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## COMMITTEE V.5 NAVAL VESSEL DESIGN

### COMMITTEE MANDATE

Concern for structural design methods for naval vessels including uncertainties in modeling techniques. Particular attention shall be given to those aspects that characterise naval vessel design such as blast loading, vulnerability analysis, specialised naval structures and others, as appropriate.

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### KEYWORDS:

Naval ships, classification rules, design criteria, progressive collapse, lightweight materials, military load effects, shock, blast, underwater explosions (UNDEX), whipping, naval masts, high speed naval vessels, naval specific structural design, naval service life.

**CONTENTS**

1.	INTRODUCTION .....	726
2.	NAVAL CLASS RULE DEVELOPMENT/PROGRESS .....	726
2.1	Introduction .....	726
2.2	Military structural requirements .....	727
2.3	Military operational safety loads .....	728
2.4	Military performance loads .....	729
2.5	Concluding remarks .....	729
3.	MILITARY LOADS .....	730
3.1	Underwater weapon effects .....	730
3.1.1	Primary shock wave .....	730
3.1.2	Shock wave reflections and cavitation .....	730
3.1.3	Bubble dynamics and jetting .....	731
3.1.4	Numerical modelling .....	731
3.2	Above water weapons effects .....	731
3.2.1	External blast .....	732
3.2.2	Internal blast .....	732
3.2.3	Bullets and fragments .....	733
3.3	Maritime improvised explosive devices .....	733
3.4	Concluding remarks .....	733
4.	NAVAL SERVICE LIFE MANAGEMENT .....	733
4.1	Introduction .....	733
4.2	Ship service life in context .....	734
4.2.1	Australian LPA class .....	734
4.2.2	Australian Adelaide Class FFG-07 .....	734
4.2.3	ANZAC Class .....	735
4.3	Determining the remaining life of a warship .....	735
4.4	Naval structural monitoring programs .....	737
4.5	Consequence of increasing displacement .....	738
4.6	Options for enhancing fatigue life of warships .....	738
5.	NAVAL SPECIFIC STRUCTURE DESIGN .....	739
5.1	Structural uniqueness of naval ships .....	739
5.2	Naval integrated permanent structures .....	739
5.2.1	Flight decks (Vertical) .....	739
5.2.2	Stern ramps (Launch and Recovery Systems) .....	740
5.2.3	Blast resistant structures .....	741
5.3	Naval modular flexible structures .....	742
5.3.1	Mission bays .....	742
6.	NAVAL MAST DESIGN .....	744
6.1	Introduction .....	744
6.2	Types of naval masts .....	745
6.3	Materials (composite vs. steel vs. aluminum) .....	746
6.4	Loads .....	747
6.4.1	Weight of equipment .....	747
6.4.2	Environmental loadings (includes wind and seaway loads) .....	747
6.4.3	Thermal .....	747
6.4.4	Shock and Blast .....	747

6.4.5	Load combinations .....	747
6.5	Vibration and resonance .....	748
6.6	Structural analysis and design .....	748
6.7	Other considerations .....	749
6.8	Classification society rules for mast design .....	749
6.9	Conclusions .....	749
7.	PROGRESSIVE COLLAPSE ANALYSIS AND RESIDUAL STRENGTH ASSESSMENT .....	750
7.1	Introduction .....	750
7.2	Progressive collapse method overview .....	750
7.3	Development of the progressive collapse method .....	751
7.4	Residual strength assessment by progressive collapse method .....	751
7.5	Use of FEA for progressive collapse assessment .....	752
7.6	Progressive collapse analysis within classification society rules .....	752
7.7	Discussion and Conclusions .....	753
8.	HIGH SPEED NAVAL CRAFT .....	754
8.1	Naval Applications .....	754
8.2	Defining a high speed craft .....	755
8.2.1	Principles .....	755
8.2.2	Hull Form .....	756
8.3	Defining operational limitations .....	757
8.3.1	Operational profile .....	757
8.3.2	Operational envelope .....	757
8.4	Accelerations effects .....	758
8.4.1	Slamming .....	758
8.4.2	Human factors .....	758
8.4.3	Fatigue .....	759
8.5	Material technologies .....	759
8.5.1	Steel .....	759
8.5.2	Aluminium .....	760
8.5.3	Fibre-reinforced plastics (FRP) .....	760
8.6	Unmanned naval high speed craft .....	760
8.7	Classification Society Rules .....	760
8.8	Conclusion .....	761
9.	BENCHMARK STUDIES .....	761
9.1	Whipping Response of Ship .....	761
9.1.1	Introduction .....	761
9.1.2	UNDEX Bubble Phenomena .....	762
9.1.3	Experimental Investigations .....	763
10.	DISCUSSIONS AND CONCLUSIONS .....	764
	REFERENCES .....	766

## 1 INTRODUCTION

Previous ISSC Committee V.5 reports have addressed various aspects of Naval Vessel Research and Design these topics have included:

- Design for Military load Effects
- Vulnerability assessment
- Class society rules for naval vessel design
- Use of alternative materials
- Ultimate Strength

In this report the committee has concentrated on both the structural difference and role differences that make naval vessels uniquely different from all commercial vessels.

There are fundamentally unique elements that differentiate the structural design of naval warship from a commercial ship. First considerations that come to mind are undoubtedly the fact naval warships are characterized by large integrated guns and armor reinforced structure to engage in hostile encounters. There are less evident unique structures that inhabit a naval warship design than her fighting attributes. To set the context and key differentiators of naval warship operations to a commercial vessel, a recurring quote from the Naval Ship Code, ANEP 77, states: *The role of Naval ships is such that the safety of the Naval ship and embarked personnel may be secondary to the safety of those under the protection of the Naval ship.*

The above statement is directly contrary to the commercial ship operation mentality that holds personnel safety as paramount to all other safety. Although naval warships are operated to meet mission requirements, their design ideology is very close to that of a commercial ship, generally speaking. Much like a container ship being built to carry containers from one port to another, the naval ship is built with a specific purpose in mind. A common misconception is commercial ships are not designed specifically to a mission and fit-for-purpose mindset. This methodology is only unique to naval ships. Commercial vessels are designed in the same manner as a naval warship, with purpose and/or mission driven specifications, and with the capability to survive a predetermined unexpected event. What drives the divergence of Naval vs. commercial designs is the ability of a naval ship to adapt to the unexpected mission or event as well as respond to this in a manner that may put ship and crew at risk. The container ship's purpose is known, as well as its mission, with very few unknowns to be accounted for; so, mission flexibility is normally not needed. While the naval ship's purpose is also known, her mission at any given instance is known to be unknown, so mission flexibility is a must. This philosophical paradigm is highlighted only to drive home the reasoning and distinct need for unique structures not common on commercial ships that enhance the naval ship's agility and support the unknown mission.

## 2 NAVAL CLASS RULE DEVELOPMENT/PROGRESS

### 2.1 Introduction

Classification rules are being used more and more as the technical standard for naval ships. The Class Societies' coverage of military design requirements for naval craft have been referred and discussed in previous ISSC V5 reports:

- ISSC (2006) report discussed the general approach to naval ship design philosophy
- ISSC (2009) report discussed the class process for military design
- ISSC (2012) report discussed the similarities and differences between commercial and naval design

Naval craft structural design has a lot in common with that of commercial craft. They all operate in the same sea environment, and are built on the same structural principles and calculation formulas. Classification Rules are now well accepted as a technical standard for the general strength calculations. The question is whether Classification Rules also cover the more specific military operational and damage scenarios for naval ships. Rules from all the Class Societies in the Naval Ship Classification Association (NSCA) were investigated. This includes the following Class Societies:

- American Bureau of Shipping (ABS)
- Lloyds Register (LR)
- Bureau Veritas (BV)
- DNV GL: (Legacy DNV Rules (DNV) and Legacy GL Rules (GL))
- RegistroItalianoNavale (RINA)
- Polish Register (PRS)
- Turk Loydu (TL)

The main focus for this report is to give a status on whether the Class Societies cover the military aspects of naval ship structures. The different levels of detail between class societies' rules have not been evaluated in this report.

## 2.2 Military structural requirements

When discussing military structural loads it is necessary to consider what category the loads belong to. For the purpose of this discussion, the two main categories have been defined as:

- Military operational safety loads
- Military performance scenarios

Military operational safety loads are typically firing of weapons, replenishment at sea, and extreme use such as maximum speed in high sea states. The "safety type" loads defines the required safety for the ship and crew under its own normal duties. Normally the safety type loads belong to the role of the Naval Flag Authority and Classification.

Military performance scenarios are typically related to the resistance to various enemy weapons and residual strength after such damage. An example is the resistance to underwater shock loads, internal or external blast etc. The "performance" type requirements for a naval ship define generally the warfighting capabilities. The Performance type loads normally belong to the role of the Owner (Owner's specification), and are normally followed up by the Owner's representative.

The two main categories of loads are listed in the Tables 1 and 2. The Table 1 covers operational loads related to normal military operations of naval vessels. The table is based on review of the different class Societies naval class rules and some feedback from the respective Class Societies. The list of rules used for the table is given under references. The load scenarios listed here are applicable for normal peace-time operations (training, patrols, firing of weapons, handling of ammunition etc.) and wartime operations. The Table 2.2 covers structural damage scenarios from hostile military weapons. These damage scenarios are only relevant for war-type operations and terrorist attacks. The table is based on a review of the respective class societies' naval rules and some feedback from the respective Class Societies.

Table 1. Military operational hull strength aspects covered by classification rules.

	ABS (2014)	LR (2014)	BV (2011)	DNV (2014)	GL (2012)	RINA (2011)	PRS (2014)	TL (2013)
Special strength assessment	C/CN	CN					C	C
Beaching loads (When applicable)	2)	C		C	C	CN		C
Dry-docking loads	2)	C		C	C			C
Deformation of hull	C				C			C
Ultimate strength Extreme strength	C/CN	CN	C		C	C	C	C
Fatigue check	C/CN	C/CN	C	C	C	CN	C	C
Fixed wing aircraft deck	C	C/CN	C		C(NFA)	C		C
Helicopter deck	C/CN	C/CN	C	C/CN	C	C	C	C
Aircraft elevators	CN	C/CN	C			CN		
Aircraft catapults	2)	C						C
Aircraft lashing	2)	C/CN	C	C	C(NFA)			C
Vertical Replenishment	2)	C/CN			C		C	CN
Gun blast	C	C	C	C	C(NFA)	C	C	C
Gun recoil	C	C	C	C	C(NFA)	C	C	C
Missile blast	C	C	C	C	C(NFA)	C	C	C
Launch & recovery of mission vessel	C	C/CN		C 1)	C	CN		
Replenishment at Sea	2)	CN	C(O)	C(O) 1)	CN	CN		C
Masts	C	C	C		C	C	C	C
Sonar dome strength	C				C			C
Towing of sensors	2)			C 1)	C			
Towing (being towed)	2)	C/CN	C	C	C		C	C
Towing (towing others)	2)	C/CN			C		C	C

	ABS (2014)	LR (2014)	BV (2011)	DNV (2014)	GL (2012)	RINA (2011)	PRS (2014)	TL (2013)
Ammunition storage	C		C	C	CN	C	C	C
Magazine flooding	C	C		C	C		C	
Hull monitoring	2)	CN	CN	CN		CN		
In-water survey	C/CN	C/CN	C		C	CN	C	C
Gas tight bulkheads	C	C		C	C		C	C
Deck loads: Armoured tracked vehicles		C		C	C	C	C	C
Extended Lifetime (beyond 20 -25 years)	CN	C		CN	C(NFA)	CN		C
Explanations: C : Covered by classification rules CN : Covered by a separate class notation (O) : Loads specified by Owner (NFA): Loads specified by Naval Flag Authority 1) : Only hull attachments 2) : Compliance verification based on Naval Administration standards								

### 2.3 Military operational safety loads

During the work of comparing the Class Societies' naval rules in Table 2.1, it became clear that for most Class Societies, the general structural calculation methods and formulas are the same for both naval and merchant ships. In most cases when Class Societies publish a complete set of Naval Rules, the general structural parts are copied from the commercial Rule book.

Table 2. Military hull performance scenarios covered by classification rules.

	ABS	LR	BV	DNV	GL	RINA	PRS	TL
Underwater shock of hull structure	2)	C/CN(O)		2)		CN (NFA)	C	
Shock details	2)	C		2)	C	NFA	C	
Shock mounts	2)	C(O)		2)	C	CN (NFA)		
Air blast, internal	2)	CN(O) 1)		2)	C(NFA)	CN (NFA)	C	C
Air blast, external	2)	CN(O) 1)		2)	C(NFA)	CN (NFA)	C	C
Fragmentation	2)	CN(O) 1)		2)		CN (NFA)		
Structural damage	C	CN(O) 1)		2)	C	CN (NFA)	C	
Small arms fire	2)	CN(O) 1)		2)		CN(NFA)	C	
Fragmentation protection	2)	CN(O) 1)		2)		CN (NFA)	C	
Armour protection	2)	CN(O) 1)		2)	CN	CN (NFA)	C	
Whipping	C	CN 1)		2)		CN (NFA)	C	
Blast bulkheads	2)	CN(O) 1)		2)	C(NFA)		C	
Residual strength, structural damage	2)	CN(O) 1)		CN	C(NFA) CN	CN (NFA)	C	CN
Fire protection of structure	C	C/CN	C	C	C	C	C	CN
Residual strength after fire	C	C/CN	C					
Vulnerability analysis	2)				CN			
Shock mounts of equipment	2)	C(O)		2)		CN (NFA)		
Explanations: C : Covered by classification rules CN : Covered by a separate class notation (O) : Loads specified by Owner (NFA): Loads specified by Naval Flag Authority 1) :Different methods of analysis and acceptance are allowed for within the Rules 2) : Compliance verification system based on Military, Owner, Naval Administration standard								

The different Class Societies cover the various naval shiptypes in different ways. Some Class Societies link the ship types to generic functions (combatant, non-combatant). Others arrange the combination of their class requirements under specific shiptypes, such as Frigate, Corvette etc. In some cases, the ship type is only used to indicate the type of ship, without any accompanying requirements. For more complex naval ships, such as Logistics Support Vessels, class notations (functions) from both merchant and naval type ships may be combined. Most Class Societies accept that the naval class notations may be combined with some merchant ship class notation when this is relevant.

The general impression from the table is that the list of military operational loads covered by class rules is quite comprehensive. In addition to the items in the table, there are items that are covered by general strength criteria without being explicitly mentioned in the class rules. Considering this, it can be said that most Class Societies has a good coverage of the typical military operational loads.

#### **2.4 Military performance loads**

The Table 2.2 indicates the different class societies approach to the military performance loads. Some Class Societies have extensive coverage of the military damage scenarios in the class rules, and others have little or no coverage. The different class societies handle the military type loads in a number of different ways. There does not seem to be a common view on how this should be handled. Table 2. identifies examples of 5 different ways of handling the military loads:

- Military loads and calculation method given by the Class Rules
- Military loads given by the Owner, and calculation method given by the class rules
- Military loads given by the Naval Flag Authority, and method given by the class rules
- Military loads and methods verified against a military standard
- When Naval Ship Code (NATO 2014) is used, the Naval Flag Authority may define the military damage scenarios, the loads, and the acceptance criteria

One Class Society, Legacy DNV, handle the military damage scenarios as a verification service against military technical standards instead of specifying these in the classification Rules. This is a different approach than chosen by the other Class Societies. It is a principal question whether the military performance loads should be in the class rules at all. Military performance loads as in Table 2.2 do not fall into a strict interpretation of class rules covering safety issues. They would normally belong in the performance specification of the ship. It is expected that these issues will develop over time as more experience is gained in the relation between Navy, Naval Flag Authority and Class Societies. This may be a subject for later ISSC reports.

#### **2.5 Concluding remarks**

From the study of different classification rules it can be concluded that:

- Military operational loads are well covered by Classification Rules.
- Military damage scenarios are either well covered by some Class Societies, and little or no coverage by other Class Societies.
- The responsibility for input loads for military damage scenarios follow different practice from one Class Society to another.
- Certification against Naval Ship Code may overrule the class requirements on military damage scenarios
- One Class Society handles the military damage scenarios as performance requirements that are verified against military standards instead of Class Rules requirements.
- There is still a way to go for Class Societies and Navies to have a common understanding of the responsibilities for defining the military damage scenarios and how to handle these.

Many Class Societies have put a lot of investment, competence and effort in the coverage of military loads and damage scenarios. Also some navies have put competence and investment in this development. It is now up to the Navies to utilize this resource so that class societies can follow up with practical experience and further development in this area.

### 3 MILITARY LOADS

Naval ships can be exposed to a vast variety of weapon effects from above and below water that can affect the survivability of naval vessels, both surface and submarines. A general overview of many different threats and their effect on the ship structure is described in Chapter 6 of ISSC 2006 committee V.5 for Naval Ship Design (ISSC 2006). Considerable efforts are needed in the design stage in order to accurately assess the appropriate loads and predict the related impact. In this chapter several methods and tools will be described to simulate the loading and structural response ranging from analytic to full finite element including fluid structural interaction. The focus is put on calculation methods presented with an experimental validation. The information given in this report is based on what is available in the public domain. It needs to be mentioned that the greater part of information about weapons effects and military loads remains classified within navies.

#### 3.1 Underwater weapon effects

The physical effects from underwater weapons such as torpedoes and mines are on the load side: primary shock wave, surface reflection of shock wave, possible bottom reflection of shock wave, bulk cavitation, hull cavitation, bubble dynamics and jetting.

The structure responds with elastic plastic deformation, low frequency vibration and shock wave transmission into the structure. The calculation methods for the different load effects will be described on the basis of recent publications.

##### 3.1.1 Primary shock wave

The main characteristics of the primary undisturbed shock wave resulting from an underwater explosion are well described due to a combination of large scale experiments and modeling since World War II. Useful summaries are given by Swisdak(1978) and Cole (1948) where analytical formula for the pressure time history are given dependent on charge weight and standoff distance. More recently Fleck and Deshpande (2004) extended the one dimensional fluid-structure interaction model described by Taylor (1963) for flat monolithic plates and plane waves to clamped sandwich beams. The structural response of the sandwich beam is split into three sequential steps: stage I is the one-dimensional fluid-structure interaction problem during the shock wave loading event, and results in a uniform velocity of the outer face sheet; during stage II the core crushes and the velocities of the faces and core become equalized by momentum sharing; stage III is the retardation phase over which the beam is brought to rest by plastic bending and stretching. The third-stage analytical procedure is used to obtain the dynamic response of a clamped sandwich beam to an imposed impulse. Performance charts for a wide range of sandwich core topologies are constructed for both shock loading and air blast, with the monolithic beam taken as the reference case. These performance charts are used to determine the optimal geometry to maximize blast resistance for a given mass of sandwich beam. For the case of shock loading, an order of magnitude improvement in blast resistance is achieved by employing sandwich construction. However, in air blast, a sandwich construction gives only a moderate gain in blast resistance compared to a monolithic construction.

##### 3.1.2 Shock wave reflections and cavitation

The primary shock wave will reflect off the free water surface, wetted structure and the elastic or rigid sea bottom. The reflection from the sea surface and wetted structure produces a tension wave that propagates downward reducing the water pressure and cutting off the increased pressure around the structure due to the primary shock wave. Typically, the pressure near the surface is reduced to zero and an area of bulk cavitation is formed, shown in Figure 1. Reflection off the bottom is a compression wave that adds additional load to the structure.

The bulk cavitation is formed due to the water's inability to support a negative pressure. The water vapour cavity that is created consists of two separate boundary regions an upper and a lower boundary which are a function of weight and depth of the detonated charge. An analytical description of the bulk cavitation region is given by Didoszak(2004).

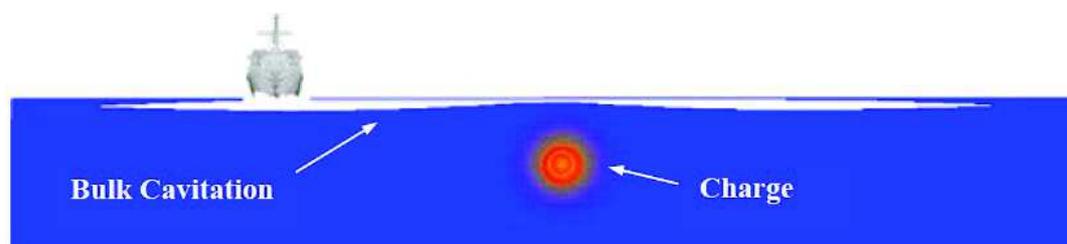


Figure 1. Bulk cavitation zone resulting from an underwater explosion (2004).

### 3.1.3 *Bubble dynamics and jetting*

As already mentioned in an under water explosion (UNDEX) loading event several phenomena occur. The primary shock wave is followed by multiple bubble expansions and collapses while the bubble migrates to the surface, causing a whipping response of the structure. At the surface the gas bubble vents in the air. Another feature of bubble behaviour is its attraction to rigid surfaces. A rigid surface exerts a weak repulsion when the bubble is expanding but during its contraction there is a strong attraction. The overall effect is that the bubble will move towards a surface such as a ships hull and remain there if contact is established, usually causing heavy damage through bubble jetting.

Riley (2010) compares various analytical models for predicting the growth and collapse of an underwater explosion gas bubble. The different models use various underlying assumptions such as the compressibility of the surrounding fluid and gas bubble, energy losses and the coupling of radial and migration motion. It is demonstrated that reduction in gas bubble radius through growth and collapse cycles is underestimated by all of the models when compared to experimental results as reported by Swift and Decius (1948).

### 3.1.4 *Numerical modelling*

Apart from analytical descriptions for the separate above mentioned under water explosion effects a numerical approach is also possible of course. In the full numerical approach detonation and bubble behaviour are modelled in the fluid mesh. Cavitation is included via the fluid response. For the finite element model an ArbitrarilyLagrangian Eulerian (ALE) approach is used where the structural response is calculated using the Lagrangian solver and the water, air and solid or gaseous phase of the high explosive with the multi material Eulerian solver. The water and air are modelled using the Grüneisen equation of state and the explosive charge by using the Jones Wilkins Lee (JWL) equation of state. Examples of full calculations using LS-DYNA and MSC.DYTRAN are given by Boyd *et al.* (2000), Petrusa (2004) and Ding and Bujik (2005). The modelling effort needed depends on the aim of the calculation. A numerical model aimed to simulate all the UNDEX phenomena should in principle cover the volume of thousands cubic meters from the detonation point to the structure. The fluid mesh sizes should be sufficiently fine (typically cubic centimetres) to avoid unrealistic damping and flattening of the pressure time curve or the primary shock wave. Consequently a large number of elements is required and it becomes very time consuming to simulate the transient response of a ship structure. To overcome this difficulty a boundary element approach is often introduced which uses the boundary surface around the structure to take into account the fluid-structure interaction effects. This eliminates the need to model the complete fluid domain. The most used method is the USA (Underwater Shock Analysis) code based on the DAA (Doubly Asymptotic Approximation) technique (Shin, 2004). This code can be used in combination with commercial FE packages such as MSC.Dytran and LS-Dyna.

An ‘intermediate’ approach also exists in which the loading is estimated using analytical formulations that are placed directly onto the structural model. The calculation effort is in that case no longer than a normal structural analysis. The accuracy is however as good as the analytical formulations used. A description of this Simplified Interaction Tool (SIT) is given by Trouwborstand Bosman (2006).

As the cost of conducting a Ship Shock Tests are high, the tremendous advances in simulation capabilities are driving the question: “Can Shock Test Trials be substituted by simulations?” by Mairet *al.* (1997). Figure 2 with advantages for both tests and simulations is presented together with strong arguments in favour of a combination of both approaches. Physics based UNDEX vulnerability simulations should be employed in the acquisition cycle for:

- Early design assessments for surface ships and submarines
- Pre-test predictions prior to the shock test
- Extrapolation of the shock test to realistic threat conditions after validation of the test
- Analysis of the differences in each ship of a class after the model is validated for the shock tested first of class

## 3.2 *Above water weapons effects*

Above water weapon effects from bullets, shells unguided and guided missiles result in the following physical loading on the structure: air blast, heat and high velocity impact form fragments and bullets. High explosive weapons may have sufficient velocity and casing strength to penetrate ship hulls and explode internally. They may also be fused to explode before contact or on contact.

Ship Shock Tests/Trials	Simulated Ship UNDEX Response
Evaluate platform under sub-design conditions	Potential to evaluate platform under realistic threat encounter conditions
Test of integrated system	Simplified representation of integrated system
Limited influence in ship design	Influence design early in acquisition cycle
Limited data obtainable	Extensive data sets obtainable
Unexpected equipment failures common	Equipment failure prediction not demonstrated
Uncover "as built" vulnerabilities	Simulate "as designed" conditions
Data accuracy not formally quantified	Data accuracy not formally quantified; strong function of analyst expertise
Representation of ship class is questionable	Potential to evaluate individual platforms
Inside performance "envelope"	Explore performance "edge of the envelope"
Formally accredited data acquisition methodology	Lack of formally accredited data acquisition tools
Maturing methodology	Developing methodology
Significant resources expended to demonstrate minimal environmental impact	No environmental impact
Partial fulfillment of LFT&E Legislation	Not currently accepted as Shock Test/Trial replacement

Figure 2. Ship Shock Tests versus simulations (Mair *et al.* 1997).

### 3.2.1 External blast

For an external blast loading event an analytical description of the pressure-time curve for the positive pressure phase is given by the Friedlander equation (Baker, 1973). The over overpressure and impulse relations are given by Kingery and Bukmash (1984) and Kinney and Graham (1985). Detonations produce an overpressure peak and afterwards the pressure decreases and drops below the reference pressure (generally atmospheric pressure). The influence of this negative phase depends on the scaled distance.

$$Z = d/W^{1/3} \text{ (m/kg}^{1/3}\text{)} \quad (1)$$

where  $W$  is the equivalent TNT mass (kg) of the explosive charge and  $d$  (m) is the distance to the centre of the charge.

For scaled distances larger than 50 the influence of the negative phase cannot always be neglected. The size of the positive impulse and the negative impulse is then nearly the same. An analytical description of the pressure time relation for the negative phase is given by Krauthammer and Altenberg (2006).

### 3.2.2 Internal blast

For an internal detonation of a warhead the initial spherical blast wave is reflected several times at the boundaries of the compartment and structural elements will be loaded by various blast waves. These blast waves are followed by a Quasi Static Pressure (QSP) build-up which is formed by the heat effects and additional gas effect. The maximum level of QSP and the total loading time are of course governed by venting of the explosion gases into the atmosphere or adjacent compartments (ISSC 2006). There is no single accepted method discussed in the open literature for simulating the time evolution to QSP. Methods presented in the open literature generally define a delay time and then dump a specific amount of energy into the explosive products over a defined time period as presented by Daily (2004).

For the numerical modelling of an internal or external blast event a similar ALE approach is mostly used as for the underwater explosions effects. Examples of this approach are given by Larcher (2007) and Zakrisson *et al.* (2010). Also here examples can be found of intermediate, more computationally efficient approaches where empirical explosive blast loads are placed directly on the air domain or structure domain. A comparison between three different approaches is given by Slavik (2010).

### 3.2.3 Bullets and fragments

Bullets and fragments can penetrate bulkheads, decks and the ship's hull but in general don't influence the failure of a structural component. They are however a danger to personnel, system components, cabling, cooling, fire main etc. Reduction of the fragmentation effects on ship systems can be achieved by designing particular geometric arrangements and using ballistic protective materials (ISSC 2006).

### 3.3 Maritime improvised explosive devices

Maritime Improvised Explosive Devices (MIEDs) such as small boats filled with explosives are likely to be a threat in future combat scenarios. Such a scenario with attacks with explosives at the water line is described by Slavik (2010) and named FLOATEX (Figure 3).

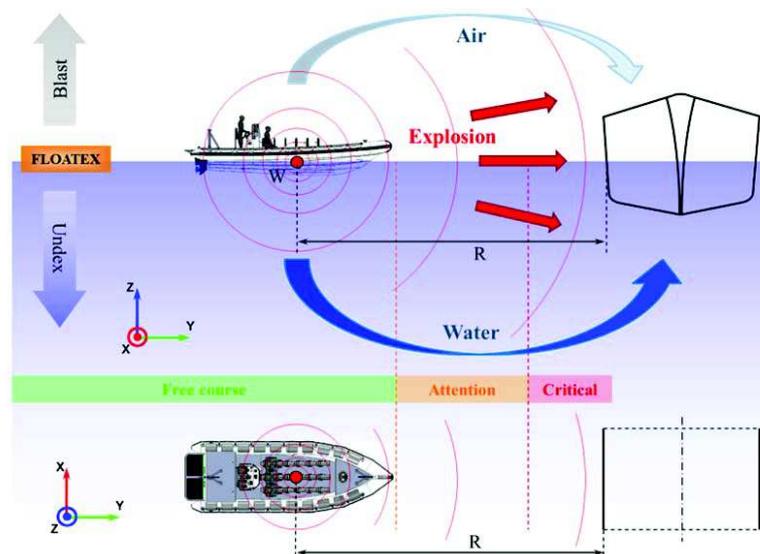


Figure 3. Floatex attack with a floating explosive (Slavik 2010).

As the explosion takes place partly in air and in water the above mentioned calculation methods for UNDEX and Blast need to be combined. Van den Heuvel *et al.* (2013) gives a comparison between experimental tests, full ALE Finite Element calculations and a simplified approach where analytical determined pressure time histories of the shock and blast loads are put directly on the structural FE model. It is concluded that the simplified approach correctly predicts the onset of hull failure but over predicts the panel's plastic deformations. The plastic deformations are correctly predicted correctly with the ALE approach for the first two shots.

### 3.4 Concluding remarks

For the main military load effects analytical and numerical methods are in place. For the presented methods however limited validation material is available especially on the full ship scale. Depending on the time available for the analysis and the needed accuracy, analytical, numerical methods or a mix of both is being used. Where in the latter case the load is determined analytically and put onto the finite element model of the structure. As however treats, naval ship structures and there materials continue to develop there will always be a need for experimental research in which validation of numerical methods should play an essential role.

## 4 NAVAL SERVICE LIFE MANAGEMENT

### 4.1 Introduction

A naval vessel, whether it is a surface ship or a submarine, is designed to operate for a certain amount of time in a safe and efficient manner. In order to achieve this requirement a platform is first designed against a set of criteria that determines sufficient safety against failure for a number of structural failure modes. These may include buckling against extreme loads and fatigue failure for through-life cyclic loads. Furthermore an effective through-life management system for the structure is required to ensure protection against progressive failure modes and that the consequences of major changes to the structural

loads is acceptable. It is the intention of this section to review the structural aspects of naval service life management.

#### 4.2 *Ship service life in context*

A merchant ship is designed for an effective life so that it can make a return of its investment for the ship owners. The process will often involve predicting the balance between the initial purchase prices of the ship, the operating costs including daily running and voyage costs and cargo handling costs with the predicted income from providing the service. However the situation is a little more complex for a naval ship as many other factors come into play.

For a warship there are a number of different measures that can be used to describe the life of type (Koenig *et al.*, 2008). The different types of life described include:

- Expected Service Life – this is determined by force level planning numbers and is generated by senior defence planners. Within a ship class, all ships are expected to have the service life and this is used to determine through life costs.
- Actual Service Life – is the life of the ship taken from initial commissioning to decommissioning and where appropriate excludes out-of-commission periods where the ship is laid up.
- Operational Service Life – this life accounts for the different rate of ship aging between operational years and years out of commission. This age will therefore assume a lower aging rate whilst out of commission.
- Assessed age – is a measure that has been agreed by interested parties that accounts for the material condition of the ship. This allows operational flexibility but means that the material condition of the ship needs to be tracked.
- Design Service Life – is the service life that the ship is designed to achieve. This life, from a structural perspective is similar to the approaches used for most merchant ships.
- Economic life – as discussed above is used by merchant ship owners to determine their return on investment. Economic factors will impact a warships life however the process for defining this is not a transparent process.
- In order to explain some of these lives it is considered worthwhile to outline the service lives of a few Royal Australian Navy (RAN) ships.

##### 4.2.1 *Australian LPA class*

The Royal Australian Navy (RAN) amphibious transport ships, HMAS's Manoora and Kanimbla. These ships started out life as the USS Saginaw and Fairfax County respectively. Under the US service they were commissioned in 1971 and decommissioned in 1994. After being sold to the RAN they were converted from the original LST format to the RAN LPA format. Each ship underwent a major upgrade with a helicopter hangar amidships and in order to provide enough space for the forward operating helicopter or the carriage of two army LCM8 landing craft the forward end was modified with the removal of the 34m bow ramps and horns. A 70 tonne crane was also installed. This major refit took several years and they re-entered service 1999. During this refit period some lives were extended and others put on hold. The actual service life in this case deviates from the operational service life. In this modification the reporting displacement of the ships remained constant (8534 tons fully loaded).

See [http://en.wikipedia.org/wiki/Kanimbla\\_class\\_landing\\_platform\\_amphibious\(2014b\)](http://en.wikipedia.org/wiki/Kanimbla_class_landing_platform_amphibious(2014b))

##### 4.2.2 *Australian Adelaide Class FFG-07*

The Oliver Hazard Perry Class frigates ordered by the RAN were classed as the Adelaide Class. HMAS Sydney (FFG-03) was the third of the class to be built in the US. At launch (1980) HMAS Sydney was 136 metres long, 13.7 metres wide and has a draught of 4.5 metres. The length was increased to 138 metres in 1987 to permit the operation of the S-70B Seahawk. The displacement at launch was 3,678 tons; by 2009, various refits and upgrades had increased this displacement to 4,200 tons. See [http://en.wikipedia.org/wiki/HMAS\\_Sydney\\_\(FFG\\_03\)\(2014a\)](http://en.wikipedia.org/wiki/HMAS_Sydney_(FFG_03)(2014a)). The impact of this increased displacement on sea keeping performance and structural loads (e.g. fatigue loads) needs to be assessed in terms of design service life given that the ship is now entering her 31<sup>st</sup> year of service (2014). This ongoing trend to increase the actual service life of warships is becoming more prevalent given the increasing costs of new acquisitions.

### 4.2.3 ANZAC Class

The ANZAC class frigates owned and operated by the Australian and New Zealand Navies were based on the German MEKO 200 concept. Although purchased through a common build program each nation has undergone an upgrade program with different requirements. Naval Technology.com reported that the New Zealand upgrade was “Designed to extend the operational life of TenixDefense systems-built Te-Kaha and Te Mana frigates for another 15 years, the upgrade programme seeks to replace hardware and software of the combat management systems of the ships and the self-defence missile system.” This was completed as a result of some major relation of equipment on the quarter deck and internal structural changes to support new bulkheads and relocated equipment. Furthermore additional solid ballast has also been added to the ship to address some pre-refit trim issues.

In a similar fashion the Australian ANZAC frigates have or will be undergoing an Anti-Ship Missile Defence (ASMD) system upgrade. In this upgrade the addition of an enclosed mast for the new radar system introduces complexity in terms of evaluating structural life assessments.

These case studies, although related to Australian ships are common across all navies and present the structural engineer with a number of challenges. These are:

- What design service life for a warship should be used at the initial design stage?
- How should the consequences of a mid-life upgrade be taken into account at the design stage?
- How do you assess the “Assessed age” of a current warship?
- How do you determine whether the service life of a warship can be extended (Life- of- Type- Extension LOTE) beyond the initial design life?
- What extra management practices can a warship manager use to enhance the life of a warship?
- What is the impact of using commercial classification societies to manage warship life?
- The above factors are to be considered along with the fact that the average achieved service life of warships is increasing. Collette (2011) presented in Table 3, shown below, which indicates the average achieved service lives of US Navy vessels.

Table 3. Average Achieved Service Life (after Collette 2011).

Ship Type	Average Service Life Years
Carriers	40.4
BB-61 Class	48.8
Amphibious Vessels	29.2
Cruisers	26.3
Destroyers	25.4
Frigates	19.8

### 4.3 Determining the remaining life of a warship

The approaches available to the Navies for determining the assessed structural condition of an aged warship are similar to those used by commercial agencies for merchant ships. The initial requirement is to carry out a detailed analysis of the warship structures based on the most current survey information and to use this to determine the feasibility of the life of type or whether a life of type extension is possible. This survey usually includes all critical and primary structures with an analysis of the problems experienced to date (if any) and an assessment of likely problems reoccurring into the future.

The terms critical structure, in naval case, relates to any highly stressed structure within 0.2L amidships and primary structure is that which contributes significantly to the main longitudinal strength, shear and torsional strength and watertight integrity and compartmentation of the vessel. The surveys will report on items such as the general condition of the structures, any deformations that have occurred, fractures and any breakdowns of the protective coatings. Once the survey has been complete it is then necessary to consider the factors that will influence the hull condition in the future. This will require an understanding of the maintenance philosophy used, the area of operation of the ship, the manner of operation (e.g. whether any speed restrictions or sea-state restrictions will be imposed upon the vessel and the type of shipboard maintenance used).

Several approaches to automate the determination of remaining life of a warship have been investigated by researchers in the past. The US Navy and the American Bureau of shipping embarked on a program which resulted in the Surface Ship Life Cycle Management (SSLCM) activity (Eccles *et al.*,

2011). The main tool behind the program is to build a finite element model for the as-built configuration of the warship and apply projected operational loadings envisioned for the ship to identify the following:

- Inherent structural margins
- Inherent corrosion allowances
- Critical inspection plans
- Plate renewal criteria
- Expected fatigue life for the ship

The latter required the use of the FEA model and navy provided data which summarised the structural loading the vessel had experienced to date so that the consumed fatigue life to date could be estimated. Once the FEA model had been updated using the results of the hull surveys the remaining fatigue life could be estimated for the ship. The ship is then managed via check sheets and finally a global representation of the ship is developed to record the ship history. The two key processes are shown in Figure 4 and 5 (Eccles *et al.*, 2011).

A second approach to this problem is described by Collette (2011). His hypothesis is based on the premise that in the future will see an increasing use modular payloads and therefore the low cost ship structure will be required to endure longer lifecycles than previously expected – possible up to 100 years. He proposes extending existing semi-empirical component-based structural design rules primarily based on safety concerns to a system performance model for ship structures.

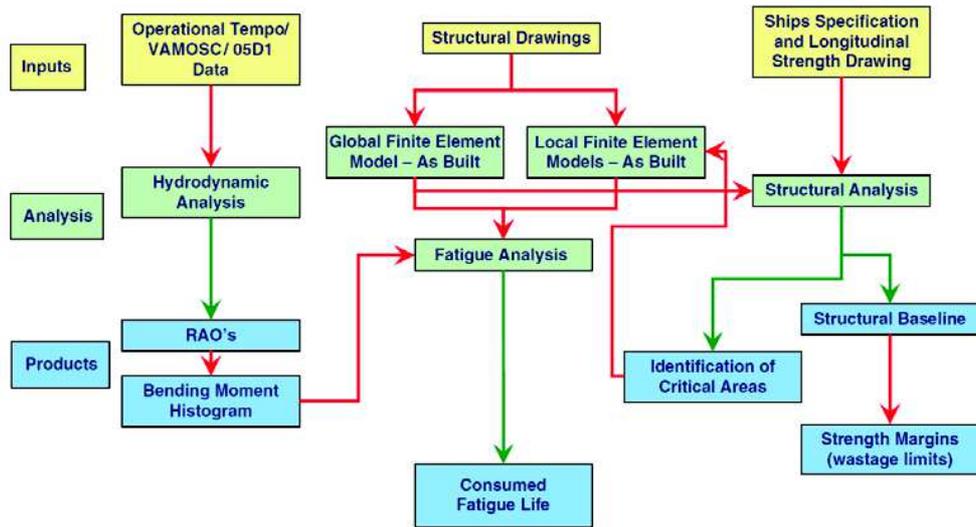


Figure 4. Fatigue Life Assessment – As Built (after Eccles *et al.* 2011).

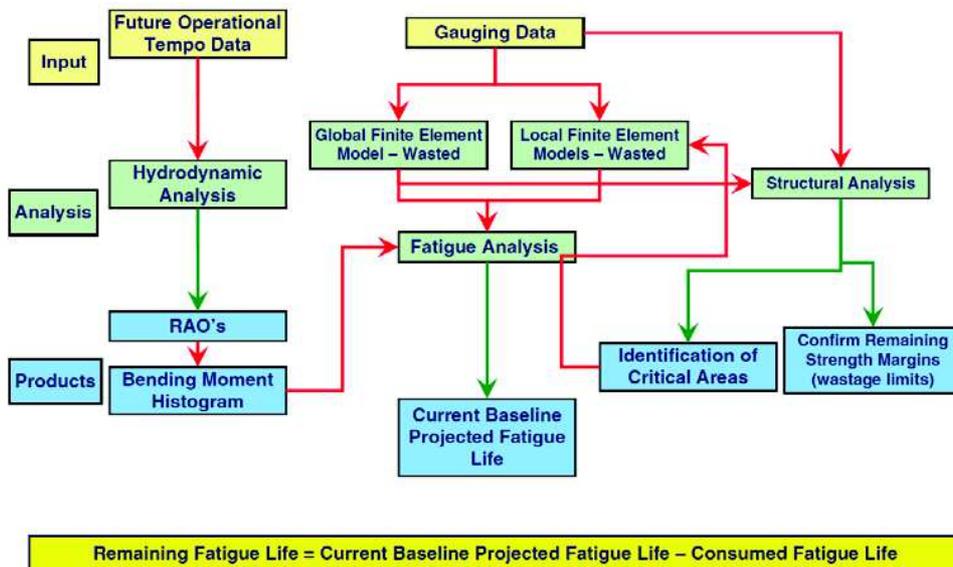


Figure 5. Fatigue Life Assessment Approach – Remaining Fatigue Life (after Eccles *et al.*, 2011).

#### 4.4 Naval structural monitoring programs

In order to facilitate the determination of a warships loading history a number of navies have embarked upon structural monitoring programs (Phelps & Morris 2013). Many of the systems are again, common with commercial systems and therefore it is not the intention to cover all platform monitoring systems but to focus on those systems that have been developed or primarily used for warships. The overall purpose of the hull monitoring system usually to:

- Provide real time guidance of loading information and trends and to warn of extreme loading events so that the risk of structural overload may be avoided, and to
- Obtain actual in-service information of the extreme and long term fatigue loads to which the ships are exposed so that this can be used for improvements in both design and the through-life management of the ship structure.

The first of these requirements is to provide operator guidance to the embarked crew and relies on techniques that are available to predict future events given the changing statistical responses obtained and to suggest effective countermeasures before the overload event occurs. The second requirement is to provide the navies with the loading history of the ships so that remaining fatigue lives can be determined. The basis here is that the hull girder fatigue calculations are based upon an assumed life-time loading profile and cross sectional properties of the hull girder, typically calculated at several sections along the hull. The well-known Palmgren-Miner linear damage hypothesis is used with S-N (Stress Range – No of Cycles) curves for welded structures to establish the fatigue life for each hull section.

There are an increasing number of commercial options available to provide requirements listed above. Furthermore the classification society requirements have led to a fairly standardized system consisting of two long base strain gauges on the weather deck, an accelerometer or pressure transducer in the bow and a data processor and graphical user interface on the bridge (Lloyd Register, 2004). Over the years there has been considerable development in the use of short base strain gauges (150 mm to 375 mm) that are considerably more compact than the long base strain gauges (2 m to 0.5 m long). These shorter gauges offer much more flexibility as to where they can be located on the ship. This means they are generally more suited to warships as they have much more complex structures and have less clear deck areas than tankers and bulk carriers for which the original systems were developed. The placement of these gauges is however sensitive to localized stress concentrations so care must be taken as to where the gauges are placed and how the results are interpreted; tri-axial rosettes are often required to correctly identify stresses in areas where stress concentrations occur.

Over the recent years a number of navy vessels have been instrumented with hull monitoring systems. Probably one of the earliest systems was the successful application of the extreme-value strain recorder by the Royal Navy and its subsequent development into the fatigue strain recorder by the Defence Evaluation and Research Agency (DERA) during the 1980s and 1990s. A full description of the system is described by Brown (Brown, 1999) which included the use of an optical grating strain transducer to avoid the problem of electromagnetic interference associated with foil strain gauges and filtering and algorithms for the separation of wave induced and slam induced strains.

The Royal Norwegian Navy have installed a ship hull health monitoring system (SHHM) on their Royal Norwegian Navy (RNoN) Oksøy/Alta-class mine counter measures (MCM) vessel the HNOMS OTRA (Torkildsen *et al.*, 2005), shown in Figure 4.3. This vessel is a fibre reinforced plastic (FRP) surface effect ship. The development of the system started in 1995 and included both a base system and an extended system. The base system uses a fibre optic system and includes a total of 36 strain gauges and 8 temperature fibre optic sensors located around the amidships section, the forepeak and the wet deck between the side hull keels. The enhanced system included measurement of the environmental parameters and global ship responses. This included ship motion data and the use of an X-band radar to determine wave height and direction measurements.

Further developmental systems have been trialed by the UK onboard the RV Triton (Kiddy *et al.*, 2002) and by the Royal Australian Navy on an Armidale Class Patrol Boat (Gardiner *et al.*, 2009), however the sole purpose of these systems is to determine the load history for the class of ships and therefore is applicable to both merchant and naval vessels. In all of the systems being developed it is deemed necessary that a detailed finite element analysis of the ship structure is used to determine the optimum place to locate the strain gauges.

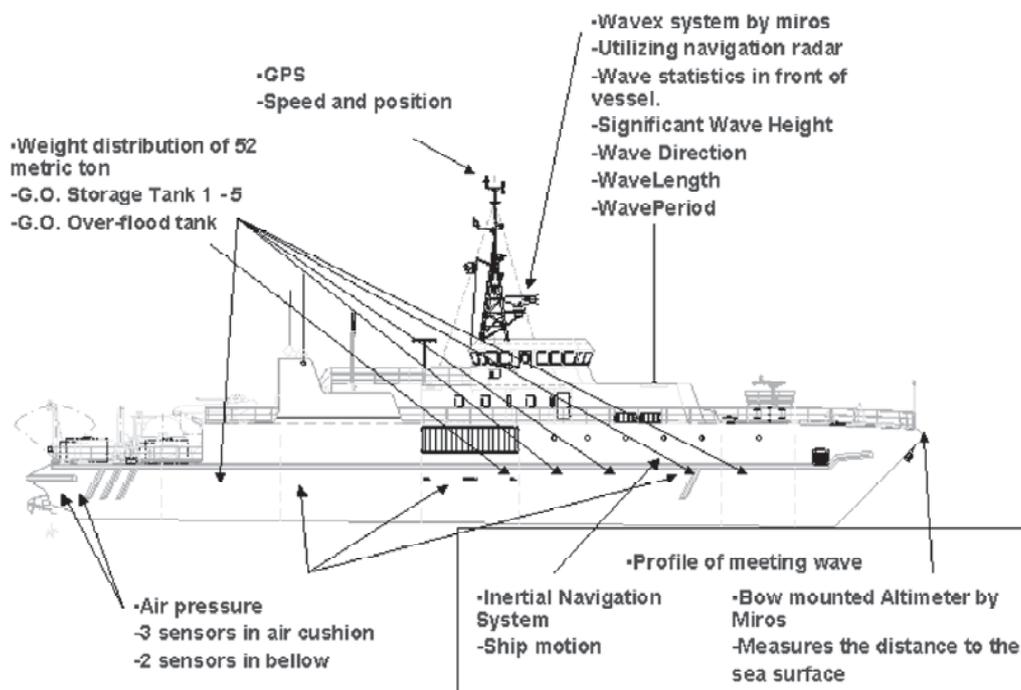


Figure 6. Overview of environmental and operating sensors on HNOMS OTRA (from Torkildsen *et al.*, 2005).

#### 4.5 Consequence of increasing displacement

As stated previously a number of navy ships undergo a mid-life upgrade. Whilst the primary purpose of the upgrade is to enhance and improve many of the systems onboard the upgrade may have a consequence on the structure. Newer systems integrated into the ship may increase the payload for the ship and may or may not require extra structure to support the new systems. The ANZAC ASMD upgrade for the Australian Navy involved the design of a new enclosed mast structure for the phased array radar system. This enclosed mast was constructed from aluminium alloys to ensure that the final displacement was close to the original design displacement. However in the event that there is a small increase in the final displacement of the upgraded vessel it is important that the consequences of this increase is known.

As the original vessel was designed to a specific limiting displacement using design rules that have migrated into the Germanischer Lloyd warship rules (now DNV-GL) it was important to understand the consequences of this small increase in displacement from a fatigue perspective. During the requirements phase the intended operational profile was set for the ship which included typical speed profiles, areas of operation and maximum number of days at sea. Critical areas of the hull were designed to ensure that the proposed fatigue design life was met for the original loads. The process for this calculation was based on one of the commercial classification society rule methodology.

The minor increase in displacement, together with the improvement in trim following the upgrade had an influence on the global response of the ship. The change in weight distribution influenced the still water bending moment and therefore influenced the wave bending moments. The net effect of this change was an increase in the bending moment range experienced by the ship. Once this new range was determined the classification society required a recalculation of the fatigue lives at the critical locations for the ship in the previous condition and for any new locations that arose as a consequence of the upgrade. Following this analysis a management philosophy had to be determined for the critical joints. In some cases the fatigue life is enhanced due to a better distribution of the loads whereas others may be more highly stressed and therefore resulting in a lower fatigue life. In the latter case this may either result in a shorter remaining design fatigue life for the ship or places a requirement to manage the locations via a methodical inspection and repair strategy to ensure the required life is maintained.

#### 4.6 Options for enhancing fatigue life of warships

Warships are typically very structurally complex and fatigue cracking, which is very dependent on the structural detail design, can occur at virtually any time in the life of the ship. The usual treatment, used by both commercial ship owners and navies is to weld repair the fatigue cracks at the earliest

opportunity. In some cases it may be required that a local design modification is made to enhance the performance. Novel repair methods such as the use of composite patching are being increasingly researched.

The RAN has used a carbon fibre composite patch overlay on the aluminium alloy superstructure of the FFG frigate HMAS Sydney. The patch itself was designed to reinforce the superstructure so that a recurrence of major fatigue cracking did not occur after initial repair. The patches have endured 20 years' service now since they were first installed (Grabovac & Whittaker 2009). They report firstly that the composite patch is effective in restoring the strength and function of the damaged structure. Secondly the durability and reparability of the composite patch itself is successful in the long term.

More recently though there has been significant interest in the use of composite patch technology as a repair method for warships with fatigue cracks. The advantage of this methodology of managing fatigue cracks is that there is an avoidance of any hot work (welding) and the ability to seal cracks. Qinetiq in the UK have demonstrated the technology to repair cracks in Type 21 frigates and Type 42 destroyers (Turton *et al.*, 2005). During these trials they report that the patches can enhance the fatigue life of a cracked plate or restore strength of a corroded or damaged substrate. They conclude that the wider use of composite patch repair to marine vessels is held back by a lack of repair schemes approved by the classification societies.

Other technologies which are starting to gain momentum include the commercial SPS Overlay repair method which involves placing a new top plate separated by an injected polyurethane resin to produce a sandwich (original plate/elastomer core/new plate). This method however appears to be most suited to larger flat areas such as decks.

## 5 NAVAL SPECIFIC STRUCTURE DESIGN

### 5.1 *Structural uniqueness of naval ships*

In this chapter novel, in addition to traditional, naval warship structures will be discussed. If the holistic design must account for mission adaptability, almost all of the described naval unique structures that will be covered are in direct support of mission survivability. Whether it is mission capability, combat readiness, endurance, or adverse environmental conditions, these structural attributes are characteristics of the ship's mission driven profile. These features aid in the adaptability as well as flexibility of the naval ship's highly volatile nature. Two categories are explored; one type is permanent in nature and integrated into the ship during construction, and the other type facilitates modularity into the design and enables structure to be removed, replaced, or upgraded throughout the ship's life. Both types are unique and ultimately part of the specification and holistic design of many naval warships.

### 5.2 *Naval integrated permanent structures*

A Nappi and Collette (2013) paper describes structural design as consisting of two tasks; achieving a true fitness-for-purpose design and meeting higher design goals of minimizing weight and production cost. Motivations for the design of specialized permanent naval warship structures inherently follow the same methodology as the ship itself. These specialized structures are true fit-for-purpose designs. Similar to a ship's mission or defined purpose, integrated specialized structures must have an overarching function in mind. Once this functional goal has been established, specific objectives will need to be identified before the naval architect will be able to arrive at a unique design solution. Convergence of the design can then be achieved.

This chapter addresses consistently emerging permanent specialized structures integrated within a naval warship. Discussed structures include flight decks, stern ramps, and blast resistant structures, all of which are fully integrated into the holistic design of the ship. These are not snap-on solutions, but structural systems in which Naval Platforms are built around. In order to achieve a precise converged design, the naval architect must also make some known sacrifices to accommodate these functional structures.

#### 5.2.1 *Flight decks (Vertical)*

Flight decks in many naval platforms are considered to be the critical component to the design. The flight decks addressed here are those which serve vertical Naval flight operations only, as shown in Figure 7. Flight decks allow resources and critical supplies to be transited to and from the ship. These structures also allow a naval ship to carry out missions well outside its geographic operational range if participating in reconnaissance or surveillance operations.



Figure 7. French Navy AS565MB landing on the helicopter deck of the La Fayette frigate. (naval-technology.com 2014a).

Space and weight are the sacrifices made for incorporation of a flight deck. Flight decks are clear of obstructions and geometrically sized to accommodate predetermined aircraft. This poses a challenge to positioning of towing/mooring stations as well as weapon locations and any other types of payload. Flight deck structures require a large array of safety equipment and machinery integrated into the design. Vertical replenishment/recovery at sea (VERTREP/RAS) equipment and winches must be incorporated below deck to retrieve payloads as well as aircraft while underway. Flight operations also require structural reinforcement to the deck itself in order to account for a variety of loads including takeoff, landing, stowage, crash, and vertical retrievals. Flight decks make upper extreme fiber of the hull girder when located within the 0.4L of the ship. Therefore, global hull girder bending effects are considerations that must be taken into account as flight decks are most times part of a continuous or stepped strength deck. Firefighting systems and stations, safety nets, JP5 systems and stations, deck lights, and the flight operations station are just some of the other items that must be designed into the ship itself when a flight deck is present; ultimately, adding to the overall weight. The integrated flight deck is a feature that is rarely found in commercial ships and truly unique and critical to naval ships.

### 5.2.2 Stern ramps (*Launch and Recovery Systems*)

The stern and bow ramp concept has been used in naval landing craft since WWII; personnel, craft, and vehicles could all be tactically launched in an expeditious manner from a slow moving or stationary craft. However, stern ramps have evolved to allow for high speed recovery and deployment of craft without sacrificing normal vessel operations. It is becoming more common that stern ramps are being found in larger patrolling ships because of the stealth it provides the ship when performing launch and recover operations. The stern ramp design is an inclined ramp built at the centerline of the stern portion of the ship and used mainly for small boat and RHIB operations. RHIBS can run-up into a ship's stern ramp or be launched aft while the vessel is making higher speeds, as shown in Figure 8. Using this technique eliminates the need for traditional rescue boat or tender davits and cranes that ultimately can require time, manpower, and a sacrifice of stealth.

Samras (2011) wrote an article summarizing the critical design elements to achieving an effective stern ramp design; they are:

- The incline of the ramp and its surface coatings.
- Entrance configuration, such as a funnel shape, and side clearances for the boat.
- The depth below the waterline of the ramp entrance, or "sill."
- Overhead clearance, if support bars or other structures are above the ramp. (In some cases, the ramps are built below a flight deck, which requires strict avoidance of flight-path interference.)
- Stern door or gate design and pivoting, operating, and securing mechanisms.

- He also stated that incorporating a stern ramp into a vessel design may increase weight, sacrifice space, as well as pose some stability challenges because of the loss of buoyancy in the aft portion of the ship. An example of this is shown in Figure 9 for small craft.



Figure 8. USCG FRC Sentinel Class stern ramp operations (naval-technology.com, 2014b).



Figure 9. Mark V Patrol Craft Stern Ramp (U.S. Navy photo by Mass Communication Specialist 3rd Class Michelle L. Kapica).

Stern ramps are close to or below the vessels waterline which, in shallower draft ships, makes for some creative solutions in laying out the aft machinery and steering compartment arrangements. The ramp itself usually consists of heavier structural material and reinforcement scantlings in order to absorb the impact of RHIB and small craft run-up during recovery operations. A securing winch or hoist is then tethered to the craft for securing it up into the higher elevations of the ramp structure. Dry and loaded ratings of the RHIBs and other small craft must be taken into consideration when the ramp and LHRS are in the design phase. Seaway accelerations should also be determined for accounting for loads imposed on the ramp when craft are secured in the ramp bay.

### 5.2.3 Blast resistant structures

Structures that are designed to withstand air blast and fragmentation from explosions are often integrated throughout the designs of naval ships. These structures are more protective in nature and not necessarily meant to absorb the force from a direct hit from a missile or bomb. These structures are often in various forms including bulkheads, doors, windows, hatches, as well as individual mounted shields protecting certain vital areas. The designer most often tries to achieve a sense of balanced survivability throughout the

ship. This concept protects all critical systems, subsystems, and resources needed for carrying out the mission at a predefined threat level (Walton, 2003). Preventing mass casualties and progressive collapse, addressed by Chapter 7 in this report, are also basic functionalities and motivations for blast resistance structures.

Most often the overarching cost of incorporation of blast structures is weight and space considerations. Blast structures have historically been constructed of steel for warships because of steel's strength and ductility as well as overall fire resisting characteristics.

### 5.3 Naval modular flexible structures

Modular design concepts in naval ship platforms have long been discussed in detail as a means of maintaining military relevance within the confines of available budgets (Doerry, 2012). If a permanent naval structure is said to follow a fit-for-purpose design methodology, modular naval designs must subscribe to the idea of flexible-for-purpose designs. The driving factor of such designs is undoubtedly the exponential growth rate of technology in correlation with the consistent change of types of threats.

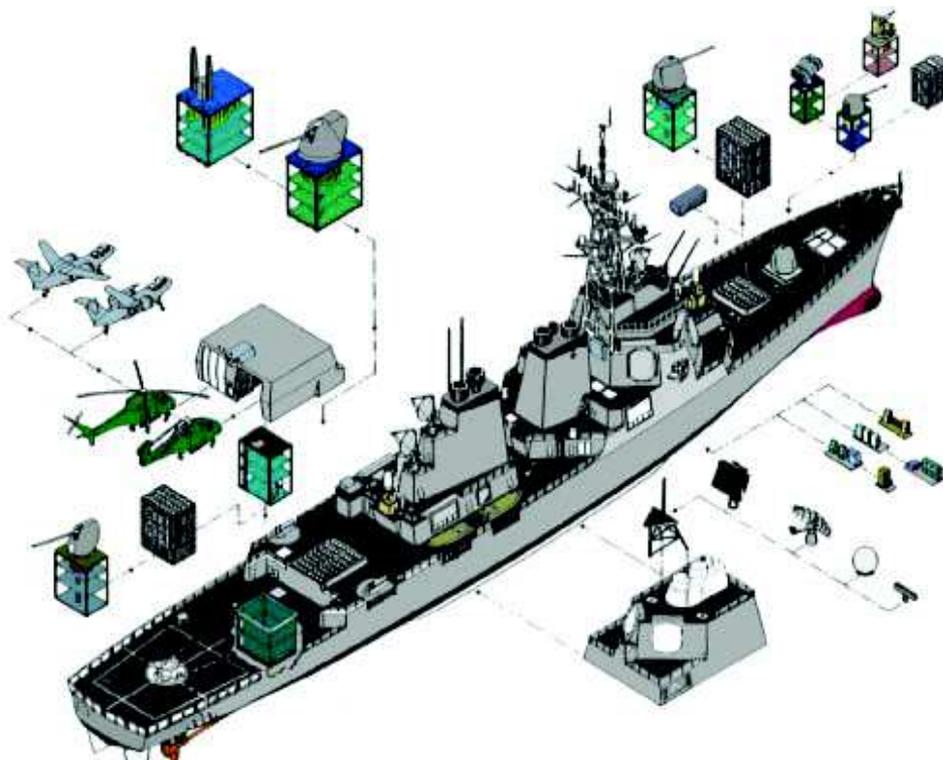


Figure 10. Cruiser Modular Concept (Doerry, 2013).

Today, modular technology has lacked the adoption of many of the world's leading navies, including the US Navy, even though one would think it to be a vital component in today's naval ship designs. Doerry (2013) presented a paper on the Modular Adaptable Ship (MAS) to industry which he described as stemming from the need for ships to be flexible yet robust. Their systems must be robust yet flexible to accommodate changing and uncertain requirements. Although the modular design concept is not unique to naval ships, they are to certain types of modular structures, as illustrated in Figure 10.

In order to highlight their unique functions, benefits, and any overall sacrifices that must be made, the naval modular structures discussed in this section will be: mission bays, hangars, weapon modules, and apertures.

#### 5.3.1 Mission bays

In many ways mission bays are shepherds to modularity for naval warships. Mission bay designs are designed to be very conducive to mission modules, and have attributes that can accommodate quick swap-outs of these modules. For this discussion flight hangars are also lumped into the same ideology as mission bays since traditional hangars are now being designed as flexible spaces to support a ship's mission more than just flight operations. Although most existing mission bay structures are not modular, new designs are emerging with this concept. The DDG 1000 platform has a composite hangar/mission bay that is fastened

onto the steel hull of the ship (Figure 11). Doerry (2012) explains in his paper that in order to capture proper specifications for mission bays during design such as the X-Craft (Sea Fighter) and LCS ships, the following issues should be addressed up front:

- Size of the Mission Bay
- Relative Value of Different Mission Bay Sizes
- Types of Distributed Services Needed for Mission Modules
- Mission Module Distributed Service Needs for Sizing of Ship's Distribution Systems
- Defining a General Mission Module Interface that is Agnostic to Ship Class



Figure 11. DDG 1000 Composite Mission Bay being integrated to the hull (Bartlett & Jones, 2013).

### 5.3.2 *Weapon modules*

Over the last 20 years, the US Navy has not had a strong need for modular weapons describe Doerry (2012) in a MAS concept paper. The weapon module concept has been largely overshadowed by the vertical launch system (VLS) and 5 inch gun's flexibility in munitions. Until recent modularity demands by the new LCS and DDG platforms, the existing classes of warships are largely unable to retrofit weapons in a modular way (Figure 12). Advancements in weapon technology as well as changing demands in mission needs now drive this concept.

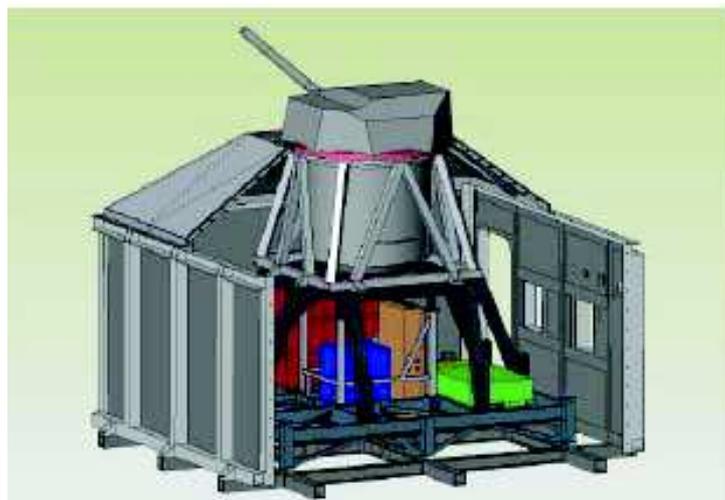


Figure 12. LCS Platform Weapon Module (Doerry, 2012).

### 5.3.3 *Advanced enclosed masts/sensor (Enclosed aperture stations)*

Chapter 6 within this report specifically addresses integrated enclosed mast design as well as the associated design factors. It is important to note advancements in integration of AEM/S, Advanced Enclosed

Mast/Sensor, systems into naval ship topside designs have been incorporated into new naval ship platforms. Doerry (2012) described the DDG 1000 program, Zumwalt Class Destroyer, is one recent example of this type of modular mast design. The AEM/S systems can be upgraded and modernized as technology advances without the necessity of large refit efforts. For her modular mast design, the DDG 1000 platform utilized composite materials that have also emerged as a possible solution to topside AEM/S and enclosed mast applications. Barlett and Jones (2013) in ASNE 2013 presented additional examples of these designs which can be seen in the LPD 17 AEM/S, CVN 77 mast, and other foreign Navy designs.

#### 5.4 Conclusion

Naval warship design is fundamentally similar yet ideologically different than commercial ship design. The uncertainty of the mission along with nobility of the role forces naval designers to consider increased probabilities. These probabilities, such as hostile threats in conjunction with adverse environmental conditions, are also related to higher consequences. All have to be accounted for in conjunction with the endurance readiness of the ship. The same considerations would not normally be a concern for a commercial ship designer. Accommodating the structural mission needs of naval warships is done through two distinct ways; permanent integrated structures and modular flexible structures. Today, traditional naval warship design has embraced the methodology of permanent, functional integrated structural design features; navies are seeing a necessity to move to more flexible naval mission structure with modular capabilities. With advancement of technology and weaponry, experts say this type of flexible and adaptable behavior will be critical to the ever evolving mission needs. With the emergence of the next generation US Navy fleet looking to these methods, such as the LCS class variants, time will tell whether there is a need to institutionalize the modular adaptable ship.

## 6 NAVAL MAST DESIGN

### 6.1 Introduction

The 2015 edition of ISSC Naval Ship Design decided to include chapters on specific naval structures that have not been covered in previous volumes. Naval masts are a unique structure, having many forms and having evolved considerably over recent years to meet changing demands. This chapter presents an unclassified overview of naval mast design.

The primary purpose of a naval mast is to extend the surveillance capability of a ship. The basic design objective of ‘the greater the height of the mast, the further the range over-the-horizon’ leads to conflict with other naval ship design objectives, namely concern for stability by creating weight high above the center of gravity, and increasing radar cross-section and visibility from over-the-horizon opponents. Topside weight has become of even greater concern as the number of sensors to be placed on a mast continues to increase in support of surveillance and combat systems.

The issue of topside weight has been addressed by the use of light-weight materials and by having more than one mast to hold all of the required sensors (which reduces height but not weight). Radar cross-section has been addressed through the use of stealth designs and specialized radar absorbing materials.

Naval masts must also be designed to withstand all of the same environmental and weapons loads as a naval ship. Being more exposed, and housing sensitive equipment, makes this a special challenge (Figure 13).



Figure 13. Issues of Concern for Naval Mast Design (Savage & Kimber, 2010).

Finite element analysis has become the primary means of structural analysis with challenges remaining in modelling complex composite materials and specialized connections to the ship structure.

## 6.2 Types of naval masts

There are four main types of masts which have been commonly used in naval vessels, stayed and un-stayed pole masts (Figure 14), tripod, lattice (Figure 15), and enclosed (Figure 16).

While lattice is probably the most common type of mast used on naval vessels, the use of enclosed mast structures (metal or composite) is an emerging technology that is being used on recent builds by countries such as the USA, UK and the Netherlands, and is quickly becoming the norm for naval mast construction.



Figure 14. Typical Pole Mast Structure ([www.masttechnologies.com/military](http://www.masttechnologies.com/military), Sept 2014).

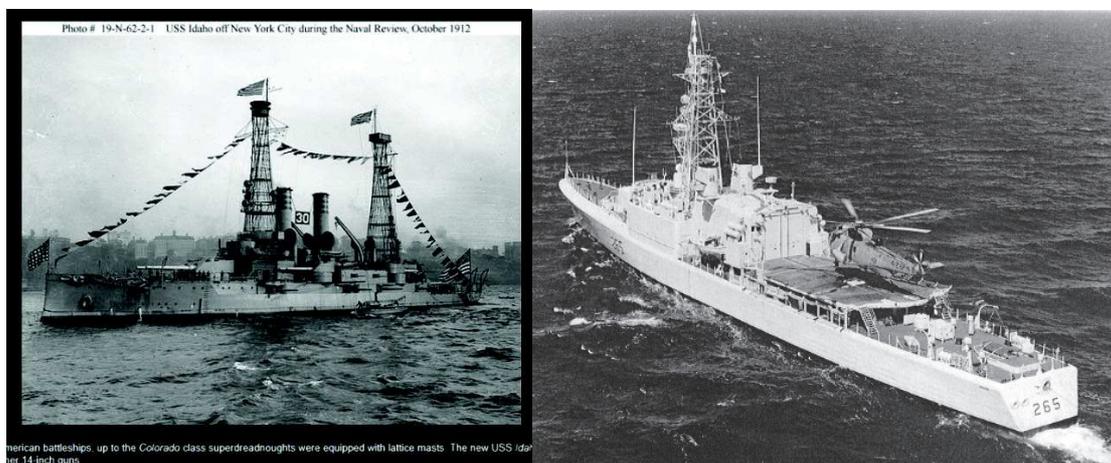


Figure 15. Cage lattice mast, USS Idaho (Photograph from the Bureau of Ships Collection in the US National Archives) and Traditional Lattice Mast HMCS Nipigon (DND Photo), websites October 2013.



Figure 16. Typical Enclosed Mast on left ([www.thalesgroup.com](http://www.thalesgroup.com)) and enclosed mast as deckhouse (Hackett, 2011).

SELEX (2013), DAMEN (2013) and THALES (2013) point to manufacturers websites for recent advances in enclosed mast design while Hackett (2011) describes the overall process of accepting composite materials into USN ships including demonstrator enclosed composite masts. Recent advances in mast and sensor technology have resulted in enclosed integrated masts of lower height and larger footprint (or more than one enclosure) which really begin to behave more like a deck superstructure (deckhouse) rather than a traditional mast (Kane *et al.*, 2010 and Savage & Kimber, 2010).

Enclosed masts have the advantages of:

- Reduced radar cross-section
- Protection of sensors from the environment
- Easier maintenance
- Possible improved survivability from weapons loads
- Use of complex embedded sensors
- Reduction in electromagnetic interference between sensors
- Improvement in lines of sight (Reduction in number of masts)

The disadvantages of enclosed masts can be:

- Heavier topside weight
- Increased surface area for wind loads and effect on air wake
- Cost
- Survivability from Fire

Another type of mast that is specific to Naval vessels are those that are designed to allow replenishment at sea (RAS) of other vessels. RAS masts may allow replenishment of liquid or solid stores or both, negating the requirement for frontline warships to leave combat areas to replenish in a non-hostile port location many miles away. Replenishment is conducted at sea, underway with both offloading and receiving vessel alongside, but at sufficient distance to avoid dangerous hydrodynamic effects that could lead to the two vessels being drawn together. As such, loading on connecting cables between vessels can vary in the forward and aft directions and vertically as the vessels move relative to each other, and machinery acts to maintain tension in connecting lines. Loading on the mast from cables and machinery can therefore be significant and in unfavourable directions.

Little specific guidance is available from Classification Societies regarding the design of RAS mast structure or its integration into the vessel's hull. In fact plan approval of the mast structure may be considered an owner requirement and outside the scope of hull plan approval unless specifically requested. However, the integration of the mast into the hull will be considered under hull plan approval and design of the mast structure to a suitable code is advisable. Lloyd's Register's Rules and Regulations for the Classification of Naval Ships (LR 2014) provides guidance on RAS mast loads and operational considerations, though directs the designer to the requirements for lifting appliances in a marine environment (Lloyds Register, 2013) for determination of acceptance criteria. As most Classification Societies publish rules for the design of offshore lifting appliances, design to such rules may be considered to be an acceptable way forward when designing RAS mast structural arrangements. Such design may be considered most complete when undertaken in conjunction with known loads from the RAS equipment manufacturer or supplier.

### **6.3 *Materials (composite vs. steel vs. aluminum)***

Previous ISSC Naval Ship Design reports have covered materials fairly extensively. Naval masts have been constructed of steel, aluminum and composite materials, each with its advantages and drawbacks.

Steel probably remains the most common material, even for enclosed masts. This is primarily due to its strength, cost, ease of construction, durability and EMC characteristics. The obvious drawback is weight.

Aluminum masts have been used to reduce top-side weight but suffer from lower strength, lower resistance to fire and higher susceptibility to fatigue failure.

Composites are becoming more popular, particularly for their light-weight and signature (imbedded sensor) properties. This has come after a long research and development phase (Hackett, 2011 and Kane *et al.*, 2010).

## 6.4 Loads

As mentioned, masts must be designed to withstand all of the same loads as the naval vessel, and in many cases these loads are exacerbated by the exposure and sometimes lighter construction of the mast.

### 6.4.1 Weight of equipment

As with any structure, the mast must be able to hold its own weight under inertial loads. In the case of naval vessels the inertial loads include accelerations from ship motions in addition to gravity. The overall weight and center of mass of the mast must also be considered in ship stability.

### 6.4.2 Environmental loadings (includes wind and seaway loads)

Wind poses significant loads on naval masts. Design values are typically 100-120 knots coming from all directions with overpressure, drag and vortex induced vibration having to be considered. Wind loads take on considerably different characteristics for lattice type masts versus enclosed masts which have a much bigger surface area. The overall force from wind should also be considered for its effect on ship stability due to a lateral overturning moment.

Ship motions (roll, pitch and heave) produce inertial loads on the mast with calculations being commensurate with design values for the overall ship motions (such as fully operational in sea state 5 and surviving sea state 8). Resulting forces and moments on the mast must take into consideration the center of pitch and roll for the ship.

Another important environmental load for naval masts is additional weight, and thus inertial loads from ice accretion. In addition to potential structural damage to the mast itself, this produces a significant danger to ship stability and may also render the sensors on the mast non-functional.

### 6.4.3 Thermal

Masts can be subject to extreme thermal loads from exhaust, weapons or fire. Masts are usually located near exhaust uptakes and hence subject to exposure from exhaust gases. The thermal effects from this can be increased when exhaust plume cooling suppression systems are used as it concentrates the heat closer to the deck and hence the mast structure.

Fire is a primary concern for masts constructed of composite materials and for aluminum where sufficient insulation must be used to maintain structural integrity and hence mast function. This may be especially important where the communication systems to bring aid during a fire or weapons attack may be all, or mostly all, on the mast structure.

### 6.4.4 Shock and Blast

Blast loads are similar in nature to wind loads in that the structure must be designed to a specific overpressure for the defined weapon as well as considering the thermal effects of the load.

Shock loads usually are a design driver for the mast, particularly where there are large suspended weights (sensors) on the upper portions of the structure. Shock loads are analyzed as for any other dynamic load on a structure, using quasi-static, shock spectra or base acceleration time history, in order of complexity and accuracy. Finite element analysis is now readily used for complex sensitive structures such as naval masts and provides effective means for dynamic analysis, either through determining natural frequencies to be used in a specified design shock spectra or a full linear or nonlinear time history analysis. It is important to remember that shock loads can come from all lateral and vertical directions. While dynamic analysis via FEA is readily available for large problems, uncertainty still exists for proper modelling techniques for joints and foundations and for complex composite materials.

### 6.4.5 Load combinations

The loads described above do not happen independently so that most naval mast design guidelines specify worst case scenarios for load combinations. While it may be reasonable to assume that weapons loading

will not coincide with the worst environmental loads, the highest wind loads usually coincide with the worst pitch and roll accelerations leading to a dominant design load case.

### **6.5 *Vibration and resonance***

Masts, being constructed of lightweight thin lattice members, or panels, often have overall or local member natural frequencies in the 1-5 Hz range. This often coincides with vertical and/or lateral hull vibration modes and with shaft rpm and propeller blade rates. This is a difficult problem to deal with and sometimes it is not possible to design a mast that falls outside of all possible excitation frequencies. In this case avoiding hull modes and propulsion excitations at common operating speeds becomes the design objective. While FEA can predict natural frequencies, numerical results may not be accurate enough to represent the real hull and mast values due to uncertainties in modelling mass distribution, connections, foundations, composite materials and damping characteristics. Full scale hull and mast vibration measurements may be necessary to accurately determine frequencies and take action to sufficiently separate excitation and mast natural frequencies and avoid resonant conditions.

Another type of vibration load concern mentioned previously is that of vortex induced vibration (VIV). This is primarily of concern for local lattice members. If not taken into consideration, local failure from low-cycle high-stress fatigue can happen very quickly into a structure's life.

### **6.6 *Structural analysis and design***

Mast structural design follows the same process as other structures; defining loads, safety factors and failure criteria. The finite element method, both static and dynamic, has become the standard analysis method for complex structures such as masts. Loads have already been described in Part 4. Safety factors are specified by design rules (Navy or Class Society). The failure criteria that must be considered for masts, as for other structures, are:

- Exceeding yield strength
- Fracture
- Fatigue
- Buckling
- Excessive displacement (may affect sensor performance)
- Vibration (discussed above)

Buckling analysis presents some challenges, particularly for lattice masts where member end-connections and effective buckling lengths must be considered. Lattice members may also be subject to a combination of axial and bending loads. Finite element discretization must also properly model the likely buckling (and vibration) failure modes. Again these are not different than what must be considered in analyzing civil lattice structures, other than needing to consider dynamic loads from ship motions and weapons loads.

Lattice structures in the civil domain, particularly hydro transmission towers and similar lattice structures are often designed via structural optimization, usually to minimize the cost. Care has to be taken when applying this approach to naval masts, as a certain amount of structural redundancy may be desired to withstand weapons loading. Naval structures are also usually subject to future weight growth. Masts are no exception to this as often more and improved sensors are added through-life. Applying structural optimization may negate redundancy and capacity for future growth.

Proper methods of modelling structural connections and foundations remain a topic of research, often with experimental programs to develop behavior properties. Construction errors such as misalignment of connections and foundations are also significant sources of uncertainty leading to premature failure, primarily by fatigue. In most cases, the mast is modelled and analyzed as a separate entity, usually with greater discretization than the rest of the ship. This poses a challenge in correctly modelling the boundary conditions of the foundation of the mast with the ship. Typically the primary supporting legs of a mast extend down below the weather deck, by several more decks. A common modelling practice is to provide a fixed boundary condition to the supporting legs one deck below the weather deck and pinned boundary conditions at the weather deck, assuming that the mast is free standing beyond the weather deck.

Further mast structural design requirements are added by the combat system. Most significant of these requirements is the "combat element to element" relative distortion allowance, which aim is to limit the

amount of relative angular distortion between specific pairs of combat system. The required assessment includes global and local effects of different loading conditions (between full load to minimum operative conditions) including environmental conditions such as wind loads as well as sea and air temperature (both external and internal air temperature gradient affecting the ship structure). Such assessment is usually solved by means of global Finite Element analyses as illustrated in Figure 17.

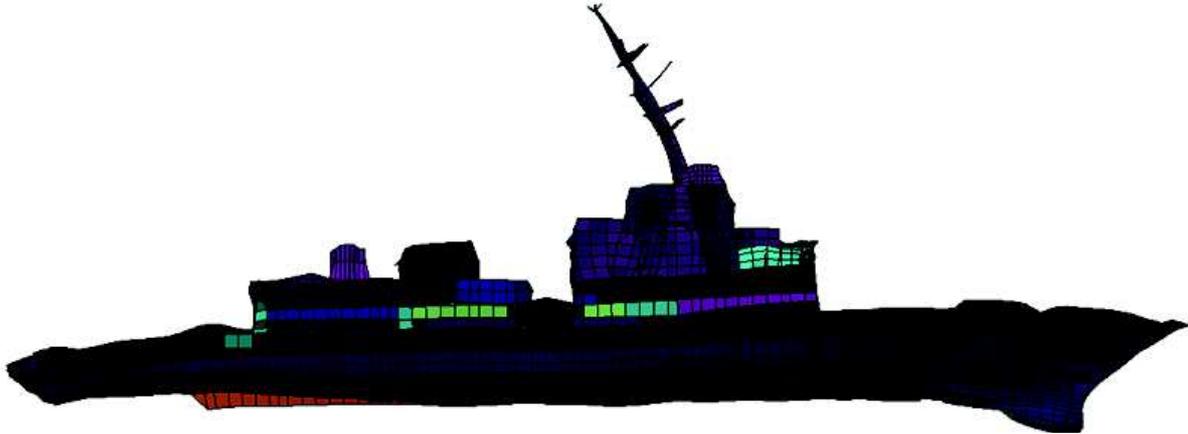


Figure 17. Example of Combat System Elements distortion due to temperature gradient and wind loading (Navantia communication).

### 6.7 Other considerations

- **Stealth:** While already mentioned as a design driver, stealth is a primary concern for naval mast design. The overall shape needs to minimize radar cross-section via flat-sided facets. Special radar absorbing materials are also used in designing composite materials or applied over metal structure.
- **Protection:** Shock and blast loads have been mentioned, but further consideration of fragmentation and small arms fire may also be necessary to protect sensitive equipment inside or on the mast.
- **Interference between structure and sensors:** While not a structural concern, overall layout of the mast in concert with other components of the superstructure needs to be considered to avoid reducing the effectiveness of sensors.
- **Height restriction for navigation under bridges:** As for civil ships, height restrictions for operating in certain ports need to be considered.
- **Airwake effect on flight deck ops:** The mast, in addition to other components on the superstructure contributes to the air flow over the helicopter or aircraft flight deck. The air flow is termed 'air wake' and can adversely affect flight operations. This is a specialized field of study usually analyzed by computational fluid dynamics, model tests in a wind tunnel and full scale trials.

### 6.8 Classification society rules for mast design

The Classification Societies cover Rules for Mast design in either specific naval ship rules or in their steel vessel rules (see Table 4). Stayed and unstayed pole masts are covered in all Rules. LR (2014) and DNV (2012) consider enclosed, integrated masts as superstructure for design and classification purposes. ABS treats masts with specific allowable stresses from military loads along with other specific ship structures. None of the rules seem to specifically cover lattice masts and the inherent issues of member buckling and VIV excitation causing fatigue.

In general, the rules cover allowable stresses, loads from ship motions and wind, vibration and ice accretion. Specific military loads are left to the additional calculations regime.

### 6.9 Conclusions

This chapter has provided a brief overview of naval mast design. There are few, if any comprehensive publications covering all aspects of mast design, and a designer are left on his own to design a mast as any other structure. Unfortunately this includes Class naval rules where various aspects of mast design are distributed throughout the rules, and some not included at all. Given the complexity and importance of a naval mast structure, this is not a particularly desirable state, and this committee recommends that Class societies, or naval design authorities, produce a comprehensive, collected rule set for naval mast design.

## **7 PROGRESSIVE COLLAPSE ANALYSIS AND RESIDUAL STRENGTH ASSESSMENT**

### **7.1 Introduction**

The assessment of ship hull girder ultimate strength has been considered and reported on within previous reports of ISSC Committee III.1 Ultimate Strength and specialist committees such as ISSC 2006 Committee V.1 Collision and Grounding, ISSC 2009 Committee V.1 Damage Assessment After Accidental Events and ISSC 2012 Committee V.5 Naval Vessels and in particular ISSC 2000 Committee VI.2 Ultimate Hull Girder Strength. All note the benefits of non-linear finite element analysis (FEA) for the assessment of the intact and residual strength and the increasing accessibility of the method as computing and software technology increase. However, it is also recognised that within the design, emergency response and salvage sectors of the marine industry, FEA is not the first method of choice due factors such as design maturity, time to complete analysis and cost constraints. Therefore, assessment of the ultimate bending strength in the intact and damaged conditions (the latter being referred to as residual strength assessment) is predominantly assessed using specialist software implementing the progressive collapse method. Example software that implements this method include, Lloyd's Register Rules and Naval Ship Rules software, Nauticus produced by DNV, Maestro produced by Maestro Marine, Paramarine produced by QinetiQ GRC, HULLST developed at Hiroshima University (Yao, 1991), etc.

Although the base level requirements of IACS (2014) is not an ultimate bending strength assessment but a comparison of midship section modulus against wave bending moment; in the plan approval and Classification of ship structures, most class societies accept or request the use of approved software implementing progressive collapse analysis for undertaking an ultimate bending strength assessment. In addition to this, Class societies such as Lloyd's Register in their Rules and Regulations for the Classification of Naval Ships (LR, 2014) offer the hull notation ESA for compliance with the Extreme Strength Assessment criteria and RSA for compliance with the Residual Strength Assessment criteria, both assessed by progressive collapse method using their NSR software. In such an assessment, the predicted ultimate bending strength is compared to the hull bending moment data from hydrostatic analysis to ensure a suitable safety margin exists between the two curves.

This chapter is focussed on the use of the progressive collapse method for the ultimate bending strength assessment of intact and damaged ship structures, developments in the method since its inception and recent comparative assessments through the use of non-linear FEA.

### **7.2 Progressive collapse method overview**

The term progressive collapse is used when collapse of a structure commences with the failure of one or a few components which then progresses over successive components (Starossek, 2009). The use of the term is not limited to the marine sector. However, when used in relation to the assessment of the ultimate bending strength of ship hull girders, specifically relates to the method originally developed by Smith and Dow (Smith, 1977 and Smith & Dow, 1981) and often referred to as the Smith method. The method implements the concept of structural idealisation, where by combining the known response of component parts of a system under a defined loading condition, the response of the whole system can be determined. In applying the concept to ship hull girders, the progressive collapse method draws on assumptions originally presented by Caldwell (1965) that plane sections remain plane under global bending and that failure of a transversely framed, longitudinally stiffened vessel will be by interframe collapse. That is, the failure will be of the stiffened structure between frames before failure of larger panels or grillages spanning multiple frame boundaries. Therefore, modelling is limited to independent sections that longitudinally span between two adjacent frames.

For progressive collapse analysis of ship hull structure, discretisation of the interframe structure is commonly made into an assembly of plate-stiffener combination units (Paik, 2006). Under global bending, it is assumed that each plate-stiffener element is under pure compressive or tensile loading depending on its location above or below the neutral axis of the interframe section. The strength characteristics of the elements are calculated and stored in the form of load vs deflection or normalised average stress vs average strain curves for both tensile and compressive loading, the latter often referred to as load shortening curves. Fundamentally, analysis is undertaken by assuming an incremental bending curvature is applied to the hull from which the strain in each element can be calculated, and the contribution to the strength of the section calculated from the appropriate strength data curve. The neutral

axis of the section is identified by adjusting its location until the sum of forces above and below equate to zero. Final sum product of the element forces with their distance from the neutral axis allows the calculation of the bending moment induced. The process is iterated increasing curvature of the hull, allowing the ultimate strength to be calculated.

### **7.3 Development of the progressive collapse method**

Initial implementation of the Smith progressive collapse method by the original authors utilised the computer program FABSTRAN (frame and beam static and transient response analysis (nonlinear)) (Dow & Smith 1986) to determine the load shortening curve data for use in the assessment. This approach ensures the strength data is bespoke for the section being assessed. In the implementation of the progressive collapse method into commercially available software, a different approach is utilised to derive the strength data for the section being assessed. Software packages such as Lloyd's Register Rules and Naval ship rules software, Paramarine and Maestro utilise a database of generic strength curves, usually derived through the use of non-linear FEA, covering a range of plate and column slenderness ratios from which the required strength data can be interpolated. This approach naturally gives the analyst less control over their model as characteristics such as initial imperfections or residual stresses can't be controlled, and the levels included in the derivation of the generic data is often not declared. As a result the analyst can expect to calculate different results through the use of different applications. Differences seen in assessments between different analysts utilising different progressive collapse tools has been demonstrated in benchmark studies undertaken by the ISSC Committee III.3, Ultimate Strength (ISSC 2006&2012) and ISSC 2000 Committee VI.2, Ultimate Hull Girder Strength.

Since its inception, development of the progressive collapse method has been in relation to the strength data captured within the load shortening curves. These include developments in the incorporation of initial imperfections, distortions and local dent damage, as well as modelling of heat affected zones. Recognising the potential limitation to the method in its current form should the hull's failure mode not be by interframe collapse, Benson *et al.* (2011, 2013a) developed a method based on the Smith progressive collapse method to include assessment of overall grillage collapse. The method utilises orthotropic plate approach to model and assess the overall or grillage collapse of the deck or keel, allowing the progressive collapse of the hull to be initiated by overall collapse, and not just interframe collapse, depending on the dominant mode. Implementation of the method requires greater modelling definition across multiple frame spaces as assessment moves towards a compartment level assessment. The method developed by Benson has subsequently been incorporated in the MAESTRO software package.

### **7.4 Residual strength assessment by progressive collapse method**

The Smith progressive collapse method is currently implemented for residual strength assessment after damage in design, in emergency response by Classification Society emergency response services, and by commercial salvage companies for vessel salvage. Current implementation of the progressive collapse method for residual strength assessment assumes that the failure mode in the damaged condition remains by interframe collapse. The damage to the hull is modelled by removing stiffened panel elements from the interframe section in advance of performing the assessment. This method of damage modelling is not changed whether caused by collision, grounding or weapon effects. Therefore, assessment of the residual strength is by assumption that the remaining structure will fail in the same manner as an intact vessel with a large opening. It is understood that to provide some conservatism to the residual strength assessment, some software applications attempt to account for the potentially reduced strength of the elements adjoining the damage aperture by modifying the strength curves to reduce their effectiveness. However, this approach and its validity are not well documented.

Recognising that in a damage condition the failure mode of a vessel may no longer be by interframe collapse, Underwood (2013) developed a method to allow the assessment of the hull girder residual strength whereby the damage aperture and resulting failure mode in the damaged condition are accounted for. The method replaces interframe stiffened panels within the damaged region with a grillage element spanning multiple frame spaces, which includes the overall size and an approximation of the shape of the damage. Assessment showed that accounting for changes in failure mode away from interframe collapse can be critical when calculating the residual strength of the hull girder. In order to be able to account for these influences within an application suitable for use in an emergency response scenario, Underwood incorporated the use of the response surface method Kriging to capture the strength data of a generic set of damaged panels, with the base strength data calculated through non-linear FEA. This has the advantage of being able to capture the influence of the damage aperture on the strength of the structure, whilst reducing the quantity of FEA required in generating a comprehensive set of base data.

A number of studies have implemented non-linear FEA to investigate the influence of a damage aperture on failure modes. Benson *et al.* (2012) simulated damage in a box girder caused by collision of a larger “indenter” with the top or side of the box girder. Analysis was undertaken through the use dynamic FEA simulation. Following the collision the residual bending strength of the box girder was assessed showing that the presence of the damage hole and the residual stresses caused by the damage event can be significant in the assessment of the residual strength of the structure.

Downes *et al.* (2013) investigated the use of progressive collapse analysis for the assessment of a lightweight naval vessel featuring side shell damage extending vertically from below the shear strake down to the double bottom and longitudinally up to two frame spaces. Comparisons of non-linear FEA with the progressive collapse method for this damage example showed the good correlation, with the FEA also confirming the failure mode to be by interframe collapse. However, analysis of different extents of transverse damage within a single frame bay presented by Benson *et al.* (2013b) showed a tendency for the Smith Progressive Collapse method to over predict the ultimate bending strength when compared to non-linear FEA.

### **7.5 Use of FEA for progressive collapse assessment**

Although this chapter has focused on the use of the simplified Smith Progressive Collapse Method, it would seem pertinent to discuss the use of FEA for progressive collapse assessment, both in its own right and in relation to its use in the derivation of load shortening curve data for use within applications of the Smith method.

FEA is becoming more widely used across the marine industry as software and computing capability increase, allowing the potential for even quite complicated analysis to be within the reach of those with only modest resources. Studies such as that presented by Storhaug (2009) demonstrate how the failure mechanism seen in the vessel MSC NAPOLI, could be well recreated through the use of non-linear FEA when detailed modelling of a known vessel can be undertaken. However, this contrasts with some of the variations in ultimate strength prediction demonstrated in the benchmark study presented by the ISSC 2012 Committee III.1 on Ultimate Strength, where following analysis by a number of analysts using a number of FE software packages, ultimate bending strength results varied from almost exact comparisons to differences of up to 28%.

Results of non-linear collapse analysis of stiffened steel structures at stiffened-plate, grillage and ship scale by FEA can be significantly influenced by the modelling details and the handling of initial imperfection sizes and shape and the handling of residual stresses. Whilst guidance on accepted imperfection levels and shapes is historically presented by Smith *et al.* (1991) and more recently by the ISSC 2009 Committee III.1 on Ultimate Strength, and methods for modelling residual stresses have been presented (Paik, 2006), analyst interpretation on how best to apply these within a model can lead to variations in predicted collapse strength. This may go some way to explain some of the variation seen in the benchmark study presented in the ISSC 2012 Committee III.1, but also seen in the ISSC 2006 Committee III.1 benchmark study comparing analysis by Smith progressive collapse method. As such, utilising FEA to predict the ultimate bending strength of a whole ship or to verify simplistic methods should be treated with extreme care, recognising the potential variations between model and real life, or the assumptions contained within different mathematical models. Similarly the influence of such variations should be considered when developing basis data for use by simplistic methods such as the Smith progressive collapse method.

### **7.6 Progressive collapse analysis within classification society rules**

In the general application of the Smith Progressive Collapse method in Classification Rules, there is no difference in how the method is applied whether concerning a commercial or naval vessel. However, as has been noted earlier, Lloyd’s Register offer additional hull notations for vessel’s that comply with the extreme strength (ESA) or residual strength (RSA) requirements. Both assessments implement the Smith progressive collapse method through the use of the Lloyd’s Register Naval Ship Rules software, with calculated ultimate strength compared to maximum wave bending moments calculated from hydrostatic or hydrodynamic analysis. Additional levels of RSA notation can also be achieved by meeting strength requirements for greater extents of damage or accounting for whipping effects caused by underwater shock in the bending moment assessment.

Table 4. Summary of Smith Progressive Collapse Method and Non-linear FEA Capabilities.

	<b>Smith Progressive Collapse Method</b>	<b>Non-linear FEA</b>
Structural Maturity	Can be implemented as soon as vessel configuration and initial midship scantlings are generated.	Vessel configuration and more advanced scantlings to be known to allow useful model to be built.
Modelling Time	Rapid modelling based on limited information.	Requires a more detailed structural arrangement to be known to be able to construct a useful model.
Solution Time	In the order of minutes.	Many hours to days depending on structural definition and mesh refinement levels.
Initial Imperfections	Often a feature of the software with no user control.	User defined and controlled.
Residual Stresses	Often a feature of the software with no user control.	User defined and controlled.
Loading	Ultimate bending strength assessment.	User defined and controlled.
Failure Type Assessed	Interframe collapse under global bending. Also overall collapse under global bending in Maestro only.	Interframe and overall collapse along with shear, torsional failure and potentially crack propagation depending on the user applied loading condition.
Ability to interrogate failure	Software may be limited to highlighting elements that fail first. Local failure modes may not be possible to identify.	Detailed failure analysis can be undertaken stepping through the load steps and refining structural details in critical areas to improve understanding.
Damage Assessment	Damage modelled by removing structure from model and assessing ultimate bending strength of remaining structure. Requires assumption that vessel fails by interframe collapse.	Damage can be modelled by removing structure or simulating damage dynamically. Failure type is not limited and will be driven by the structural configuration in relation to the user define load type.
Damage Assessment Timescales for Emergency Response	Rapid modelling and rapid solution timescales allow method to be used in an emergency response scenario.	Time to build or edit models and run a solution do not currently favour the use of non-linear FEA in emergency response.

## 7.7 Discussion and Conclusions

Table 4 provides an overview of the different capabilities offered by the Smith Progressive Collapse method and non-linear FEA. It can be seen that whilst FEA may have advantages of offering more detailed modelling and analysis, and what may be considered a more accurate assessment of the ultimate strength of a ship's hull girder, the Smith method still has a significant role to play in both early design stages and emergency response, provided the analyst is confident in the assumptions made in its application. Caution must be taken when implementing the method as factors such as modelling details e.g. initial imperfections, residual stresses, etc., and variations between the true failure mode of the vessel (interframe, overall, torsion, shear, etc) compared to the assessed interframe failure mode could lead to incorrect prediction of the ultimate strength of the vessel.

Whilst FEA may be the obvious solution for performing more complex bespoke analysis, time constraints along with factors such as design maturity, analyst experience, local model detail handling can all affect the quality and accuracy of the results obtained and their value in answering to the question being asked.

In conclusion, whilst the capability and accessibility of FEA has increased significantly since the Smith Progressive Collapse Method was originally conceived, the method continues to hold a valuable place in the design and analysis of ship structures.

## 8 HIGH SPEED NAVAL CRAFT

### 8.1 Naval Applications

In previous a specialist committee during the 2000 & 2003 ISSC the structural design of high speed vessels were addressed, but not in the context of naval craft. This discussion is meant to provide an overview of the various structural design aspects of high speed naval craft and how these types of vessels are being utilized in government and naval applications.

There has always been the need to use high speed craft in the commercial industry. Speed is necessary to sustain the ever increasing pace of economy. Traditional commercial use of high speed craft range from ferries to pleasure fishing boats to the offshore industry's need for crew boats. The procurement and use of high speed craft within navies and government agencies have become more common within the last few decades. This chapter discusses the application of high speed craft in naval scenarios as well as what makes this type of craft unique to the naval community. A summary of high speed craft types and their naval applications are shown in Table 5.

Table 5. High Speed Naval Craft Types.

	NAVAL APPLICATIONS	EXAMPLE
<b>Rigid Hull Innerbottom (RHIB) &amp; Inland Craft</b>	Craft that operate on near shore or inland waterways. RHIBs are used as a tender or rescue boat on naval ships. Serve short tactical missions for special force operations and general utility due to size, speed, and weight.	
<b>Coastal Patrol and Insertion Craft</b>	Used for coastal security or light patrol missions involving high speed maneuvering and pursuits as well as supporting insertion and extraction of military/security personnel	
<b>Offshore Patrol and Support Craft</b>	Serve medium duration missions providing support to offshore facilities and aid in coastal protection.	
<b>Littoral Combatant Craft</b>	Used mainly for strategic long term deployments with a range of missions involving littoral waters throughout the world. Craft are able to undergo blue water crossings if needed.	

There is a growing necessity for countries to secure their borders and coastlines as opposed to worry with blue water issues. Special operations units as well as national security and coast guard naval forces have become a focus of governments as more international terrorist groups mobilize and become homeland threats. Creating small high speed craft in order to support these groups now grows in demand. The oil and gas industry has expanded its reach to all parts of the world allowing countries to harness offshore energy resources, while a rise in pirate presence has alarmed the world with recent successes in commercial ship

takeovers. These and other factors now drive the need to have craft that can quickly provide security and access to shallower waters. A littoral craft are those that primarily operate in littoral waters offshore within and up to ocean depths of around 60 m (Figure 18).

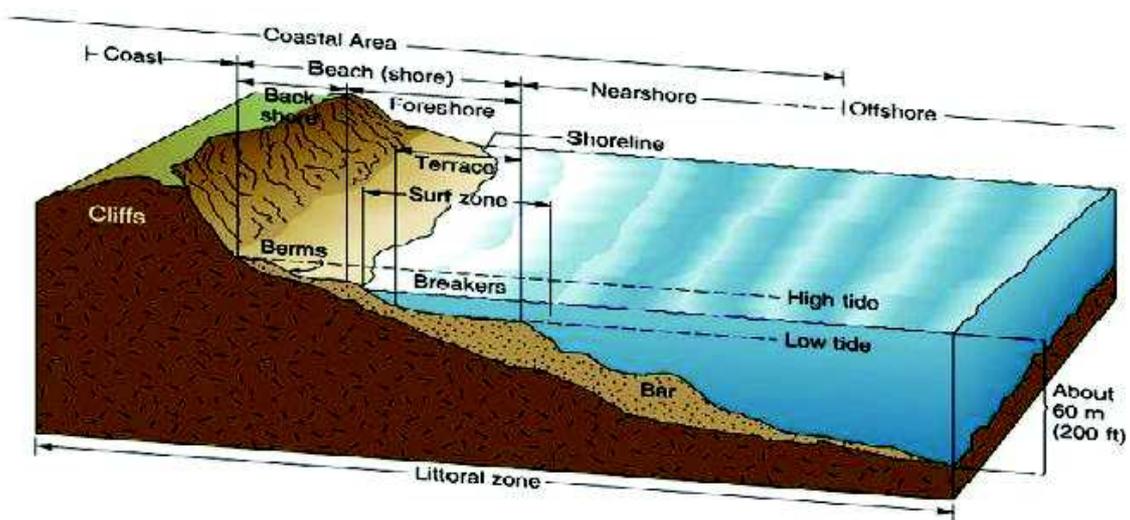


Figure 18. Offshore Littoral Region (Wikipedia, 2014c).

This shift in attention can be seen with the US Navy developing the recent Littoral Combat Ship (LCS) platform variants, as well as the Joint High Speed Vessel (JHSV) platform. This naval triad consists of monohull, catamaran, and trimaran craft all over 90 m in length and all having semi-planing hull forms. These attributes allow the vessels to operate efficiently in shallow littoral seas, but engage in open ocean crossings when necessary.

## 8.2 Defining a high speed craft

A ship or craft achieves high speeds differently depending on a number of factors including various combinations of naval architecture principles, hull form characteristics, as well as propulsion selection. The common phrase “High Speed Craft” is used in discussions of many of today’s naval platforms as well as defined quite clearly in international standards and regulatory publications. Depending on the approach; all are correct definitions of high speed craft, yet all are slightly different in criteria.

### 8.2.1 Principles

“Hull speed” or speed-to-length ratio is a principle which defines the required length of a ship’s hull in order to achieve a desired speed. Naval platforms have traditionally fallen into several groupings of speed-to-length ratio. Figure 19 shows the placement of commercial and naval ship classes grouped according to this ratio.

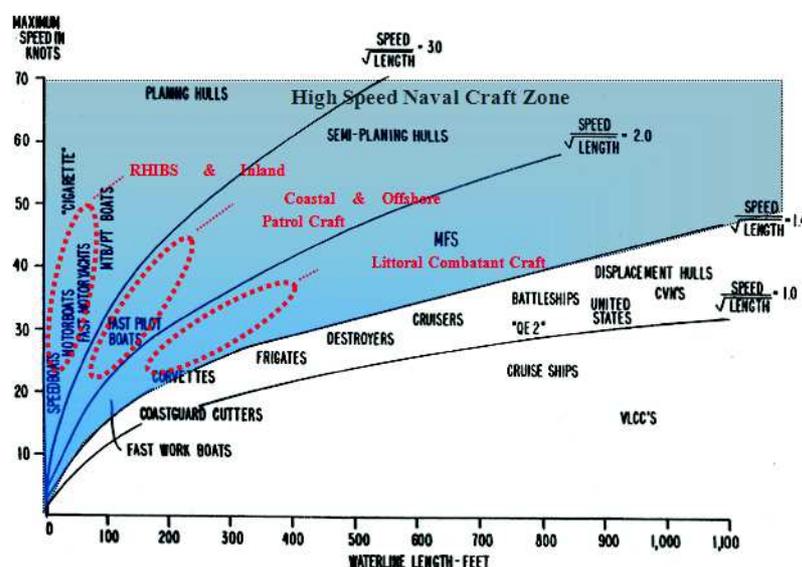


Figure 19. High Speed Naval Craft According to Speed-to-Length Ratio.

### 8.2.2 Hull Form

Characteristics of the hull form and its performance while under propulsion play a significant role in providing the conditions necessary as described in naval architecture principles for a ship to achieve high speeds. Savitsky (2003) describes the negative resistant pressures that occur at high speeds as directly dependent on hull form performance and characteristics. These hydrodynamic pressures increase substantially on the submerged portion of the hull as the ship's speed increases. This phenomenon has subsequently led to a range of high speed vessel types touting various types of hull forms and appendages to mitigate this effect. High speed naval craft are typically those that have small displacements and are hard chined in order to achieve a planing mode under high speed. Contrary to craft, high speed naval warships are fine hulled with rounded bilges and maintain a displacement mode under high speeds. Examples of some of the common high speed naval craft types and hull characteristics are shown below in Figure 20.

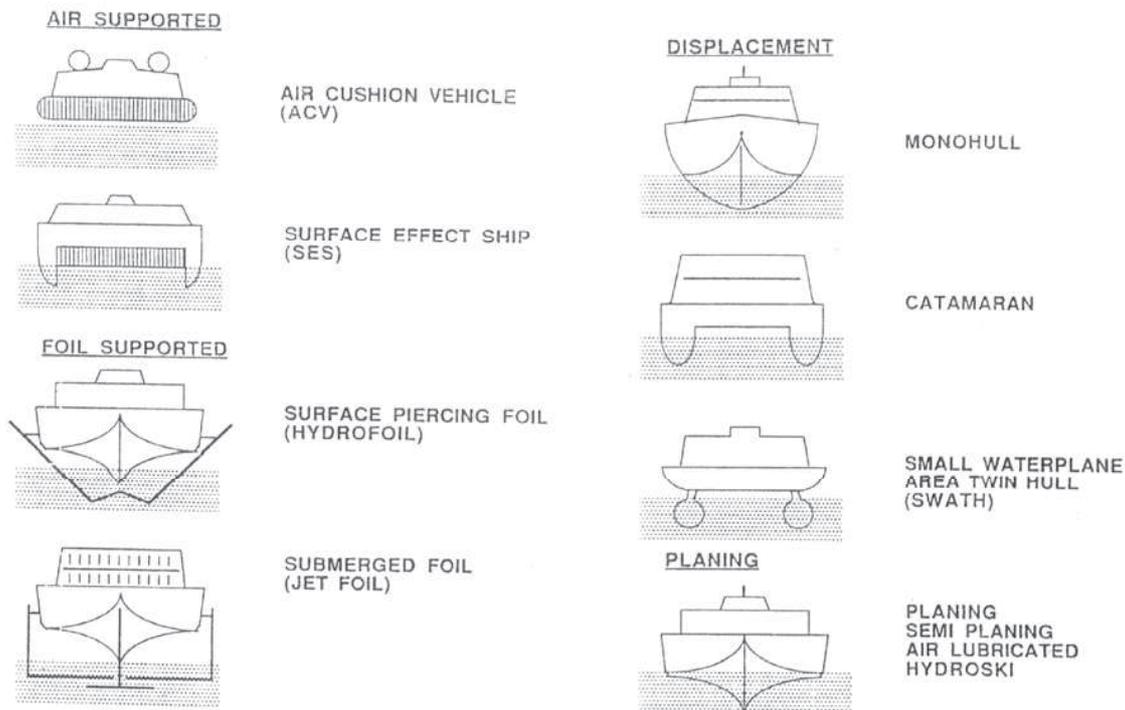


Figure 20. Example showing some high speed naval hullforms.

### 8.2.3 Standards and Regulations

The specialized design of high speed craft are pushing more and more navies to leverage and reference International Standards as well as Regulations within their specifications to incorporate safety features as well as mature design techniques. Modern naval technical communities have much less experience with this type of vessel than traditional ships of the blue water fleet. This also compliments the movement of many navies to a commercialized design and building methodology by incorporating partnerships with Classification Societies and commercial shipyards. The following are current definitions of high speed craft in international regulations:

IMO (2000) High Speed Craft Code and ANEP 77 (Naval Ship Code) (NATO 2014):

A high-speed craft is a craft capable of a maximum speed,

$$V \geq 3.7\bar{V}^{0.1667} \text{ (m/s)} \quad (1)$$

with a volume of displacement,  $\bar{V}$ , corresponding to the design waterline ( $\text{m}^3$ ), excluding craft the hull of which is supported completely clear above the water surface in non-displacement mode by aerodynamic forces generated by ground effect. (SOLAS X/1.2, HSC Code 2000 para 1.4.30).

### 8.3 Defining operational limitations

#### 8.3.1 Operational profile

During the design process, like any vessel, a high speed naval craft must be given the beginnings of an operational profile in order to provide the window of design criteria that will apply to an existing design or used for a new design. The operational profile is usually much like a master use case during design and likewise a historical archive for the craft during operation. The crewing, payload, geographic operating locations, necessary mission endurance, speed, and sea state design criteria would all be specified under this profile. The profile is a living set of criteria that will not be able to provide the baseline for a vessel until the design is complete. Iterations of the criteria will usually be vetted before a final set of parameters is completed. This profile is iterative throughout the lifecycle of the craft which can drive the basics such as the general arrangement all the way through the maintenance considerations and lifecycle upgrades for a high speed naval craft.

#### 8.3.2 Operational envelope

An operational envelope is a supporting element and outcome of a craft’s operational profile. The envelope is created as a limiting set of data from the craft’s final design particulars and scantling sizes. The main purpose of this information is to expose to the master of the vessel the operating limitations as it relates to speed and sea conditions for certain headings. A common naval term is Safe Operating Envelope (SOE), but this can also be interpreted Structural Operating Envelope (SOE) as well. This presents an issue as the structural limitations of a design would not be appropriate safe operating conditions for crew and equipment. The context and analysis used to derive the envelope could be either structural in nature but could also be based on other factors including human and payload limitations.

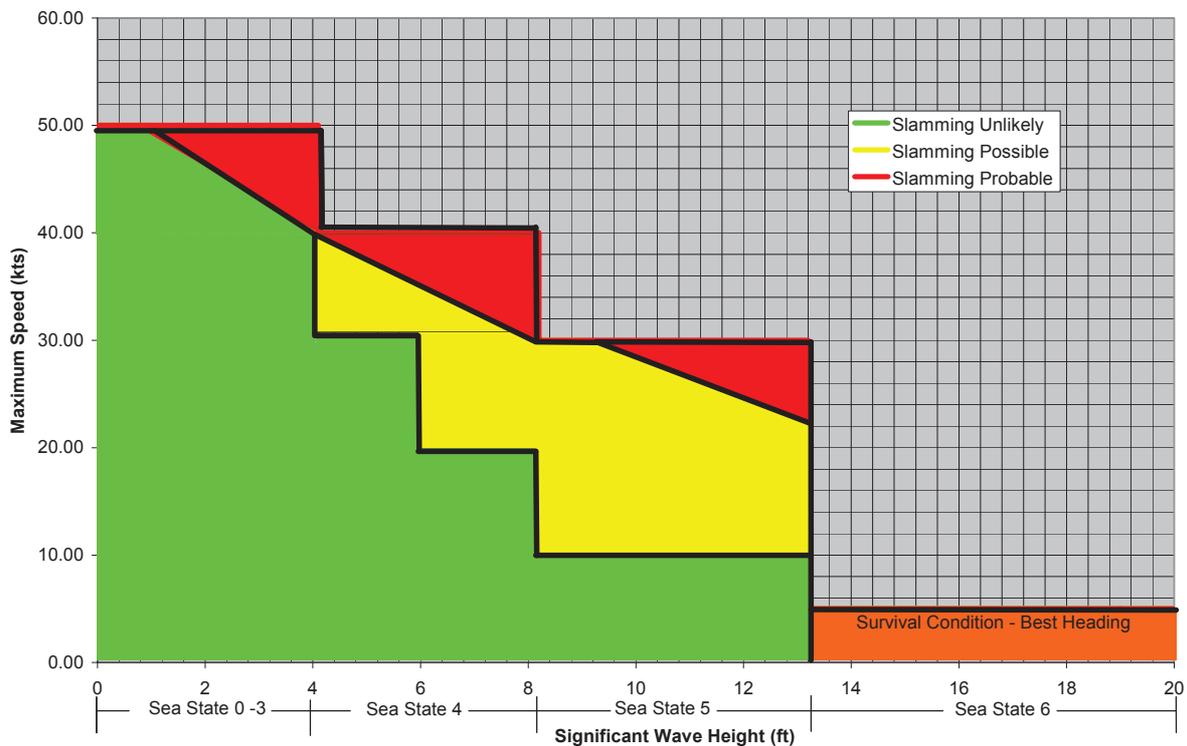


Figure 21. Sample Operational Envelope for Head/Bow Seas.

Therefore, each envelope is a combination of elements folded into a graphical format and should be supported with instructions or narratives that clearly define the context in which they were constructed. This would prevent a structural envelope being used under the assumption that this was the safe operation limitations of the craft. An example of a commonly used operational envelope is shown in Figure 21.

## 8.4 Accelerations effects

One of the major design restrictions in high speed naval craft is the direct correlation of accelerations with high speed operation. Accelerations, especially in excess, cause a number of problems on craft and more so on high speed-to-length ratio smaller vessels. Commercial type high speed craft usually avoid higher sea states when operating at high speeds and reduce their speed to take a best course approach when seas become rough. Larger naval ships can accommodate higher sea state operations because of their sheer size and hull form as seen in Table 6. However, smaller naval craft inherently operate in a capacity and that dictates the craft be operated into high sea states in conjunction with high speeds.

Table 6. ABS HSNC Design Criteria.

Service Type	Operational Condition		Survival Condition	
	H1/3	V	H1/3	V
Naval Craft	4m (13ft.)	V <sub>m</sub>	6m (20ft.)	10 knots
Coastal Naval Craft	2.5m (8.5ft.)	V <sub>m</sub>	4m (13ft.)	10 knots
Riverine Naval Craft	0.5m (1.75ft.)	V <sub>m</sub>	1.25m (4ft.)	10 knots
V <sub>m</sub> = max speed in design condition				

### 8.4.1 Slamming

Part of designing a high speed craft is accounting for hull slamming, but this can become more of an issue when trying to predict the accelerations produced by a naval craft design. Empirical methods exist for designers to estimate equivalent static slamming loads by using accelerations derived from methods such as model testing, theoretical calculations, or instrumented vessels and then utilizing these in sizing scantlings. For instance, the American Bureau of Shipping minimum design criteria regarding speed and sea states for a high speed naval craft is shown in Table 6.

In the real world, slamming loads fail to behave the same on any two naval craft. Slamming events can occur along the entire length of the craft's hull during planing, but will also be focused within the forward lengths of the vessel's bottom and sides during semi-planing. Slamming loads are driven by accelerations which is comprised of two major variables, wave height and speed. For design, the craft's scantling loads should be derived at full speed under the lightest loading condition in head seas as a worse case condition.

Slam-induced whipping should also be evaluated within the hull girder as a global load case. Once a converged design has been achieved, an operational envelope should be developed to articulate the design's limitations graphically to the craft's operator.

### 8.4.2 Human factors

Excessive accelerations at sea can cause humans to suffer head, neck, and spinal injuries that could permanently damage one's way of life. The shock of weighted accelerations of 2.5g over the course of 1 hour could cause serious permanent damage to a human body [ASTM F1166 2013]. Furthermore, the same type of accelerations in the 6g range for any length of time would have an even greater traumatic effect.

The fact is that high speed naval craft experience these ranges of accelerations all the time. Many planning naval craft may see high accelerations in the hull over short time periods during high speed missions similar to Figure 22. Shock mitigating seats are common staples in small planning patrol craft in order to alleviate some of these injury risks. Other techniques include shock absorbing hulls as well as reducing speeds during rough seas. Drone vessels may be an emerging technique that could prevent the need for human occupancy on small high speed naval craft, but this concept has limited traction so far. Whatever the preventative measure, this human factor is almost always the limiting factor in craft operation and should be reflected in the vessel's operational envelope.

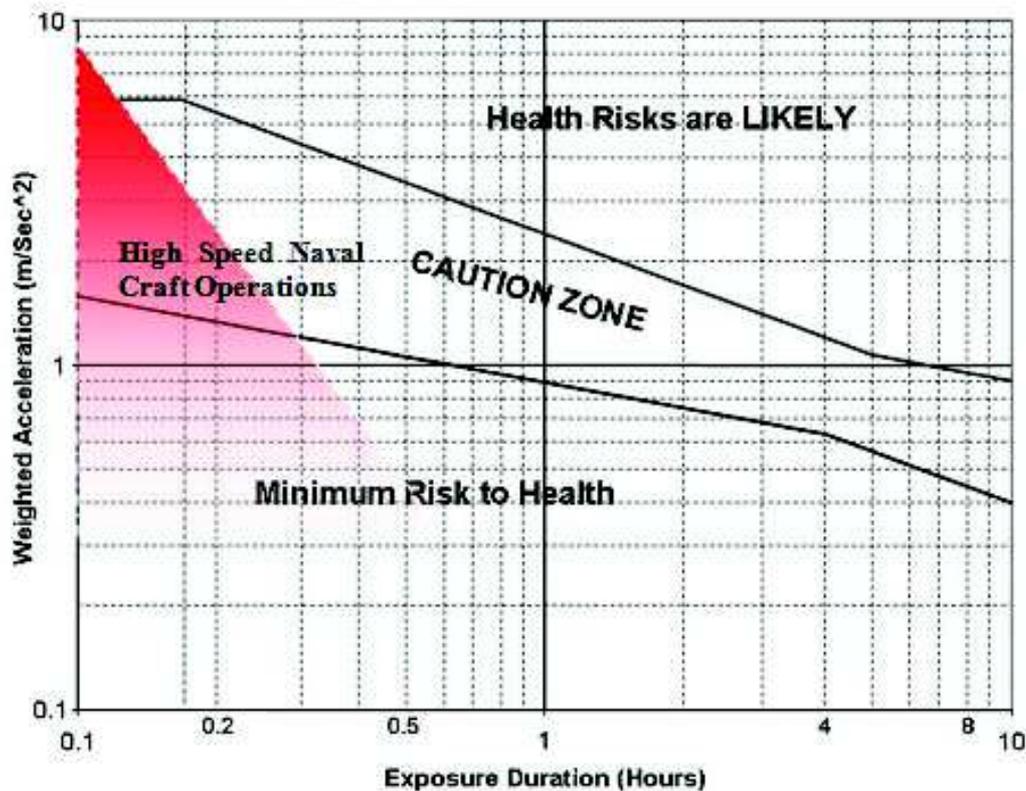


Figure 22. ASTM F1166 (2013) Human Acceleration Tolerance with High Speed Naval Craft Operational Accelerations.

### 8.4.3 Fatigue

Accelerations directly amplify fatigue in high speed naval craft when they occur in large cycles and at high amplitudes. Since large portions of small high speed naval craft are constructed of lightweight material such as aluminum, fatigue cracking can be a serious issue. Fatigue critical joints should be monitored on a more frequent basis when high speed craft have experienced heavy use in high seaways where slamming and hull whipping are present. The preventative method would depend on the material used in the craft as well as the location and range of the stress concentrations. Fatigue should also be considered in areas subject to vibration due to propulsion machinery as well as payload securing fittings. These areas with the use of lightweight thin material are many times the first to show signs of fatigue and overstress in new first of class naval craft.

## 8.5 Material technologies

The ISSC 2012 V.5 Naval Vessels specialist committee paper previously addressed lightweight material selection from a design and lifecycle perspective, so material technology will be briefly touched on. Along with hull form and speed, weight shedding is another key component to rounding out and reducing displacement footprint in a high speed naval design. The majority focus is on structural weight since structural scantling weights makeup approximately one third of a craft's displacement. Material selection is critical in producing efficient and lightweight scantlings. By using high performance materials it is entirely possible to reduce a craft's structural weight by as much as 40% as compared to traditional steel construction techniques (Furio, 2002). Fortunately, there are many state-of-the art material options for achieving lightweight designs. The following are some technologies that have emerged allowing craft to do more with less (weight.)

### 8.5.1 Steel

In lieu of traditional steel construction, proponents of steel can still benefit from some advances in construction and analysis techniques for design. Decisions on steel placement can be dictated by running advanced analyses on designs prior to construction to target overdesigned and lacking areas. The maturity of welding advancements in automation as well as a progression in protective coating effectiveness will allow steel weights to be further reduced for high speed designs in the near future.

### 8.5.2 Aluminium

The big opportunity for aluminum use is the 1/3 density of steel that can achieve a 30% weight savings right up front with minimal optimization. To further the ability of aluminum weight savings and efficiency is to utilize it in extruded sandwich planking configurations. The sandwich planking construction leverages thin sheets of series 6000 aluminum in an extruded truss-like sandwich panel that can be used in deck and bulkhead applications. This is a further variant to the US Navy's Light-Weight Metallic Sandwich (LMS) program progressed in the late '70s for topside weight savings. LCS variants have shown significant weight savings by incorporating aluminum sandwich extrusions into their designs as described by Furio (2005.)

### 8.5.3 Fiberglass reinforced plastics (FRP)

Composite advantages were discussed in the 2012 ISSC Naval Vessel paper as having significant maintenance and overall weight savings costs accumulated over the life of a naval vessel. A technical thesis by Torrez (2007) touches on the uses of composites in the DDG 1000 and LCS platforms as critical materials in reducing topside weight. The paper goes on to list a number of advantages within naval applications as referenced by Furio (2002) in his naval assessment of lightweight composite design.

Despite the number of advantages and studies suggesting that composites are the most effective material in high speed craft designs, navies have still not embraced this material technology as a holistic answer to structural weight savings. This is partly due to the lack of naval institutionalized knowledge of the material and design techniques in conjunction to the major disadvantage revolving around high combustibility and toxicity which composite materials exhibit in a fire or explosion. An example of this horrific scenario played out in 2012 as a brand new Indonesian Naval fast missile patrol vessel (FMPV), KRI Klewang -625 (a composite trimaran), burned to the waterline off of the coast of Banyuwangi, East Java while undergoing routine maintenance.

## 8.6 Unmanned naval high speed craft

One novel concept becoming more of a reality is the building of unmanned high speed naval surface vessels. While many of these are currently only smaller drone unmanned surface vessels known as USVs, some more recent developments have shown a naval interest is maturing these craft into larger, more functional sizes. Navies have deployed these unmanned craft mainly to hunt and neutralize subsurface mines, but some are now being utilized to detect more than just mines below the surface. SAIC (Science Applications International Corporation) and DARPA have recently begun construction and testing on designs for an ACTUV (Anti-Submarine Warfare Continuous Trail Unmanned Vessel) due for delivery in 2015 (Figure 23), which will be built as a full-scale vessel for operation for months at sea without maintenance or refueling. This vessel will use computerized logic by leveraging pre-programmed algorithms within its operation and monitoring systems in order to make decisions depending on a number of factors. She will also be remotely controlled much like her smaller surface and subsurface predecessors.



Figure 23. SAIC ACTUV Concept (Drones of the Navy).

## 8.7 Classification Society Rules

The current rules for classification of high speed naval craft from the major societies can be found in Table 7 with the applicability limitations, if any.

Table 7. Classification society rules applicable to high speed naval craft.

<i>Classification Society</i>	<i>Rules</i>	<i>Applicability</i>										
ABS	ABS Rules for Building and Classing High-Speed Naval Craft (2014)	<p>The HSC Rules or HSNC Rules is applicable to high-speed craft or high-speed naval craft constructed of steel, aluminum, or FRP and having <math>L/V</math> not less than 2.36 (1.30) where <math>L</math> is as defined in 3-1-1/3 and <math>V</math> is as defined in 3-2-2/1.1.2. Applicable craft type and length are as follows:</p> <table border="1"> <thead> <tr> <th><i>CraftType</i></th> <th><i>ApplicableLength</i></th> </tr> </thead> <tbody> <tr> <td>Mono-hull</td> <td>&lt; 130m (427ft)</td> </tr> <tr> <td>Multi-hull</td> <td>&lt; 100m (328ft)</td> </tr> <tr> <td>SurfaceEffectsShip</td> <td>&lt; 90m (295ft)</td> </tr> <tr> <td>Hydrofoil</td> <td>&lt; 60m (197ft)</td> </tr> </tbody> </table>	<i>CraftType</i>	<i>ApplicableLength</i>	Mono-hull	< 130m (427ft)	Multi-hull	< 100m (328ft)	SurfaceEffectsShip	< 90m (295ft)	Hydrofoil	< 60m (197ft)
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Hydrofoil	< 60m (197ft)											
DNV-GL	DNV Rules for Classification of High Speed, Light Craft and Naval Surface Craft (2014)	The rules for naval surface craft are intended to define technical safety requirements for such craft of frigate/destroyer size or smaller. The rules are limited to marine safety and its interfaces with military aspects (fit for purpose).										
LR	LR Rules and Regulations for the Classification of Naval Ships (2014)	The Rules are applicable to naval ships designed and constructed for the purpose of carrying and operating naval systems.										

## 8.8 Conclusion

The use of high speed craft by navies worldwide will continue to grow in demand as countries race to secure coastal and littoral waters. The speed capabilities, payload agility, and range that high speed craft offer governmental agencies and the naval force will be driving factors for the continued acquisition of new platforms. Today, the commercial shipbuilding industry is leveraged by naval authorities for their extensive experience in design and construction of high speed craft such as ferries and pleasure craft. Classification societies are used as third party validators for design and construction and also in order to supplement the knowledge gap within naval technical authorities. As state-of-the art technology in lightweight materials continues to mature and techniques for mitigating slamming consequences progress, naval technical communities will continue to acquire knowledge and understanding in small high speed craft design. This will hopefully propel a new era of research and development specific to this area. In conclusion, the projection of high speed design techniques into the traditional processes and framework of naval standards will ultimately redefine the next generation of naval fleet.

## 9 BENCHMARK STUDIES

### 9.1 Whipping Response of Ship

#### 9.1.1 Introduction

Underwater explosion (UNDEX) induced hull girder whipping, as distinct from the early time shockwave response, involves the excitation of the ship's low frequency global vertical bending modes in response to pulsations of the explosion gas bubble. If whipping loads become too great, the hull girder may fail globally in bending - "breaking the ship's back". The ability to assess whipping response of a warship early in the design phase is necessary to ensure the global ship structure is capable of withstanding potential weapon threats. Simplified analytically based explosion bubble models (Riley, 2010) have been formulated for predicting, under far-field assumptions, the growth and collapse of an UNDEX gas bubble and the associated fluid pressure and velocity field impinging on the ship. It is rare to find experimental whipping results in the open literature which may be used to verify the application of the available bubble models for whipping problems.

A benchmark study completed by the International Ship and Offshore Structures Congress (ISSC) naval vessel design committee aims to compare different numerical codes for UNDEX whipping analysis. The Naval Design committee were given access to a unique set of experiments that involved a segmented scale model of a warship subjected to various UNDEX events. This section of the report compares the

whipping data obtained from the experimental tests with numerical predictions obtained using a number of different approaches.

### 9.1.2 UNDEX Bubble Phenomena

The physical phenomena associated with an UNDEX event is comprehensively described by Cole (1948). Following passage of a detonation wave through the submerged explosive, thereby converting the solid explosive to an approximately spherical bubble of gaseous detonation products, a high intensity, spherically spreading shockwave is propagated into the surrounding water. Immediately following emission of the shockwave, the pressure in the gas bubble, although considerably decreased from the initial detonation pressure, is still much higher than the local ambient pressure (i.e. hydrostatic + atmospheric pressure). The bubble therefore expands rapidly to reduce the internal gas pressure. Bubble expansion and the associated outward flow of displaced water continues until the bubble reaches a point of maximum radius and minimum pressure. Due to the inertia of the displaced water, the minimum bubble pressure falls below the local ambient pressure. Thus after reaching a maximum radius, the bubble begins to contract. The inward motion continues at an increasing rate until the compressibility of the gas acts as a check against further contraction and causes a rapid reversal of the motion. The inertia of the water, together with the “elastic” properties of the compressible gas, provide the conditions for an oscillating system and the bubble undergoes repeated cycles of expansion and contraction. Of the total chemical energy released from the explosive, approximately 50% is associated with the shockwave with the remaining 50% available for the later bubble oscillation phase.

Figure 24 shows a schematic of the far-field pressure-time history experienced at point in the water following an underwater explosion. The peak of each bubble pulse corresponds to a bubble minima and rapid flow reversal. The relatively larger duration of under pressure between peaks corresponds with the bubble expansion phase. Compared to the initial shockwave, the bubble pulses are of less magnitude and have longer rise and decay times. The peak pressure of the first bubble pulse is typically 10-20% of the shockwave peak pressure. For subsequent bubble oscillations, a significant decrease is observed in the peak bubble pulse pressure, the maximum bubble radius and the bubble oscillation period. The reduced peak pressure however is accompanied by broadening of the pulse such that the impulse is less affected, at least for the first 2-3 cycles.

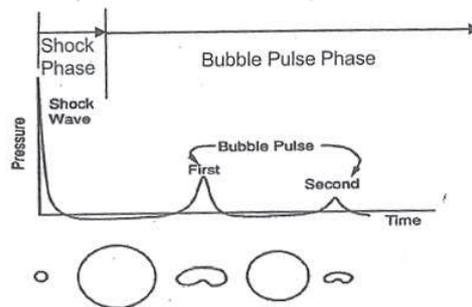


Figure 24. Schematic of a far field pressure-time history of an underwater explosion and the relative gas bubble size and shape.

The decrease in bubble pulse pressure with successive cycles is caused by energy losses which occur primarily around the time of bubble minima. One obvious source of energy loss is the radiated energy of the bubble pulse itself which is not returned to the bubble. However, other more complex energy dissipation mechanisms are known to occur during the bubble collapse phase which may have a dominant effect. Although the details of such mechanisms are not completely understood (Cole, 1948 and Hicks, 1972 & 1986), they are known to be dependant on bubble size. In the case of relatively large bubbles for which the difference in hydrostatic pressure between the top and bottom of the bubble is significant with respect to the “average” hydrostatic pressure at the bubble centre, the bubble remains approximately spherical during expansion but distorts into a toroidal shape around the time of the bubble minima, recovering the spherical form upon re-expansion. The toroidal bubble generates a dissipative flow of high velocity water directed through the centre of the toroid, referred to as a water jet. In the case of smaller bubbles, particularly at larger depths, bubble distortion is much reduced. For such bubbles however, evidence as been observed for the occurrence of so-called Taylor instabilities of the bubble surface during the bubble collapse phase. Such instabilities allow thin jets of water to penetrate into the bubble, thus

cooling the bubble and reducing its pressure. Analytical bubble models necessarily adopt a simplified approach to account for complex energy loss mechanisms during bubble oscillation.

Buoyancy force (displacement volume of the bubble) causes the pulsating bubble to migrate upwards toward the free-surface. The vertical migration velocity of the bubble is much greater when the bubble volume is near minima than during the expansion phase. This can be understood by noting that although buoyancy forces are smallest at bubble minima, the inertia of the surrounding water (added mass effect) is much reduced in comparison to the bubble maxima. The proximity of the free-surface has a marked effect on the bubble oscillation period, maximum bubble radius, migration rate and, therefore, the number and magnitude of the bubble pulses impinging on the vessel. Larger bubbles relatively close to the surface are characterised by both high migration rates and high multi-cycle energy dissipation due to the aforementioned bubble distortion.

### 9.1.3 Experimental Investigations

The ISSC Naval Vessel Design committee has been given access to a unique set of experimental results for a scaled warship model subjected to various UNDEX events. The ship model, Figure 25, consists of a segmented beam type arrangement with 8 external steel hull segments and 7 internal steel cylindrical tubes along the length. The ends of each tubular member are welded to transverse bulkheads with supporting longitudinal brackets. These connections provide a flexible joint between the tubular members which together form a multi-segment beam backbone for the model. The external structure of the model consists of eight hull segments which are welded to the bulkheads and connected to each other by means of soft rubber transverse strips to provide a watertight joint. The inclusion of the soft rubber strips ensures that the external hull sections contribute negligibly to the global bending stiffness of the model, the later stiffness being provided almost entirely by the internal tubular backbone. The external hull segments contribute some structural mass to the model, however a much larger added mass of external fluid is determined by the hull section geometry.

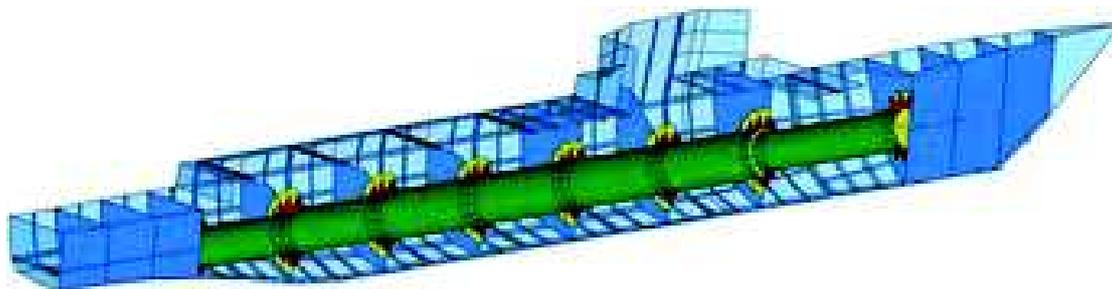


Figure 25. Segmented scaled warship model used in UNDEX whipping experiments.

The main particulars of the scaled ship model are given in Table 8 includes measured values of the first (lowest) two vertical bending mode natural frequencies of the model structure in water (wet frequencies) and the damping ratio of the first bending mode. The first and second modes correspond to the familiar 2-node and 3-node modes respectively for a free-free Euler beam. The materials properties of the model are given in Table 8. Details of the moments of inertia and segment masses are given in Table 9.

Table 8. Key parameters of the scaled ship model

Main Parameters	Experimental Model
Length overall L(m)	7.95
Breadth B(m)	0.89
Draught $D_t$ (m)	0.23
Structural Mass M(kg)	906
1st bending mode frequency- wet (Hz)	10.7
2nd bending mode frequency - wet (Hz)	22.9
Damping ratio of 1st bending mode	0.3%

Table 9 Material properties of the model.

Property	Steel	Sealing Rubber
Young modulus ( <i>MPa</i> )	2.11E5	784
Poisson ratio	0.3	0.47
Yield stress ( <i>MPa</i> )	235	-
Ultimate tensile stress ( <i>MPa</i> )	375	29
Elongation ( %)	26	900
Density ( <i>kg/m<sup>3</sup></i> )	7850	950

The scaled ship model was subjected to three UNDEX events as described in Table 10. The charge depth is defined as the depth of the charge below the water surface,  $\alpha$  is the angle from the base of the keel to the charge location, R is the distance from the charge to the closest point on the keel and the bubble frequency ratio is defined as the ratio of the bubble oscillation frequency to the wet natural frequency of the first vertical bending mode of the model. The longitudinal location of the charge was at amidships ( $L/2$ ) for Cases 1 and 2 and at quarter of the length from the bow ( $L/4$ ) for Case 3.

Table 10. Moments of Inertia and segment mass for the model.

Cylinders No.	Inertia moment (m <sup>4</sup> )	Segments No.	Segment mass (kg)
1	1.967E-05	1	155
2	2.975E-05	2	102
3	4.016E-05	3	99
4	4.078E-05	4	116
5	3.543E-05	5	97
6	2.885E-05	6	86
7	1.876E-05	7	83
		8	168
			Total = 906 kg

Table 11. Experimental UNDEX events.

Case No.	Charge-Mass. W(kg)	Charge Long. Position	Charge Depth. D(m)	Attack Angle. $\alpha$ (°)	R(m)	Bubble-Freq. Ratio $\xi$	R to Bubble. Radius Ratio $\gamma$	
1	0.05	L/2	1.77	46.7	2.12	1.041	3.74	
2	0.02	L/2	1.77	90	1.54	0.763	3.71	
3	0.04	L/4	1.77	48	2.07	0.961	3.96	

Further information and results from this benchmark study are presented in ANNEX 1.

## 10 DISCUSSIONS AND CONCLUSIONS

In this report the committee have tried to highlight differences between military and commercial structural design and also to concentrate on naval specific structural requirements.

From the study of different classification rules it can be concluded that:

- Military operational loads are well covered by Classification Rules.
- Military damage scenarios are either well covered by some Class Societies, and little or no coverage by other Class Societies.
- The responsibility for input loads for military damage scenarios follow different practice from one Class Society to another.
- Certification against Naval Ship Code may overrule the class requirements on military damage scenarios

- One Class Society handles the military damage scenarios as performance requirements that are verified against military standards instead of Class Rules requirements.
- There is still a way to go for Class Societies and Navies to have a common understanding of the responsibilities for defining the military damage scenarios and how to handle these.

Many Class Societies have put a lot of investment, competence and effort in the coverage of military loads and damage scenarios. Also some navies have put competence and investment in this development. It is now up to the Navies to utilize this resource so that class societies can follow up with practical experience and further development in this area.

For the main military load effects analytical and numerical methods are in place. For the presented methods however limited validation material is available especially on the full ship scale. Depending on the time available for the analysis and the needed accuracy, analytical, numerical methods or a mix of both is being used. Where in the latter case the load is determined analytically and put onto the finite element model of the structure. As however treats, naval ship structures and there materials continue to develop there will always be a need for experimental research in which validation of numerical methods should play an essential role.

Naval warship design is fundamentally similar yet ideologically different than commercial ship design. The uncertainty of the mission along with nobility of the role forces naval designers to consider increased probabilities. These probabilities, such as hostile threats in conjunction with adverse environmental conditions, are also related to higher consequences. All have to be accounted for in conjunction with the endurance readiness of the ship. The same considerations would not normally be a concern for a commercial ship designer. Accommodating the structural mission needs of naval warships is done through two distinct ways; permanent integrated structures and modular flexible structures. Today, traditional naval warship design has embraced the methodology of permanent, functional integrated structural design features; navies are seeing a necessity to move to more flexible naval mission structure with modular capabilities. With advancement of technology and weaponry, experts say this type of flexible and adaptable behavior will be critical to the ever evolving mission needs. With the emergence of the next generation US Navy fleet looking to these methods, such as the LCS class variants, time will tell whether there is a need to institutionalize the modular adaptable ship.

In Chapter 6 a brief overview has been provided of naval mast design. There are few, if any comprehensive publications covering all aspects of mast design, and a designer are left on his own to design a mast as any other structure. Unfortunately this includes Class naval rules where various aspects of mast design are distributed throughout the rules, and some not included at all. Given the complexity and importance of a naval mast structure, this is not a particularly desirable state, and this committee recommends that Class societies, or naval design authorities, produce a comprehensive, collected rule set for naval mast design.

Chapter 7 discusses progressive collapse techniques and Table 7.1 provides an overview of the different capabilities offered by the Smith Progressive Collapse method and non-linear FEA. It can be seen that whilst FEA may have advantages of offering more detailed modelling and analysis, and what may be considered a more accurate assessment of the ultimate strength of a ship's hull girder, the Smith method still has a significant role to play in both early design stages and emergency response, provided the analyst is confident in the assumptions made in its application. Caution must be taken when implementing the method as factors such as modelling details e.g. initial imperfections, residual stresses, etc., and variations between the true failure mode of the vessel (interframe, overall, torsion, shear, etc) compared to the assessed interframe failure mode could lead to incorrect prediction of the ultimate strength of the vessel.

Whilst FEA may be the obvious solution for performing more complex bespoke analysis, time constraints along with factors such as design maturity, analyst experience, local model detail handing can all affect the quality and accuracy of the results obtained and their value in answering to the question being asked.

In conclusion, whilst the capability and accessibility of FEA has increased significantly since the Smith Progressive Collapse Method was originally conceived, the method continues to hold a valuable place in the design and analysis of ship structures.

The use of high speed craft by navies worldwide will continue to grow in demand as countries race to secure coastal and littoral waters. The speed capabilities, payload agility, and range that high speed craft offer governmental agencies and the naval force will be driving factors for the continued acquisition of new platforms. Today, the commercial shipbuilding industry is leveraged by naval authorities for their extensive experience in design and construction of high speed craft such as ferries and pleasure craft. Classification societies are used as third party validators for design and construction and also in order to supplement the knowledge gap within naval technical authorities. As state-of-the art technology in lightweight materials

continues to mature and techniques for mitigating slamming consequences progress, naval technical communities will continue to acquire knowledge and understanding in small high speed craft design. This will hopefully propel a new era of research and development specific to this area. In conclusion, the projection of high speed design techniques into the traditional processes and framework of naval standards will ultimately redefine the next generation of naval fleet.

Chapter 9 gives an overview of benchmark problems carried out by the committee. The results of which are presented in the Annex to the report.

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