16th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS
20-25 AUGUST 2006
SOUTHAMPTON, UK

VOLUME 2

COMMITTEE V.5

NAVAL SHIP DESIGN

COMMITTEE MANDATE

Concern for structural design methods for naval ships including uncertainties in modeling techniques. Consideration shall be given to applicability of classification society rules to design of naval ships. Particular attention shall be given to those aspects that differentiate naval ship design from merchant ship design such as blast loading, vulnerability analysis and others, as appropriate.

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KEYWORDS

Navy, naval, military, classification, Rules, criteria

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1. INTRODUCTION

Structural design is the oldest and most fundamental of the technical disciplines which together comprise the art of naval architecture. Over the past decades, structural design as it is applied to naval ships has diverged from and converged with that for commercial ships for a variety of reasons. In recent times, resource constraints have made it necessary for governments around the world to seek out alternatives to established practices in many areas including naval vessel acquisition. Fortunately, the convergence of commercial and naval design practices has made it possible to look at commercial processes. One development arising from these conditions is that navies have increasingly turned to the application of classification society processes and resources to help them in establishing and applying technical criteria for naval ship design and construction including those related to the ship's structure. It is the purpose of this Committee to explore the current state of this general trend as it relates to ship structures.

2. HISTORY OF STRUCTURAL DESIGN – COMMERCIAL VS NAVAL

The structural design of warships has diverged from and converged with commercial ships throughout history. The Greek and Roman ramming ships (triremes and biremes) were built light but with a heavily reinforced keel, compared with the heavier but more uniform amphora ships of the era. In the Middle Ages few nations had standing navies and most warfare was conducted from merchant ships adapted to carry light guns. In the 1500s the advent of heavy guns and gunports led to the creation of fleets of specialized ships-of-the-line, having reinforced decks and hulls to absorb the weight and recoil of the guns and resist the impact of shot. Even so, warships were often constructed in the same shipyards as commercial ships; both designers and workers had little or no difficulty in switching between the two and in fact often shared technological advances between the naval and commercial ships. For example, during the late 1700s many of the European East Indies fleets built their armed commercial ships using naval practices; and in the early 1800s, hull strength improvements pioneered by the British East Indies Company were improved upon and incorporated into British warships (later, by other navies as well).

The growing use of iron in shipbuilding from 1820-1860 caused both navies and commercial ship-owners to rethink design and build practices. Once again, there was considerable sharing of new ideas and technologies between the two sectors. Most of this advance occurred in Britain, the centre of the Industrial Revolution, where civil engineers working on railways and bridges were bringing their hard-won knowledge of structural design practices into the shipbuilding arena; in particular, the box-girder system developed for the Britannia Bridge became the paradigm for longitudinal iron framing in ships. In fact, with most navies at this time (soon after the Napoleonic Wars) operating under austere budgets, much of the fundamental research into metallurgy and the design of joints was carried out for the commercial sector, which was undergoing a rapid expansion due to the increasingly-reliable marine steam engine. At this time, commercial classification societies – in particular Lloyd's Register in Britain and the French Bureau Veritas – led the way to rationalizing iron shipbuilding practices with their Rules published in (respectively) 1855 and 1858. However, most of these Rules gave very empirical formulae for scantlings based on experience, a model that would serve the commercial sector well but was increasingly unsuited for naval ships.

Beginning in the 1870s, the British navy led the way in developing structural design practices using calculations based on fundamental engineering principles. For example, warship designers began calculating bending moments based on the static balance of a ship on a wave and a careful enumeration of the weight distribution along its length. By contrast, most classification societies at the time settled on semi-empirical formula that related bending moments to the length and displacement of the ship. This rule was quite adequate for the large number of relatively similar merchant ships that were constructed under classification Rules. Navies, however, developed and built relatively small numbers of ships, and the requirements for each one tended to evolve faster than for merchant ships; so naval constructors tended to revert to basic engineering principles and lessons learned in their designs. More importantly, the ability of naval constructors to develop scantlings was directly related to the rapid progress of naval architecture education that was specifically directed to serving navy needs. Put simply, by the early 1900s many navies around the world had funded schools of naval architecture, whose graduates overwhelmingly went back to work for the "sponsor". Most naval design bureaus possessed both the ability and managerial support to carry out complex calculations. By contrast, the number of graduate engineers in commercial shipyard design offices (versus designers coming up from the shop floor) was still limited.

This situation slowly changed during and after World War II for two related reasons. First, the number of graduate engineers increased dramatically as companies and governments recognized the need for higher levels of knowledge and skill in the new economy, insisting on university degrees for their engineering workforce. Second, investment in science and technology also grew sharply, much of it directed to universities and research centres to advance the state of the art and to solve practical problems. An early example of this was the formulation in 1946 of the Ship Structure Committee (SSC) as an outgrowth of a US Navy Board of Investigation to determine the causes of the brittle fracture of welded merchant ships during the war. Similar investigations were conducted by the Admiralty Ship Welding Committee (later the Advisory Committee on Structural Steel) in the UK. It is interesting to note that both of these government committees included their respective national classification societies as integral members – recognizing that technology transfer between commercial and naval practices could be of benefit. The research sponsored by these organizations included several full-scale tests that greatly advanced the development of fundamental engineering requirements for structural rules and ship specifications, while the new breed of university-trained engineers now possessed the requisite knowledge to apply advanced technologies. Over time, the development of improved methods of calculation such as probabilistic analysis, and the use of computer-aided design tools such as finite-element codes, were promoted by classification societies using state-of-the-art engineering techniques. The ability to perform detailed structural analyses with high degrees of confidence has aided the rapid growth in specialized vessels such as LNG carriers, FPSOs and ultra-large container ships.

Although the computational design and analysis processes and supporting tools applied to naval and commercial vessels were converging, there were still elements of significance which made them unique from one another. Navies continued to develop and refine their own design standards based on “lessons learned” from battle damage experience and extensive research into structural response. From the mid-1940s to the 1960s, many navies carried out numerous full-scale trials using decommissioned or captured warships to examine everything from hull girder bending to the response of foundations under shock loading. From the 1980s to the 1990s, full-scale trials were largely replaced by scale model tests and increasingly sophisticated computer-aided analysis programs, in many cases based on the same principles as commercial software codes. The results of these tests and trials have led to the development of specialized steels for naval ships, and comprehensive standards and specifications for construction details to improve damage resistance. For example, most navies specified the use of symmetrical “T” stiffeners and continuous welding of members to inhibit structural failure after shock loading.

Differences such as operations and maintenance also contributed to the divergence of naval and commercial ship design standards and methods. Most cargo-carrying ships had a great variation in loading conditions (fully laden or in ballast), resulting in greater fatigue cycles than found on naval vessels, resulting in heavier scantlings for comparable sizes. For another example, navy crews continuously inspected and painted hull structures, whereas for commercial ships these activities were carried out only periodically, e.g., during drydockings; so in most class Rules, a corrosion (wastage) allowance was specifically called out, which was generally not present in naval ship design criteria.

Perhaps the most important reason for the continued difference in naval and commercial design methods was the relative “democracy” of the classification society Rules process, compared with the “single party rule” generally present in naval design bureaus. Simply put, classification societies had to (and still must) adjudicate changes to Rules among numerous stakeholders, including owners, operators, shipyards and government regulators. This does not mean so much a “drive for the minimum acceptable” as much as a balance of many, often strongly-held, views on the relative importance of cost, risk, efficiency and safety. By contrast, naval design bureaus have been fairly small, and though they too must be accountable to numerous stakeholders as well, in actual fact the changes to structural design methods and standards were made and approved by a small cadre of highly experienced technical staff.

This is now changing. In the post-Cold War era starting in the 1990s and evolving to the present day, many navies have experienced sweeping cuts in their technical staffs, as governments changed the way they acquired warships. In the past these navies had designed their own warships, to their own specifications. Now, the ship design and construction process is handled by commercial organizations with the navies providing only performance criteria to be met and technical guidance as necessary. In short, many navies can no longer develop and maintain their own standards and specifications. Starting with the British navy, but rapidly expanding to others, the responsibility for these standards have been transferred to commercial classification societies, under close naval oversight. Although this process is still evolving, early experience has indicated that many commercial-like ship design processes with modified naval structural standards are, in fact, quite comparable to traditional military standards, and in some cases such as high-speed vessels, certain military-like standards are needed for the ever-more stringent requirements of commercial fast ferries. It is likely that naval and commercial vessel Rules will continue to evolve in parallel and may show some overlaps, given the current concern by commercial ship owners to consider survivability against terrorist-like threats. The fact that classification societies commonly use the same fundamental-engineering principles as do navies means that naval and commercial structural design can be developed side-by-side using comparable means of analysis, so that differences between them can be properly attributed to required use, and not to any misunderstanding of methodology.

3. RECENT TRENDS IN NAVAL VESSEL DESIGN

Some of the current trends that will affect the way naval vessels are designed and built are:

- *Modularity, flexibility and multiple missions:* The rapid development of open software standards, “plug-and-play” systems and leaps in autonomous, remotely-operated vehicles means that future naval vessels may be configured to carry out a variety of missions that span the traditional roles of force projection, combatant and support, either simultaneously or in sequence; thus, conventional “rules” will have to be re-examined (for example, will flexible-mission ships need to be shock-hardened for mine warfare, if the actual operations are carried out by remote unmanned vehicles?).

- *Enhanced Stealth:* In the post-Cold War era, warships will likely operate far more in littoral regions rather than in open ocean. Signature management (stealth) is increasingly seen as important to reducing vulnerability to detection and attack in such environments. Novel structural arrangements, features and materials are being developed to reduce radar cross-section, acoustic and thermal emissions, and even visual signatures.

- *Changing Threats:* Since the end of the Cold War the nature of the threats faced by naval vessels has radically changed. Although prudent designers will always consider “blue water” threats such as submarine launched torpedoes and nuclear attack, it is far more likely that the ships of the near future will face low tech weapons such as simple mines, easily available missiles and high-speed boat attacks. Operations in the littoral will make platforms more vulnerable to low tech attack and allowances must be made for survivability in these areas.

- *High speed:* The age of 40-knot warships was thought to have ended in World War II, but the emphasis on littoral operations have revived interest in the tactical advantages of high speed. Extensive research is needed in the areas of hull slamming response, fatigue strength and vibrations in thin structures, in order to develop means to reduce maintenance and increase hull life.

- *Multihull/ advanced hulls:* Although novel hull types such as catamarans, SWATHs, trimarans, hydrofoils, surface-effect ships, etc. have been in existence for a long time, requirements for increased speed as described above, improved seakeeping and design flexibility (in both naval and commercial markets) are creating new demands for novel hull types. There is still a very limited knowledge base of effects such as structural interaction between hulls, stress flows, etc. on which to base new rules and criteria.

- *Materials:* Shipyards and owners (including navies) continue to search for newer materials and material systems that will improve performance and / or reduce construction and through-life costs. Composite materials and systems (e.g., metal-and-plastic sandwiches), novel metals such as titanium, and coating systems all are being considered to provide such attributes as lighter weight, ease of fabrication and higher resistance to corrosion. Another factor is the increased awareness of terrorist threats that may drive both naval and commercial vessel owners to consider additional hardening measures.

- *Naval construction by non-indigenous shipyards:* During most of the 20th century, developed nations built their own naval ships in their own shipyards. In recent years, some of those nations have begun to contract with foreign (i.e., non-indigenous) yards to build their naval vessels, and the trend appears to be on the rise. In some cases, this is due to lower costs at the foreign yards; in other cases, the sophisticated integration capabilities required simply do not exist locally. The implication for structural engineering is a move away from naval standards to commercial standards, which are well understood by the foreign yards.

4. NAVAL STRUCTURAL DESIGN PHILOSOPHY

Naval ships have traditionally been designed to in-house standards. A vision was developed for a system of naval ship regulation based on classification and combining the strengths of the naval and the commercial regulatory regimes to provide through life care of naval ships. This chapter gives a brief survey of known traditional approaches used by different navies and a brief survey of various approaches by different classification societies that have published rules for naval ships.

Recognizing that there is no body equivalent to IMO for naval ships, a NATO Specialist Team on “Naval Ship Safety and Classification” has been established to develop a “Naval Ship Code”. The Code aims to fill the void by providing the framework for navies to gain assurance that acceptable levels of safety are achieved. In doing so, the Code will replicate the link between IMO and Classification Societies and promote improved ship design and a greater consistency and transparency of safety standards (Rudgley et. al. (2005)).

4.1 Traditional Navy Approaches

Naval ships have traditionally been designed to in-house standards. These standards and design approaches were developed by various navies in the past based on extensive experiences.

4.1.1 United Kingdom Royal Navy (RN)

In the United Kingdom, naval ships have been subject to self-regulation by the Ministry of Defence (UK MoD), using a wide range of procedures. The system contains all the elements of a sound regime, namely: defined standards for design and build, defined responsibilities, defined schemes of maintenance, allocation of time for inspections and maintenance, feedback mechanisms, and external audit. It has served the Royal Navy well, and has resulted in high levels of ship and weapon availability.

The corner stone of traditional system in the United Kingdom is the Naval Engineering Standards (NES) published by UK MoD (1972, 1999). They were first developed formally in 1972 and aimed to capture the corporate knowledge of good naval design practice. The approach has been mostly deterministic, taking into account seaway loads such as wave bending and slamming, operational loads like tugs and aircraft landings, complimented by model and full scale test results, and weapons effects such as shock and blast. Structural capability is assessed through a combination of stress approach, mostly for local structures, and an ultimate strength approach. Advanced design techniques such finite element and fatigue strength analysis are commonly used.

There are some 700 NES, covering every aspect of warship design and construction. Since their inception in 1972, NES have been used for 5 new ship designs covering 49 surface ships and for 3 classes of submarine. In recent times, navies have a de-facto preference for ordering ships designed and built to classification rules.

4.1.2 Canadian Navy (CN)

With only minor exceptions, the Canadian Navy has used its own structural design standard Canada Department of Defense (DoD) DMEM 10 (1978) for new builds. Of all the Canadian warships currently in service, only the KINGSTON Class ships were built to class rules. DMEM 10 consists of four parts: (1) Design Procedures for CP Surface Ship Structures; (2) Standard for the Structural Design of Ship Surface Ships, (3); Structural Practices Standard for CF Steel Surface Ships and (4); Structural Survivability Requirements for the CF Surface Ships. Although updates have been made to DMEM 10, it remains largely unchanged since it was first published. Over the years, certain aspects of it have proven to be very difficult to use, and it does not lend itself well to the design of a next generation of warships. Efforts have been made to integrate parts of it to advanced structural analysis tools (e.g., incorporation of its limit states into Maestro), but there is a general realization that the standard is frozen in time, and does not allow for the progresses that have been (and still being) made in “virtual” structural analysis, see Canada DoD publications (1999, 2002).

4.1.3 German Navy (GN)

The German Federal Armed Forces “Bundeswehr“ have introduced a procedure for the determination and meeting of their demand under the name CPM 2001 (Customer, Product, Management). This procedure aims at obtaining the required capabilities through a timely, economic and operational supply of products and services. It is recognized that the industry more and more sets the pace in technological development due to its high innovative speed. Therefore, close cooperation between the Bundeswehr and industry is deemed absolutely necessary to be able to maintain modern and efficient armed forces, see German Federal Ministry of Defense publication (2002). The entire process is governed by the principles of cost effectiveness. In line with these principles, the German Naval Standard (BV) issued by the “Federal Office of Defense Technology and Procurement” (BWB) has been revised. These naval construction rules shall describe only that navy-specific portion of a naval vessel – for application on ships of the German Navy – that cannot be specified by industrial/class rules.

4.1.4 Korean Navy (KN)

Naval ships in Korea have been deterministically designed for environmental and military loads based on the internal naval ship design regulations, which were jointly developed by KN, KR and domestic naval shipbuilders. The regulations, which are being updated to be issued as Rules, made main reference to customary Korean Navy practices, US Navy procedures and general shipbuilding technologies. For more rational design of hull girder strength, direct load and spectral analysis techniques are usually used for comparatively fast and long naval ships to consider lifetime seaway loading according to the ship type and design characteristics. A numerical simulation method using finite element analysis codes is often applied as a way of investigating structural responses and seeking more effective reinforcements for military loading such as air blast and underwater explosion.

4.1.5 Italian Navy (IN)

Historically Italian Navy has looked to the structural assessment of vessels design with more attention paid to the past experience on some in-service ships. The global structural assessment of the hull girder is assessed in according to RINA naval rules that were jointly developed by the Navy, Fincantieri Shipyard and RINA Company, taking into account the expertise in this field and the leading procedures and methodologies.

4.1.6 Royal Netherlands Navy (RNN)

The RNN naval structural design is not different from other ships. In the first place there is a mission description, staff requirements, with a derived payload. The initial structural design of hull girders follows the traditional rules. These are a set of “normal” design loads like wave bending moment, tank and deck pressures etc. combined with a set of strength requirements like allowable stresses and safety factors for collapse. In most cases the design rules are subsets of class society rules adapted for the materials used or rules developed by class society rules for naval application. The RNN rules are more distinctly different from the contemporary class rules. The design against weapon effects in most cases is treated as an add-on to the existing structure.

4.1.7 US Navy (USN)

It has been long recognized that US Navy ships must be designed to endure both environmental extremes and military action. Throughout the 20th century, but especially during and after World War II, the nature and magnitude of ship structural loads has been analyzed through model tests, full-scale trials and battle damage assessments. The traditional approach has been deterministic, taking into account seaway loads such as wave bending and slamming, operational loads like tugs and aircraft landings, and weapons effects such as shock and blast. These practices were thoroughly documented in a series of Design Data Sheets (DDS) and referenced in various ship specifications.

Since the mid-1990s, two changes to this approach have been developing. The first is the incorporation of structured, machine-based computational approaches to the development of loads derivation and prediction of the structural response to those loads. Most recently, this is being backed up with the requirement for imbedded sensors in the structure to provide real-time feedback to the operators as well as validation data for tool improvement. Secondly, and more long term in nature, naval structural designers have recognized that a probabilistic approach would provide a more rational means of quantifying these uncertainties that might not be properly considered by a deterministic approach. A reliability-based approach called Load and Resistance Factor Design (LRFD) has been under development. This approach, which is in line with structural design practices being developed in civil and offshore engineering, is still being phased in, while the traditional approach continues to be used as a benchmark.

4.2 Naval Classification Rules Approaches

With the decreasing number of ships being designed, built and maintained to naval own standards, the pressure on budgets available to maintain the quality of these standards, and the reduced availability of in-house expertise, the traditional approach to the design of ships and the technical support to the navy is in need of fundamental change. In the past, navy design authorities have been in the forefront of technical innovation and development in the fields of naval architecture and marine engineering, but more recently there have been significant advances in the civilian sector. Such examples are advances in the offshore field and, most relevantly, the rise of the high speed craft industry with its many and varied designs of mono- and multi-hull vessels and novel propulsion systems. Moreover, the demands on performance by passengers and civilian authorities (for example, low noise and vibration, low pollution, high efficiency, high speed and good damage survivability) have rendered many of the concerns that were traditionally the preserve of naval ship design commonplace.

In short, while there is considerable attraction in maintaining navy’s own in-house standards, the practical realities of limited ship numbers and severe budget constraints render this approach increasingly less viable. A vision was developed for a system of naval ship regulation based on classification and combining the strengths of the naval and the commercial regulatory regimes to provide through life care of naval ships.

Fitness for purpose, reliability in-service and value for money are the three axioms typically specified by commercial ship owners and the same is applicable in the procurement process and in-service operation of naval ships. The use of the classification process for naval ships offers navies an alternative to traditional naval practices and recognises processes and procedures that are well established in the commercial merchant ship industry.

Class Rules have been published, or are to be published, by the majority of members of the International Association of Classification Societies. These published rules, surveyed here, are mainly framed on the basis of their respective merchant ship rules.

4.2.1 American Bureau of Shipping (ABS)

Since 1998, ABS has worked with the US Navy to develop the Naval Vessel Rules, the first guidelines of which were available in mid-2004, ABS (2004). The Rules effectively follow the traditional Navy design approach using the quasi-static analysis of bending moments developed by the US Navy and the addition of a probabilistic approach to determine hull girder bending. The Rules require a finite element analysis and fatigue analysis for all new ships. Unique and special load cases may be considered based on full description and justification in common with all rules. Sections have been developed which facilitate the drive for higher speed naval hull forms with the capability to rapidly change mission focus through modularity, Sullivan *et al.* (2004).

4.2.2 Det Norske Veritas (DNV)

DNV Rules for Naval Surface Craft (2004) include structured verification through design, construction and operation of naval vessels. Due to the absence of pure commercial and flag authority processes for naval vessels, requirements and interests, the rules blend traditional naval standards and commercial practise. Similar to other naval class rules, available class notations ensure safety, equivalent to IMO regulations, accommodating naval operational requirements for combatant or non-combatant vessel, and of various construction and design.

4.2.3 Germanischer Lloyd (GL)

In the year 1999, GL was commissioned by the “Federal Office of Defence Technology and Procurement” (BWB) to coordinate a revision of the German Naval Standard (BV) and to carry this work out in close cooperation with the German naval authorities. Above all, these naval construction rules of the BWB describe the navy-specific portion of a naval vessel, for application on ships of the German Navy.

GL rules (2004) are concerned with the naval ship as a platform. Weapons and sensors are only examined with regard to their foundations and the supply of power. The construction rules of GL cover the decisive safety and environmental aspects for naval vessels, a whole series of special naval ship types, and also special materials for naval vessels.

The entire body of the GL Rules on “Naval Ship Technology” is complete and independent. Cross-references to other Rules of GL and to standards have been reduced to a minimum, Petersen (2004).

4.2.3 Lloyd’s Register (LR)

In 1998, LR published the world’s first set of naval rules for the design, construction and classification of naval ships, framed along the same line as the commercial ship classification standards. The rules are now in its seventh edition. These rules cover all sizes and types of vessel; including aircraft carriers, assault ships, frigates, corvettes, patrol craft and allow for different military and non-military operational capabilities. LR rules (1998-2006) address all aspects of naval ship design including hull, machinery and engineering systems to reflect arrangements pertinent to military capability and survivability.

The methodology of demand, capability and acceptance criteria approach is adopted in the LR rules, Cheng *et al.* (2000). Demand is defined by operational requirements which, in turn defines the environmental conditions. The loadings are presented in such a way that direct calculation if available from analysis or model testing can be applied for any load value throughout the ship. In addition to the conventional load and strength assessments, increased bending moments are derived for the enhanced strength assessment for extreme conditions. Similarly reduced bending moments are calculated for the residual strength assessment as a damaged ship will not be expected to survive in the same environment as one without damage. Guidance is given the rules for design against military loads.

Where there is a navy requirement to demonstrate compliance with an international convention, or a particular naval standard, LR Rules recognise naval ship features and permit various alternative arrangements whilst maintaining the provisions of classification, Pomeroy *et al.* (2000), Rattenbury (1999) and Lloyd’s Register (2000).

4.2.4 Registro Italiano Navale (RINA)

RINA Rules for the Classification of Naval Ships (2003), cover all the aspects related to the platform of naval surface steel ships and give due consideration to their specific features in terms of confidentiality; operational aspects and ship management practice; naval ships performance aspects, such as sea-keeping capabilities needed for correct operation of weapon systems, vulnerability analysis, ability to operate in contaminated areas, etc.; ad hoc verification of military structural limit states, such as resistance to internal, external and submarine explosions see Boccalatte *et al.* (2003); ad hoc on board comfort and working environment; and enhanced protection of the marine environment.

While based on the philosophy of the merchant ship classification rules, RINA rules greatly differentiate from them in order to properly account for the highly specialized nature of military ships and the peculiar characteristic of their payload (military personnel and combat systems), which require an ad hoc and self-standing approach rather than merely the application of merchant rules.

5. STRUCTURAL DESIGN FOR ENVIRONMENTAL AND OPERATIONAL LOADS

5.1 Introduction

In recent years, the attempt to reduce the cost of procurement and through-life logistic support has pushed many navies to a closer cooperation with Classification Societies and major shipyards with the aim to adopt commercial standards, wherever possible, and define specific rules for the classification and building of naval vessels. While the use of merchant rules was already typical for auxiliary ships, like LPDs and LSVs, their calibration in view of an application to first and second line combatants was something new and required several calculations, leading to formulations that have anyway to be validated by seagoing experience. The environmental loads naval vessels have to cope with do not substantially differ from those typical for merchant ships. Most local loads can be considered equivalent and scantling procedures for them are the same used for conventional vessels. Wave induced loads differ a bit as a consequence of the peculiar characteristics of naval vessels with respect to usual merchant ships.

The major difference between naval and merchant ships, leading to different effects while sailing in similar environmental conditions, is their operational profile. There are two main implications: the first is that combatant vessels must be capable of withstanding design defined sea states, without any decrease in their fighting ability or aviation support activities (if any). This implies a considerable amount of sea-keeping predictions and trials. Such a constraint means that the vessel might undergo significant accelerations, which could indeed increase many loads. The latter is related to fatigue: generally, merchant vessels are designed for an estimated life of twenty years at rather high sailing factors (up to 0.85÷0.9), while naval vessels are designed for an assumed lifetime of thirty years with a sailing factor rarely exceeding 0.5÷0.6. Moreover, while merchant ships almost always operate at the design speed (approximately obtained at 90% of Maximum Continuous Rating), naval vessels normally sail at cruise speed, being the maximum speed often reached by using extra booster engines. Another significant factor, which leads to differences in loading conditions and structural response to same, is the remarkable difference, between naval and civilian ships, in terms of hull shape. That is the reason why some Classification Societies, in their approach to global loads as a calibration of IACS formulations for merchant vessels, had to introduce suitable corrective factors for C_B. Boccalatte *et al.* (2003) showed that including this factor in the Weibull distribution means that rule long term distribution of wave induced bending moment comes close to the results given by direct sea-keeping calculations.

Other loads, neither depending on the environment nor on military threats, are typical for naval vessels, even though in some cases not exclusive: examples are the loads deriving from RAS (replenishment at sea) or VERTREP (vertical replenishment) activities as well as all loading conditions connected to the take off, landing and parking of aircraft.

Basically, the design methods adopted for naval and merchant vessels are the same. Nevertheless the peculiar operating conditions of naval ships often oblige the designer to a wider use of model test results, numerical simulations and structural direct calculations. Sometimes, for novel designs, full-scale measurements may become necessary for a complete structural assessment of the vessel.
The necessity to ensure low underwater noise emission, the correct functioning of combat and navigation systems and the survivability of hull structure and machinery foundations, when subjected to various kinds of military threats, generally implies the use of more sophisticated analyses than usually carried out for merchant vessels.

5.2 Design for Environmental Loads

As defined by Lloyd’s Register’s Rules and Regulations for the Classification of Naval Ships, *environmental conditions include natural phenomena such as wind, wave and currents and also ice and thermal conditions.*

5.2.1 Wave induced loads

Global design loads can be divided as follows:

- **Hull girder loads** are common to both commercial and military vessels. These include still water shear forces and associated bending moments, low frequency vertical wave shear forces and associated bending moments deriving from hydrodynamic pressures, high frequency shear forces and associated bending moments, consequence of slamming phenomena;
- **Extreme hull girder loads** are those used to assess ultimate strength and must be derived after an overall examination of the matrix of all loads which can be expected;
- **Hull girder loads for residual strength assessment** are usually defined to be a specific set of conditions for a specified period of time. Additional considerations for residual strength assessment are covered in more depth in Chapter 6.

Still water maximum global loads are to be evaluated taking account of the worst loading conditions, which are defined by the Rules and/or the Owners and may vary as a function of the ship type. It should be noted that the still water bending moment for a naval ship is, as a rule, less than that of a commercial vessel.

Like for merchant ships, wave induced loads are defined by means of physical principles rather than empirical formulations. As suggested by Boccalatte *et al.* (2003), the influence of the main parameters, which govern the ship response at sea, is to be taken into account. Starting from IACS procedure, in line with STANAG 4154, this leads to the definition of coefficients, which consider the peculiar slim hull shapes of combatant ships, their generally non-vertical sides and their speed. The formulations proposed by the Classification Societies, starting from the merchant ship rules, hence include correction factors that may be also derived by direct calculation methods up to non-linear ship motion analyses.

Like high speed craft or some merchant vessel types (i.e. container or cruise ships), bow flare impacts can give rise to additional bending moments, which can significantly increase the design sagging. The evaluation of such pressures can be carried out as mentioned at § 5.2.3.

The calculation of ship motions is fundamental for a correct definition of the dynamic loads acting on the vessel. Not only such an evaluation allows obtaining the dynamic portion of local pressures, but also the components of acceleration in the three directions, both those acting in way of ship centre of gravity and their distribution along the vessel. A reliable definition of these accelerations is essential in order to correctly evaluate the structural behaviour of important components, like for instance combat systems equipment foundations, and the dynamic factors that increase loads like those deriving from parking of aircraft.

5.2.2 Slam induced whipping loads

Whipping is a transient hull response resulting from bow flare or bottom slamming, which generally induces low frequency (mainly first mode natural hull frequency) hull girder bending moments. The effect of whipping loads on fatigue damage may be significant for more slender and higher speed vessels (Hansen *et al.*, 1995). Longitudinal stresses may be significantly affected by slamming impacts, especially in small and medium size ships. Generally high wave-induced stresses and high whipping stresses appear to occur at the same time, but there tends to be a phase between the whipping initiation and the peak of hogging ranging from -20 to 70 degrees (Jiao, 1996). The occurrence of slamming is predicted in the analytical approach based on the relative velocity against waves (Hansen *et al.*, 1995).

From the measurements of bending moments for four monohull ship trials, Birmingham *et al.* (1979) showed that average midship vertical whipping bending moments are a function of ship length and beam by $L_{BP}^2 B$, where the maximum whipping moment was found to be 4.6 times the average value. Jiao (1996) proposed probabilistic models predicting extreme combined stress, considering correlation and independence of wave-induced and whipping stresses. Sieve *et al.* (2000) formulated an empirical equation of lifetime maximum wave-induced plus whipping bending moments amidships for the determination of maximum permissible stress for fatigue design of naval ships based on the study of Sikora *et al.* (1983):

$$BM_{MAX} = C1\left(L^{2.5} B\right)^{C2}$$

where the coefficient values are given according to ship life (e.g. 30, 40, 50 years), loading condition (e.g. hogging or sagging), and naval ship type (e.g. frigates, auxiliary, etc).

5.2.3 Local slamming

Not only slamming pressures are important for the whipping effects they may generate, but also for their giving rise to local loads, which can severely affect bottom structures, bow and even stern area. Formulations for the definition of equivalent design pressure loads are generally based on the Ochi-Motter slamming methods; impact loads can be anyway evaluated by means of direct calculations. While for civilian ships the design slamming pressure can be sometimes limited, considering a certain (low) frequency of slams on the assumption that the vessel will respect the operational profiles given by the Rules and will try to avoid slams by reducing speed, changing heading, etc., on the occurrence of severe slams, in certain circumstances naval ships might hardly have these options and could be obliged to press on regardless of slams.

An exhaustive review of slamming phenomenon and of the structural response induced by it can be found in ISSC 2000 – Specialist Committee V.2 and ISSC 2003 – Specialist Committee V.4 reports.

5.2.4 Impact of environmental loads on naval vessel topside

The topsides of naval vessels are generally designed as the best possible compromise among several factors, i.e. needs for operative spaces, of which some may have to be ballistically protected, need for a low radar cross section (RCS), need for fitting combat systems (CS) equipment, taking account of mutual constraints between one apparatus and another and the possible impact of hot exhaust gases on them and their performances.

Apart from accelerations due to ship motion and vibrations, strong wind and the presence of ice are the most important environmental loads, which can affect topside design. They can be treated as for conventional ships, taking into account that often the real constraint for naval vessel superstructures is not their intrinsic strength, but their capability of ensuring the correct functioning of CS even when subjected to severe weather conditions.

5.2.5 Thermal Loads

Thermal loads, such as those resulting from intense sunlight, might be a significant factor to consider depending upon operational missions or systems performance requirements. Resulting deflections could impact the accuracy of sensors or sensor-dependent combat systems and should be taken into account during design.

5.2.6 Ice Loads

Loads due to ice formation on superstructures and other unsheltered areas have been briefly mentioned at § 5.2.4. As regards the presence of floating ice on water, issued Classification Rules make reference to merchant ship ice classes or equivalent – like Canadian or Finnish/Swedish ones. Taking for granted that the Owner is fully responsible for the choice of the reference environment, once operating conditions are defined, the materials for hull construction and the whole hull structure can be assessed. Ice class notations are given accordingly.

5.2.7 Ultimate Strength

The ultimate strength of the hull girder as a whole needs special attention in the case of naval vessels. Not only the ultimate strength in intact condition and in post-accidental condition after a collision/grounding, but also the ultimate strength in damaged condition after a weapon impact has to be considered. However, the methods to assess the ultimate strength for a certain configuration are the same. The main difference – apart from the structural differences due to the assumed damage – lies in the considered sea loads. While the intact ship must withstand all design waves without leaving the elastic stress range – and thus only giant accidental waves may bring it close to its ultimate limit state –, the damaged ship will reach its ultimate strength under significantly lower loads.

The importance of ultimate strength assessment has been pointed out by several ISSC Technical Committee III.1 reports on Ultimate Strength (1988÷2003), by ISSC Special Task Committee VI.2 report on Ultimate Hull Girder Strength (2000) and ISSC Specialist Committee V.3 report on Collision and Grounding (2003). These reports give a very thorough review of the fundamentals of ultimate strength assessment, experimental data and numerical as well as analytical methods. Also for the ISSC 2006, the committees about Ultimate Strength and Collision and Grounding continue their work. Reviews on the history of ultimate hull girder strength can also be found in Yao (1998, 2003).

5.2.8 Fatigue

Fatigue design methodologies and improvements focused on commercial ships have been widely and thoroughly reviewed in the literature (ISSC Technical Committee III.2 - 1997, 2000 and 2003). Main areas subjected to fatigue in naval vessels are structural discontinuities such as the ends of deckhouses and superstructures, deck openings in way of machinery spaces and weapon systems, deck knuckles, and the intersection of longitudinal stiffeners with transverse frames. Typical structural details for combatant naval ships and design practices have been reviewed by Glen *et al.* (1999). Sielski *et al.* (2002) reviewed fatigue analysis methods for commercial and naval ships, focused on the ABS and US Navy approaches, pointing out that the main difference is lifetime loading spectrum due to different operating environment.

Commercial ships generally operate at sea the most of the time, e.g. 85 percent of a 20 year design life, while naval ships spend much less time at sea in a more benign sea condition, e.g. 35 percent of a design life of 30 to 40 years. LR (2005) requires direct spectral fatigue analysis (FDA Level 3) for major naval ships. GL (2005) and RINA (2005) adopt the simplified method, based on commercial ship criteria, of allowable stress ranges for naval ships with an increase of design life, e.g. 25 years in GL and 30 years in RINA. Besides wave induced loads, slam induced whipping moments due to wave impact on the bow flare or bottom of the ship may significantly affect fatigue as discussed above.

5.3 Design for Operational Loads

5.3.1 Vibrations

Apart from their possible impact on structure reliability and noise, vibrations may significantly affect the correct functioning of CS equipment. Depending on the nature of supported weapons or antennas, as well as on their location onboard, CS equipment foundations must be carefully designed to ensure that they can fulfil all requirements, both from a quasi-static (extreme environmental loads, shock and blast loads, etc.) and a dynamic (response to vibration sources) point of view. These imply an extensive use of numerical simulations and sophisticated FEA, like non-linear transient calculations in both frequency and time domain. CS equipment requirements, as well as calculation inputs and outputs are often classified. Another significant constraint for such foundations is that they must often satisfy strict stiffness minimum values.

5.3.2 Loads deriving from the take off, landing and parking of aircraft

A typical example for dimensioning substructures with respect to ultimate strength is the crash zone around helicopter decks of frigates and corvettes. While the structures of the designated landing spot are dimensioned against initial yielding under operational load (e.g. three to four times the helicopter weight), the whole deck area has to withstand a possible crash. For such a crash scenario, a higher load (e.g. six times the helicopter weight) is considered, but the structures are dimensioned against ultimate strength only – permitting permanent set, but no collapse. Although FEA can be well applied in this case, most designs are in practice evaluated by analytical calculation of plastic beam bending.

For such a design approach, tearing/fracture becomes an important limit state that has to be avoided.

For challenges in fracture prediction, see Lee *et al*. (2002).

5.3.3 Own weapons loads

An additional operational load on a naval vessel is the muzzle blast of its guns. Firing at low elevation angles, the deck plating around the gun is subjected to rather high-pressure loads. This becomes an ever more important load case for newly designed frigates and corvettes, which feature a very thin deck plating to minimize the structural weight. If the response of the deck to the dynamic pressure load is not analysed by FEA in the time domain considering the propagation of the pressure wave, the ultimate strength of an isolated plate panel under lateral pressure and ignoring membrane effects can serve as a practical basis for dimensioning the plating for this load case. As in case of guns shots, the pressures and the thermal gradients subsequent to missile release have to be analysed by direct calculation. Medium and small calibre gun bursts oblige to carry out dynamic analyses to ensure that both weapon foundations and surrounding structures are not affected by dangerous vibrations, which may give rise to fatigue cracks.

5.3.4 Loads due to replenishment activities

Replenishment activities at sea are peculiar of naval vessels. VERTREP and mainly RAS, with either side or astern methods, generate loads on decks and deckhouses. Test loads generally include safety factors with respect to operating ones: hence the use of such loads in the calculation of related structures normally can guarantee a sound scantling, as confirmed by positive past experience.

6. STRUCTURAL DESIGN FOR MILITARY LOADS

6.1 Overview

Naval surface ships and craft are required to retain a high standard of operational effectiveness when under attack. Since a naval ship needs to withstand combat conditions, an additional factor beyond normal design requirements must be considered in its architecture. This factor is the ship's ability to survive weapons effects. The effects that need to be taken into account are: Above water attack, primarily internal and external blast; Underwater explosions, shock and whipping; Fragmentation and Residual Strength.

In order to minimise the platforms vulnerability special measures must be taken, such as incorporation of protective or hardened structures and equipment. Structural and Systems arrangements must be configured in such a way that the highest probability of survival during combat is assured. The role of the ship will define the minimum acceptable standards of vulnerability to attack.

Also of importance when considering the design of a warship is the subdivision policy adopted. The extent and standard of subdivision has a major impact upon ship safety and resistance to damage from weapon effects. Subdivision policy should address aspects of ship design from the point of view of resistance to spread of fire, smoke and flooding. Layout and strength considerations are addressed only to the extent that they influence the disposition and construction standards of watertight and smoke-tight subdivision.

A warship, like a frigate, can be exposed to a vast variety of weapon systems from above (e.g. missiles, bombs, shells and nuclear detonations) and below water (e.g. torpedoes and mines) and the effects of each are markedly different. In either case the weapon can detonate on or following impact, or at a standoff using a proximity fuse.

In the underwater case penetration following impact but before detonation is likely to be very limited as the velocity of the weapon is low, and damage will therefore be restricted to the vicinity of the impact point. Frequently greater damage can be done underwater from a standoff explosion which can cause extensive shock damage over a large part of the vessel, and may also damage the primary structure through whipping (Geers 1971, Keil 1956, Keil 1961). Conversely, above water attacks can be at high velocity and the weapon may penetrate far into the hull before detonating, causing a very large volume of damage, while a stand-off weapon in air will only generally shower the target with fragments (except in the case of fuel-air explosives). To perform the vulnerability reduction satisfactorily the effects of all these weapon systems have to be taken into account in the ship design process.

6.2 Above Water Weapons Effects

Above water weapon effects include attack from bullets, shells, unguided rockets, terrorists, bombs and guided missiles. High explosive weapons may have sufficient velocity and casing strength to penetrate ships hulls and explode internally. They may also be fused to explode before contact, on contact or after penetration. Damage is caused by heat, air blast, fragmentation or a combination of these effects.

6.2.1 External Blast Events

As previously stated these result from proximity/stand-off blasts from, Far field nuclear warheads; stand-off, proximity or contact bursts from conventional high explosive (HE) warheads; enhanced blast warheads e.g. fuel air explosions (FAE), asymmetric/terrorist activity and discharge of one's own weapons: muzzle blast and missile motor efflux.

Design Requirements

In principle all air blast effects follow the same scaling law ($R/W_e^{1/3}$) independent of the kind of explosion, nuclear (Glasstone 1957) or non-nuclear (Baker 1983).

The significant differences originate from the relationships between the characteristic length of the blast wave and the characteristic lengths of the loaded structure. The absolute length of a nuclear blast wave is about 100 times bigger than that of a conventional one. Thus the characteristic length of a nuclear pulse is in the order of the ship's length and therefore the loading mainly causes global effects, while the characteristic length of conventional explosions is in the order of frame spacing or deck height respectively, therefore the loading mainly causes local effects only. The blast-influenced area is comparable to that characteristic wavelength.

The time of action of the blast wave is also related to the wavelength. Therefore the response of the structure is strongly influenced by the response times (natural frequencies) of the system. Consideration of these relationships establishes whether impulse effects or quasi-static behaviour will prevail in the response, thus determining the most adequate methods of analysis to be adopted during design.

All components of the ship's structure which affect the operational and survival capability of the ship should be designed to meet a set of pre-determined criteria. These criteria are normally determined by the role of the vessel and set out in the operational requirements. This may be accomplished by calculation (Biggs 1964) as discussed in the previous paragraph and/or by use of pertinent data from large-scale blast experiments

In view of the time dependence of the impulsive loadings involved in Air Blast, the use of static analysis to compute the structural response to air blast loadings has severe limitations, however if coupled with a suitable dynamic loading factor they can be used to provide a first approximation for design purposes Forrestal *et al.* 1977).

6.2.2 Internal Blast

Internal blast occurs when the hull is breached before detonation and is usually caused by conventional weapons, probably with an armour piercing (AP) or semi armour piercing (SAP) capability with delayed action detonation used to optimise the location of the burst within the ship.

Blast Characteristics - Actual blast waves caused by internal explosions are dependent on the mass, shape, type and location of the charge in respect to its surrounding structure.

The initial blast wave characteristic is similar to that of the free field blast wave, the main differences resulting from multiple boundaries leading to multiple reflections and, the confinement of the hot gases, which leads to the build up of a quasi-static overpressure. The loading from an internal HE detonation can therefore be considered in a number of distinct phases:

Blast Waves - Depending on the geometry of the compartment, the originally spherical blast wave is reflected several times at the boundaries or at internal equipment while damping out. Although the loading varies considerably around the structure, for computational purposes it is possible to simplify this initial phase into 3 reflected blast waves. The total impulse of these 3 waves can be typically estimated from:

$$I_{imp} = 1.75 \times R_f \times I_i$$

where: I_i = determined empirical data,
R_f = the reflection factor = P_r/P_i
1.75 = the factor which incorporates the effects of the 3 reflected waves.

Quasi-static Overpressure – Two main effects contribute to this phase, the heat effects (detonation heat, shockwave heat and after burn heat) and additional gas effects.

This phase can be simplified by a gas overpressure that linearly rises to a maximum value. The maximum value can be approximated by the Weibull equation:

$$P_{qs} = 2.25 \times 10^6 \, (W_e/V)^{0.72}$$

where: V = the compartment volume (m^3)
W_e = the TNT equivalent mass of the explosive charge (kg) based on heat of combustion.

Loading of Ship Structure - In general the loading by the time dependent pulses (blast waves) is about the same as the load during the linearly increasing quasi-static overpressure phase. Therefore for simplicity it is sufficient to use as the loading function a rectangular step function with the maximum value of P_{qs}.

Venting - It is possible that venting of the compartment will occur through openings such as doorways and trunking and also through holes caused by the weapon. This venting may reduce the maximum pressure build up in a compartment; it can also allow pressure build up in adjacent compartments.

Structural Design For Internal Blast - Once the quasi-static overpressure in the compartment has been calculated a simplified methodology to derive the extent of damage from the internal explosion, involving incrementally increasing the extent of damage across adjacent compartments until the quasi-static overpressure falls to a level which can be contained by the bounding structure, can be employed. This is a purely static approach to a problem which is dynamic in nature.

Three types of structural analysis may be considered, in ascending order of sophistication: static calculation, in which the dynamic loads are replaced by static loads; simplified dynamic analysis, in which structural elements and units are replaced by "equivalent" single- degree-of-freedom systems; detailed dynamic analysis using finite element computer codes, possibly incorporating fluid and structural interaction effects.

6.3 Underwater Weapons Effects

Underwater weapons consist of torpedoes and mines, although near miss bombs exploding underwater may produce similar effects. Both mines and torpedoes can be activated by ship signatures to seek out a target and explode in close proximity. Underwater weapons usually explode close to the hull, producing damage by shock and whipping. The shock may damage equipment, machinery and personnel or cause distortion or rupture of the hull if sufficiently severe. Whipping, which is resonant vibration of the hull girder at high amplitudes may induce buckling of the deck or bottom structure or even break the back of the ship. Explosions in contact with the hull will produce hull rupture (USS Cole) and internal explosion effects to some degree including fire and blast effects.

6.3.1 Shock wave parameters

The detonation of a high explosive charge underwater transforms the solid explosive material into gaseous reaction products that have an extremely high temperature and high pressure. This pressure is transmitted to the surrounding water and propagates as a spherical wave disturbance (shock wave) moving approximately at the speed of sound in water.

With arrival of the shock wave, the pressure rises discontinuously to the peak value; the peak is followed by a decay that in its initial portion can be approximated by an exponential function. The time until the pressure decreases to 1/e of its maximum value is on the order of milliseconds, after which the pressure decay rate becomes slower than the exponential one. The shock wave peak pressure and the decay constant depend on the charge material, charge weight, and the distance to the point of observation (Harris *et al.*, 1976). The velocity of the shock wave is about five times that of an air blast wave. The explosion gasses form a bubble which can cause additional damage if beneath or close to the hull. This gas bubble expands and contracts emitting further shock pulses as shown in figure 1. These shock pulses decrease in magnitude and even the first bubble pulse is fairly weak compared to the original pressure pulse. Typically the pressure in the first bubble pulse is around 10% of the main pulse but its time constant is approximately 10 times greater, resulting in an impulse comparable to the impulse from the main shock wave.

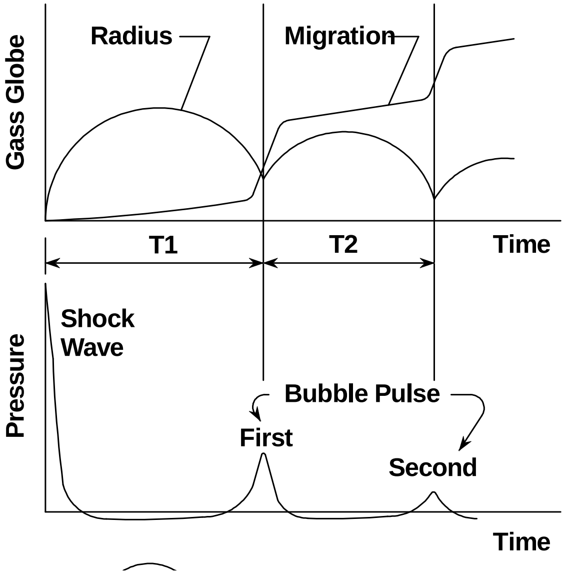

Figure 1 Bubble behaviour and bubble-pulse loading

The period of the bubble pulsation is very long when compared with the duration of the high pressure (shock wave) portion of the pressure time history of an explosion. During the motion of the bubble there is time enough for gravity to become effective, so buoyancy forces lead to an upward migration of the bubble. The rate of rise is largest when the bubble is near its minimum size, but is almost zero when the bubble is large. Thus, even though the buoyant forces acting on the bubble are the greatest when the bubble is at its maximum size, the associated drag forces prevent the bubble from accelerating until it is near its minimum size.

As the bubble collapses it is unstable and may not reduce to a spherical shape, but may divide into a number of smaller bubbles which can join together at the next expansion. 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. If, however the attacking weapon detonates at or near the seabed, the seabed will tend to attract the resulting bubble, reducing the effects on the vessel of the bubble pulses. A free surface, such as the surface of the sea will repel the bubble which can, in some cases, balance the buoyancy effect and cause the bubble to pulsate at constant depth.

6.3.2 Cavitation Effects

Cavitation occurring from underwater explosion phenomena is generally separated into two categories local hull cavitation and bulk cavitation.

Local cavitation is formed by the shock wave impingement upon a target. The plating of the target is accelerated and may separate from the water, reflecting back into the water a tension wave creating a localized cavitation region. Then, as the plating decelerates due to structural constraints, the cavitation region is closed and reloading imparted to the plate. This can lead to a very high local load.

In the case of water-backed plates, the loading at the side hit by the shock wave never falls to zero. The normal assumption has always been that cavitation does not occur in this condition. Past the plate, the pressure wave is transmitted resembling the incident wave, but rounded off due to acceleration of the plate. So the plate results nearly transparent to the incident wave. In the case of a ship hull, the shell plating will acquire a lower velocity than in the air-backed case, even if the inner structure will develop a higher velocity than the outer plating.

Cavitation also occurs in water by the reflection of a shock wave at a free surface. The reflected shock wave becomes a rarefaction wave when it encounters a second medium less dense than water and propagates downward by relieving the pressure behind the primary incident shock wave. At surface the pressure due to incident and reflected waves must be zero satisfying the boundary condition. Below the surface, however, the two pressures do not sum to zero at the time of cut-off. If calculated, the resulting total pressure may be negative depending on the depth below the surface. Since the water is not able to support tension for a long time, cavitation will occur at points, where the total pressure is calculated to be negative. When the region of water which cavitates is large, as in the case of shock waves reflecting at a free surface, the phenomenon is called ‘bulk cavitation’, and the region in which it occurs is called ‘bulk cavitation region’. The upper and lower boundaries of the bulk cavitation region form the ‘bulk cavitation envelope’. The bulk cavitation envelope indicates the maximum extent of the cavitated region in the water. The total pressure is the sum of the wave disturbances, plus the hydrostatic pressure, plus the atmospheric pressure. Water remains in cavitation as long as the total pressure is below the vapour pressure of water. The water vapour pressure corresponds to a small negative value (about 2 kPa / 0.3 psi). For most purposes the cavitation pressure value can be assumed to be zero absolute. Closure of the bulk cavitation region will occur due to gravitational effects, when this closure occurs a high reloading pressure is generated, the timing of this reloading pressure pulse may cause resonant loading of parts of the ships structure.

These phenomena must be accounted for in any approach used to predict the loading or structural response due to Underwater Explosions.

Structural Response

The response of a submerged or partially submerged structure to Underwater Explosion effects is a transient, three-dimensional fluid-structure interaction problem. Prediction of either the loads or the structural response to the loads due to shock and bubble loading requires a complex coupling of fluid and structure response usually solved by using CFD methods for the fluid behaviour and Finite Element methods for the structural response. This type of behaviour is usually carried out by using one of the following analysis methods:

1 Coupled lagrangian finite element Structure model with a boundary element method (such as DAA/DAA2) to represent the fluid (Geers 1971, 1978). This is valid in situations where the structure does not influence the physics of the bubble, so called far field problems. The DAA method is the basis of the USA (Underwater Shock Analysis) code which is coupled to a number of both explicit and implicit structural Finite Element Solvers (DeRuntz 1989).

2 Fully coupled Fluid-Structure interaction, where the fluid is modelled using acoustic or fluid volume elements to accurately model the effects of the shock and bubble loading and then coupled to a lagrangian finite element model of the structure and the full fluid-structure interaction problem solved, usually explicitly. This approach can also be further coupled to a boundary element formulation, such as DAA, at the boundary of the acoustic/fluid volume elements to model the far field effect of the shock and bubble loadings.

6.3.3 Whipping Effects

An important and complex case of fluid-structure interaction is the whipping of ships and submarines caused by an underwater explosion (Hicks 1972, 1986). Whipping is defined as the transient beam-like, low frequency response of a ship or submarine caused by external transient loading. The source of loading is in most cases the fluid flow field associated with a pulsating and migrating gas bubble created by a nearby, but non-contact, underwater explosion. Because the period of the gas bubble is often close to the lowest bending vibration frequencies of the ship, the induced ship motion can lead, in severe cases, to an overall hull failure. On the other hand, the influence of the shock wave, whose spectrum is dominated by high frequencies, is considered small on the bending moment of the ship. The shock wave acts mainly against the hull plating, eventually causing severe local damage. Although the momentum of the plating motion converts itself into a motion of the whole hull, the fraction of the shock wave energy transferred into the bulk whipping motion was shown to be less than 1%. Even if recent calculations seem to show that, in particular cases, the amount of shock wave induced whipping can be compared with the bubble induced whipping, the degree of whipping coming from the shock wave is generally considered to be minor in the analysis.

No simple rules of thumb are available for confidently estimating the hull whipping response. The current modelling practice to predict, at the design stage, the whipping response of the hull girder to the bubble load generally involves the following three steps:

1. A model describing the dynamics of the pulsating and migrating gas bubble, together with the prediction of the loading effect that the flow induced by bubble motions exerts on discrete points along the ship length. An underwater explosion bubble theory and a hydro-dynamical flow theory are generally applied, that lead to the assessment of the transient dynamic loading functions.

2. A model for the hull girder representation of the ship to predict the global girder response to the dynamic loads. The hull girder is generally modelled as a beam of variable cross section with mass lumped at the nodes, and analysed through a linear finite element computer code. Either a step-by-step direct integration algorithm or a modal superposition algorithm can be adopted. Cross sectional properties, hull form and structural mass distribution are required in this representation, together with buoyancy and hull added mass properties, derived from the hull form hydrodynamic drawings.

3. The specification of strength criteria associated with the linear elastic response limits, in the form of limit bending moments or limit stress for each discretely represented cross section. Computer codes as NS94/ULTSTR (Dow 1997) can be used to predict the bending moment (or stress) value at which the flexural response of the hull girder becomes non-linear.

Once the transient loads have been calculated (step 1), they are applied to the hull girder grid points of the structural model and then the whipping transient analysis is performed (step 2), finally an assessment of the severity of the hull whipping can be obtained by comparing the results of the transient analysis with the ultimate strength calculations (step 3).

The determination of the limiting elastic bending moment at a ship cross section is straightforward once the section modulus and distances from the neutral bending axis and outer fibres are known. The controlling bending moment associated with the outer fibres just reaching yield can be readily computed for each ship cross section. In most cases, the ultimate moment determined by considering the level of flexure at which the outer fibres just begin to yield is greater than the level at which the flexure of the hull girder becomes non-linear. This is due to the fact that some members in the ship cross-section, experiencing flexural induced compressive stresses, tend to buckle at stresses lower than yield. As a result, the ultimate bending moment capacity of a cross section never fully realises its maximum elastic potential and is thus reduced to a somewhat lower level. To ensure elastic behaviour, this reduced level of stress becomes the limiting elastic stress criteria. This is illustrated in figure 2, where a typical moment-curvature relation is plotted.

Then the *local ultimate bending moment* can be defined as the lowest bending moment at a particular hull cross section for which one of the two following conditions is met: the outer fibres at the main strength deck or keel region begin to yield, or, structural members in the main strength deck or keel region begin to buckle elastically.

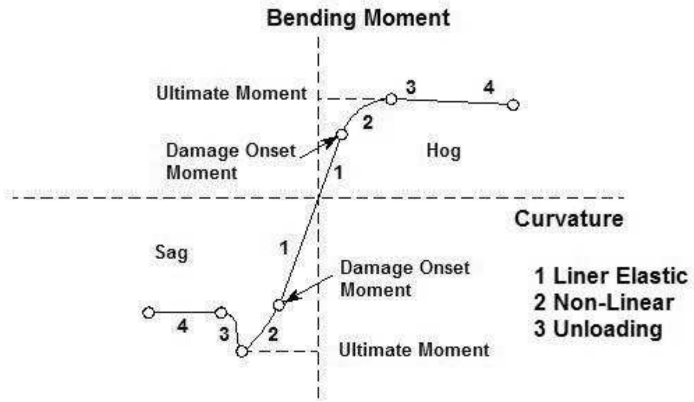

Figure 2 Typical moment-curvature relation

The maximum value of the ratio of the maximum computed bending moment to the local ultimate bending moment for all positions along the length of the hull girder is called Whipping Index (WI). In symbols:

$$WI = \max_{all \cdot x \cdot and \cdot t} \; of \; \left(\frac{M(x,t)}{M_{ult}(x)} \right)$$

A WI less than unity implies that the hull will not experience any whipping induced damage from that particular geometry and charge.

6.4 Fragmentation/Penetrations

Naval ships are subjected to various damage mechanisms to which ballistic protection measures could be taken. The main problem in this area is that there is a wide variety of such mechanisms, ranging from small fragments with limited capabilities to penetrate common ship-structure scantlings (stiffened mild steel plates, thickness 5 – 15 mm) up to projectiles with high perforation capacity even in armoured steel. An old rule of thumb states that the required thickness of a steel plate to stop the penetrator equals its diameter. Requirements or recommendations for ballistic protection of ship compartments should account for the probability to be subjected to and hit by these particular mechanisms.

Fragments or penetrators originate from: High Explosive (HE) warheads, shells, bombs, etc. detonating outside (at stand-off) or inside the ship, activated by their own fuse; Debris hitting the ship as a result of exploding warheads, shells, bombs, etc. destroyed by the ship's self-defence systems, e.g. a Close-In Weapon System (CIWS); Fragments of ship structure or equipment (secondary fragments) generated by primary fragments (as above); Small and medium calibre weapons.

The structure or equipment hit by a fragment is loaded by a shock impulse. Depending on the fragment energy and physical properties it either stops or perforates. When the fragment perforates it creates a hole and - in some cases - generates secondary fragments. Where the loading is associated with a blast loading, this may arrive prior to the arrival of the fragments, but this depends on the distance from the detonation point and fragment velocity.

The effects of fragments depend on mass, velocity, angle of impact, shape and physical material properties. Spatial fragment distribution and target characteristics determine the resulting damage. Small and medium calibre projectiles are a serious threat to naval ships. Small calibre projectiles can be fired e.g. by terrorists with hand held small calibre weapons. Medium calibre projectiles can be fired by aircraft or small attack vessels. The initial damage (perforation) in the structure may cause secondary damage due to: flooding of compartments; reduction or loss of structural fire isolation tank leakage (fuel, ballast, fresh water); loss of citadel-integrity (degradation of collective NBC-protection).

Damage to wiring/piping/equipment can cause degradation in the ship's primary mission areas, and the damage control systems. Fragments hitting munitions or propelling charges or accumulation of heat due to fires may cause ordnance fire or detonation and potentially cascading detonation of stored munitions in the magazine. Weapon systems may be left inoperable. Perforation of life-raft containers may cause loss of floatability of raft and consequently loss of life-saving capabilities. Fragment-hits may cause operators to be incapacitated due to injuries or being killed by fragments.

Protection Techniques

The effect of ballistic protection on the ship's survivability can only be estimated with detailed vulnerability analysis. It must be decided which compartments have to be protected and to what level. A first approach could be to protect high value compartments only. The structure designed to protect against fragments must also be sufficiently resistant against the blast loads associated with the detonation of the warhead considered. Dependent on the type of ship, the importance of the compartments and the available weight budget the level of protection of each compartment has to be determined.

Transverse bulkheads must be designed to contain fragmentation (and blast) from an internal explosion (depending on the mass of the warhead). Bulkheads in compartments adjacent to a hit compartment should be capable of arresting the fragments, which have perforated the bulkheads of the hit compartment (and the residual blast). Bulkheads with such resistance capabilities should extend to the uppermost deck of the superstructure. Requirements for blast and fragment resistance are additional to the structural loading requirements.

Examples of components to be protected are: power and electrical cable trays, running through more than one compartment; ammunition stores; walls of the superstructure behind which important equipment is located; key components of sensors and weapon systems; life rafts; etc.

6.5 Residual Strength

Survivability measures in a ship are useful only if the structural strength after damage is sufficient to sustain the service loads in sea. Combat readiness and system performance in a hostile environment rely directly on the actual capability of the ship's hull. Therefore an assessment of structural strength is necessary (Dow, 1997). This section describes procedures and input data required as minimum to prove an adequate level of survivability.

Usually the primary presumptions are that adequate residual strength is provided such that after one missile hit the ships hull girder will be able to survive for 100 hours in mean sea conditions. Experience shows that a conventional design is prone to considerable loss of strength after an internal detonation, whereas the design threat can be coped with a specially adapted damage tolerant structure contributing to sufficient damage-resistance. This can be accommodated under conventional structural layouts. An alternative method to ensure the required residual strength is the use of longitudinal box girders of adequate rigidity as part of the hull girder strength. These girders must be strong enough to withstand the blast load from the specified threat without loss of performance, and should provide adequate load carrying capacity under high tension or compression stress. Emphasis should be laid on buckling considerations for stresses in the yield regime. The advantages of providing residual strength after attack and providing means of protecting vital systems within the box girders are very attractive. In any new warship design the idea of using box girders over the central critical length of the ship, where wave loading is greatest and where the probability of missile strike is highest, should be considered and the advantages and disadvantages balanced against those of more conventional arrangements.

6.5.1 Design Criteria

As a basis for design, since no detailed weapon effects can be considered because of the indeterminate nature of an attack, the damage assumptions usually follow the Damage Radius Concept. Here different ship types are designed to withstand specific weapon threats, assumptions about damage levels are based on the assumption that these weapons have an associated damage radius within which the structure is assumed to have been destroyed. The effectiveness of the remaining structure around the damaged area then has to be assessed; generally speaking this is assumed to be ineffective and removed back to the nearest major structural feature (Deck, Bulkhead, etc). Then conventional strength assessment methods can be applied to estimate the residual strength of the damaged structure.

This residual strength will then be compared with a prediction of the required environmental wave load envelope for the ship to ensure the required level of damaged strength. Calculations are required in order to show adequacy not only for maximum bending but also for the combination of bending and shear strength.

7. MATERIALS

Whatever the driving factors for the choice of the building material are, they have to be balanced against cost, ease of fabrication, maintainability, etc., taking into account that through-life costs need to be carefully examined in order to quantify the benefits of using one material rather than another. The report of ISSC 2000 Specialist Committee V.2 – Structural Design of High Speed Vessels – already presented an interesting comparison among high strength steels, aluminium alloys and FRP. Present chapter aims to highlight the peculiar aspects related to the use of such materials in naval vessels.

7.1 Steels

The choice of steel mainly depends on the vessel type, its operating profile and the possibility of easy purchasing (geographical constraint). Merchant type vessels are sometimes built in mild steel, which is still explicitly required by some navies in order to purchase from national suppliers and limit maintenance problems.

In most of countries, use of high strength steels is no more a critical matter. 355 MPa yield stress steels are nowadays typically adopted in lieu of mild steel as they can be purchased practically at the same price and give no welding problems. Some suppliers do not produce mild steel any more. HSLA steels are of major interest: the LCS monohull is being designed considering HY80 for the hull. 460 to 520 MPa yield stress steels are commonly used for peculiar applications like flight decks and hangar decks, as their higher strength can allow significant savings in structural weight wherever static, quasi-static and impact loads define the scantling loading conditions. HSLA steels (low carbon, copper precipitation strengthened ones, whose strength and toughness are equivalent to those of HY steels, and that can be easily welded without preheating) can ensure a higher resistance when subject to sudden impact loads, like underwater explosions. On the other hand, there is no practical advantage in using such steels when cyclic loads are dominant as fatigue behaviour is not dependent on the steel used but on the geometry of structural details and the quality of production. In this case the use of HSLA may lead to significant problems due to the much more accurate production procedures required (welded joints, if not correctly carried out, may become fragile and more notch sensitive – thus more likely to experience fatigue cracks). Where fatigue is the dominating scantling criterion, it is generally better to adopt steels having higher toughness so to reduce notch sensitivity. High strength structural steels, characterized by high hardness, are used for ballistic protection. Following paragraphs give an overview of recent developments of high strength steels, fabrication techniques and dynamic fracture toughness unique to naval applications.

7.1.1 Developments in high strength steel

In addition to fatigue problems, as mentioned in previous paragraph, buckling limits, requiring additional stiffening, may prevent optimum use of HY/HSLA-80 for weight reduction. Fabrication costs are obviously much higher than in case DH/EH36 class steels are adopted. Based on steels for pipelines and offshore application, HSLA-65 rolled with TMCP (Thermo-Mechanical Control Process) was recently developed.

Japan Defence Agency recently standardised low carbon, copper precipitation strengthened steels rolled with TMCP, NHS550 and NHS690 and NHS550-HiAREST that is improved NHS550 with ultra-fine grain surface layer for excellent crack arresting purposes. Non-magnetic, austenitic high strength stainless steels with excellent corrosion resistance, like AL6XN, are now investigated for future surface combatants.

7.1.2 Developments in fabrication techniques

Major fabrication techniques for joining steel plates are arc welding like GMAW, SMAW and SAW. Due to the use of high strength and high toughness steels in naval vessel construction, cost of welding has been usually much higher than for commercial ships. However, in the post cold war era, the reduction of military budget of many countries has pushed to the development of both high strength steel with improved weldability and advanced welding methods. The concept of performing welds by means of a filler wire having lower mechanical properties than those of the parent metal (called under-matched welds) was developed. The US Navy is working with the researchers of Japanese Defence Agency on a cooperative program focused on this matter. Because not only cost associated with distortion correction is high but also structural deformation, so-called *hungry horse*, may affect radar signature, developments of joining technology with less distortion will be required. Application of advanced fabrication methods for ship construction, such as FSW and laser welding, is currently investigated in several countries.

7.1.3 Dynamic Fracture toughness

Concurrent with the development of high strength steel HY-80/100 during the sixties and the seventies, fracture toughness of high strength steels was intensively investigated and test measures such as Dynamic Tear (DT), Drop Weight Test (DWT), Bulge Explosion Test, and Hull Toughness Elements (HTE) test were established for evaluation of dynamic fracture properties of base metals and welds. In addition to those methods, the so-called J-integral method is also used for evaluation of steels under development for the U.S. Navy. Test method for the determination of fracture toughness under high rate is standardized. Although fracture toughness of steels and weld metal used for naval vessels is important, just strength and impact toughness (CVN) value are defined by the Rules.

7.2 Aluminium Alloys

A rather exhaustive review of aluminium alloys for shipbuilding applications, as well as of cutting and welding/joining techniques can be found in ISSC 2000 – Specialist Committee V.2 and ISSC 2003 – Specialist Committee V.4 reports.

From naval point of view, the use of aluminium deserves special consideration: up to the Nineteen Seventies, many military vessels had been designed and built with aluminium alloy superstructures, which could grant a remarkable savings of weight, even taking account of the higher amount of insulation needed for fire protection purposes, with low impact on both intact and damaged vessel stability. A number of events in the Eighties caused naval designers to rethink the general use of aluminium. In recent years, due to the extensive use of light alloys in high-speed craft, aluminium alloys have begun to play again a limited but significant role. For example, they have been utilized for masts, funnels and deckhouses. Some fast medium size combatant vessels, presently at the design stage, will be provided with complete aluminium alloy superstructures. In addition, at least one corvette size vessel is being built all in aluminium. The acceptability of the use of aluminium on naval vessels varies at this point in time between the various navies mainly depending on their prior experience. Apart from fire-fighting (see Chapter 8), other possible disadvantages of aluminium alloys in the naval field, with respect to steel, which must be addressed by the overall design approach, include criticality of fabrication, difficulty of repair, blast resistance, lack of ballistic properties and reduced EMS (electro-magnetic shielding). When used for masts, aluminium alloys give the chance to considerably reduce weight, if compared with equivalent steel solutions, and reach higher structural normal modes. On the other hand, due to their low Young modulus, sometimes they cannot provide the stiffness required for the foundations of certain combat system apparatuses.

7.3 The Use of Composites in Naval Shipbuilding

The scope of this section is confined to applications of composites to primary structures and larger modules of naval vessels. Following paragraphs aim at explaining the main reasons why composites are used in naval shipbuilding, identifying the factors that limit their use and the benefits such materials can offer, giving some highlights on joint design and the assessment of their structural performance. Other key arguments, which are worth discussing, are the selection of materials, structural reliability, the management of technical risks, fatigue behaviour and other practical items like inspection, repairs and damage assessment. No attempt is made at providing a rigorous overview of composite design, manufacture and construction. For information of this nature, the reader is directed to reports of previous ISSC Specialist Committees V.2 (2000) and V.4 (2003) and textbooks such as the one by Smith (1990).

7.3.1 Advantages

When composite materials are chosen for naval structures, it is generally because they can offer properties, which are particularly attractive for that specific application. For example, composites are used in mine countermeasure vessels (MCMVs) due to their nonmagnetic properties. A major advantage of composite sandwich structures, compared to traditional stiffened steel structures, is weight reduction (typically 30% to 70%). This alone can motivate the use of composites in smaller fast vessels, such as the Skjold class fast attack craft and the Visby class corvettes, where the light weight allows to achieve operational capabilities that would not be possible with traditional steel construction. Both vessels are entirely made of FRP sandwich, the former primarily with glass fibre reinforcement and the latter using carbon fibre. The low weight of a composite superstructure offers lowered centre of gravity and increased military payload for major warships. However, at basic design stage, a cheaper alternative than adopting a hybrid structure could be to build the ship somewhat larger using traditional materials. This is expected to explain why composites are still not much used in major warships to reduce topside weight. Weight reduction may offer greater advantages if late design changes occur or if a ship requires upgrading. Another reason for adopting composites in the primary structure of major warship new builds would be strict signature requirements. An example is given by future US Navy destroyers DD(X). Another interesting application of composites in major warships is in integrated masts, where a composite structure encloses sensors and antennas providing stealth properties and protection. To achieve this, special frequency-selective materials, transparent only to the frequency used by antennas and sensors inside the mast, are used. Other advantages of composites, compared to steel, include reduced maintenance, reduced life cycle costs and extended service life; the latter aspects primarily in cases of full composite rather than hybrid structure. Despite the examples and possibilities discussed above, the use of composites in naval shipbuilding is still limited. It seems appropriate to briefly discuss some possible reasons for this. Firstly, conservatism in navies and among naval ship designers favours the use of traditional materials and solutions. Lack of understanding of how composites are used may mean poor designs and poor quality, hence leading to poor performance in tests and trials. While steel shipbuilding is widespread, there are few experienced builders in composites and the technology is limited to few geographical areas. If in-service damage should occur, it may be more difficult to find a repair yard within reasonable distance, particularly for a navy with operations worldwide. More training and qualification of the crew may also be necessary to enable them to make temporary repairs at sea.

As explained above, composite materials offer properties that provide advantages in specific cases. However, the hope to achieve these advantages and keep the well-known advantages of steel structures at the same time is unrealistic. For example, the internal blast resistance of a composite structure can hardly match that of a well-designed steel structure. To do so, weight and costs may have to be added, making composite structure no longer competitive. Therefore, composite structures are likely to be competitive only if their distinct properties are effectively required and when there is willingness to find ways of fulfilling overall requirements, which are different from those traditionally used with steel designs. Consequently, to obtain a cost effective composite design, a balanced set of requirements, capable of reflecting the distinct properties of composite structures, must be used. A cost benefit assessment would allow establishing such balanced requirements. A brief outline of it was provided by Hayman *et al.* (2001) and used in the design of a frigate superstructure by McGeorge *et al.* (2002). To make successful use of this method, the designer must however tackle the major challenges of composite construction:

1. the poor mechanical properties in perpendicular direction to that of the reinforcement fibres (this is particularly a challenge in structural details with complicated geometry, such as joints. See Par. 7.3.2);
2. the combustible nature of the composite materials, which is discussed separately in Ch. 8.

7.3.2 Joint design, performance and assessment

The assessment of the structural response of a frigate superstructure to typical weapon induced loads (McGeorge *et al.* (2002)) has revealed that the joints govern the vulnerability of the structure when traditional joint design is used.

The joining of a composite superstructure module to a steel hull represents particular challenges. Due to lack of confidence in bonded joints, bolted ones are often chosen in practical designs as noted by Mouring (1998). Bohlmann and Fogarty (2002) showed an example of a bolted and bonded joint intended to connect a composite sandwich superstructure panel to the steel hull of a naval ship. The main drawback of bolted joints is that they are expensive to make and maintain. Comparisons between bonded and bolted joints, by Le Lan *et al.* (1992) and Hentinen *et al.* (1997), suggest that the bonded joints are the most efficient ones for typical applications. For this reason, bonded joints have received considerable attention. Le Lan *et al.* (1992) studied bonded as well as bolted joints and recommended a bonded joint for the French Lafayette frigates, where the sandwich core was tapered down to the thickness of the steel plating to which the sandwich was joined, and the sandwich skins laminated over the tapered core section extending a further distance over the steel plate to form a bonded joint to it. Clifford *et al.* (2002), Grenestedt (2003) and Cao and Grenestedt (2003) reported on studies of joints of similar design: they exposed their joints to a particular cantilever bending loading condition, producing almost pure bending of the joint with maximum bending at the thin steel plate. They observed that the bending capacity of the steel plating was reached before the best joints failed. Their articles do not discuss the bearing of tested load-cases on real applications. Actually, the loading mode they used is not representative for the critical loading of such joints in real applications because the bending flexibility of the thin steel plate will prevent any significant bending from developing near the joint. By considering the response of a panel supported at its edge with such a joint, one may deduce that failure resulting from a transverse loading on the sandwich panel (e.g. due to blast or sea pressure) would be primarily due to the transverse shear force. Hentinen *et al.* (1997) showed a test configuration that would reproduce such loading. Other loads, like e.g. indirect effects of underwater explosions or inertia forces from the motion of the ship, may cause transfer of axial (in-plane) loading between the sandwich and steel parts. McGeorge *et al.* (2002) tested joints of similar design, as well as stronger tuning fork joints (tuning fork joints consist of an asymmetric welded steel assembly/profile with a cross section somewhat resembling a tuning fork allowing the edge of the sandwich panel to be bonded into the profile), to several load cases representative of a range of different load effects. For a frigate superstructure, they showed that joints similar to those studied by Clifford *et al.* (2002) Grenestedt (2003) and described in Le Lan *et al.* (1992) would be critical, whereas well-designed and manufactured tuning fork joints would not be critical.

Out-of-plane sandwich connections, such as T-joints, can also be critical parts of a composite structure, particularly in naval ships where internal overpressure can occur due to explosions inside the ship. In traditional sandwich T-joints, the edge of one sandwich panel is bonded and overlaminated onto the surface of another one. This results in a joint that is stiff in bending. Therefore, the maximum bending moments, arising in response to a transverse pressure on the adjoining panel, would occur at its edges where the T-joints are located. These joints are particularly vulnerable to such loading. Many authors have studied T-joint variants, e.g. Pattee and Reichard (1988), Shenoi and Violette (1990), Wallat *et al.* (1998), Kildegaard (1992) and Theotokoglou and Moan (1996), and other out of plane joints, like Vredeveldt and Janssen (1998), aiming at understanding the failure mechanisms or improving the bending capacity of the joints. An alternative strategy was used by McGeorge *et al*. (2002), who, instead of strengthening the joint, tapered the sandwich panel down to single skin at panel edges introducing rotational flexibility. This would reduce the edge bending moment almost to zero so that bending would no longer be the critical loading condition for the joint. This significantly improved internal blast resistance and may be desirable e.g. for decks and tank bulkheads that may be exposed to transverse loading. In other cases with no significant transverse loading, traditional rigid T-joints would be appropriate.

Weapon-induced loads result in very high loading rates: their effects on the failure modes and capacity of traditional T-joints were studied by Van Aanhold *et al*. (2002), showing very limited effect of loading rates for the joints they studied.

7.3.3 On selection of materials and forms of construction

Chalmers *et al*. (1984) describe the hull construction of MCMVs, which had been built in the Seventies in single skin construction. The selection of single skin construction seems to be the result of underwater shock tests showing inadequate performance of some tested sandwich configurations. Later, sandwich designs have been developed, showing good shock performance in full-scale trials. On this basis, sandwich construction has been chosen for MCMVs in Scandinavian countries.

Lately attention has been paid to the use of sandwich construction in superstructures of larger combatants, for which fire is a key issue. The polymeric foam core materials used in the MCMVs have little temperature resistance and produce toxic and corrosive fumes in case of fire. For these reasons, balsa wood is favoured as a core material. Balsa wood core material shows brittle failure both in idealised tests (see e.g. Feichtinger (1988)) and also in full-scale sandwich panels (McGeorge and Hayman (1998)). A peculiar phenomenon was reported in both these references as well as in Wallat *et al*. (1998): the shear stress at core fracture decreases with increasing core thickness. This behaviour, a size effect not uncommon with brittle failures (see e.g. the classical work of Weibull (1951)), has been included in design codes (DNV (2003, 2005)). It should be mentioned that Abot and Daniel (2002) reported ductile behaviour of balsa, but their observation is contradicted by all other known sources.

7.3.4 Structural reliability and management of technical risks

Mouring (1998) reported that a lack of accurate design and analysis methods applicable to composites implies high technical risks. However, Classification Rules for composite high speed craft have been available for decades and have proven their adequacy by extensive successful service experience. Recently, a recommended practice for design of offshore composite structures and components with modern LRFD format has been issued by DNV (2003). Furthermore, the IMO HSC Code covers particular issues regarding fire. Notwithstanding this, there are some matters worthy of further discussion. There is a general lack of reliable failure criteria for joints based on test data from cheap small-scale tests. Complicating factors include strong material nonlinearities and brittle modes of fracture. For applications such as high speed craft, where extensive service experience already exists, well proven joints are normally accepted without explicit assessment of their capacity. In other cases, representative full scale testing of joint samples is required as the basis for qualification (see DNV (2003)). Examples of such joint tests are described in Section 7.3.2. The durability of composites structures has been questioned e.g. by Mouring

(1998). Many years with classed high speed craft in service have not revealed particular durability problems. To avoid compromising the durability of composites, only raw materials suitable for use in the maritime environment should be used. The use of inappropriate materials may indeed lead to durability problems. Class Societies offer type approval programmes that allow to exclude unsuitable materials. Nevertheless, when dissimilar materials are combined, care should be taken to ensure that a durable system is obtained. Limited data from service experience are available with bonded steel to composite joints. The surface preparation of steel prior to bonding requires particular care (see e.g. Le Lan *et al*. (1992)).

7.3.5 On the significance of fatigue damage to naval composite structures

Fatigue of metal structures is discussed in Section 5.2.8. Fatigue life is governed by the slope of the SN or crack growth curve, which for metals is typically 3 to 4 in a log-log scale. Because of the large number of fibres in the composite, fatigue damage accumulation is quite different from that in metals. As it should be expected, the fatigue behaviour also differs as accumulation is much slower. Echtermeyer (1996) reported slope parameters in the range of 8-10 for a wide range of laminates and McGeorge and Vredeveldt (2000) and Boyd *et al*. (2004) reported similar damage accumulation rates for joints thus implying fatigue accumulation 4 – 7 orders of magnitude slower than in metals. This explains why service experienced with composite vessels has never shown fatigue problems.

7.3.6 Inspection, repair and damage assessment of composite structures

Non-destructive testing and methods have been evaluated for application to both single-skin and sandwich composites. Although being derived from naval research projects, the results are applicable not only to naval ships. The reader is referred to Weitzenböck *et al*. (1998, 1999), Artiga-Dubois *et al*. (1999), Daniel *et al*. (2000), Hayman and Zenkert (2004) and Hayman (2004) for more information. The results can be used as a basis for shipyard production QA systems, on-board decision support systems and in-service maintenance. The open literature lacks information about the residual strength of composite structures after receiving combat damage. This may partly be due to the fact that composites have traditionally been used in smaller vessels not expected to survive a direct hit. The possible use of composites in the primary load bearing structure of major naval ships would need specific attention.

8. STRUCTURAL FIRE PROTECTION

8.1 Fire Safety and Survivability

Fire safety and survivability is a key issue for naval ships. In general, two goals need to be met: *Firstly*, to maximise availability of the ship's functions in combat and *secondly*, to provide a safe working place for the crew in peacetime operations.

To achieve the *second* goal, the same objectives as those applicable to civilian ships need to be considered (IMO 1974) even though the best means of reaching the objectives would normally differ:

1. prevent the occurrence of fire and explosion;
2. reduce the risk to life caused by fire;
3. reduce the risk of damage caused by fire to the ship, its cargo and the environment;
4. contain, control and suppress fire and explosion in the compartment of origin; and
5. provide adequate and readily accessible means of escape for the crew.

It should be noted that this issue is currently being addressed by a NATO working group looking at the development of a Naval Ship Safety Code (Naval SOLAS).

8.2 General Approach to Structural Fire Protection

A key element in achieving the above fire safety objectives is division of the ship into main zones by thermal and structural boundaries. Another is to restrict the use of combustible materials. The structural design of the ship with respect to these two elements will be discussed. Nevertheless, other elements not discussed herein are also critical to the fire safety and survivability of naval ships such as detection and extinction of fire, protection of means of escape and access for fire fighting and minimization of possibility of ignition of flammable or explosive cargo.

Since the purpose of any naval ship is to perform its intended mission in a crisis, the goal to maximise availability in combat would normally govern the design of naval ships. In civilian ships, the zoning requirements are codified based on a classification of the ship’s compartments according to their fire risk and criticality (IMO 1974). In a naval ship in a combat situation, the fire risk cannot easily be classified because any compartment can be hit by a weapon and thus poses a high fire risk. Therefore, the layout of the fire zones in a naval ship does not lend itself as easily to codifying and its definition tends to become an integral part of the overall design of the ship and its systems with the aim to minimise vulnerability and maximise survivability.

The main zones are normally bounded by transverse bulkheads that are both watertight and protected against the spread of fire. In some cases, e.g., in large open hangars and vehicle stowage spaces, there are also longitudinal fire zone bulkheads and the overheads are also protected against spread of fire. In addition, fire-resistant bulkheads must surround “vital spaces” within a zone, e.g. command and control rooms, steering gear spaces and fan rooms, weapons systems spaces and machinery rooms. Escape trunks from vital spaces must be similarly protected to ensure that the personnel can safely escape. A continuous fire-zone boundary is aligned with the damage-control bulkhead deck to prevent vertical spread of fire. The protection levels are usually specified in standards and not determined from an assessment of the significance of the protection level for the survivability of the ship in combat.

The fire zones provide the first barrier to the uncontrolled spread of fire. With the severe weapon threats relevant to naval ships, the passive fire protection is insufficient to provide acceptable availability in combat. Thus, emphasis is also placed on active fire fighting measures. However, with reduced manning goals of navies, consideration is being given to the use of additional passive structural fire protection similar to the SOLAS approach used on commercial ships (IMO 1974).

8.3 Use of Alternative Materials

Despite active and passive measures, examples exist of large uncontrolled fires. Some of the worst cases involved ships with aluminium structure. For this reason, most navies are reluctant to use aluminium in the primary structure of naval ships. Although an aluminium structure can be protected to survive a specified period in a fire, this may not be sufficient to provide adequate combat survivability. Firstly, if the fire protection gets damaged, the aluminium will be exposed to temperatures above its melting point. Structural integrity will soon be lost. Secondly, since the temperature in most fires is far above the melting point, the structural integrity will also be lost if a fire lasts for longer than the fire protection time.

In general, the US Navy will accept fire protection for steel structures based on either demonstration or analysis of the structural integrity. For aluminium and composite structures, structural integrity under fire can only be demonstrated by specific fire testing.

Section 7.3 shows examples of naval ships constructed from composite materials. From a fire safety and survivability perspective, the use of combustible composite materials presents some challenges. For composite ship structures, a common practice within some navies in recent years has been to adopt fire requirements from the IMO HSC Code (IMO HSCC), sometimes with slightly modified acceptance criteria and/or test procedures. This practice seems to have emerged from a military collaborative research project on naval applications of composites back in the 1990's (Gutierrez 2000).

A well-known example of composite naval vessels is the Norwegian Oksøy class MCMVs. They have for long proven their outstanding performance in their tasks due to their advanced surface effect ship technology that could only become a reality through advanced lightweight composite sandwich structure technology. Unfortunately, a recent fire onboard one of these vessels, the Orkla, which caused a total loss of the vessel (but no loss of life), triggered discussions regarding the suitability of using composites in naval ships. Investigations following the accident concluded that the unpleasant outcome was due to several organisational and design causes, none of them being the use of composites as the structural material (Sigurdsen *et al*. 2003). It is also clear that today's state of the art fire protection systems are much more efficient than those onboard the Orkla, which was designed in the early 1990's. Two recent independent studies have concluded that composites can be used with confidence onboard major naval ships Potter (2002) and McGeorge *et al.* (2002), the latter also showing adequate performance after receiving combat damage. A key element in both these studies was careful fire protection of the composite structure using modern protection systems. An overview of modern passive fire protection systems can be found in McGeorge *et al.* (2002) and additional information on the performance of many such systems was reported in Gutierrez *et al.* (2005). Considerable progress has been made with developing less flammable composites as shown in Sorathia *et al*. (2005).

8.4 Need for Further Development

The current fire safety and survivability regulations are largely prescriptive ones based on past experience. This makes it difficult to introduce new technologies. Therefore, there is a need to develop methods and tools that would allow modelling the development of a fire and its consequences such as to make the best trade-off between various active and passive measures. This could include optimisation of fire fighting organisation by improved training of crew, improved equipment and routines and would allow to optimise structural fire protection and tailor it to the particular form of construction of a particular ship.

9. VULNERABILITY CONSIDERATIONS

9.1 Introduction

Survivability is the capability of a naval ship to avoid and/or withstand a man made hostile environment while performing its mission. The three main elements of survivability are: (1) susceptibility, the ability to avoid detection; (2) vulnerability, the ability to withstand a hit; and (3) recoverability, the ability to reconfigure and restore the damaged systems after a hit. The elements of survivability are described schematically in Figure 3. Advancements in defensive weapons, sensors, countermeasures and reduced signatures have increased the chances of avoiding hits, but naval ships must be designed based on the position that such ships will be hit, and when they are hit, they must be able sustain the damage and retain a certain capability for continuing their mission. Susceptibility is addressed insofar as signatures related to structure is concerned in paragraph 9.5. The remainder of this Chapter is concerned with vulnerability assessment.

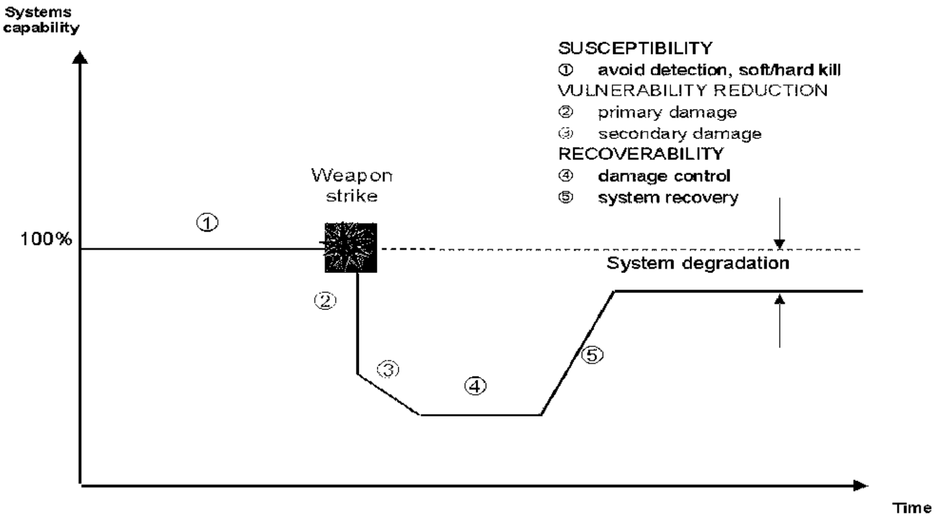

Figure 3: The Three Elements of Survivability

9.2 A Balanced Approach

Reese *et al.* (1998) state that in naval ship design, vulnerability reduction has not been given the same priority as susceptibility reduction. This has lead to an unbalance in operational requirements. However, when maximizing survivability is the objective, the current thinking is that there must be a balance between susceptibility and vulnerability reduction. Threshold requirements based on acceptable levels of both vulnerability and susceptibility must be established. However designers must be given sufficient latitude to improve overall survivability by balancing, or trading off susceptibility and vulnerability.

9.3 Implementation at the Design Level

Hazards to a naval ship can come from weapon effects as addressed in Chapter 6 and accidents. The vulnerability of a ship under the threat of such hazards can be reduced considerably by applying survivability enhancements at the design level. Such measures include: (1) system layout optimization; (2) damage containment; (3) ballistic protection of vital components, equipment, pipes and cables; (4) structure reinforcement; (5) dynamic reconfiguration of power and cooling water distribution systems; and (6) shock hardening. Ideally, if taken in to account in the early ship design stage, implementation of vulnerability reduction measures can be realized through relatively minor structural adaptations. With the advanced assessment methods available today, these design considerations can be incorporated at relatively low cost and little weight penalty.

A recent development is the simulation based design approach. Ultimately it is the objective to create a design optimized for given missions instead of providing capabilities. These tools, in which survivability is only one aspect, require the definition of scenarios. This means that a complete setting and weapon deployment is defined. The main problem of simulation-based designs is that the ship is optimized for specific threats and scenarios. For example, for a ship that is optimized for above water threats, most of its equipment will be below the water line, thus making it more vulnerable for underwater explosions. It is therefore important to maintain a minimum generic loading level for threats not considered.

9.4 Assessment Methods

Damage due to a hit can be of two types: primary (caused by threat weapons such as warhead penetration, blast, shock, hull whipping, fragments, heat, etc.), and secondary (occurring after damage, and caused by fire spread, flooding, smoke, etc.). In general, primary damage is inflicted in tens of milliseconds. Secondary damage, on the other hand, can take place over a much longer time period. An enormous effort has been put into the development of modeling and simulation tools to deal with the wide range of physical processes represented by these two types of damage. In the end, however, vulnerability assessment is achievable only through the combined application of field trials and numerical modeling.

Until recently, vulnerability assessment of ships has been given in a deterministic manner, (Lau). However, naval ships are subject to uncertainties in structural configurations, material properties, etc. Probabilistic methods have been applied extensively to quantify such uncertainties, and also uncertainties in sea environments, and thus allowing the estimation of the reliability of naval ships under normal seaway generated loads. However, the extension of these methods to naval ships subjected to the extreme dynamic loads being addressed here has received relatively little attention. Under such loads, experimental observations have shown that the loading process is non-Gaussian and non-stationary. Also, the initiation and evolution of multiple local damages (such as local plastic deformation, stiffener tripping, panel buckling, fracture, etc.) result in highly nonlinear structural responses. The conventional approaches based on linear random vibration theories and peak statistics are inappropriate for the probabilistic vulnerability assessment of naval ships subjected to such extreme loading environments.

However, given the stochastic nature of the process, the required computational effort and the level of detail required, detailed models/analyses are unsuitable for assessment of the ship survivability at the design stage. Instead high level, low-resolution computer simulation methods are used to design and evaluate (even justify) system layout and the effect of structural measures for containment of the weapon effect. These low-resolution, relatively simplified vulnerability assessment methods are developed using more detailed numerical models and experimental results.

One such high level, low-resolution system used by the Canadian Navy, GVAM (General Vulnerability Assessment Model), Fortier (1995), offers a fast series of programs addressing the blast (external and internal), fragmentation and fire threats at the primary, component (including personnel) and system levels. The analysis of attack is performed through a series of damage algorithms for each component and through system default trees. A GVAM model of a naval ship is shown in Figure 4.

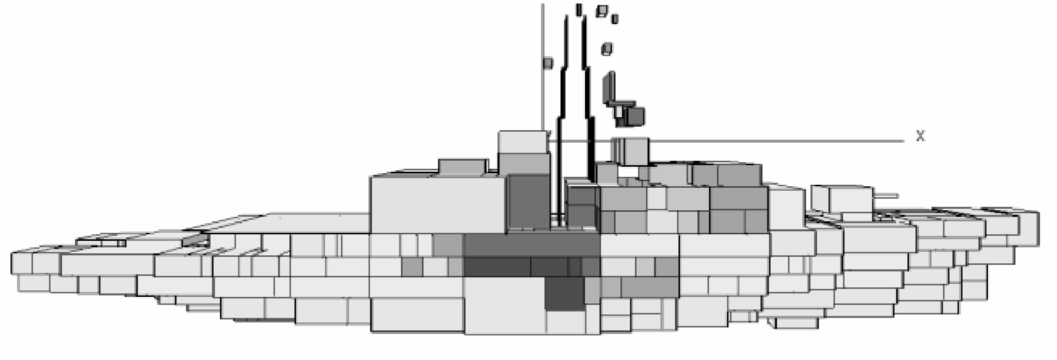

Figure 4: High Level Low-Resolution Vulnerability Assessment Model

SLAMS (Survivability and Lethality Assessment Modeling Software), Dumas (2004), is a new generation of low-resolution software for vulnerability assessment. It is also used by the Canadian Navy and integrates several algorithms and software into a single program shell. It is flexible enough to be used for the design and optimization of new concepts. It has the capability of direct-fire, indirect-fire and multi-hit attacks, allows complex scenarios with multiple targets, and offers a large catalogue of materials to describe the target-weapon scenarios. Geometry can be imported from CAD.

The UK MoD uses a system called SURVIVE(Customer Contact Team). It offers a tool to assess the effects of an attack or accident, not only on the structure, but also on the systems and crew. It can perform both the audit and design improvement function by tracking the vulnerability of a design's key systems through the design process and helping the design team to reduce vulnerabilities when they occur. SURVIVE has an ever-expanding range of damage mechanisms, including kinetic energy, impulse and blast, fragmentation, fire, flooding, shock and whipping. One of the more important current developments is the ability to model the recovery of the vessel and systems from damage. Recent developments of the SURVIVE provides for: (1) the automatic generation of a basic ship model from limited input data; (2) simple edit facilities to aid concept generation; (3) automatic generation of an attack scenario from limited input data; and (4) graphical visualization of results suitable for rapid concept evaluation.

GVAM, SLAMS and SURVIVE are just three of a number of such vulnerability assessment models used by navies throughout the world. Most of them are listed in Table 1.

Table 1: Vulnerability Assessment Models by Navy

Navy	Model
Australia	XVAM, CVAM
Canada	GVAM, SLAMS
France	MINERVE
Germany	REMOS
Italy	SAVIUS
Netherlands	PROGRESS, RESIST, TARVAC
Norway	GVAM(N)
United Kingdom	SURVIVE, PREVENT
United States	ASAP

9.5 Signatures

Naval ships generate "signatures" that are detectable by ever-increasing sophistication of (opposed) hostile sensor and weapon systems. A ship's vulnerability and survivability depends heavily on its being able to operate undetectable by such systems against its background.

Operational stealth can be considered a measure of the ability of a naval ship to operate undetected against threats in mission areas. It is important for a ship to be able to embark on an assigned mission with a degree of stealth that provides a low level of vulnerability to detection and classification. A major element of a naval ship's stealth is its signature characteristics. It has been the nature of naval ship design to require progressive signature improvement to maintain an acceptable level of stealth.

Signatures can be acoustic (propagation by mechanical vibration of physical properties), electromagnetic (propagation by periodic variations in electro and magnetic fields), or other observable entities that result from ship-design or ship-system components. Signatures can be passive (such as acoustic target strength, static electric and magnetic fields, etc.) and active (such as radiated acoustic noise, low frequency electromagnetics, etc.). Both can be reduced by incorporation of specific countermeasures (such as shaping, novel materials, shielding, configuration, etc.).

In the design of new naval ships, increasing attention is being paid to signature reduction. Some of the more common design concepts employed are: shaping (flat hull sides inclined outwards and flat superstructure and mast surfaces arranged as truncated pyramids); use of composite structures on the topside enabling the integration of absorbing and reflecting materials; composite hull forms that allow the insulation of internal components from the water; new steel double-hull designs that allow for flooded compartments which can act as thermal and acoustic barriers; concealed installation of weapons, sensors, cranes, etc,; external doors and hatches with conductive coaming; use of flush-mounted, cavity-backed antennas; special design for air intakes/outlets, windows, etc.; and more electric power architecture allowing the replacement of drive shafts and reduction gears with electric drives.

10. CONCLUSIONS

We have explored those aspects of naval structural design which make it unique in the field of naval architecture and attempted to outline the considerations and approaches currently in use. We can see how the state of the art and the power of computing tools currently available have made it possible to converge many of the techniques and processes for naval structural design with those for commercial vessels. This is especially welcome in light of the current necessity for most governments to leverage their naval ship acquisition programs with commercial processes. A part of this is the ability to develop and apply classification society Rules which address the criteria relevant to the naval vessel mission and operational expectations. In adopting this approach, navies must work closely with classification society partners both in the development and application of such criteria. In the specific area of ship structures, this approach offers a number of benefits:

- a harmonized certification approach, from design phase to delivery, including surveillance during construction;
- an established method for updating of the criteria to be applied;
- a closer link with International Organizations facilitating technology transfer between naval and commercial communities;
- an established core process for inspection and maintenance planning for the through-life logistic support of vessels;

- the adoption of civil standards, wherever possible, as well as COTS products and solutions, to contain global costs and ease the logistic support with no impact on reliability and overall quality.

11. RECOMMENDATIONS

It is recommended that this committee continue concentrating on

- an actual design study comparing application of several Rule sets to a structure.
- reference to the ongoing activities towards a *Naval Ship Code* and its possible impact on structural design (for example the probabilistic approach to flooding and consequent evaluation of damaged stability and vessel survivability).

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