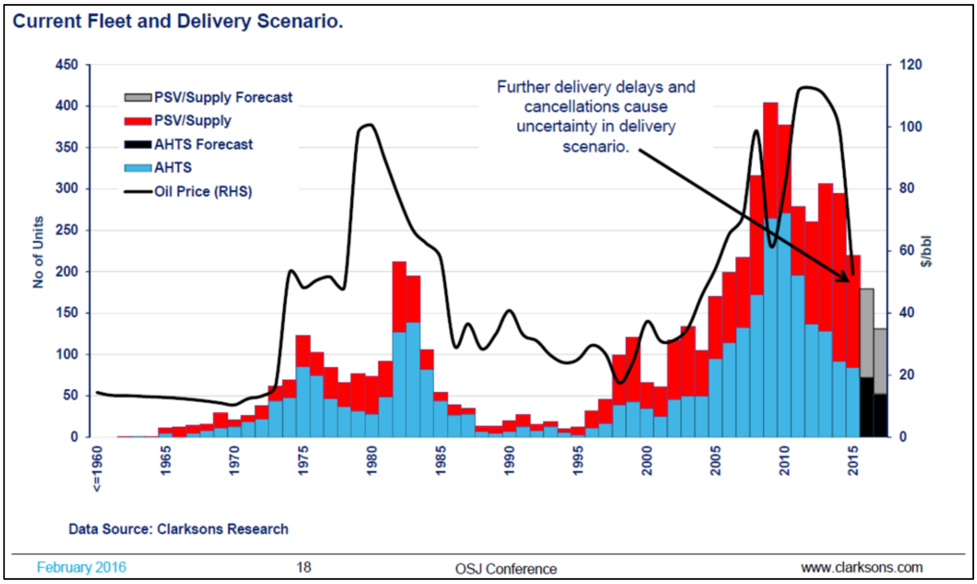

Figure 3: Rapid Decline in the Work Boat/OSV Market (Clarksons Research 2016)

1.1.3 Market Analysis of Yachts

The previous two ISSC V.8 yacht committees (2009 and 2012) focused on sailing and motor yachts respectively. This report focuses on larger pleasure yachts, primarily in excess of 30m, and so-called mega yachts – those at the extremes of the industry.

It is now widely recognized yachts over 24m length overall are considered to be superyachts, primarily due to the change in design regulations that occurs at this length. Despite the continuation of the struggling oil and gas industry, 2017 has seen a steadiness in the superyacht market with 760 yachts on order or under construction compared to 755 in 2016. These values are an advancement from previous years (refer to Table 1) indicating the market is improving.

Table 1: Build orders for Yachts >24m (Global order books 2013-2017)

Year	Build Orders
2013	692
2014	735
2015	734
2016	755
2017	760

Figure 4 shows the new yacht orders split into various categories for 2016. Evidently, there is significantly more demand for motor yachts with 74% of the market coming under this category.

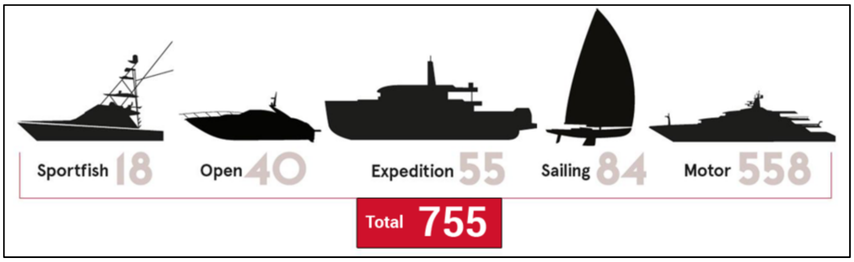

Figure 4: New yacht orders by type 2016 (Montigneaux, 2015)

The variation of market share with respect to yacht length, shown in Figure 5,shows the increase in demand for yachts over 40m in recent years. Some yachts are well in excess of 100m, the largest currently afloat being the Motor Yacht Azzam with an overall length of 180m and a gross tonnage of 12600te.

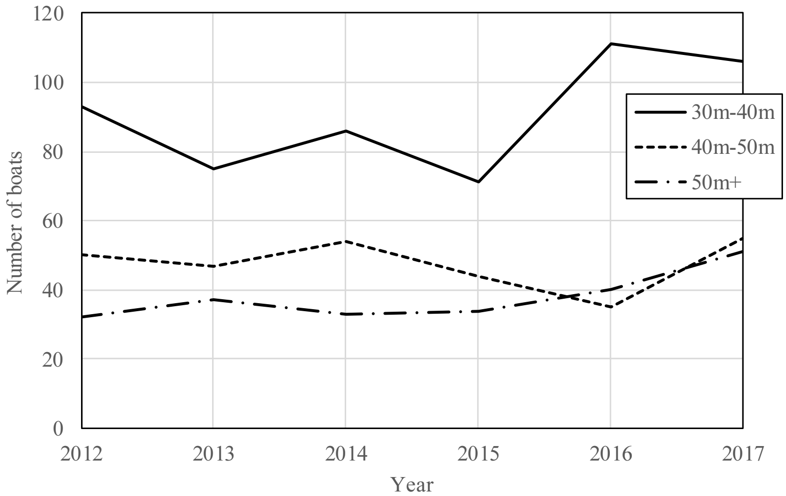

Figure 5: Yachts delivered > 30m from 2012-2017 (The Superyacht Intelligence, 2017)

2 RULES AND STANDARDS

This chapter highlights the most relevant rules and standards for the structural configurations of special craft covered by the Committee's mandate. Since this committee is a newly formed committee the aim is to give an overview of the existing regulations, its systematics and background rather than giving an insight in the technical details of the specific standard's requirements. To a certain extent related Rules and Regulations chapters from former ISSC reports of related committees were consolidated and updated.

2.1 HSC Rules

A set of rules that deals with several of the special craft covered by the committee's mandate are the International Code of Safety for High-Speed Craft (HSC Code) and the related adoptions from most classifications societies.

With the development of many new types of high speed craft in the 1980s and 1990s, IMO decided in 1994 to adopt the HSC Code (IMO 1994) and made it mandatory via a new SOLAS chapter X - Safety measures for high-speed craft.

The HSC Code applies to high-speed craft engaged on international voyages, including passenger craft which do not proceed for more than four hours at operational speed from a place of refuge when fully laden and cargo craft of 500 gross tonnage and above which do not go more than eight hours from a port of refuge.

According to the Code a High Speed Craft is defined as a craft that is capable of a maximum speed in knots equal to or exceeding

$$V = 7.16\ \Delta^{0.1667}\ (\text{knots}) \tag{1}$$

Whereas Δ is the displacement corresponding to the design waterline in tons.

Due to rapid pace of development in the HSC sector, in December 2000, the Maritime Safety Committee adopted amendments to SOLAS chapter X to make the High-Speed Craft Code 2000 (IMO 2000) mandatory for new ships. The 2000 HSC Code updates the 1994 HSC Code and applies to all HSC built after the date of entry into force, 1 July 2002. The original Code will continue to apply to high-speed craft built before that date.

Almost all Classification Societies implemented the HSC Rules and extended it by further ship and/or special service types. This was especially true for Light Craft, Naval and naval support vessels are covered by most Societies' HSC Rules.

All societies except ABS follow the above IMO definition of a high-speed craft, whereas the ABS criteria is $V=2.36\sqrt{L}$. While it is not possible to directly compare the definitions as the IMO criteria is displacement vs. speed and the ABS criteria is length vs. speed it is nonetheless useful to show the two criteria together and to compare a specific vessel. Consider a corvette sized vessel that is classed as a HSC. It is 61 m long with a full load displacement of 950 tons. Under the IMO criteria a 950 tons vessel must have a design speed of at least 22.5 knots to be considered a high speed vessel. The same vessel, 61 m long, can have a design speed of only 18.4 knots under the ABS Rules and still be considered a high-speed craft.

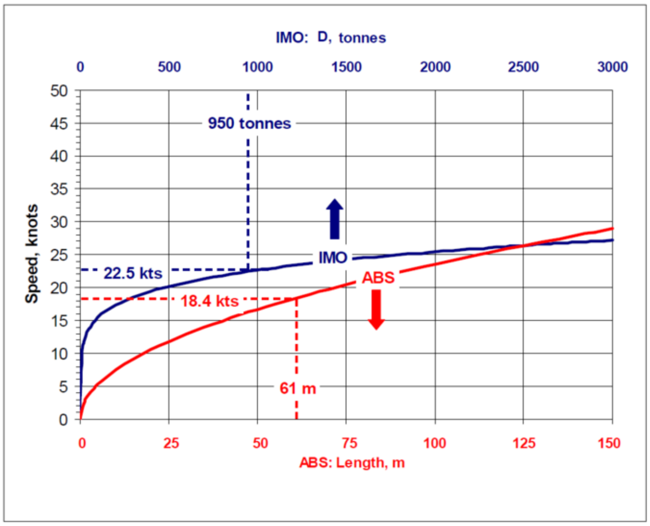

Figure 6: IMO and ABS Definitions of High Speed Craft (SSC 2005)

A light craft is defined as a craft with a full load displacement not exceeding

$$\Delta = (0.13\ L\ B)^{1.5}\ \text{tons} \tag{2}$$

where L is the length at the design water line and B the full breadth at L/2 (m) (DNVGL 2015c).

2.1.1 ABS Rules for Classification of High-Speed Craft 2017

The HSC Rules or HSNC Rules are applicable to high-speed craft or high-speed naval craft constructed of steel, aluminium, or FRP. Applicable craft type and length are as follows:

Craft Type	Applicable Length
Mono-hull	< 130 m (427 ft)
Multi-hull	< 100 m (328 ft)
Surface Effects Ship (SES)	< 90 m (295 ft)
Hydrofoil	< 60 m (197 ft)

Further restrictions are given for coastal and riverine craft.

2.1.2 DNV GL Rules for Classification – High speed and light craft 2015c

In the DNV GL Rules it is distinguished between the High Speed Light Craft (HSLC) and Light Craft (LC) notation. All high speed, light craft and naval service craft shall, in addition to the main class, have a ship type notation as well as a service restriction notation as a part of their classification as defined in Table 2.

Table 2: Service area restrictions (DNVGL 2015c)

Service area notations	*Seasonal zones (nautical miles)*		
	Winter	*Summer*	*Tropical*
R0	250	No restrictions*	No restrictions*
R1	100	200	300
R2	50	100	200
R3	20	50	100
R4	5	10	20
R5	1	2	5
R6	0.2	0.3	0.5

*) Unrestricted service notation is not applicable for craft falling within the scope of the HSC Code, i.e. ship type notations **Passenger**, **Ferry** or **Cargo**

Several ship types, specifically Passenger and Cargo Craft, Car Ferries, Crew – and Patrol Boats, Small Service Craft, Naval and Naval Support vessels as well as naval landing craft are addressed. The materials steel, aluminium, fibre composite and sandwich constructions are specifically addressed in individual Chapters.

Scantling reductions for high speed and light craft steel and aluminium structures as compared to the Rules for Classification of Ships, are captured within these Rules and based on:

- thorough corrosion protection of steel, carried out under indoor conditions
- a certain stiffener spacing reduction ratio s/sr

  s = chosen spacing in mm

  sr = basic spacing = 2(240 + L) for steel and 2(100 + L)/1000 [m] for aluminium
- longitudinal framing in bottom and strength deck
- extended global longitudinal and local buckling control
- sea and weather service restrictions

The reduction factor s/sr shall not be taken less than 0.5 or greater than 1.0.

For the Naval Landing Craft special structural requirements are defined. Bottom plating and stiffening within the beaching protection length shall be increased by 20%. For impact areas the spacing of longitudinals not to be greater than 500 mm. A formula for an average beaching pressure is given for dimensioning of the girders and web frames within the beach protection length. If the craft has to be pushed out from the beach, the front ramp shall have to be dimensioned for push-out loads. For the push out area a load corresponding to 50% of the displacement is proposed. The ramp structure is to be designed according to the rules for Car Ferries.

2.1.3 LR Classification of Special Service Craft Rules 2016

LR Rules distinguish between the High Speed Light Craft (HSC) and Light displacement Craft (LDC) notation. The notations are appended by a service area restriction, service type and a craft type notation. The following service types are possible: Cargo, Passenger, Passenger Yacht, Patrol, Pilot, Yacht or Support Yacht Craft, Wind Farm Service Vessel, Workboat.

The following craft types are foreseen: amphibious air cushion vehicles, catamarans including wave piercers, hydrofoil craft, rigid inflatable boats, surface effect ships, small waterplane area twin hull ships (SWATH).

The Rules are applicable to the following craft types constructed from steel, aluminium alloy, composite materials or combinations of these materials:

- High speed craft
- Light displacement craft
- Multi-hull craft
- Yachts of overall length, LOA, 24m or greater
- Craft with draught to depth ratio less than or equal to 0.55

The following craft types will be considered upon request on the basis of the Rules:

- Amphibious air cushion vehicles
- Rigid inflatable boats
- Hydrofoil craft

All craft classed under the LR SSC Rules are assigned a service area restriction and a service type notation as follows:

- G1: Craft intended for service in sheltered waters adjacent to sandbanks, estuaries, etc. and in reasonable weather where the range to refuge is, in general, 5 nm or less
- G2: Craft intended for service in reasonable weather, in waters where the range to refuge is 20 nm or less, e.g. craft operating in defined coastal waters
- G2A Service Group 2A covers craft intended for service in reasonable weather in waters where the range to refuge is 60 nautical miles or less.
- G3: Craft intended for service where the range to refuge is 150 nm or less
- G4: Craft intended for service where the range to refuge is 250 nm or less
- G5: Craft intended for service where the range to refuge is 350 nm or less
- G6: Yachts and patrol craft having unrestricted service.

Depending on the service type a correction factor $\omega > 1.0$ is defined for the determination of the minimum thickness of plating and stiffeners.

Table 3: Service type correction factor (ω)

Service type notation	ω
Cargo	1,1
Passenger	1,0
Patrol	1,0
Pilot	1,1
Yacht	1,0
Workboat MFV	1,2

2.1.4 CCS China Classification Society 2017

In 2017, CCS revised its Rules for Construction and Classification of Sea-Going High Speed Craft. The main revisions are:

- A craft assigned with the class notations does not necessarily have to comply with the requirements of the HSC Code
- Trimaran as well as Open Sea Service Restrictions are now also covered by the Rules
- Requirements for distance between butt welds and fillet welds have been included
- A new section covering Supplementary Requirements for Aluminium Alloy Stiffened Plates is introduced.

The structural requirements like design pressures, global cross sectional loads, and equipment number are strongly linked to the chosen service restriction for a vessel which is related to the maximum value $H_{1/3\ max}$ of the assumed wave heights.

Table 4 Service Restrictions

Service Restriction	Wave height
Greater Coastal Service Restriction	$H_{1/3\ max} = 6.0$ m
Coastal Service Restriction	$H_{1/3\ max} = 4.0$ m
Sheltered Water Service Restriction	$H_{1/3\ max} = 2.0$ m
Calm Water Service Restriction	$H_{1/3\ max} = 1.0$ m

2.2 Yachts

There is a wide variety of national and international rules and regulations which motor yachts must adhere to. In addition to the rules from classification societies, the International Maritime Organisation (IMO), National Regulations, and Port State Regulations, large motor yachts must meet the following International Conventions:

- Safety of Life at Sea (SOLAS);
- International Load Line Convention (ILLC);
- MARPOL, devoted to the control of the marine pollution;
- International Regulations for Preventing Collisions at Sea (COLREG), which
- provides requirements for steering and sailing, navigation lights and sound signals;

- Standards of Training, Certification and Watchkeeping (STCW).
- Maritime Labour Convention (MLC 2006)

The rule's applicability depends on yacht characteristics such as dimensions (represented mainly by load line length and gross tonnage), the type of service and the number of passengers. Yachts are subdivided into two main categories: superyachts with a freeboard length over 24m and yachts below 24m.

Rules and regulations governing commercialized pleasure craft were discussed in some detail in the ISSC 2012 Report of the V.8 Committee. The updates with regard to rules and regulations applicable to yachts over 24m in length (private and commercial) are shown in Figure 7.

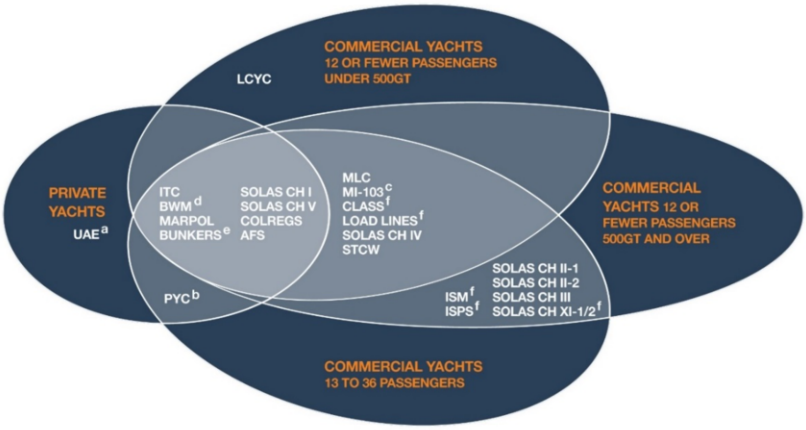

Figure 7: Rules and regulations applicable to yachts > 24m (Manta Maritime 2015)

The primary updates to the regulations for super and megayachts are the release of an update to the Large Yacht Code from the MCA in the form of LY3 (Maritime and Coastguard Agency 2012), yearly updates to the Passenger Yacht Code (PYC) and most recently the latest updates to both of these at the end of 2017 combined as two parts of the whole now known as REG-YC – the Red Ensign Group Yacht Code (ref REG-YC).

Except for the just recently released DNVGL Rules and the CCS Rules a synopsis of structural requirements and issues contained in the rules and regulations of most of the following Classification Societies Rules was already presented in ISSC 2012 and with respect to sailing yachts in ISSC 2009 report.

The DNVGL rules for Yachts (DNVGL 2016) cover all aspects of classification of yachts, including motor yachts, passenger yachts, sailing yachts and sail ships. The rules are based on the former GL rules and guidelines and the technical requirements are updated to represent the latest experience with classification of yacht projects. The structure of the rules is aligned with other rule books, and all applicable yacht types are included. Content from other rule books is reused as far as possible ensuring a consistent approach to classification. The structural design requirements are mainly covered in Part 3 Hull of the Rules. In Chapter 2 requirements with respect to subdivision, compartment and access arrangement are devoted. In Chapter 3, ‘Hull design loads’, it is stated that the wave-induced hull girder loads may be determined by direct calculation alternatively to the rules loads based on wave scatter diagrams. Chapter 4, ‘Metallic hull girder strength’, accounts for the special structural design of yachts characterized by many and large openings. It is described how structural members not contributing to hull girder sectional area are to be determined (e.g. shell large openings exceeding 2.5 m in length or 1.2 m in breadth are to be deducted from the sectional area used in hull girder moment of inertia and section modulus.) Chapter 6 describes generic modelling techniques, loads, acceptance criteria and required documentation for finite element analysis of different type of yachts built in steel or aluminum. Methodologies for finite element analysis of yachts built in composites and other composite related requirements are defined in Chapter 5. In Chapter 7 the detailed requirements for rudder, foundations and appendages can be found.

The Chinese Classification Society (CCS) published in 2012 its Rules for Construction and Classification of Yachts. In line with the international regulations the Rules distinguish between yachts of less than 24 m in length and those above 24m but less than 90m. The structural requirements like design pressures, global cross sectional loads, and equipment number are strongly linked to the chosen service restriction for a vessel which is related to the maximum value H1/3 max of the assumed wave heights.

Table 5 CCS Yacht Service Restrictions

	Wave height	Distance to shore
Category I	$H_{1/3\ max} = 8.0$ m	> 200 n miles
Category II	$H_{1/3\ max} = 6.0$ m	< 200 n miles
Category III	$H_{1/3\ max} = 4.0$ m	< 20 n miles
Category IV	$H_{1/3\ max} = 2.0$ m	< 10 n miles
Category V	$H_{1/3\ max} = 1.0$ m	< 5 n miles

2.3 Naval craft / Surface Combatant

Due to the increasing complexity of naval ships and the need to reduce ship construction costs in the face of ever decreasing defence budget funds, a great deal of attention has been given in recent years to addressing ways to improve Naval ship design and construction practice in many countries.

2.3.1 NATO and national standards

Naval ships have traditionally been designed to in-house standards. These standards and design approaches were developed by various navies based on extensive experience and research. An overview of the different national regulatory approaches was given in ISSC report 2006 (ISSC 2006). Since then two new German Naval Standard (BV) were issued. In 2007 the BV 1040-1 Structural Strength of Surface Ships was revised (BAAINBw 2007). These naval construction rules shall describe only that navy-specific portion of a naval vessel – for application on ships of the German Navy – that cannot be specified by industrial/class rules. The standard is not restricted and contains consequently no military loads. Those are specified e.g. in the classified standard BV 0230 Shock Resistance (BAAINBw 2017). This standard has been developed as a joint regulation with the Dutch Defence Materiel Organisation and under the Dutch designation D5050-0599. In contradiction to its revision 2004, which required threat and design specific determination of shock loads by direct global shock simulations, the 2017 revision contains again empirical shock design spectra.

Also the United Kingdom Royal Navy revised its Shock Manual. The former Shock Manual BR 3021, which was already superseded by the BR8470-8473, was revised by MAP 01-470, Shock Design Manual (MoD 2012). The shock loading to be withstood is associated with equipment location and based on Shock grade schemes. Each shock grade zone represents a different region within the vessel. From the Shock Response Grade Scheme also transient parameters can be derived allowing shock calculations in the time domain.

Standards developed within NATO have been written by committee membership representing various navies and aimed at providing a common minimum requirement. A Standardization Agreement (STANAG) is a NATO standardization document that specifies the agreement of member nations to implement a standard. Because of its consensual nature as an agreement between several countries a STANAG can often be considered as a minimum requirement only. Besides STANAG NATO publishes Allied Engineering Publications (ANEP). The most recognized ANEP is the ANEP-77 known as the Naval Ship Code (NSC). ANEP-77 forms a naval alternative to the commercial ship safety standard SOLAS. The code is a goal based standard that determines a minimum level of safety for naval vessels. It is however not intended to apply to combat operations or their associated threat conditions. The NSC contains three distinct parts as shown in Figure 8.

The code is primarily written as a “Standard for the selection of standards” rather than a standard for direct application. The goals are given on a high generic level and it is expected that the more detailed prescriptive requirements will be found in underlying technical standards such as Classification Rules. In practice, the code is aimed to act as calibration and a framework for rule development of Classification Rules for hull strength of naval craft.

Being a generic code, the ANEP-77 can be applied for any type of naval craft. The differences between the different ship types are mainly related to various functions and operating conditions of the ship.

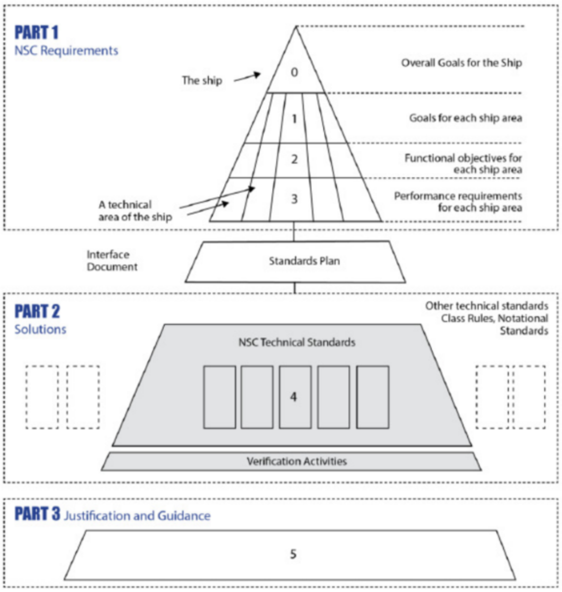

Figure 8: Arrangement of the Naval Ship Code

The structural requirements stipulated in Chapter II of ANEP-77 are that for the design life of the ship, the structure shall be designed, constructed and maintained to:

- Provide weathertight and watertight integrity;
- Carry all loads that may be foreseen;
- Permit embarked persons to carry out their duties safely;
- Protect the embarked persons and essential safety functions in the event of all foreseeable emergencies and accidents at least until the persons have reached a place of safety or the threat has receded;

- Minimise the risk of loss of the ship under non-combat related maritime scenarios.

The Goals relate to the main functions of the ship structure, and one may observe that the goals give a wider scope for the hull structure than is normally found in standards for structural strength.

2.3.2 Class Rules

Naval classification is a relatively new concept especially because naval ships are not required to comply with international Conventions and Codes, like IMO and other institutions. Over the last 25 years navies have however undergone significant changes in the pursuit of efficiencies in the areas of acquisition and support of their platforms. This included adapting their own approach to be more compatible with commercial standards and practices.

Naval Class Rules have been published by several members of the International Association of Classification Societies. An overview of the ship type related notations explicitly handled by the different societies' rules is shown in Table 6.

Some Classification Societies like ABS define only few higher-level categories embracing several different ship types. It should however be noticed that some societies offer the possibility to extend the notation by any further description which indicates the operational role for which the ship is designed.

ABS rules for naval ships are covered by the International Naval Ship Guide "INSG" (ABS 2017a) and High-Speed Naval Craft "HSNC" (ABS 2017b).

Both the former GL and DNV rules for naval vessels are brought forward as DNV GL rules. The GL naval rules were incorporated in the DNV GL rules as a separate rule book; "NAVAL" (DNVGL 2015a). The DNV rules for Naval are incorporated as an integral part of the rules for Ships "SHIP" (DNVGL 2015b) and the rules for High Speed and Light Craft "HSLC" (DNVGL 2015c).

Table 6: Coverage of Ship types notations by Class' Rules

	ABS	LR	BV	DNV GL		RINA
				DNV	GL	
NAVAL COMBATANT	INSG			SHIP		RINAMIL
- Cruisers		NS2			NAVAL	
- Destroyers		NS2			NAVAL	RINAMIL
- Frigates		NS2	NR483		NAVAL	RINAMIL
- Corvettes		NS2	NR483		NAVAL	RINAMIL
NAVAL FORCE PROJECTION	INSG					
- Aircraft carriers		NS1	NR483		NAVAL	RINAMIL
- Helicopter carriers		NS1				RINAMIL
- Amphibious assault vessels		NS1	NR483		NAVAL	RINAMIL
NAVAL SUPPORT	INSG		NR483	HSLC / SHIP		RINAMIL
- Fleet replenishment		NS (SR)				
- Landing ships		NS3		HSLC		
- Logistic support		NS (SR)				
- Mine warfare		NS3			NAVAL	RINAMIL
NAVAL CRAFT (high speed)	HSNC					FPV
- patrol craft		NS3		HSLC		
- fast attack craft		NS3				
COASTAL NAVAL CRAFT	HSNC	NS3	NR483	HSLC		RINAMIL
RIVERINE NAVAL CRAFT	HSNC	NS (SSC)		HSLC		
GOVERNMENT SPECIAL PURPOSE	INSG					
COAST GUARD	INSG					

In addition to its rules for Naval Ships “RINAMIL” (RINA 2017), RINA has published a special rule book only for fast patrol vessels (Rules for the Classification of Fast Patrol Vessels - FPV -, which are intended for the classification of high speed ships up to 65 m and built in steel, aluminium alloy or composite materials - RINA 2007). Specific rules also cover Combat System Physical Integration and existing naval ships. It is anyway to be noted that the approach to classification is generally more articulated, starting – for each new build – from the definition of a specific and comprehensive “Regulatory Framework”, which outlines the complete set of reference rules and regulations to best fit the ship type and its operational features.

BV “NR483” (BV 2017) and Lloyd’s “Nx” (2017a) compiled all navy Rules in one Rule book.

2.4 Polar Ship / Icebreaker

On 21 November 2014 and 15 May 2015, the International Maritime Organization (IMO 2014, IMO 2015) formally adopted the safety and environmental parts of the Polar Code at its Maritime Safety Committee (MSC) and Marine Environmental Protection Committee (MEPC) meetings. The goal based Polar Code introduces a broad spectrum of new binding regulations covering elements of ship design, construction, onboard equipment and machinery, operational procedures, training standards, and pollution prevention. The code entered into force for new ships on 1st January 2017 and for existing ships on 1st January 2018. Two primary hazards which pose risks to hull structures are addressed by the Polar Code in Chapter 3, low air temperature and the presence of ice, resulting in the ship structural goal to provide that material and scantlings of the structure retain their structural integrity based on global and local response due to environmental loads and conditions. Two IACS standards are referenced for demonstration of compliance.

- IACS Unified Requirement UR S6 - Use of Steel Grades for Various Hull Members – Ships of 90 m in Length and Above (IACS 2015)
- IACS Unified Requirements UR I Requirements Concerning Polar Class (IACS 2016)

IACS UR S6.3 has selection criteria for minimum steel grade requirements for ships operating in low air temperature environments. Based on the ship’s design temperature, a structural member’s thickness and material category, minimum steel grades are prescribed. IACS has incorporated changes to IACS UR S6.3 to account for the new definition of the Polar Service Temperature introduced by the Polar Code. If a ship has a Polar Class notation, IACS UR I2 contains ice class-dependent prescriptive material requirements that should be used.

Beside the first functional requirement of operation in low air temperature, the second functional requirement deals with appropriate levels of ice strengthening. The Polar Code established three categories linked to recognized IACS Polar ice classes. Table 3 shows which ice classes are required for each category.

Table 7: Polar Ship Categories (ABS 2016b)

Category	Description	Ice Class
A	Designed for operation in Polar waters in at least medium first-year ice which may include old ice inclusions	IACS PC1, PC2, PC3, PC4, PC5*
B	Designed for operation in Polar waters in at least thin first-year ice which may include old ice inclusions	IACS PC6 - PC7*
C	Designed to operate in open water or in ice conditions less severe than those included in Cat A or B	Scantlings adequate for intended ice types and concentrations

*Or alternative standard offering an equivalent level of safety

The Finnish-Swedish Ice Class Rules (FSICR) were generally considered as the industry standard for ships operating in first year ice. A detailed description on the evolution of the FSICR is given in Riska and Kämäräinen (2012).

Steel plastic design of hull structure has become the new norm for ice class ship design. The new IACS unified polar rules (IACS UR I), the Canadian Administration (ASPPR 1996) and the Russian Maritime Register all employ plastic design methods.

Navigation in coastal waters within Canadian jurisdiction north of latitude 60°N is governed by the Arctic Shipping Pollution Prevention Regulations (ASPPR). The ASPPR deal with the construction of ships (certain construction requirements for different navigation zones). Four Canadian Arctic Categories (CAC) have replaced the previous Arctic Classes. Details of the structural classifications are provided in the Transport Canada publication "Equivalent Standards for the Construction of Arctic Class Ships - TP 12260". Under the ASPPR no ship carrying more than 453 m^3 of oil shall navigate in any of the zones illustrated unless the ship itself meets prescribed construction standards as either an Arctic Class ship, or a Canadian Arctic Category (CAC) ship or a Type A, B, C, D or E ship.

The Northern Sea Route (NSR) is a significant issue not only for the Russian Federation but for the entire international community. The main regulatory act to be applied to the area in Russia is Federal Law 132-FZ of 28 July 2012 often referred to as the NSR Law. Regulatory measures vessels sailing along the NSR have to comply with are: Guide to Navigating through the NSR, Regulation for Icebreaker and Pilot Guiding of Vessels through the NSR, and Requirements for Design, Equipment and Supply of Vessels Navigating the NSR all adopted in 1996.

Winterisation measures are those which ensure an offshore vessel is prepared for operation in cold climates focusing on the adverse effects and the control of icing, freezing and wind chill. DNV GL developed a new offshore standard which came into effect in April 2014 and covers the technical requirements to control these adverse effects (DNVGL 2014).

2.5 Offshore Operations Vessels

A not necessarily exhaustive overview of some classification societies' rules and non-class standards addressing structural specialties of the offshore ships covered in Chapter 4 are shown in Table 8. Swath specific rules are incorporated by most Classification Societies in their High Speed Light Craft Rules, see above.

2.6 Special Structures Rules and Standards

2.6.1 Moonpools

A moonpool is a vertical well extending through the vessel from deck to bottom, providing a direct access to the sea and allowing safe and easy deployment of equipment used for drilling, diving, cable laying or any other subsea operation. The following Guidelines from Classification Societies address moonpools specifically in their rule requirements.

ABS (2014) provides prescriptive formulations for the dimensions of plates and stiffeners of longitudinal and transverse moonpool bulkheads. Guidance is also given for the strength assessment of the hull structure in the moonpool region based on a 3-D finite element model.

Bureau Veritas (BV 2016d) Guidelines for Moonpool address resonant pumping, sloshing, vortex generation as hydrodynamic phenomena having potential undesirable effects to be considered in the design of the vessel moonpool. As a rule the scantlings of moonpool bulkheads are to be calculated as side shell according to the Rules applicable to the vessel.

DNVGL's Offshore standard (2015i) requires that stress distribution in areas with global stress concentrations and discontinuities, e.g. moonpool openings, turret openings, etc. shall be derived from fine mesh FE analysis.

Table 8: Rules and Standards for Offshore service vessels and work boats

	Offshore Drilling Units	Self-Elevating Vessels (Liftboats)	Heavy Lift (Semi-Submersibles)
ABS	Rules for Building and Classing Mobile Offshore Drilling Units (ABS 2017c)	Guidance Notes on Structural Analysis of Self-Evaluating Units (ABS 2016a)	Guide for Building and Classing Semi-Submersible Heavy Lift Vessels (ABS 2017d)
BV	Classification of Drilling Ships (BV 2016a)	Rules for the Classification of Self-Elevating Units - Jack-ups and Liftboats (BV 2016c)	Rule Note Semi-Submersible Cargo Ships (BV 2016b)
CCS	Rules for Classification of Mobile Offshore Units (CCS 2016)	X	Rules for Classification of Sea-going-steel Ships (CCS 2015)
DNV GL	Rules for Classification Offshore drilling and support units (DNVGL 2015d)	Rules for Classification Self-elevating units (DNVGL 2015e) Structural design of self-elevating units - LRFD method (DNVGL 2015f)	Rules for Classification - Vessels for special operations (DNVGL 2015g)
LR	Rules for the Classification of Offshore Units (Lloyds 2017b)		
RINA	Rules for the Classification of Floating Offshore Units at Fixed Locations and Mobile Offshore Drilling Units (RINA 2013)		Rules for Checking the Arrangements intended for Sea Transportation of Special Cargoes (RINA 2014)
non-Class Standards	IMO – Resolution A.1023(26) MODU Code (IMO 2009)	Guidelines for Site Specific Assessment of Mobile Jack-Up Units (SNAME 2002)	X

2.6.2 Helicopter Decks

Table 9 gives an overview about load specification during helicopter landing while Table 10 relates to helicopter in the stowed position as specified by the referenced standards and Class' Rules.

With the assistance of experts from both the large yacht and aviation industries, the Maritime and Coastguard Agency of the United Kingdom has also developed technical standards for helicopter landing areas on board large commercial yachts. The standards were designed to amend section 24.2 of the Large Commercial Yacht Code (LY2). Lardner (2007) had explained the rationale behind the development of these standards, published as Amendment 1 to the Large Commercial Yacht Code. Further to this, the process of compliance is explained with an introduction to the newly appointed aviation inspection body delegated the responsibility for approving landing areas against aviation-specific criteria. In explaining the development of the Amendment, this paper outlines the main findings of a study group established to highlight issues and propose solutions.

The numbers of large offshore structures and fixed jacket type platforms are rapidly increasing for oil and gas companies. Generally, a shuttle vessel or helicopter is used to access offshore structures such as a fixed platform, floating platform, jack-up rig and so on. The helideck structure should be installed in these offshore structures for landing and taking-off of the helicopter. The helideck structure comprises of pancakes, girders using aluminium materials and supporting steel structures. The helideck structure should be designed to accommodate a safe landing area suitable for the largest and heaviest helicopter that is anticipated to land on the helideck. The helideck and its supporting structure are safety critical elements as a result of their role in emergency evacuation, as well as during normal operations. The codes and standards applicable for the structural design of the helideck will be determined by where the helideck is to be operated and the national jurisdiction governing the installation or vessel of which the helideck will become part. International standards such as ISO, Eurocodes, or national standards, e.g. BS 5950, NORSOK N-004 or AISC (American Institute of Steel Construction) may be specified for detailed design. The results of structural analysis and design that has been performed for a 28.54 meter diameter octagonal standard aluminium helideck with support truss & lower steel support structure of jackup drilling rig based on the NORSOK requirements had been presented by Park et al.(2016). The supporting structure is designed to provide the adequate resistance to the external force produced by the design helicopter and environmental conditions.

The report is specifically targeting the structural configurations of free standing non-integrated helicopter decks, but there are many naval ship types with integrated helicopter decks structures or "flight decks". These ships can host organic and/or external aircraft, providing not only take-off, landing and shelter capabilities, but also other services like JP5 refuelling, Vertical Replenishment (VERTREP), afloat maintenance, etc. These flight decks were discussed in report V.5 of the 2015 ISSC Specialist Committee on Naval Vessels.

Table 9: Helideck Loading Specifications - Helicopter Landing

Authority	ISO 19901-3 (2014)	CAP 437. (2016)	HSE (2001)	ABS (2015)	BV (2000)	DNV·GL (2015h)	Lloyd's (2013)	CCS (2015)
Heavy Landing	-	1.5M	1.5M	-	1.5M	-	-	1.5M(6) 1.75M(7)
Emergency Landing	2.5M	2.5M	2.5M	1.5M(1)	3.0M	3.0M	1.5M(2) 2.5M(3)	-
Deck Response Factor	1.3	1.3(4)	1.3(4)	-	-	-	-	-
Super-imposed Load kN/m^2	0.5	0.5	0.5	2.0(5)	2.0(5)	As normal class	-(2) 0.2(3)	0.5
Lateral Load	0.5M	0.5M	0.5M	-	-	-	0.5M	0.5M
Wind Load	Max. Oper.	Sect'n 11	Sect'n 11	Normal design	-	vel=36m/s	-	-

M maximum take-off weight
(1) Or manufacture's recommended wheel impact loads
(2) For design of plating
(3) For design of stiffing and supporting structures
(4) Additional frequency dependent values given for the Chinook helicopter
(5) Considered independently
(6) For normal landing
Having activity of human under the helideck

Table 10: Helideck Loading Specifications - Helicopter at Rest

Authority	ISO 19901-3 (2014)	CAP 437. (2016)	HSE (2001)	ABS (2015)	BV (2000)	DNV·GL (2015h)	Lloyd's (2013)	CCS (2015)
Self-weight	M	M	M	M	M	M	-	M
Super-imposed Load kN/m^2	2.0	0.5	0.5	0.49	0.5	As normal class	2.0	0.5
Wind Load	100yr storm	Sect'n 11	Sect'n 11	Normal design	Normal Design	vel=51.5m/s	-	-
Platform Motions	As calc.	As calc.	As calc.	As calc.	As calc.	As calc.	-	As calc.(1)

M maximum take-off weight

(1) Or 0.5M

For standards regarding helicopters decks integrated into naval vessels, the overall configuration (including outfitting, provisions and lighting for night and day operations, safety matters, etc.) is generally ruled by NATO standards (NATO APP2). In terms of structural scantling, Classification Societies suggest possible approaches, which can also refer to FE verifications, but it is worth mentioning - as an internationally recognised reference - the US Design Data Sheet (DDS) 130-2, used to analyse the structural strength of helicopter flight and hangar decks on naval ships.

2.6.3 Free-Fall lifeboats

Free-Fall lifeboats are designed and built in accordance to the requirements of IMO SOLAS and LSA regulations and MODU codes.

Ronold & al (2009) presented a new standard for site-specific design of free fall lifeboats, developed aiming at providing for sufficiently safe lifeboat designs. The objective has been to develop a standard that follows the same reliability based safety philosophy and design principles as those implemented and used for design of conventional fixed and floating offshore structures. The standard is intended to cover all aspects involved in the design process for a free fall lifeboat, providing requirements that shall be met in design as well as guidance on how to meet these requirements. The following aspects are covered: Safety philosophy and design principles, metaocean conditions, loads, materials, structural design, operational requirements, occupant safety and comfort, model testing and full scale testing, installation, equipment, and qualification of lifeboat concepts. The new standard is published both as an OLF Guideline by the Norwegian Oil Industry Association OLF and as a DNVGL Standard (2016a). The paper presents the highlights of the new standard with emphasis on topics which are critical for design of free fall lifeboats, first of all structural safety, human safety and comfort, and headway.

3 NAVAL CRAFT

The ultimate purpose of naval craft is: "to deliver ordinance on target". This unique performance requirement distinguishes naval craft from other ship types and explains why they are special. The simple mission statement is compounded by the need for naval craft to perform while in harm's way and under arduous conditions. Unlike most commercial craft, there is no expectation of profit or financial return from the operation of naval craft and hence rather different criteria need apply to quantify their merits and justify design requirements. Commercial (e.g. profit driven) practice based on trade-off rationalization for cost saving makes little sense when considering, for example, whether a warship's magnetic characteristics are more important than its radar cross section.

Jane’s Fighting Ships (Saunders & Phillpott 2016) identify 27 types of naval craft in addition to a group of navy specific miscellaneous designs. The miscellaneous category covers specialized vessels including submarine and diving tenders, torpedo recovery boats, bridge erection vessels, barges, tug boats, fire boats, hospital ships, and many others. Naval vessels typically include coast guard ships and harbour craft that in all, number about 7,000 worldwide but comprised less than 10% of the more than 70,000 ocean going merchant and passenger ships registered in 2016. The range of ship types presented in Table 11 suggests a broad and complex set of potential design standards and specifications. Application of traditional (generic) classification society notation to such special craft requires significant interpretation of design rules.

Table 11: Types of Naval Craft

SUBMARINES	Ballistic missile	Cruise Missile	Fleet	Patrol
AIRCRAFT CARRIERS				
CRUISERS				
DESTROYERS				
FRIGATES				
CORVETTES				
FAST ATTACK CRAFT	Missile	Torpedo	Gun	
PATROL CRAFT				
MINELAYERS				
MINEHUNTERS	Ocean	Coastal	Inshore	Minesweeping
ASSAULT SHIPS				
LANDING	Ships	Craft		
DEPOT REPAIR SHIPS				
SURVEY RESEARCH SHIPS				
SUPPLY SHIPS				
TANKERS	Large	Small		
HYDROFOILS & ACV's				
MISCELLANEOUS				

3.1 Why Naval Standards are Special

Naval standards for the design and fabrication of the ship types listed in Table 12 have been developed by many navies, out of necessity, and apply to vessels owned and operated by naval forces. Of particular interest to, and in keeping with the ISSC special craft committee mandate, it turns out that naval standards specifically address the structural challenges and uncertainties in established design methods and modelling techniques with a focus to endure specific extreme loading conditions that arise from the environment as well as the threat of combat. Public access to naval design standards varies between countries depending on national classification restriction policies, however even a cursory examination of those in the public domain provide important insight into the type and nature of prescriptive design direction is not explicit in commercial classification society notation based standards. Naval standards tend to restrict the ship designers options of specific requirements and direct choices toward selection of materials and features that result in more: damage tolerant structural details; battle hardened electrical and mechanical system design detail; fail-safe design methods; structural optimization for weight reduction; compartmentalization to survive collisions and weapons effects and general arrangement criteria for inherent vulnerability reduction; stealth and susceptibility criteria; EMI/EMC/EMP compliance; underwater noise related vibration reduction; shock, blast, fragmentation, fire, flooding and smoke protection; verification and validation programs; among others.

Table 12: Naval Craft Type (Category) Definition

Ship Type	Role	Definition	Examples
I	Combatant	Ship intended to operate in harm's way: • Ships intended to engage in combat • Ships intended to deploy combat systems for offensive, defensive or surveillance purposes; and Troop transport vessels	Aircraft Carriers, Cruisers, Destroyers, Frigates, Patrol Boats, Troop transports
II	Combat Support	Ships expected to operate in harm's way in close support of combat operations. • Fleet Replenishment vessels • Ships considered of tactical or strategic "high value"	AOR's, Tankers, Hospital Ships
III	Naval Auxiliaries	Ships not intended to operate in harm's way (all Ships not type I or II)	Tugs, Ferries, Training Vessels, Research vessels, Work boats, Barges, Range vessels etc.

A good example that describes the nature of naval standards can be found in the UK Ministry of Defence Standard 02-154 dealing with Surface Ship Structures. Its scope covers:

"This NES (Naval Engineering Standard) defines the structural strength standards that are to be achieved in the design, construction and modification of all surface warships. It is also applicable to the military requirements of Royal Fleet Auxiliaries and other non-military craft owned by the MOD where these requirements are in addition to the Rules of Lloyd's or another Classification Society to which the ships are designed. The provisions of this NES apply only to conventional mono-hull vessels and not to multi-hulled or high-speed planing craft."

The NES-154 opening technical paragraph directs and delimits the choice of material for construction of naval ships to the 4 steel types listed in Table 13, with an immediate focus on why the selection is important:

"The particular concern in relation to material and assembly quality in the construction of steel ships is the avoidance of brittle fracture of the structure under high rates of loading or cold conditions. The choice of steel is therefore to be made in accordance with the following paragraphs. However, brittle failure may occur in all steels under specific, albeit rare, conditions and so the quality of construction is also important and the requirements of NES 147, NES 155 Part 1, NES 706 and NES 769 must be followed in addition to the requirements set out in the following clauses so as to ensure that avoidable crack initiating points are not built into the structure."

Table 13: NES-154 Steel Selection Table

Description	MOD Standard	Classification Society Grade	British Standard
Mild steel	NES 791 Part 1	A	BS 4360 grade 43A
Mild steel with guaranteed toughness	NES 791 Part 2	D	BS 4360 grade 43D
'B' Quality mild steel	NES 791 Part 3	EH32	BS 4360 grade 50EE
'BX' Quality steel	NES 791 part 4	no equivalent	

Of specific interest for steel selection and structural design detail, the NES goes on to state that for Hull Plating:

- Category A (Ship Type I)The whole external hull envelope, that is the hull shell, upper deck(s), and first level of superstructure (that is up to and including 01 deck) is to be of steel of guaranteed toughness, that is Part 2 or Part 3 steel. If Part 2 steel is used then crack arresting strakes of Part 3 steel of minimum width two metres must be introduced to ensure that there is not more than 25% of the girth continuously in Part 2 steel, at any cross section along the length. This will usually mean introducing Part 3 steel at the sheer strakes, I deck margin strakes and at the turn of bilge and/or the garboard strakes and flat keel. Consideration is to be given to the use of Part 4 steel in thicknesses above 18mm where lamellar tearing is a possibility.

- Category B (Ship Type II) Any steel from Table 13 may be specified, but if Part 1 or Part 2 steels are used then crack arrestors must be fitted as for Category A ships. Note that this requirement is more severe than normal Classification Society rules for vessels less than 250m in length and for steel less than 15mm thickness.
- Category C (Ship Type III) These are to comply with the relevant Technical Requirements as laid down in the contract.

3.1.1 The Argument For Maintaining Naval Standards

Using the reference above, there is an important argument for properly maintaining and applying Naval Standards. As an example, the EH steel grade designation has outstanding notch tough ductility characteristics that allow the material to absorb a lot of energy through plastic elongation without propagating fracture cracks during a rapid elongation response as is common for shock, blast and fragmentation loading scenario. Arguments that cold temperature toughness is not required for ships not expected to see “Arctic" climates, simply fail to understand that any material with good low temperature notch toughness also has superior notch toughness at room temperature than materials specified for non-Arctic operations and hence build in superior ability to absorb damage from weapons effects without weight penalty. The NES hence avoids the typical commercial trade-off debate by simply directing the need to use EH material for warship construction. The merit of such direction is graphically illustrated by the USS Cole incident shown in Figure 9 for a USN design built to similar USN Gen Spec rules. Without the shear strake and other military features, the consequences of the improvised weapon contact detonation blast damage could have been far more severe. The standards include a need for not only retaining strength under damaged conditions, but stress the need for resisting the type of load arising from dynamic, rather than static application characteristics.

Figure 9: USS Cole following contact air blast detonation showing the protection against crack propagation afforded by the ~2m wide high strength steel sheer strake[1]

Legacy naval design standards tend to focus on lessons learned from combat. A good example of this was provided by Keil (1961) as shown in Figure 10. Classic analysis considers the need for longitudinal strength under intact conditions to be met using bending moment and shear arising from a static bending moment curve derived from placing the ship on a standard wave.

[1] e.g. as required by NES Category A Type I ship from Table 2.

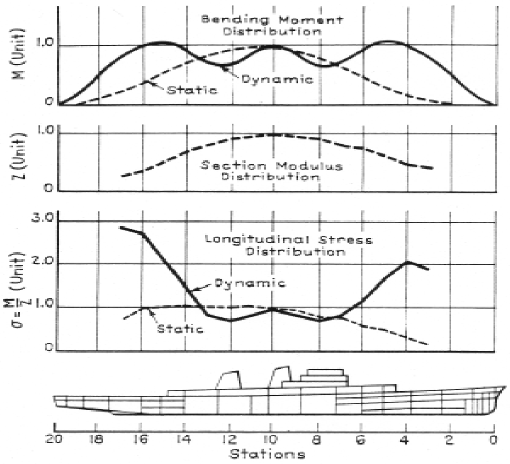

Figure 10: Illustration of load curves under static and dynamic response, (after Kiel 1961),

Under such a condition maximum stress, and hence section modulus peak at about midships (dashed line). Under the dynamic condition induced by underwater explosions however, the bending moment peaks not only at midships but also at the two quarter points (solid lines).

A review of ships lost to actual underwater weapon whipping effects shows the need to strengthen the forward and aft quarters in addition and more so than midships. Such strengthening using higher strength notch tough steels or specially designed box girders is even more important to retain longitudinal strength in damaged conditions as would arise from anti-ship missile or contact mine attacks. In general, naval standards tend to provide more "positive guidance" than "performance based requirements". They tend to be based on previous experience and extensive verification (albeit not well publicized) by naval staff. Such direction avoids potential degradation of proven performance and nugatory work in debate over better options during the exceedingly short duration design cycle. While it is acknowledged that naval design and construction experience may have degraded somewhat during extended peacetime (e.g. disbandment of the British Corps of Naval Constructors in the mid 2000's), the benefit of a non-partisan, not-for-profit skilled organization with a research budget in this field cannot be overstated.

Many Naval forces (e.g. UK, US, CA, IT, FR, AUS, GER, NL...) maintain in-house Ship Design Authorities while others support integrated or co-operative Government/Industry teams. The military design offices maintain responsibility for regulating the navy's standards and are empowered by mandate to undertake various studies individually or co-operatively to advance state of the art knowledge and capability intended to exploit technological advancement. While classification society standards address naval rules for classification, such rules inevitably refer to the need to have naval staff participate or provide more specific requirements for combat survivability involving weapons effects and signature control among others.

Despite the shrinkage in allocated budgets for new builds and maintenance, which pushes towards the research of more and more cost-effective solutions and hence affordability, it is important to understand that the best value, in terms of naval use, is biased towards better through-life capability rather than simply lower acquisition price. Knowing that a naval platform expected to sail in harm’s way was designed, built and outfitted by the lowest bidder who was allowed to bypass "overly" demanding naval standards and test verification programs has proven time again to be a false economy that does not instil confidence in those who sail them. Accordingly, various nations have legislation requiring that warships undergo specific objective based verification. OPNAVINST 9070.1 issued under authority of Vice Chief Naval

Operations of the US Navy, defines roles and responsibilities for various naval organizations charged to uphold Public Law 95-485 under a series of orders to incorporate nuclear hardness, fire protection, damage control and shock hardening of surface ships as well as direction on how to achieve and verify appropriate levels of performance. OPNAVINST 9070.1 restates the mission as: *"Warships are expected to perform offensive missions, sustain battle damage and survive."* It goes on to identify hardening requirements and training to accomplish the goals of survivability by incorporating survivability features early in the ship design process with another goal of making the features affordable (e.g. rather than trading them off). The OPNAV defines three levels of affordable protection as follows:

Level I represents the least severe environment anticipated and excludes the need for enhanced survivability of designated ship classes to sustain operations in the immediate area of an engaged battle group or in the general war-at-sea region. In this category, the minimum design capability required shall, in addition to the inherent sea keeping mission, provide for Electro-Magnetic Pulse (EMP) and shock hardening, individual protection for Chemical Biological and Radiation (CBR), including decontamination stations and Damage Control as well as Fire Fighting (DC/FF) capability to control and recover from conflagrations and include the ability to operate in a high latitude environment.

Level II represents an increased severity that includes the ability of sustained operations when in support of a battle group and in the general war-at-sea area. This level provides the ability for sustained combat operations following damage from weapons impact. Capabilities include requirements of Level I plus primary and support system redundancy, collective protection system, improved structural integrity and subdivision, fragmentation protection, signature reduction, conventional and nuclear blast protection and nuclear hardening.

Level III, the most severe environment projected for combatant battle groups, includes the requirements of Level II plus the ability to deal with broad degrading effects of damage from anti-ship cruise missiles (ASCMs), torpedoes and mines.

The protection requirements by ship class are summarized below and provide a representative and consistent understanding accepted by most navies. Table 14 affirms the important distinction that exists between design requirements for vessels designated as warships and other non-military or auxiliary craft. In particular, requirements for “combatants” are distinct from those of non-combatants in that they rely on expectations of mission capability following action damage. Combatants are expected to retain some degree of mission capability (e.g. ability to place ordnance on target) following action damage whereas non-combatants do not. The degree and nature of warship hardening follows from a more precise understanding of exactly what the warship must be able to do following an attack; how quickly it must be able to do this; and for how long.

The need for warships to “fight-hurt” was highlighted by the official discusser (Keuning 2015) who, in his critique of the Naval Ship Design Committee V.5 report at the 2015 ISSC, stated that mixing military and commercial standards may result in unforeseen incompatibility and degrade overall performance, particularly given that general structural design aspects influence vulnerability. Material specifications including steel quality; structural details; welding specs; stiffener types; and quality control need to form part of an integrated package. In many cases, commercial standards rely on specialized direction from naval experts, yet those experts are not aware of specific details in the commercial standards. Legacy naval ship standards which evolved over many years do address such requirements and need to be better understood by the non-naval community in keeping with the intention to harmonize efforts and integrate initiatives undertaken by Classification Societies and NATO groups (e.g. ANEP 77) to establish more compatible, albeit, commercial-naval standards.

Table 14: Protection Requirements by Ship Class (per OPNAVINST 9070.1)

SHIP CLASS	NUCLEAR/CONVENTIONAL WEAPON PROTECTION LEVELS		CBR PROTECTION LEVELS	NUCLEAR/CONVENTIONAL PROTECTION LEVELS (1)
	SHIP	EQUIPMENT	SHIP	PERSONNEL
AIRCRAFT CARRIERS	III	III	III	III
BATTLE FORCE SURFACE COMBATANTS	III	III	III	III
FRIGATES	II	II	II	II
AMPHIBIOUS WARFARE SHIPS	II	II	II	II
UNDERWAY REPLENISHMENT STATION SHIPS	II	II	II	II
UNDERWAY REPLENISHMENT SHUTTLE SHIPS	I	I	I	I
PATROL COMBATANT AND MINE WARFARE SHIPS	I	I	I	I
NAVAL STRATEGIC SEALIFT	I	I	I	I
MATERIAL SUPPORT SHIPS	I	I	I	I
ALL OTHER AUXILIARY SHIPS/CRAFT	I	I	I	I
(1) Note that personnel hazard environments include fragments and debris, thermal radiation, initial and residual nuclear radiation, chemical and biological agents, temperature extremes, fire, smoke and toxic products of combustion and laser irradiation.				

ANEP-77 is a NATO document intended to "provide a standard for naval ship safety based on and benchmarked against IMO conventions ... it does not include measures specifically designed to address the effects of military attack." The ANEP philosophy is summarized as taking a goal based approach that is amenable to become prescriptive so long as decisions are based on meeting higher level intent. The General provisions of ANEP-77 require the Code to be applied as a comprehensive set of requirements and clearly state it contains requirements for design, construction and maintenance of naval ships, and set levels of safety which are equivalent to those of merchant ships (Chap. 1 Part a Reg. 1a, Art 2.). Given that the ANEP does not address the effects of military attack and limits provisions to those of merchant ships, the concern raised by Keuning (2015) regarding mixing military and commercial standards seems to be reinforced.

Similarly, not all current commercial rules for high speed vessels address hull girder whipping loads. Hull girder whipping due to ship bow slamming vertically into the sea occurs repeatedly in high speed over the service life of the ship. Semi-probabilistic approach can be used to account for slam-induced loads due to random nature of the sea environment and the variable nature of the operational service of naval craft. The initial whipping moment should be combined with the peak wave moment to form a combined design hull girder bending moment. This slam induced bow whipping load becomes even more critical for lightweight high speed multihull naval craft. The high speed naval combatant (HSNC) rules developed by ABS provide formula for calculating these dynamic loads including bow slamming but do not directly apply to multihull ships. In this instance, a navy would need to develop their own requirements and incorporate them within the program specification documents.

Combatant requirements clearly recognize the need to avoid brittle fracture at high strain rates and invoke the need to avoid stress concentrations and provide notch tough steel for crack arresting purposes as a priority. They (e.g. NES 154 Art. 1.3) recognize that long stalk symmetrical Tee section stiffeners show significant advantage over bulb flats and angle sections by avoiding premature tripping under compressive and lateral loads in response to weapon effects and enabling and thereby maintaining efficient light weight inherently stable structures. On the other hand, Tee sections are less production-friendly and do not ensure that shear stresses can correctly flow from common stiffeners to primary ones. This often obliges to add a remarkable number of lugs, which unfortunately are quite difficult to weld, giving rise to potential crack initiations, especially in case of cyclic loading conditions. The ability of steel to absorb energy under high strain rate provides an important advantage for warship construction. So why would major new naval combatant programs select aluminium as a preferred material for construction?

3.1.2 The Cost-Benefit of Naval Standards.

Costs relating to combat and weapon systems are the single largest driver in shipbuilding even when costs of the weapons themselves are excluded (Sullivan 2006). Design trend aims for more sophisticated capability along with reduced crew size coupled with fewer but more capable ships of reduced displacement all lead to tighter volumes and accordingly, a commensurate and significant increase in fabrication and quality assurance costs. According to the US Secretary of the Navy, technology has provided us with extraordinarily capable ships but we cannot afford to buy as many of them as we would like (Winter 2006). While there may be some interest, it has been found that trends towards a globally integrated production system for naval shipbuilding are unlikely (Dombrowski 2002). The NATO Frigate Project (NFR-90) was cancelled, despite large investment by many navies, because inter-naval agreement on common requirements could not be reached, and only a few binational programs have been developed in the last twenty years (one example being the Horizon Destroyers, jointly developed by Italy and France).

Warship design in a way parallels several "expensive sports car" features. Warships need to be light, fast and stiff. Lightness is important to maximize payload. Extra weight added to structure reduces the payload capacity of the ship. The lighter the ship, the faster it could accelerate and enjoy the benefit of agility while avoiding weapon strikes. Stiffness adds a number of benefits for signature control, sea-keeping and machinery plant well-being. Accordingly, naval structural standards evolved more complex structures to improved structural continuity and optimize payload capacity at the cost of fabrication and schedule for construction. As an example, simulation studies conducted by Canadian Navy (late 1980's) found that comparable sized ships in terms of displacement and dimension built following Lloyds Rules would have a hull capable of surviving the same level of shock as one built to Canadian Naval Standards. The significant difference was found to be that the naval standard ship design had a payload capacity 30% greater than if it were designed using Lloyds Rules simply due to carrying 30% less structural weight to achieve the necessary strength of hull structure. Accordingly, a comparable ship built to commercial standard would require 30% greater displacement to carry the same payload as a naval design. Once again, the use of naval standards over commercial rules can yield structural efficiency benefits, but only if the navy or government is able to stomach the cost of time and money.

Weight reduction by use of aluminium, particular for warship superstructures, was popular for more than half a century. Issues began to emerge during nuclear simulation tests that found aluminium lost significant strength to the thermal pulse preceding the blast wave and required significant and costly measures to remain intact. In addition, shipboard fires such as the one that cost many lives on HMCS KOOTENAY in 1969 significantly reduced survivability of the aluminium construction. The KOOTNAY fire arose when a reduction gear casing exploded during full power trials and started a large oil spray fire in the main machinery space that rapidly spread to main passageways. The fire quickly melted the aluminium escape ladders and trapped machinery space operators and the rescue teams that fell through the weakened ladders and walkways. Also, the 5xxx-series aluminium alloys with magnesium content of greater than 3% are susceptible to sensitization and stress corrosion cracking at temperature higher than 50 °C. Highly sensitized aluminium alloys are not weldable and cannot be repaired. Figure 11 shows the damage to an aluminium superstructure arising from a collision with a steel ship bow.

Figure 11: On left: collision damage to aluminium superstructure. On right: only slight collision damage to the steel (naval) ship bow responsible for destroying the al superstructure.

Naval ships in many countries tend to remain in service for more than 35 years, or more than twice as long as merchant ships. Certainly a close watch on the fatigue life of aluminium vessels will be warranted on any naval vessel utilizing aluminium as a building material. The lessons from the KOOTENAY fire were applied by the Canadian Navy directly into ship design standards. Aluminium ladders and related structures were forbidden and a back-fit program implemented to correct the fleet. Secondary escape routes were verified suitable and back-fitted into the fleet as required. Electrical and communications systems were provided with improved action damage survivability features. Firefighting stations and practices were revised to account for a far greater range of "what-if" scenarios. While such efforts are possible within the context of naval practice, it is unclear how such lessons would find their way into quasi-commercial naval codes.

A good example of problems in this regard is emerging from the recent efforts to upgrade the survivability characteristics of the LCS (Littoral Combat Ship) variants (Eckstein 2016). Independence variant LCS ships are of trimaran hull form and are entirely constructed from aluminium including the main hull and are built to commercial ABS HSNC rules. These ABS rules are mainly applicable for mono-hull ships and do not address weapon or shock loading for ship platforms. Implications of commercial standards for structural design without augmenting with naval standards for shipbuilding clearly show the cost of performance penalties by recent attempts to “better militarize” the LCS project. The LCS project recently wrote down $115 million (USD) to comply with "arising" contractual requirements in order to meet the military shock standard and US Naval Vessel Rules that were introduced into the class performance requirement, likely in keeping with the OPNAVINST 9070.1 well after the initial fixed price contract was negotiated with the Pentagon. The USN LCS ships were originally contracted without call to follow military standards. Eventually the need to survive the naval combat environment and avoid cheap-kill was realized and extra-ordinary effort taken in an attempt to back fit appropriate combat survival capability. The recent shock trials (Figure 12) proved that back fitting can cost more than new build and unlikely to bring the LCS capability up to full grade (Eckstein 2016).

Figure 13 shows the relative effectiveness of naval opposed to commercial construction in that proper steel selection and scantling design remained relatively intact when compared to the extensive structural collapse in what should have been collision bulkheads in the bow of the much larger displacement merchant ship

Figure 12: USS Jackson (LCS 6) undergoing shot 1 of 3 full scale shock trial.

Figure 13: On left, collision between merchant and warship. Center: Warship damage. Right: Merchant damage.

Given the reliance of certain navies to adopt more commercial shipbuilding practice, there remains a need to better integrate naval design standards with those of commercial classification societies to ensure combat survivability does not degrade in an effort to save cost. The challenge remains on how to verify and address issues with commercial practice.

3.2 Recommendations

The design is the primary driver of quality, cost and schedule. Design variables become locked-in during early stages. The power of a fit-for-purpose structural design needs to be leveraged earlier, broader and deeper. That means that an early fix is less expensive than a later fix. Multi-functional teams are the key to solving the total design equation. There is a need to look at the life cycle from earliest stages. It must be recognized that since ship electronics and combat system are responsible for more than 60% of the program costs, a far greater saving can materialize by applying control measures there than by degrading structural requirements.

Most importantly it must be understood that the navy definition of “best value” differs from the commercial definition.

4 OFFSHORE OPERATION VESSELS

The Offshore industry is a vast and complex market that utilizes a number of various vessel types to support drilling, storage, processing, construction and other subsea activities. This chapter briefly highlights a few of the unique and recently relevant vessel types and their roles in offshore operations. These vessels each have their structural uniqueness that warrant them the title of “Special.”

4.1 Subsea Drilling/Construction Vessels

Ships that are designed for the installation and construction of the shallow section of subsea wells and seafloor infrastructures providing support for activities such as:

- Subsea and well activity
- Conductor and casing installation
- Well de-risking
- Pre-drill activities
- Well decommissioning and abandonment

Construction and subsea support vessels are used to support complex offshore construction, installation, maintenance and other sophisticated operations. They are significantly larger and more specialized than other offshore vessels. Some sub-types can be identified, such as:

- Cable lay vessels, built to lay pipelines on the ocean floor.
- Pipe lay vessels, to lay pipelines on the ocean floor, linking floating or subsea oil production units with onshore facilities, at increasing values of water depth of 2,000 meters and more.
- Subsea Crane vessels

Recent examples of subsea crane construction vessels are the "Far Sleipner", of abt. 8,790 dwt and an overall length of 142 meters and the “Skandi Afrika”, of about 16,000 dwt, both designed and built by VARD (RINA, 2016). It is expected that ultra-deep-water activities will increase in the next decades, which raise new type of problems with the structural integration of above deck equipment and ever increasing subsea cranes. Graaf and Zandwijk (2014) have developed a new concept to handle the logistic of above deck pipe reeling operations. The concept of exchangeable reels has been developed and implemented in the multi-purpose vessel "Aegir" to increase flexibility in quick reel mobilization and elevated foundational design to eliminate reeling downtime.

4.2 Self-Elevating Vessels (Lift Boats)

Jack-up Barges, Self-elevating Platforms, Lift boats & Spud pontoons are a type of mobile unit that consists of a rectangular hull fitted with usually three or four legs. These legs can have either a round or square cross section or truss type construction, and can raise its hull over the surface of the sea. Jacking or lifting takes place by rack & pinion, hydraulic cylinders or wires. The hull enables towing of the unit and to a desired location although some units have self-propulsion. Once on location the hull is raised to the required elevation above the sea surface supported by the sea bed. The legs of these units require a sea bead surface which prevents them to sink into it, although some may be designed to slightly penetrate the sea bed or may be fitted with enlarged sections or footings. Except for the larger types, generally Jack-up Barges and Self-elevating platforms are not self-propelled and manoeuvre on site by means of mooring equipment consisting of four winches with long wires and anchors. Over long(er) distances transport takes place with tugs dedicated barges for transportation or with semi-submersible / heavy lift ships.

These types of units are used for all kinds of stationary activities in relative shallow waters such as:

- Marine construction
- Oil well intervention activities (e.g. wireline and coiled tubing)
- Maintenance and repairs of offshore platforms
- Upgrading of offshore platforms

- Removal of old platforms
- Operational support of offshore platforms
- Temporary housing for construction and service crews
- Salvage

4.3 Heavy Lift (Semi-Submersible) Ships

A brief history of the evolution of the heavy-lift ships, characterizing some configurations such as the semi-submersibles and dock ships can be found in Van Hoorn (2008).

Cullen (2007) has presented an analysis of the use of existing heavy-lift vessels to marine maintenance and repair applications, avoiding the need to build a dedicated ship. A system to provide support for ship maintenance and repair was developed to be adaptable to any heavy lift vessel configuration available commercially. The feasibility of the solutions was demonstrated using 3D CAD system and applying it to three existing ships with different configurations.

The operation of heavy lift ships raises critical stability considerations that need to be assessed prior to conducting a heavy lift task. Handler et al (2012) have focused on the analysis of the de-ballasting of a heavy lift carrying another vessel and discussed the critical stability phases of the operation and the methods and the methods and practices to reduce the effects of reduced stability during those phases.

Yasseri (2012) has discussed the importance of the perception of factors in the environment and the understanding of their meaning and impact during critical marine operations such as heavy-lift. A systems engineering approach to Marine Domain Awareness (MDA) is presented and a model for developing the information exchange system during complex marine operations is proposed. The objective is to develop safer procedures and training programs to promote the use of MDA as a decision support tool.

The dynamics of offshore heavy lift is complex due to the interaction between the ship and the lifting object under severe environmental loads. Khac et al (2014) proposed an analytical formula using the double pendulum, based on the Euler-Lagrangian equations, to explore the insight of the heavy lift dynamics. The paper presents a practical approach to obtain reasonable results to improve the safety of offshore heavy lift.

Hatecke et al (2014) presented a fast numerical method to analyse heavy-lift operations of ships in short crested waves. The developed seakeeping method takes into consideration the coupled motions of the heavy-lift vessel and a freely suspended load. The speed of the method makes it especially suitable to situations when very long or a very large number of simulations are required.

4.4 Accommodation Vessels

Accommodation units also known as Flotels have several typical configurations, which strongly depend on the intended operation sites. In order to operate in harsh environments, for instance, it is necessary to have great seakeeping performance, thus only semi-submersibles are usually operating in North Sea’s Norwegian and British sectors. A few monohulls however have also operated in the North Sea (Danish sector and a state-of-the-art monohull for 600 POB in UK). Other regions more suitable to semi-submersibles are the Gulf of Mexico and Australia due to recurrent hurricanes and cyclones. Brazilian waters are considered benign, thus both semi-submersibles and monohulls may operate there. A Compact Semi-Submersible (CSS) in the accommodation vessel market had also operated in Brazil – Bacia de Campos. Lastly, barges do not have sufficient seakeeping performance to operate in any of the abovementioned seas and are usually not equipped with Dynamic Positioning Systems (DPS), thus they only operate in mild seas or close to the shore (Malaysia, Caspian Sea and West Africa). On the other hand, due to their relative low cost, they are actually the preferable solution for these operation sites.

Recent research done on the design of an accommodation unit was published starting from Pardo & Fernandez (2012), where a preliminary and strictly qualitative study on flotels was performed. It includes even accommodation units not designed for the offshore industry and coastal, i.e. accommodation units located by the coast and therefore built in accordance with different requirements, having to operate under different regulations, sometimes having also to meet luxury standards.

Research on the dimensioning of offshore platforms has also been performed, e.g. by Sharma et al (2010), where different optimization methods are discussed for the dimensioning of a semi-submersible platform. Their approach however is a general one and it does not consider the particularities of accommodation units.

A total of 72 dedicated floating accommodation units, 27 of them semi-submersibles – including 1 non-conventional compact semi-submersible (CSS), 27 barges, 17 monohulls currently operate within the offshore industry

4.5 SWATH Offshore Vessels

A review of the SWATH technology and market in general can be found in Grannemann (2015).

One of the applications of this type of vessel is crew transfer. Actually, the larger and fastest crew vessel available, the "Muslim Magomayev", is a semi-SWATH with 70 meters length, able to carry 150 passengers, a crew of 14 and 130 tonnes of deck cargo, in wind speeds up to 40 knots and seas of 3 meter significant wave height.

Smid et al (2014) presented a study where SWATH is compared with monohull and catamaran alternatives for the most cost-efficient crew transfer vessel to offshore wind park maintenance. The study concluded that the SWATH alternative could result in savings of about 50 million Euros over a one-year period.

Other offshore applications are the installation of wind turbines. The main design aspects of this concept, such as seakeeping, model testing in seakeeping tank, wind turbine landing sequence, and the workability are presented in Bereznitski (2011). One recent example of this type of vessels is the Wind Turbine Shuttle (WTS) developed and built by the Dutch company Huisman Equipment BV, which can transport and install two wind turbines simultaneously in high seas.

5 YACHTS

This chapter provides an update to the recent structural challenges faced in the field of yacht design and construction, with a focus on megayachts as stated in the committee mandate.

The ISSC 2012 V.8 committee was the last to discuss developments in yacht design, with the report focused primarily on motor yachts. The ISSC 2009 V.8 committee report mainly discussed sailing yachts, with a short update on the topic also included in the 2012 V.8 report.

As stated in Chapter 1, it is widely accepted that yachts in excess of 24m in length are classified as superyachts.

This gives rise to the most appropriate definition of yachts over 24m: as previously mentioned they are currently all widely regarded as superyachts, but terms such as ‘megayacht’ and ‘gigayacht’ are becoming more prevalent. The primary reason for the division at the 24m length is the significant change in regulations the vessel must adhere to for operation from (in Europe) the ISO standards to the Large Yacht Code (LY3) (Maritime and Coastguard Agency 2012), however with a significant number of vessels now in existence, and on order, up to, and well in excess of, 100m LOA this results in the newer terms being utilized. There is little consistent definition, however, of either the term ‘megayacht’ or ‘gigayacht’. Some state that megayacht applies to vessels over 60m LOA (Motta et al 2011) and some over 100m in length (Žanić 2015), however it is at this stage that not only length should be considered. Another big step in regulation change occurs for vessels in excess of 100m in length and with a gross tonnage of

3000te or more which are, in effect, classified as ships (Manta Maritime 2015, and previous V.8 report 2012). It is for this reason that the definitions stated in Table 15 have been applied and will be used throughout this Chapter.

Table 15: Yacht Types by Definition

Type	**Definition**
Superyacht	$24m \leq LOA < 60m$
Megayacht	$60m \leq LOA\ GT < 3000te$
Gigayacht	$LOA \geq 100m$ and $GT \geq 3000te$

5.1 Motor Yachts

The ISSC 2012 V.8 committee defined motor boats as 'vessels whose main propulsion is provided by a mechanic propulsion system represented, in most cases, by internal combustion engines but can include steam engines or more modern gas turbines'. This broadly still holds true; however, electric engines are also becoming more prevalent as battery technology improves and the engines themselves are more efficient. Owners of motor boats used for recreational purposes are also keen to be seen to be helping the environment with both hybrid and pure electric propulsion systems becoming more common in smaller craft.

1073 motor yachts over 30m LOA were delivered, launched or are in build from 2012-2021 (The Superyacht Intelligence 2017). 89% of these are superyachts, with only 8% qualifying as megayachts and 3% as gigayachts. The largest privately-owned motor yacht is Azzam, launched in 2013, Figure 14. She comes in at 180.61m LOA and gross tonnage of 13,136te.

Figure 14: 180m gigayacht MY Azzam (McNicoll 2013)

5.1.1 Megayachts and Gigayachts

The demand for increasing the size of pleasure craft has led those kind of vessels to reach, in recent years, the biggest dimensions ever seen, typical of small- to medium-sized passenger vessels. Recently, some yachts were even classified as passenger vessels instead of pleasure craft. However, this demand for growing dimension remains strictly linked to the design issues typical of a yacht (large glass surfaces, big openings in the shell due to the presence of shell doors, very irregular general arrangements with big unsupported spaces, etc.) and forces the structural designer to pay a deep and continuous attention to the structural details as well as to find every possible way to guarantee the structural continuity in both vertical and longitudinal directions. Ivaldi (2015) gives a good overview of the main stages of the structural design highlighting its peculiarities and the principal differences with the design of other kinds of ships. Alternative propulsion systems also provide structural design challenges, from supports to insulation. Lamberti et al (2013) assessed the applicability of an onboard Fuel Cell system to reduce the environmental impact, testing the feasibility of the proposed design through design changes of a Mega Yacht draft called XProject based on a LNG fuelled engine provided by Fincantieri. Kikkila & Erkintalo (2017) state that the general expectation for electric propulsion vessels is that Azipod propulsion is considerably lighter compared to shaftline propulsion with the same thrust, especially when taking into account savings in hull steel weight and conventional shaftline equipment due to components such as rudders/sterntubes/shaftline etc. not being required.

Design methods used for megayachts are trending towards those used in modern ship structures, due to their ever increasing size and hence applicability of such methods utilized for ships. Žanić et al (2015) assessed the benefits of modern rational design support techniques in the form of Finite Element Modelling and optimisation techniques, on an example megayacht of 100.8m in length for the concept, preliminary and detailed design phases. Use of ship design techniques resulted in a reduction of weight/cost and increased safety of the vessel indicating that such methods are well suited to application to megayacht design.

Korbetis et al (2015) explored the ability of ship design software to output CAD models of varying levels of details for use in parametric design optimization using an automatically updated Finite Element model. Design information and details concerning material properties, stiffeners, cross sections, tank loading and equipment masses are kept through the design process and used as input data for the FE model. Ascic et al (2015) investigated the PYC and its probabilistic approach to damage stability by describing the methodology of calculating the probabilities for flooding and surviving as well as its application on a 90m megayacht. They compare the use of deterministic damage assessment method to the probabilistic method for the PYC for the 90m yacht in the case study and found less than 1% difference between the two.

Another approach suggested by Bosma (2013) is the implementation of human comfort factors into the preliminary megayacht design stage, as opposed to the detailed design stage. A new approach to concept mega yacht design is considered by presenting a framework of how these identified human comfort factors can be implemented as early as possible within existing classical process of mega yacht preliminary ship design.

Design-driven innovation, the development of a design scenario by engaging with a range of interpreters in technology and cultural production, is widely used in product design and more recently McCarten (2013) and McCarten & Edens (2013) promoted its use in the field of megayacht design. A multidisciplinary superyacht design project engaging in Design-Driven Innovation through the application of a technologically advanced high speed platform combined with the implementation of a culturally specific emotional design framework has developed an Art Deco high speed superyacht coastal cruiser for the Chinese market based on a 130m pentamaran concept (McCarten 2013). McCarten & Edens (2013) discussed the use of Design Driven Innovation to create a new market between luxury cruising and superyacht charter for the American Market consisting of a main entertainment vessel (cruise liner) acting as a mothership, which transports SWATH floating apartments to various destinations where they are launched and recovered similarly to standard dockwise yacht transport.

With the increase in size associated with megayachts, and gigayachts, and the increasing number of such vessels in the market construction materials have become a subject of interest in order to improve performance and facilitate construction. Composites have long been implemented in the small boat industry, marine renewables, transportation and civil engineering and, as such, the technical knowledge of advanced composite materials has grown rapidly. Dassi (2015) highlighted the benefits of utilization of composites in the mega and gigayacht industry gained from these alternative industries, with focus on ease of processing and manufacture. Ghelardi et al (2015) assessed the concept of shear lag effective breadth of plating for a large composite hull comprised of stiffened plating. FE models were developed and validated to investigate the behaviour of the effective breadth of stiffened laminates when varying geometrical and other typical parameters of composite made ship structures. It was found that it is noted that boundary conditions, stacking sequences and structural configuration have an important influence on effective breadth.

A good understanding of the structural response of megayachts is key to proper optimization of the structure, be it globally or locally. In Pie et al (2015) the differences in structural response between a steel and aluminium mega yacht superstructure in waves are discussed. Larger overall deformations were observed in the aluminium structure, which then transmitted larger loads to the steel hull structure.

Comfort is a key design parameter for all luxury yachts, with maximum vibration levels being carefully assessed and minimized. Dellepiane & Boote (2013), Boote et al (2013) and Boote et al (2014) reviewed the so-called "Comfort Class Rules" – those issued by Classification Societies for the evaluation of vibration maximum levels. A detailed FE model of a 60m case study megayacht was carried out in order to investigate the dynamic behaviour of hull and superstructures. The results of modal and transient analyses are compared with a first series of experimental data gathered during the vessel construction. Noise Vibration Harshness (NVH) analysis, already well established in the automotive industry, and has only recently come into its own in the megayacht industry as part of Comfort Class Rules. Bermano et al (2015) investigated the dynamic behaviour of large yacht structures and applied an NVH methodology to a 60m megayacht in order to optimise a passive control device (a tuned mass damper system) or adaption to the deck geometry. This solution reduced vibration levels with the addition of only 600N of weight which is significantly less than the increase in structural mass and potential deck thickness in the conventional structural stiffening approach. Kikkila & Erkintalo (2017) found that the use of Azipod® propulsion systems, in place of conventional propellers and rudders, reduced perceived onboard noise and cavitation by 30-35%.

5.1.2 Superyachts

Various reasons have seen an increased level of caution from large yacht buyers recently; however, 122 sales of yachts over 24m in length were reported in the first four months of 2017 alone. This is similar to the 124 reported during the same period in 2016, and up 8% on 2015's figure of 113 sales suggesting that, even with increased caution, the industry is not showing any signs of slowing (Montigneaux 2017). As with megayachts, features only associated with the luxury yacht market govern the structural design of such vessels. A bespoke tender garage/beach club design and its impact on the vessel design is discussed by van Loon (2015), with Uithof et al (2015) proposing use of a Hull Vane ® on a 50m trimaran to reduce resistance – however this will bring structural challenges in itself.

McCartan et al (2015) employed the approach of Design-Driven Innovation to take advantage of the reduced regulatory framework for superyachts under 500GT which offers a significant opportunity for a greater percentage of interior volume to be assigned to guest activities, due to a reduction in both crew area requirements and fire insulation and the absence of certain requirements such as an emergency generator.

Archer & Roy (2013) investigated the application of Platform Engineering to the 25-50m yacht market and highlighted some of the barriers that result from production boat builders, traditionally focused on yachts of less than 24m, increasing the size of their product in order to enter the superyacht market.

Optimisation tools are becoming increasingly commonly suggested as a method for improving the design of large yachts. Mutlu et al (2017) explored various optimisation algorithms with regards to the design of composite stiffened panels for large yachts. A top-hat stiffened composite plate was optimised for the objectives of mass/stiffness and mass/strength with Pareto fronts for each Genetic Algorithm, and their relationship to the variable space and computational times were compared. Nazarov (2013) presented the review of design experience for catamaran superyachts 30-35m long. Comparison of catamarans with traditional monohull motor yacht is presented in terms of usable space and layout concepts with parametric optimization of initial key design variables.

The industry is seeing more suggestion of the use of novel hull forms, such as SWATHS as a method of limiting slamming/seakeeping loads and bringing yachts in like with Comfort Class Rules. (Begovic & Bertorello, 2015; McCracken, 2015). Abeking & Rasmussen already construct SWATHS for commercial applications and have recently been collaborating with Reymond Langton Design to develop a luxury 62m SWATH with interior volumes equivalent to that of an 80m monohull.

Aesthetics are key for all luxury vessels, and defects such as bumps and hollows due to welding are not acceptable on the surface finish in the industry. Vessels of composite manufacture often have improved surface finishes, but this is highly dependent on the method of construction and type of mould used. All vessels require some level of filling and fairing to produce a surface suitable for painting. Giannarelli et al (2015) investigated of the influence of temperature on the mechanical behaviour of steel plates coated by filler layers. The study included FEM structural analyses calibrated by experimental measurements performed on laboratory specimens simulating yacht hulls exposed to solar radiation in various conditions. Gaiotti et al (2015) focused on the macro-mechanic properties of fillers currently applied on yacht hulls and superstructures. Two types of tests were carried out for different fillers: a compression strength test on isolated filler specimens and three-point bending test on specimens made by filler applied to a steel substrate. Load-displacement curves of test specimens were determined.

One common component throughout the luxury yacht industry is the large amount of glass incorporated in various ways in the design of vessels. This is key structurally, with the dynamic response of laminated glass to vibrations and the quasi-static response key in the structural assessment of the material used in each yacht. Gragnani et al (2015) presented a method for identifying a dynamic model of laminated glass that can be used to carry out acoustic calculations for a numerical yacht model. The owner’s cabin windows of a superyacht are assessed using the proposed method.

5.1.3 Expedition Yachts

An expedition yacht is a versatile vessel which has the ability to cruise self-sufficiently for long periods of time at sea. The vessels travel through extremes of temperature, from the South Pacific to ice filled waters of Alaska, and are required to withstand a myriad of conditions for extended periods of time. Designed and built with power, stability and efficiency foremost to mind, with the addition of a deep displacement hull, they often incorporate extreme structural design challenges associated with ice breaking capabilities for example, whilst maintaining the same high standards of interior design of their shorter-range counterparts (Lyons 2015). Current expedition yachts are in the length range of super and megayachts, however there is one in development in excess of 160m putting it firmly in the gigayacht category. Nonetheless, the unique environmental challenges these yachts must withstand put them in a category on their own.

McCartan et al (2017) utilised their Design-Driven Innovation approach to present a 300m sustainable luxury Ice-Class Arctic explorer vessel which supports scientific research and curated luxury experiences. The vessel is to be hydrogen powered, incorporating a further level of structural challenge. Other propulsion solutions for the novel vessels include Azipods® (Kokkila, 2017), due to better vessel manoeuvrability, improved passenger and crew safety, greater fuel efficiency and lower total cost of ownership. Azipods ® are currently fitted on the polar discovery yacht Scenic Eclipse – the world's first passenger vessel to be constructed explicitly to Polar Code standards.

In 2015, Damen developed a range of purpose built globally capable expedition yachts (65m, 90m and 100m) – the SeaXplorer. Designed specifically for the expedition market, the yacht has the operational profile of an expedition vessel, with Polar Code requirements implemented in the core design. The hull shape has been optimised, ice breaking capability defined alongside the propulsion system and other purpose specific requirements without compromising the safety and luxury comfort of the yacht in any way (Van der Velde et al, 2016). EYOS expeditions provided insight into the unique operational envelope for the vessel with in excess of 150 design criteria, and the hull form was assessed and optimised through HSVA model tests which helped define the ice strengthening regions along the hull with respect to the Polar Class Demands. The first SeaXplorer 65m has been sold for delivery in 2019. The vessel will be capable of full autonomy for 40 days and complies with the environmental and safety standards in the IMO Polar Code's B category.

Figure 15: The REV (http://rosellinisfour-10.no/)

VARD (2017) are also to enter the expedition vessel market with the 181.6-metre Research Expedition Vessel (REV), Figure 15. Construction of the vessel will take place in several stages, with the hull to be built at VARD's Tulcea facility in Romania. It will then be towed to the company's shipyard in Brattvaag, Norway for outfitting, and following hand over to her owner in Norway in the summer of 2020, the ship will be returned to Romania where fairing, deck-laying and finalisation of the accommodation areas will take place. The vessel has a length of 181.6m, Beam of 22m, draft of 5m and a gross tonnage of 16,000te. With a maximum speed of 17 knots, the vessel can hold up to 60 scientists and 40 crew members. During luxury expedition trips the REV is designed to host up to 36 guests together with a company of 54 crew members.

5.1.4 Small Yachts

With the committee mandate focussing emphasis on larger yacht structures, this section is a short update as to the developments in the small yacht (under 24m) industry. Of key note in the motor yacht industry is the use of Fluid structure interaction (FSI) methods to optimise the structural design of vessels. Fong & Chang (2014) and Fong (2011) used validated ALE and SPH simulation approaches to calculate slamming impact loads for a 58' planing yacht for use during structural design. Further discussion as to slamming loads on vessels is undertaken in the Sailing Yachts section.

5.2 Sailing Yachts

Sailing yachts differ from motor yachts insofar as they have a primary method of propulsion that uses sails, powered by the wind, to propel the vessel. While they comprise a much smaller share of the yacht market than motor yachts with only 123 yachts over 30m LOA were delivered, launched or are in build from 2012-2021 (The Superyacht Intelligence 2017), their size range these days is growing with 96% of these superyachts, 2.5% megayachts and 1.5% gigayachts.

5.2.1 Giga, Mega and Superyachts

The largest sailing yacht launched to date is SY A, Figure 20, which comes in at just under 143m in length and 12,600GT and is shown in Figure 20.

Figure 16: SY A (Horn 2015)

Whilst many design methodologies are just as applicable to sailing and motor yachts, some case studies have been carried out focusing wholly on sailing vessels. Shaw (2015) explored the possibilities for performance, function and form achievable through refocusing the design drivers in the development of a superyacht, with a fresh emphasis on the design and engineering aspects of construction, hull form, sail plan and appendages.

McCartan & Kvilums (2013) explored the principles of 'Passive Design' to produce a sailing catamaran design concept that addresses the 'green luxury' gap in the market for luxury charter performance orientated vessels, which implement ecological technologies that enhance the user experience and also benefit the environment.

Sail and rig system design is evidently key to the success of a sailing yacht. Gaiotti & Rizzo (2015) moved away from the more traditional empirical approach to rig design and applied numerical simulations to assess effects of load variations in time of a pre-tensioned slender structure. The dynamic buckling of the bottom panel of a typical large mast is evaluated, showing significant differences from the widely applied quasi-static approach. The obtained results provide a new perspective for the scantling assessment of sail systems, overcoming the current empirical and prescriptive approach proposed by rules of classification societies and international standards. Fossati et al (2015) provided an overview of the experimental research carried out in the Politecnico di Milano Wind Tunnel aimed to support the sail inventory development for the high-performance superyacht Magic Carpet[3]. Sail shape and the effect of flexure on performance is discussed.

Composite materials have long been prevalent in the racing yacht industry, with sailing megayachts such as Mirabella V constructed from composite materials since 2002. With an increase in scale, autoclave production is negated and out-of-autoclave prepregs become the construction material of choice for high performance marine craft. Voids are not collapsed by the low external compaction pressure, and have potential to cause structural instabilities. Hickey & Bickerton (2015) presented the development of experimental techniques to accurately measure the as-laminated void content, compaction response and in-plane and through thickness air permeability of two prepreg materials.

While the majority of the motor yacht market is often seen as a competition for the largest yacht, the sailing industry produces some truly unique vessels. In 2012 BANQUE POPULAIRE V a 40 m LOA sailing trimaran circumnavigated the globe non-stop and without external assistance in 45 days and 13 hours at average speed of 26.5knots, which is a record at present unattainable by motorised craft. Bertorello & Begovic (2016) discussed the specific design aspects of the most recent boats for the circumnavigation record and showed how the latest available technical and technological resources have been exploited.

Köhlmoos et al (2012) reported on “Tûranor PlanetSolar”, the world’s largest solar powered vessel. The aim of the vessel was to demonstrate the capabilities of current photovoltaic solar cell technology. The vessel comprises a wave piercing catamaran hull design, powered by electric motors and semi-submerged carbon-fibre propellers. The combination of these technologies allows the 85te craft to cruise at 7knots consuming an average of 20 kW of installed power, buffered by lithium-ion batteries. Load prediction mechanisms for boats which do not fit the standard rules have been developed with the class society agreeing "best engineering principles" be employed for structural analysis.

5.2.2 Racing Yachts

Racing sailing yachts, especially America’s Cup vessels, are at the forefront of pushing technologies into the marine industry. Key developments in this field in recent years are primarily in the field of composite materials and their response to the loads imposed by the inherently harsh environment racing yacht are subjected to. Seo et al (2015a) investigated the current trends of composite applications in the marine and leisure fields to study the development of a 33ft America’s cup training CFRP sailing yacht. Lake et al (2012) used the manufacture of the AC45 catamarans as a case study of the efficiencies and accuracies gained by using CNC machining technology in manufacturing high performance racing yachts and multihulls. CNC machining was found to reduce the amount of time to manufacture the hulls by at least 15% and the costs by around 10%.

Different types of porosity found in traditional racing yacht structures were presented by Bayle et al (2015). Current developments to improve racing yacht composite quality such as thin ply technology, out-of-autoclave processing and automated fibre placement were assessed and their implications for porosity discussed.

Detailed assessment of the effects of salt water and xenon light, salt water spray test and xenon test were undertaken on CFRP specimens with a total of 15 plies by Seo et al (2015b). Tensile strength of each specimen was compared both before and after exposure to the environmental conditions. The resulting tensile strength of composite specimens was adversely affected by salt water (2-9% decrease) but improved with exposure to xenon light by around 8%.

Slamming is an inherent issue with racing yachts which are being pushed to their design limits in a wide variety of environmental conditions. Allen & Battley (2015) characterised the variations in both applied pressure and panel response due to hydroelasticity of panels, previously assumed to be rigid. They found changes in both loads and responses were largest at the centre and chine edge of the panel. These variations were related to the significant changes in local velocity (centre) and deadrise angle (chine).

Goutard et al (2012) developed a Finite Element - Finite Volume (FE - FV) coupled method to assess slamming and the effect of hydroelasticity on slam induced pressures. It was shown that the coupled numerical model captured well the underlying physics of slamming, and the predicted pressure field and structural response agree well with the experimental results.

Weber et al (2015) and Battley et al (2012) both stated that the majority of slamming assessments to date have been carried out on flat panels; however, racing yachts are rarely comprised of flat panels and there is likely some difference in the reaction of curved panels to slamming as opposed to flat. Weber et al (2015) investigated the effect of curvature on slamming loads through the use of constant velocity experimental testing and coupled Finite Element-Smoothed Particle Hydrodynamics numerical simulations. The work showed that curved bodies experienced a much higher initial loading than rigid wedges, which then abated to a quasi-constant residual load. Battley et al (2012) described the results of a parametric study investigating the effects of stringer stiffness on panel skin stresses and core shear stress distributions for curved sandwich panels. Analytical results, finite element modelling and experiments were conducted on flat and curved sandwich panels, with various boundary conditions under a uniformly distributed load. The results showed that responses of curved sandwich panels differed significantly from those of flat panels, and that the stringer compliance had important effects on the panel responses.

Appendage design has long been a source of design for racing yachts, particularly with the advent of foiling multihull America’s Cup contenders. Keel flutter, vibration which is due to the excitation forces of the fluid on the keel, has appeared as a major technical issue for designers with potentially catastrophic outcomes. In Mouton & Finkelstein (2015) an FSI method under assessment was validated through examination of three as built’ keels, representing a wide range of known flutter behaviour. The presented results showed a good correlation between on-the-water experience and the calculated predictions.

5.3 Recommendations

The total number of yachts over 30m in length on order alone in 2017 up at 760 shows a positive increase in the superyacht market compared to 692 in 2013. There is also an increase in demand for longer, larger vessels with terms such as ‘megayacht’ and ‘gigayacht’, as defined by means of LOA and GT in this Chapter, becoming more prevalent. Such large vessels come with their own inherent structural challenges and it is these that the chapter have focused on, with an update as to new and novel work done in other areas of recreational yachting.

The development of large vessels that are capable of expeditions into hostile environments and comply with Polar Class rules is on the rise, and it is recommended that the next committee focus in on this expanding fleet with many structural challenges apparent balancing luxurious accommodation and facilities with practicalities of travel in hostile seas and use/storage of scientific exploration equipment. Alongside this, there are more Gigayachts in build, and it is recommended that the challenges of application of Ship Class rules to such large vessels are examined. Other areas that may be considered include fast pleasure craft and pleasure submersibles.

6 SPECIAL HULL AND APPURTENANCE STRUCTURES

Within the last decade there are numerous examples of innovative and special-purpose hull forms which require various structural configurations to achieve speed, payload capacity and mission complexity. As discussed from a regulatory stance in Chapter 2, the vessel types addressed in this Chapter include free-fall lifeboats, SWATH vessels, heavy lift vessels, icebreaking vessels, wave-piercing vessels and others. Their geometries, structural topologies and materials required for the structural configurations did not fit well with traditional design methods and procedures rooted in empirical approaches. Instead, these ships and their appurtenance structures, such as moonpools and helidecks, require direct analysis or first-principles approach, mainly requiring computer aided processing.

6.1 Freefall Lifeboats

Freefall lifeboats were designed to be fast and reliable evacuation systems. For example, the launching of a freefall lifeboat is to simply slide from a skid before the freefall. Immediately after the water impact, the propulsion system will start and the lifeboat will then sail away from the parent vessel. The trajectories of freefall lifeboats during the launching process depend on the headway and advance speed after water entry and surfacing of the lifeboats. In the years prior, research work has focused on the different aspects of the structural design, such as the materials and the loads (ice loads, impact loads).

Browne et al (2008) developed a practical design and prototype of an Ice-Strengthened Lifeboat (ISL). This lifeboat was designed to reduce the risk of damage or loss due to crushing by ice during evacuation from offshore installations or vessels in ice covered waters. This novel design combines new hull shape features with a composite shell, reinforced structurally to resist the ice loads.

Similarly, the work developed by Kennedy et al (2010) focused on the determination of the structural limitations of the existing freefall lifeboats (non ISL) which would be subject to ice impact loads in order to develop operating procedures for a safer operation in icy waters.

Based on field trials with conventional freefall lifeboats, Simões Ré et al (2011) investigated the extent of the ice limits operational capabilities. Measurements were made with ice loads from different ice conditions and in different types of operations.

A Freefall Lifeboat (FFLB) must be able to avoid irregular motion and resurface at a sufficient distance away from the host ship. In Tregde and Nestegård (2014), a FFLB drop simulator was developed and used to produce a database of random drops from a floating ship in storm conditions, intact or damaged. The database was used as a basis for regression analysis to estimate the responses for different wind, waves and host ship conditions. The objective of the study is to analyse the motion trajectory of the FFLB and to check its ability to escape the host after resurfacing in accordance with the design standard.

Hwang et al (2014) developed a method for design modification of structurally damaged FFLBs based on the results of skid launching freefall tests, analysing the four phases of the fall: sliding, rotation, free-fall and water entry. The aim of the work is the improvement of the structural design of existing FFLBs.

The work of Rahman et al (2015) presents an analysis of local ice loads measured during full-scale field trials conducted in 2014 with a totally enclosed motor propelled survival craft (TEMPSC) in controlled pack ice conditions. The event-maximum method of local ice pressure analysis was used to analyse the field data in order to improve the understanding of the nature of ice loads for such interactions. This analysis was also used to evaluate the suitability of the approach for design load estimation for TEMPSCs (i.e., lifeboats) in ice. The work established links between extreme loads and the exposure of the lifeboat to ice for different operating conditions. The work also concluded the event-maximum method provided a promising approach for establishing risk-based design criteria for lifeboats if field data are available which adequately represent ice conditions encountered during the design life of the lifeboat.

Simões Ré et al (2012) presented ideas for improving the capabilities of lifeboats while complying with the regulations in the sea ice conditions, understanding they can be met in offshore operations. Model scale and full scale trials were carried out with special attention to select design aspects, such as powering and propulsion, manoeuvring, structural resistance to ice loads, and arrangement of the coxswain's cockpit.

Simões Ré & Veitch (2013) carried out full-scale field trials of a conventional lifeboat in pack ice to investigate design considerations such as powering and propulsion, hull form, manoeuvring, ice loads and ergonomics. This paper focuses on local ice loads measured on the hull during aggressive operations in pack ice. Field measurements are presented and the implications for design and safe operations are discussed.

Kennedy et al (2014) investigated design considerations for a conventional Totally Enclosed Motor Propelled Survival Craft (TEMPSC) operating in ice. Local ice impact forces were measured in field testing. The results are presented and the operational performance discussed.

Hwang el al (2016) presented design modifications to reduce the impact pressure during water entry of free-fall lifeboats (FFLB) based on full scale tests carried out with a damaged FFLB. The test analysed four phases of the launching process: sliding, rotation, free-fall and water entry. In the water entry phase, structural damage can be avoided by reducing the top deck impact area and by increasing the modular factor of the roof deck which ultimately modifies the structure of the deck and its shape.

6.1.1 Impact Loads

In the sequence of unacceptable structural deflections found in the roof of FFLB resulting from offshore installation tests, an extensive research project was carried out at MARINTEK to study the main performance factors in rough weather conditions (100-year storm - Kauczynski et al 2009). An extensive program of model tests for different types of FFLBs was carried out. FFLBs were launched by a vertical drop method or from a skid in different weather conditions, still water, regular and irregular waves. The results were then compared with full-scale tests and the conclusions were used to propose and discuss new structural performance and technical criteria for the hulls.

The work of Sauder and Fouques (2009) focused on the safety of occupants of FFLB during water impact. A theoretical method was developed to predict the trajectory in six degrees of freedom of a body entering water waves and to compute the slamming forces and moments. The model was validated by extensive model testing in calm water and irregular waves.

Luxcey et al (2010) focused on the numerical evaluation of acceleration loads during water impact of FFLB launched from the skid. Two wave models are considered. Linear waves are compared with regular Stokes waves of the 5th order and linear irregular waves are compared with irregular waves of the 2nd order. The modeling detail of the launching skid is also taken into consideration.

Tregde et al (2011) used CFD to obtain design loads on a FFLB. The results were then validated with full scale tests. The larger structural loads, such as those due to hydrostatic, dynamic and slamming pressure, correlated very well with the full scale testing results.

The work of Ji et al (2015) focused on the assessment of the structural integrity of lifeboats launched from FPSO vessels. The pressure distributions on the impact were computed by CFD simulations, for different load cases, and quasi-static finite element (FE) analyses were performed. The non-linear load/response effect when the load factor is applied to the load was studied by a sensitivity analysis. Also investigated was the time-varying pressure distribution for selected cases and the dynamic effects that resulted from them.

Designing against impact loads (slamming) can be challenging and time consuming, involving advanced analyses and complex calculations. In the work of Heggelund et al (2015), the application of simplified, quasi-static calculation approaches to the design of freefall lifeboats is discussed extensively. The authors concluded although the results are on the conservative side, simple hand calculations including non-linear geometry can be used to predict the maximum strain on the fiber reinforced plastic hull structure due to impact loads. They also investigated linear methods, but concluded they should be used with more rigid structures such as stiffened steel and aluminium panels.

Zakki et al (2016) developed a new type of FFLB for the quick evacuation from offshore platforms. A new hull form was designed and the acceleration response due to slamming was studied, using a Fluid Structure Interaction (FSI) analysis with the penalty coupling method. The numerical results were then compared with the requirements of the IMO regulations.

6.1.2 Simulation

Berchiche et al (2015) presented the results from model tests and CFD simulations of lifeboat launches in regular waves. The validation shows that predicted accelerations agree well with the measured ones. The simulations provided near accurate or relatively conservative estimates of the local pressure at various locations on the hull except on one location on top of the canopy where the pressure was slightly under-predicted. Furthermore, it has been shown to improve the predictions of the pressure loads on the aft wall of the lifeboat, the compressibility of air has to be taken into account in the simulations in order to capture the behaviour of the air-pocket behind the lifeboat.

Zakki et al (2015) investigated the influence of some launching parameters such as sliding distance, angle of skid and the falling height on the motion pattern of the freefall lifeboats by using Fluid Structure Interaction (FSI) analysis. The results of the numerical simulations provide the magnitude of launching parameters for safely launching of the freefall lifeboat.

6.2 SWATH Hulls

SWATH, Small Water-plane Area Twin Hull, typically have two submarine-like lower hulls which run completely submerged. When in the water, a SWATH resembles a catamaran. There are two other components to the hull: 1) the struts and 2) the haunches. The haunches, which blend into the decks and bridge, are connected to each submerged hull by one or two relatively thin vertical members, called struts. The longitudinal cross-section of each strut is roughly half the width of the submerged hull, and is streamlined to decrease wave-making resistance.

There are two key advantages for designed SWATHs: (1) the ability to provide big-ship platform stability and ride quality in a smaller vessel; (2) the ability to maintain normal cruising speed in rough head seas. The cross-structure load and strength is one of the key points from the view of the SWATH structure. Figure 17 shows the typical load cases that need to be considered (ABS, 1999).

Thomas Mathai (2006) carried out research on the Wave-induced cross-structure loads for a SWATH vessel. The hydrodynamic problem is solved using the higher-order boundary element method and the generalized modes approach available in the radiation-diffraction program WAMIT (Lee and Newman, 2001). The difference between cross-structure loads computed in earth-fixed coordinates and the same loads computed in body-fixed coordinates is illustrated. In the absence of any damping from viscous effects and separation, the computed free surface elevation in the gap between the hulls exhibits large sloshing at resonant frequencies. The effect of sloshing resonance on the computed loads is shown. A technique was proposed by Newman (2004) to simulate the additional damping and thereby obtain more realistic predictions of free surface elevations and cross-structure loads.

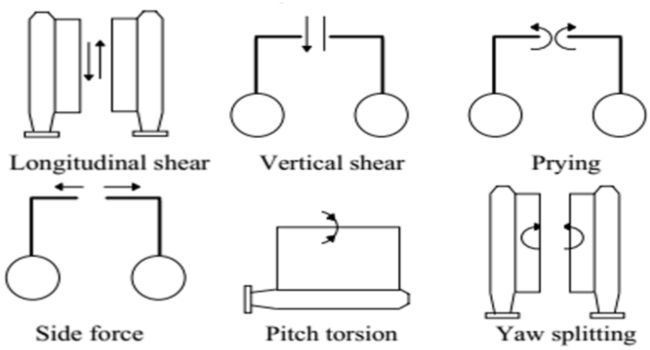

Figure 17: Considered Design Loads on SWATH Hull Structure

Chen Ying et al (2012) presented one corrected formula for the lateral force of the SWATH by comparing CCS Rules (2005), ABS Rules (1999) and model tests. Finite element analysis is carried out for the vessel in six typical load cases. One more dangerous load case - 60^0 oblique wave - is suggested for the structural strength.

The stress concentration of SWATH's cross-deck structure is serious. Zhen Chunbo et al. (2014) studied the structural strength in heading and oblique waves using the 3-D global FEA model. Ren Huilong et al (2015) analysed the high stress concentration problem of the SWATH connecting bridge local structures using FEA method. Sub-model method was used to analyse a fine mesh model of the connection of a sponson platform and pillar. The SWATH structure optimization solution using the parametric sub-model method is proposed.

Complex lateral load, special structural form and extensive use of high-strength steels cause serious fatigue strength problems of typical details of SWATH. Zhen Chunbo, Ren Huilong et al (2012) carried out a model test on the fatigue of a SWATH ship's cross deck structure.

6.3 Heavy Lift Hulls

The heavy lift vessel is also known as the floating crane. It is widely used in offshore large lifting, salvage, bridge construction and port construction, etc. Many heavy lifting vessels are used for offshore platform construction or demolition. With the gradual development of offshore oil and gas development to the deep sea, the offshore platform is becoming large-scale. Lifting capacity of the crane ship is increasing.

For the mono hull ships, more attention is paid to the overall strength of the hull and the local strength of the base. Xu Fan-fan et al (2015) analysed the strength of a 12000t heavy lift vessel by FEA, ZhenHua30, whose lift capability is the largest now among mono hull ships. The stress distribution of three cargo holds and crane foundation of a 12000t heavy lift vessel under some typical load cases were obtained.

The semi-submersible ship is another type of ship hull which is suitable for the heavy lift vessel. Yi Caiying et al (2012) analysed the global strength of one 16000t deep-water semi-submersible pipe-laying crane vessel. SESAM code was used to predict wave induced loads and corresponding structural responses. 35 wave load conditions together with four different loading conditions were considered. Stress concentration was obviously found in the connections of pontoon and pillar of the vessel. Structure strength was checked using ABS rules.

For twin-hull ships, more attention is paid to the strength of the joints of the two hulls. 'Pioneering Spirit', 382 meters length, 124 meters width, is one of the largest twin- hull ships ever built. The bow of the ship is equipped with a 48000 tons lifting capacity crane, which is the largest facility for the installation and removal of large offshore oil platforms. The ship, once equipped with the pipeline laying system, will become the largest vessel.

Two key recommendations for a heavy lift vessel's structure design are be wary of shear strength and stress concentrations. In order to avoid stress concentrations, the longitudinal components of floating crane hull should be strengthened, such as the longitudinal bulkhead and the inner bottom near the crane. The longitudinal bulkheads and side panels near the base of crane need to be properly thickened to ensure shear strength.

6.4 Icebreaking Hulls

Ships navigating in ice-covered waters experience local and global ice loads due to ice-hull interaction. The design of a ship with good ice performance requires adequate assessment of these ice forces, including distribution in time domain and also along the ship hull.

Erceg et al (2014) presented a quasi-static numerical approach to model the initiation of icebreaking pattern in level ice. The model accounts for the bow geometry and the properties of the encountered ice. The icebreaking pattern for a case study ship is simulated using the developed model. The sensitivity of the model with respect to the bow shape is discussed.

Li Zhou et al (2017) showed a method to simulate non-simultaneous crushing failure in time domain based on previous research on simulations of bending failure between intact ice and the hull. The simulated results are also compared with model test results. Simulated ice loads are in good agreement with the experimental results in terms of mean value, standard deviation, maximum and extreme force distributions, though there are some deviations between predicted and measured results for certain cases.

SY Jeong et al (2015) performed model tests in the ice model basin in Korea Research Institute of Ships and Ocean engineering (KRISO) with the model of icebreaking ship Araon. The Self-propulsion tests in level ice were performed with three different model ship speeds. Three tactile sensors were installed to measure the spatial distribution of ice load acting at different locations on a model ship, such as the bow and shoulder areas. Variation in the distribution of ice load acting on a model hull with ship speed is discussed.

In various ice conditions, icebreakers generally suffer significant ice load on ship's hull. Normal operating conditions are expected from the planned field ice trials and also from general ice transits. Sometimes an icebreaker may encounter extraordinary ice conditions during unplanned transits and / or unusual weather conditions.

Choi, Kyungsik et al (2015) revealed the peak ice pressures results recorded from the Korean icebreaking research vessel ARAON, during her normal operations and also unplanned ice transits trials in the Antarctic sea during the 2012 summer season. Strain gauge signals were recorded during her planned icebreaking performance tests and also during the unplanned ice transits in heavy ice conditions. The peak ice pressures on the ARAON's hull during the planned and the unusual ice transits were then compared.

In order to further optimize the hull forms and enable more efficient ship operations, Mård (2015) performed experimental studies on the icebreaking process of an ice breaking trimaran in Aker Arctic's model basin. The side hull encounters an ice field with micro cracks caused by the middle hull. These micro cracks enable the side hulls to break the ice with a small resistance. The model test results show the minimal ice resistance of the icebreaking outer hulls are due to a beneficial icebreaking efficiencies of the middle hull.

6.5 Wave-Piercing Catamaran Hulls

The Wave-piercing catamaran was developed on the basis of a high-speed catamaran, which is the product of the combination of small waterline and deep V ship's good navigation performance and the structure of the catamaran and hydrofoil arc struts. Wave-piercing catamarans are used extensively for both defence and commercial sea transportation. Advantages such as a large deck area, stability and high speed make these catamarans suitable for transporting roll-on roll-off cargo and passengers. However, issues such as the impact of the bow into the water when operating in large waves, better known as wet deck slamming, can affect their mission capability and can cause structural damage. Slamming of the wave piercer bow is a complicated unsteady hydrodynamic process as the bow enters a wave. Slamming occurs due to the rapid unsteady confluence of water displaced by the demi-hulls and Centre bow at the top of the arches in the hull cross section.

A Shahraki, Jalal Rafie et al (2013) study focused on the centre bow design for a wave-piercing catamaran. In order to evaluate the effect of various centre bow hull forms on motions and slamming loads, a hydro elastic segmented model was designed and constructed. This segmented model is a scaled model of a 112m INCAT wave-piercing catamaran and has two transverse cuts and a separate Centre bow. The Centre bow segment was equipped with two six degree of freedom force/torque sensors to allow for slam loads to be measured. Three Centre bow volumes (lengths) were designed and tested in head seas in the AMC towing tank in regular waves. The results show a significant variation in slam loads when comparing the three Centre bow lengths, with the highest loads found on the longest Centre bow, caused by larger water volume constrained between the Centre bow and demi hulls. Results also showed that the longer Centre bows have higher pitch motions in slamming conditions.

Lavroff el al (2015) from Australia conducted research on slamming and corresponding whipping energy for wave-piercing catamarans. The model tests carried out were intended to identify the most severe slams possible. For a 112-m vessel with 2500 tonnes displacement slams in 5.4 m height, regular waves would reach a maximum force of 2115 tonnes weight with a duration of 1.14 seconds and an impulse of 918 tonne seconds. The energy imparted to structural deformation would reach 3.9 MJ at full scale, of which approximately 1.0 MJ would be transferred into structural whipping. The results obtained in these model tests are broadly consistent with the most severe slam loads observed during sea trials.

Lavroff et al (2017) studied the wave impact loads on wave-piercing catamarans. Wave slamming is investigated for the 112 m INCAT wave-piercer catamaran with reference to experimental work conducted at full scale, numerical computation by CFD and FEA and testing at model scale using a 2.5 m segmented hydro-elastic model. The segmented model was tested in regular head seas to investigate the magnitude and location of the dynamic wave slam force and slam induced hull bending moments. Scaled slam forces of up to 2150 t weight (21.1 MN) were measured during model tests for a full-scale vessel with a loaded displacement of 2500 t. These slams can impart impulses on the bow of up to 938 t weight-seconds (9.20 MNs) and strain energy of up to 3.5 MJ into the ship structure based on scaled model test data. The impact energy is transferred primarily to the main longitudinal whipping mode. Thisdecays with an overall structural damping ratio of 0.02–0.06, strongly dependent on internal frictional mechanisms within the ship structure.

In order to analyse the applicability of different high speed craft rules and select suitable ones for the design of a high speed wave piercing catamaran, Wang Xueliang et al (2010) evaluated the global design wave loads according to regulations in DNV, ABS, CCS and LR rules. Meanwhile, model tests of this catamaran are performed in the seakeeping basin of CSSRC to confirm the design values in heading and quartering seas. It is concluded that the methods from DNV and CCS rules are rational for the structure design while those from ABS and LR rules gave relatively conservative design value for this catamaran.

Wang Weiwei et al (2013) carried out research on fatigue strength assessment of typical spots in wave-piercing catamaran using Miner's rule of linear damage accumulation and S-N curves by employing spectral-based analysis. Fatigue strength assessment of the hot spots was conducted using wave scatter diagrams of the North Atlantic as the wave loading spectrum. The result is helpful to structural design of the joints of similar wave-piercing catamarans. The cumulative fatigue damage is relatively large for structures near the waterline. Appropriate measures should be taken to strengthen the point to reduce the stress at the hot spots to meet the fatigue life design requirements.

6.6 Moonpools

One of the common characteristics of these types of vessels considered is the existence of a moonpool. Moonpools are vertical wells onboard floating vessels and offshore structures that provide open access for several types of underwater activities. The relative motions that occur inside the moonpool and their impact in several aspects of the ship design have been the subject of several research work.

Sharanabasappa and Surendran (2013) studied the influence of the shape and depth of a moonpool and the frequency range of the waves in the response of a drillship. Tank model testing has been carried out, with circular, square and rectangular moonpool shapes. The mooring lines have also been modelled. The different modes of oscillation of the water column were measured with a wave gauge and the corresponding response of the vessel determined.

Yang & Kwon (2013) carried out experimental work to investigate the effect of the operational performance of a floating offshore structure near the moonpool resonance frequency, both in fixed and motion free conditions. Special attention was given to the effect of the cofferdam inner structure inside the moonpool.

Industrial research has also been active in this field. Ulstein developed an innovative design of the moon pool doors, which differ from industry standards by a special foldable link mechanism, reducing the span of the centre door. This reduces the construction cost and increases safety during operation. The foldable link mechanism further allows these top hatches to be used more practically in combination with large bottom doors, as the compact design eliminates clashes in simultaneous opening positions. All moving parts and systems that require maintenance are accessible from a safe and practical position. Ulstein h developed the moon pool hatches to fit the offshore construction vessel Island Venture's main moon pool opening of 11.2 x 12 m and coping with a 450 tonne hang-off load.

Moon pools of large dimensions such as those found in drill ships have an impact in resistance and propulsion are difficult to estimate at the early stages of design. In Krijger and Chalkias (2016) RANSE CFD was used to optimize the hull and appendages of a drillship with a special hydrodynamically shaped moonpool. These authors claim this design reduces the added moonpool resistance by 37% compared to a conventional one while at the same time eliminates sloshing in transit.

Ma et al (2016) presented a real case study aimed at the reduction of the added resistance due to the moonpool in a drillship. Model tests and CFD simulations have shown that the ship resistance has large fluctuations due to the added resistance induced by the moonpool. This added resistance is mainly due to the vortices shed from the moonpool front wall, which enter into the moonpool and impinge on the rear wall. A parametric study revealed that smaller moonpool dimensions result in smaller added resistance.

Chalkias & Krijger (2017) performed potential flow frequency domain calculations to predict the natural frequencies and water motions for several moonpools. Two vessels with different moonpool dimensions and shapes were studied and model tests were carried out for one of them. Based on this work a motion reduction device was designed to increase the operability of the ships by reducing the motions in the moonpool.

Lohrmann et al (2017) investigated the dumping of waves in moonpools. Numerical simulations of the effect of perforated bulkheads were carried out using a viscous solver and the results were compared with those from model tests. The study found a dependency of the natural frequency of the surface elevation inside the moonpool on the ship speed. Based on this elevation, the resulting dumping of different layouts is discussed.

Yoo et al (2017) presented results from experimental and numerical simulation studies to reduce the internal flow of a moonpool. In particular, it was studied the effect of larger damping devices for four moonpool designs: ordinary plain moonpool, moonpool with a recess deck, moonpool with an isolated recess deck (island deck) and moonpool with a combination of island deck, splash plates and wave absorber. The internal flow of the moonpool has been investigated using RANS based CFD code. The CFD analysis considered regular waves, which calculated the water surface responses inside the moonpool. The flow pattern and resonance frequency were then compared with model test results and showed reasonably good agreements.

6.7 Offshore vessels Helideck Design and Integration

Generally, offshore vessels and floating structures have integrated a helideck structure in order to provide for offshore helicopter landing to transfer personnel and equipment to and from the drill or construction site. The helideck structure should satisfy key safety requirements in accordance with some offshore regulations and rule notations. The aim of these requirements and rule sets is to evaluate the buckling/ultimate strength of the developed pancake under helicopter landing impact and vessel motions. An example of this evaluation with regard to the structural safety and stability of the developed aluminium pancake was carried out by BS EN 19999-1-1:2007 to comply with the design requirement by Koo et al (2014). For verification with respect to an evaluation by EUROCODE 9, a 3-dimensional finite element analysis is performed with FEA program. Various offshore structures and vessels with helideck are shown in Figure 18.

Figure 18: Examples of Helidecks in Offshore Applications

Offshore helideck structures use aluminium because of its light weight, low maintenance requirements, cost effectiveness and easy installation. The aluminium helideck structure should satisfy requirements in accordance with some offshore regulations and rule notations such as the Australian/New Zealand Standard and EUROCODE 9. The width-to-thickness ratio and the yield stress are recognized as the governing design parameters in the design of cross sections in these specifications. The aluminium helideck design with relevant EUROCODE 9 was based on the strength calculation by Park et al (2015). Figure 19 shows the flow chart for the typical design process of an aluminium helideck structure.

However, section designs of aluminium pancakes tend to modify and/or change from the steel pancakes. Therefore, it is necessary to optimize section design and evaluate the safety requirements for aluminium helidecks. A design procedure was developed based on section optimization techniques with experimental studies, industrial regulations and nonlinear finite element analyses by Seo et al (2016). To validate and verify the procedure, a new aluminium section was developed and compared strength capacity with the existing helideck section profiles.

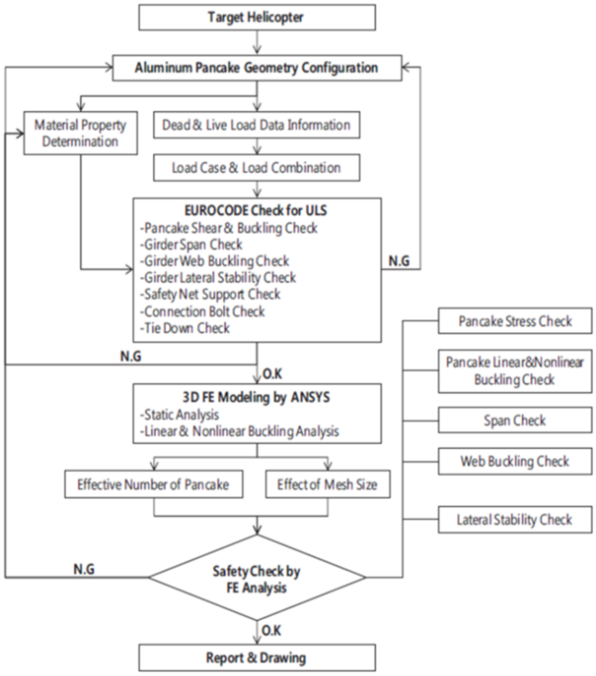

Figure 19: Flow chart showing the design process of an aluminium helideck structure

6.7.1 Materials and Analysis Techniques

Generally, offshore helideck structures are constructed by using steel material. However, aluminium helideck structure is widely used for reasons such as weight savings, no-maintenance, anti-corrosion, and convenience of assembly etc. Ha et al (2015) had mentioned the large scaled SAFE (Samsung Aluminium Fire-fighting Enhanced) helideck structure based on the code checked design through collaboration of experimental verification. In the structural engineering stage of the SAFE helideck, it was found the design factors in the EURCODE 9 were not clearly defined. Therefore, engineering decisions for some un-cleared design factors as well as methodology were carried out. Furthermore, it was strongly recommended to ensure safety for the SAFE helideck structure in accordance with offshore regulations such as CAP437, NMA, NORSOK etc. Through the experimental tests such as coupon load test, fire test and friction test, the SAFE helideck structure was verified by a certified authority. The newly designed large scale SAFE helideck structure displayed excellent benefits with regards to overall structural safety.

Since there is always the probability of helicopter emergency landing in a lifetime of such structures, evaluation of structural performance to achieve structural capacity beyond the elastic range by non-linear analysis can create new approaches in the design codes of offshore facilities. Despite the approaches of current design codes had changed from design-based on force method to design-based on performance method, the helideck design codes still recommended users to use the force method (Vaghefi et al 2013). Therefore, by using nonlinear analysis to review the capacity of structure in the elastic range, estimating its resistance and assessment of the current codes, appropriate results for the next generation of design codes could be reached.

Helidecks are vital structures acting as a last exit in an emergency. Helicopters transport people and goods to and from ships and offshore plants. When designing the structure of a helideck, it is necessary to comply with loading conditions and design parameters specified in existing professional design standards and regulations. Finite element analysis (FEA) was conducted with regard to a steel helideck mounted on the upper deck of a ship considering the emergency landing of the helicopter by Park et al (2016). The superstructure and substructure were designed, and the influence of various design parameters was analysed on the basis of the FEA results.

6.7.2 *Structural Configurations*

The required helideck diameters for various classifications under NORMAN 27 are listed in Table 16 and an industry sampling of existing offshore helideck structural configurations are listed in Table 17.

Table 16: List of the NORMAN 27 Classifications of Helidecks

NORMAN27	DIAMETER OF HELICOPER DECK(metre)	<15	H1
		15~24	H2
		>24	H3

Table 17: Typical Helicopter Particulars

Classification	Helicopter deck diameter (m)	APPLIED	Helicopter deck type	Helicopter type	D-value (m)	Rotor diameter (m)	'T' value (t)	Landing net size (m ×m)
H3	25.24	Offshore platform	Vertical	EH101 Sikorsky S92A	22.8 20.88	18.6 17.17	14.6 12	15x15
H2	22.2	Offshore platform	Inclined	EC 155B1 Sikorsky S76	14.3 16	12.6 13.4	4.9 5.3	12x12
H2	22.2	Offshore platform	Inclined	Sikorsky S76 EC225	16 19.5	13.4 16.2	5.3 11	12x12
H3	25.24	Offshore platform	Vertical	EH101 Sikorsky S92A	22.8 20.88	18.6 17.17	14.6 12	15x15
H2	22.2	Offshore platform	Inclined	Sikorsky S76 Super Puma AS332L	16 18.7	13.4 15.6	5.3 8.6	12x12
H2	19.5	Offshore platform	Inclined	Sikorsky S76 EC155B1	16 14.3	13.4 12.6	5.3 4.9	12x12
H3	26.65	Shuttle Cruise	Vertical	Super Puma AS332L	18.7	5.6	8.6	15x15
H2	22.5	FSO	Vertical	EC225 Sikorsky S76	19.5 16	16.2 13.4	11 5.3	12x12
H2	22.8	Offshore platform	Vertical	EH101	22.8	18.6	14.6	12x12

6.7.3 *Thermal Loads*

API (2006) and DNV (2001) recommend fire safety facilities such as fire extinguishers, water sprays, fire resistant equipment, etc. are installed to prevent such a structural damage. Also, SOLAS (2015) suggests the fire-fighting appliances regarding categories in Regulation 18 (Helicopter facilities). There are only recommendations for fire suppression facilities in the rules and standards. The guidelines for structural fire safety, fire fighting and the definition of required design fire loading are very unclear and open to interpretation. In particular, a helideck made from aluminium is sensitive to temperature and heat flux, compared with other materials such as carbon steel, stainless steel, nickel alloy, etc. A structural design standard for an aluminium helideck should specifically address the risk of fires and the associated criterion. This makes such a standard's development critical.

The helideck structure must satisfy the safety requirements associated with various environmental and accidental loads. There have been a number of fire accidents offshore due to helicopter collision (take-off and/or landing) in recent decades. To prevent further accidents, a substantial amount of effort was directed toward the management of fire in the safety design of offshore helidecks. Kim et al (2015, 2016) introduced and applied a procedure for quantitative risk assessment and management of fires by defining the fire loads with an applied example. The frequency of helicopter accidents in the Gulf of Mexico and the North Sea were considered, and design accidental levels for both regions were suggested. The proposed procedures for determining design fire loads can be efficiently applied in offshore helideck development projects, and the application includes the assessment of design fire loads and the quantification of the effects of risk control options, such as optimization of the helideck pancake profile, the location and the number of water deluge systems.

In recent years, the demand for ships and offshore platforms operating within the Arctic Ocean has been rapidly increasing due to global warming and the discovery of large reservoirs of oil and natural gas in the area. Bae et al (2015) discussed winterization design as a key issue to consider in the structural design and building of ships and their helidecks that have the possibility of operating in the Arctic and Sub-Arctic regions. International regulations for winterization design in Arctic conditions regulate only those ships and offshore platforms with a Polar Class designation and/or an equivalent standard. To cope with the rising demand for operations in the Arctic region, existing and new non Polar Class vessels were called to operation, but lacking adequate winterization design standards for refitting the vessels. These existing ships and offshore platforms were not designed utilizing reliable data based on numerical and experiment studies. These vessels were designed only to performance and functional criteria. Bae described the importance to obtain reliable data and to provide design guidance of the anti-icing criteria on structure, such as helidecks, by taking the effects of low temperature environments into consideration when evaluating the use of a specific vessel in a specific environment. Therefore, the main objective of this paper considered the retroactive anti-icing design of aluminium helidecks structures using heating cables. In the paper's discussion, finite element methods were carried out using thermal analysis with cold chamber testing for the required performance and capacity of the heating cables. According to the results, the method can be used as a standardized regulation and design guidance for retroactive winterization design of equipment, ships and offshore platforms. This will provide a more systematic, comprehensive guidance for helideck structural winterization design.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Recommended Research for Future Special Craft Committees

The Committee members of the 2018 ISSC V.5 Special Craft Committee have created a list of recommended vessel types for future Special Craft Committees to address specifically in greater depth and detail. As stated, the maiden 2018 ISSC V.5 Special Craft report was intended to be a wider and more shallow discussion in order to cover many references and topics on specialized vessels as compared to follow on reports. The recommended vessels below and emerging research topics are based on current trends and evolving market demands in these areas. Papers, articles and other research material is expected to be more readily available over the next three years.

7.1.1 Autonomous and Unmanned Vessels

The need for marine drone-like vessels is now becoming a reality with many projects in both the naval and offshore industry currently underway. Soon vessels will travel point-to-point through the seaways without a human element on-board. Much like Aerial Unmanned Vehicles (AUVs), the controls will be held by a shore based pilot guided by a series of automation and surveillance equipment. The effects on the structural design will be profound for these new sea-going vessels as the emphasis and limitations of the human-element on board will have been removed. It is unclear whether these vessels will be fully automated or be piloted shore-side, but it is clear this shift can lighten the structural design aspects of these special craft. Conversely, it can also drive more robustly designed vessels able to encounter headings and sea states that are agnostic to on-board mariner safety.

Advances in autonomous vessels may soon allow the human factor to be eliminated in structural designs, ultimately opening any operational and service restrictions that limit performance. As these programs begin to emerge and materialize, it is recommended future Special Craft

Committees investigate the direct impacts to structural configurations, weights and loads on unmanned and autonomous marine vessels.

7.1.2 Research and Polar Vessels

Deep water and Polar Regions are being explored for new trade routes and natural resources. This is bringing future structural challenges to ship design, requiring a revamping of research and testing to support the need for research and heavy icebreaking vessels, larger vessels and cranes for subsea exploration, and extreme cold and pressure tolerant structural materials. New standards are being developed to aid in the surge of these required vessel types and their structural necessities. Both research and polar vessels are part of an aging worldwide fleet where knowledge is lacking and new research conducted by utilizing the latest technologies. It is recommended an emphasis be put on these vessel types for future reports.

7.2 Emerging Structural Trends to Watch

To help governments sustain new construction within their respective countries, advanced construction techniques for mitigating vessels lifecycle costs are now involving modular and multi-party production schemes. These new strategies will affect how designers and production teams design structural scantlings to ensure fiscal viability, adequate alignment and fitting of units. Also printing of structural material and possibly scantlings may possibly be the 3D printing techniques of the future for construction and repair.

7.2.1 Total Cost of Ownership

Economical solutions for vessels in the form of lighter structural configurations and designs with the vessels structural lifecycle maintenance and disposal in mind are becoming part of the acquisition conversation. Soon designers will need to consider the materials used in design and how the vessels' recyclability is economically advantageous to the owner. Where owners were only concerned on the initial capital cost of the vessel and her structure, they are now asking the structural design lend itself to fiscally viable repair and maintenance solutions. Consideration must be given to worldwide material availability for repair, multi-party construction and the overall reduction in complexity of the structural configuration. De-complicating structure would allow ease of maintenance and painting by eliminated such items as sharp corners to prevent coating failures leading to corrosion. Today, owners are more cash strapped, feeling the economic impacts of oil prices and new regulation, on vessel service lives' lasting much longer than the typical 25-30 years. Tomorrow they will ask for an evaluation of the total cost of ownership in the concept design phase, and demand creative foresight to reduce monetary burdens down the line.

7.2.2 3D Printing for Structures

Metal-based additive manufacturing, or three-dimensional (3D) printing, is an emerging technology across various industries including the marine industry. Manufacturing metal components layer by layer increases design freedom and manufacturing flexibility. Therefore, complex geometries can be easily created, product customisation can be enhanced and time to market can be shortened. However, only a few number of alloys can currently be reliably printed (Martin et al, 2017). Metal-based additive manufacturing often involves the deposition of layers of an alloy feedstock in the form of powders or wires, which are melted together by a rapidly moving heat source to form a solid mass. The rate of solidification is often an order of magnitude higher than that is seen during conventional casting techniques, and the process of building up layers causes non-uniform cooling. This leads to thermal stresses in the alloy which can generate cracks known as hot tears (Todd, 2017). A new approach has recently been proposed by introducing nanoparticles of nucleates that control solidification during additive manufacturing (Martin et al, 2017).

For the marine industry, 3D printing technology can enhance new product developments and reduce the cost of development by allowing to verify and improve design parameters and ideas so that design level and efficiency increases. Moreover, 3D printing technology makes the production of auxiliary products more economical and quicker. 3D printing technology can manufacture complex parts with higher accuracy and smoothness where traditional manufacturing methods may encounter difficulties. Currently, 3D printing technology is mainly used in shipbuilding industry in small-sized parts with a complicated structure such as impellers, engine blades, radiators and small propellers (Chao et al, 2017).

Complex and large components operate in harsh and corrosive marine environment. These components are assembled into various ship types. There is a significant potential of 3D printing technology to be used in marine sector. However, there are still substantial technological issues that need to be resolved before the mass acceptance and utilisation of additive manufacturing in marine industry (Strickland, 2016). In order to make all the components to be printed useful, it is essential to have printed material property at least the same as those made by traditional metallurgy.

7.3 Concluding Remarks

Technology is moving at an alarming pace and with new construction of specialized vessels requiring flexibility, collaboration and modularity to remain economically viable options for owners, the future is exciting for structural design techniques in addition to uncertainties.

The overall intent of this first report of the V.5 Special Craft Committee was to cover a very broad area of vessels across three major marine market segments and to highlight the ones considered "special" or "specialized" due to their unique operations and associated structural aspects. The difficulty but advantage of having the ability to choose craft that have specialized structural features is the abundance or lack of reference literature in which to evaluate from. Future Special Craft Committees now have a baseline report upon which they may focus on very specific vessels relevant or significant to current markets which would lead to the ability to perform useful benchmark studies for industry. As a lesson learned, it is the recommendation that the V.5 Special Craft Committee be considered under the naming V.5 Special Vessel Committee for future ISSC Specialist Committees in order to eliminate any reader expectations or confusion on the word "Craft".

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