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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

In the ISSC 2006 report, this Committee 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 saw how the state of the art and the power of computing tools available have made it possible to converge many of the techniques and processes for naval structural design with those for commercial vessels. This remains welcome in light of the continuing necessity for most governments to leverage their naval ship acquisition programs with commercial processes. The ensuing three years have seen a great many naval vessel projects which have incorporated to one degree or another commercial practices or have been based on commercial parent designs. A significant contributor to 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 have worked and continue to partner closely with classification societies 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; and
- 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.

In our last report, we recommended the following for the ensuing effort for the 2009 ISSC report:

- 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).

We are pleased to report that we have accomplished these goals as well as provide some additional relevant information which we believe will be of value to our community.

2. CLASSIFICATION OF A NAVAL COMBATANT – THE PROCESS

2.1 Introduction

Classification Rules are being used more and more as the design basis for naval ship strength, replacing many of the Navies` Rules & Regulations. In light of this, the structural aspects of naval ships may in many cases be a subject of how Classification Rules are being applied in a naval shipbuilding regime. The technical aspects of Classification Rules are covered in more detail by other chapters of this report, so this chapter will try to highlight some key questions related to the use of Classification Rules as a design basis for naval ships:

- How are the technical requirements applied?
- How much authority are the Classification Societies given to handle the technical aspects of a naval craft?
- Who resolves issues such as "equivalency" and "deviations"?
- Who makes the final technical decisions?

It is apparent that whatever the technical Rules require, the end result depends on how they are being practiced.

The following terms are used in this chapter:

-Naval Flag Authority: the national naval authority responsible for naval ship safety
-Flagstate: the civilian national maritime authority

2.2 The Survey

The work on this chapter is based on input from a survey made among the participants in the ISSC Committee V5. The input comes mainly from the Classification Societies in the Committee, all of them involved in classification of naval craft. National security plays an important role in matters related to naval craft, and the survey tried to highlight this by covering relations to both domestic and foreign Classification Societies. In this report the term "domestic" and "foreign" class society is used for these cases. We have looked at both relations described above:

- Navies in this survey with a relation to a "domestic" Classification Society
  - French Navy - Bureau Veritas
  - German Navy - Germanisher Lloyds
  - Korean Navy - Korean Register
  - Norwegian Navy - Det Norske Veritas
  - Royal Navy - Lloyds Register
  - US Navy - American Bureau of Shipping

- Navies in this survey with a relation to a "foreign" Classification Society

- Australian Navy
- Canadian Navy
- Danish Navy
- Mexican Navy

The purpose of the survey has not been to study in detail the relation between the individual navy and Class Society, but rather to see the general trends for naval shipbuilding. For this reason, both the identity of the navies and Classification Societies have been neutralised in the report. It should be pointed out that besides the navies mentioned above, there are a number of other navies in the world that use classification as part of their ship acquisition programs. Those navies have not been covered by this survey. The main focus of the survey has been to cover the class process of a combatant. When the report addresses other vessels than combatants, it is indicated in the text.

2.3 Classification of a Naval Combatant – Survey Results

The results of the survey are shown in the Table 2.1. The description below gives a condensed summary of the results.

Question A: The role and responsibility of the Class Society with respect to the Navy
The majority of navies are using class in a normal class role.
For combatants, one of the navies does not use class at all, in spite of having a Class Society in the country.
For coastguard vessels there is a high use of Classification Societies in a normal class role.
There is a clear trend for navies using a foreign Class Society to use Class Societies in a normal class role.

Question B: The role of Classification Rules in relation to Navy Regulations and Standards
The majority of the listed navies use class rules as their technical standard for their ships.
One of the navies uses Classification Rules as a technical standard without using the Class Society in their approval process.
Again, the trend for navies using a foreign Class Society is to use Classification Rules as part of a normal class role.

Question C: The authority/empowerment conveyed to the Class Society
There is a clear trend that all the navies in the survey want to have the final word in the relation to a Classification Society.
Navies using foreign class societies have an equal split between giving Class an independent Class role and a final word in the end result.

Question D: The accountability of the Class Society

Two of the navies rely on the Class Society within their normal relation as for civilian projects.

In some cases the accountability is given for specific projects, and in one case the Classification Society is not given any accountability by the navy.

For the navies using a foreign Class Society it is an even distribution between navies giving full accountability and navies involving themselves in the final result from the Class Society.

Question E: Lines of contact between the Class Society and the Navy

The lines of contact between the Class Society and the Navy seem to be consistently through the contact lines in the project. In one case there is direct contact with the Naval Flag Authority. In this case the Classification Society is used as a Recognised Organisation, and the Classification Society acts on direct authority from the Naval Flag Authority.

Question F: The processes for interpretation, equivalency determination, waiver and deviation

In the majority of cases, the Classification Society does interpretations and equivalency considerations, but the navy makes the final decision on this.

For the navies using a foreign Class Society, the majority of navies let the Classification Societies do the class interpretations.

Question G: Who functions as the final point of adjudication?

In the majority of cases the final point of adjudication lies with the navy.

For navies using a foreign Class Society the balance is more even between Class Society and Navy.

Question H: Lessons learned thus far

Merging traditional naval regime with a class regime is a continuous learning process for all parties.

The list of lessons learned is mainly based on responses from the Class Societies.

Here are some of the reported lessons as seen from a Classification Society:

- Navy projects have longer timescales than civilian projects
- Navy projects have more special requirements than civilian projects
- Navy projects need more flexibility from class
- Navy people move more within the organization, meaning more frequent change of contact persons

2.4 Comparison with a Civilian Vessel

To put the results for naval craft in perspective, an example of the classification of a civilian vessel is listed for reference. When comparing civilian and naval practice of classification one should keep in mind that there is not necessarily a right or wrong way to do things. What is right for civilian vessels does not have to be right for naval vessels. One must assume that the different ways of handling classification issues are used for specific reasons. However, the civilian case highlights the “standard” relations for classification of a ship.

The comparison with a civilian regulatory regime is based on a vessel in international trade complying with the SOLAS Code. For ships under the SOLAS Code, the following applies:

- The practice of the SOLAS Code shall be uniform under different Flagstates.
- Classification Societies are “authorised” to handle the structural strength of ships
- The Classification Societies define the technical standard for hull strength with few “instructions” from the SOLAS Code.
- The empowerment to Classification Societies is given under strict requirements to the Classification Societies` QA system, experience, research capability, ethic behaviour etc. The requirements to Classification Societies are given in IMO resolution A739.

The SOLAS Convention requires uniform practice which limits the Flagstates’ ability to deviate. Under this regime, the class requirements are in most cases followed without deviations. It is also common practice to get approval from the Flagstate, if there are any deviations from the Classification Rules. As a summary it can be concluded that under a SOLAS regime, the Classification Societies are generally given full empowerment for setting the rules and verifying strength of ships.

2.5 A New Element – The Naval Ship Code

A Naval Ship Code (ANEP-77) is being developed under NATO. This may on a longer term influence the empowerment given to Classification Societies. This is discussed in Chapter 7.

2.6 Summary of Survey Findings

The result of the survey can be summarised by the following main statements:

- Classification Societies are being used extensively in the design and building of naval ships.
- Navies use Classification Rules extensively. The formal standing of those rules in the naval regime varies from Navy to Navy.
- The lines of contact between Navy and Classification Society are normally through the project lines.
- The Navies use Classification Societies for design verification, interpretations and advice, but are reluctant to give them full empowerment. The Navies in most cases want to have the last word.
- There is little use of formal authorisation of Classification Societies to act as

Recognised Organization.

2.7 Summary Table

The table below gives a condensed version of the replies in the survey. Each cell in the table represents the relation between one Navy and a Classification Society.

Table 2.1
Summary table of questionnaire replies

Question	**The role of national class society**	**The role of a foreign class society**
A **The role and responsibility of the class society with respect to the Navy**	Class role for support ships Case by case responsibility for Combatants Advisory services	Normal Class role Consultant role Issuance of Statutory certificates Assistance/troubleshooting
	Give recommendations on safety	
	Class role	Normal Class role
	No role for combatants Class role for coastguard vessels	Normal Class role Staturory certificates
	Class role Consultant role Recognized Authority role Technical adviser Case by case tasks	Normal Class role Consultant role Recognized Authority Technical adviser Case by case tasks
	Normal class role	
B **The role of Classification Rules in relation to Navy Regulations and Standards**	As normal class rules for support ships Integrated for combatants	Used as normal Class Rules
	NA	
	As Normal Class Rules	Used as normal Class Rules
	Class Rules used as technical standard As Normal Class Rules for coastguard vessels	Used as normal Class Rules
	Normal Class Rules	Used as normal Class Rules
	Used as “mandatory “ technical standard	
C **The authority/empowerment conveyed to the class society**	Independent authority for given areas	Independent competent authority
	Advisory role	
	Advisory role	Independent authority (for given areas)
	No authority conveyed to Class for combatants Normal Class Society authority for Coastguard	Normal Class Society authority

	vessels	
	Independent authority for given areas Advisory role	Independent authority (for given areas) Advisory role
	Non-military areas follow class authority, but last word by Navy	
D **The accountability of the class society**	Individual agreements for each project	The Navy look at the end result
	case by case engagement	
	Ensured by regular audits	The Navy look at the end result
	No authority given to Class for combatants Independent class role for coastguard vessels	Independent class role
	Independent class role	Independent class role
	Class accountable for end results, plus parallel discussion between Class and Navy	
E **Lines of contact between the class society and the Navy**	Through project line Through shipyard Through a single point in the Navy.	Through project line Contact line direct to Naval Flag Authority
	Through project lines	
	Through project lines	Through project line
	Not applicable for combatants Through project lines or shipyard	Through project line
	Through project lines Direct contact	Through project line Direct contact
	Mainly contact through shipyard	
F **The processes for interpretation, equivalency determination, waiver and deviation**	Class does: -interpretations -equivalence -waivers for support ships. Class does interpretations for combatants Final decision is with the Navy	Class does: -interpretations (class Rules) -equivalency evaluations -Advice on statutory issues Navy handles: -deviations -waivers
	Class do suggestions Navy makes final decision	
	Class does suggestions Navy makes final decision	Class does: -interpretations -equivalency evaluations -deviations -waivers
	None (combatants) Class does -interpretations -equivalency For coastguard vessels	Class does: -interpretations -equivalency

	Class does -interpretations -equivalency	Class does: -interpretations -equivalency evaluations
G **Who functions as the final point of adjudication?**	Final decision by Navy	Final decision by Navy Class can withdraw class certificate
	All principal decisions by Navy	
	Final decision by Navy	Navy accepts class decisions as final
	Coastguard vessels as for civilian vessels	Class decisions to be approved by Navy
	As for civilian projects	As for civilian projects
	Class rules mandatory, but final word by Navy	
H **Lessons learned thus far**	Navy projects have longer timescales Navy projects have special requirements	-continuous learning process for Navy and Class -navies need more flexibility from Class -navy people move in the organization -more advisory role -more documentation
	Technical matters	
	-(Surprisingly) similar to civilian projects	Class process similar to civilian projects Naval projects have longer timescales
	Navies have achieved more transparent regulations and processes	Navies have achieved more transparent regulations and processes
	Navy projects have longer timescales Navy projects have special requirements	-continuous learning process for Navy and Class -navies need more flexibility from Class -navy people move in the organization -more advisory role -more documentation

3. NAVAL STRUCTURAL ANALYSIS PHILOSOPHY

3.1 Overview

Naval structural analysis philosophy against environmental loads adopted by class societies is broadly similar to that of merchant ships. The initial step is the definition of the environment after which the local and then global loads can be determined. Loads are either combined with other concurrent loads or are considered individually. The types of loads considered are also dependent on the sizes of the vessels. For large capital ships such as aircraft carriers, global bending moments will be the primary loads as opposed to local loads which are more important to smaller ships such as patrol boats. It is difficult to provide a definitive comparison between class societies, as some rules are not published in the public domain, while others are tailor-made to their own navies. Nevertheless they have generally adopted similar approaches. All published rules provide prescriptive formulae for determining global and local loads, but direct hydrodynamic analysis and load synthesis can also be accepted in lieu of prescriptive requirements.

The main difference in load definition between merchant ships and naval ships are the combat loads resulting from weapon effects such as blast and explosion resulting in hull damages and whipping. An exhaustive review of loads and load effects can be found in ISSC 2006 – Specialist Committee V.5 report.

Once the loads are defined, scantling determinations at the component level are prescribed in the same way as merchant ships. During this process the adequacy of each component to perform satisfactorily against various strength criteria in yield and buckling is assessed. Fatigue performance and vibration aspects are also checked against prescribed limits. A full three dimensional analysis is normally required for the whole ship especially for larger size ships such as frigates, landing ships and aircraft carriers.

3.1.1 Structural Analysis Process against Environmental Loads

Structural integrity of components is checked using prescriptive formulations to determine scantlings of plates, stiffeners and girders. For larger ships, the process starts from considerations of overall bending moment, creating a beam to withstand that bending moment, and then subsequently designing the local structure to withstand the secondary and tertiary loads. For smaller ships, usually with length below 70 meters, the reverse procedure is used, that is the local structure is designed against local pressure and is then integrated into the whole which is then checked against the global loads to ensure the overall integrity is not impaired.

The loadings are generally 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 assessments, increased bending moments are derived for the enhanced strength assessment for extreme conditions and weapon efforts, as illustrated in Figure 3.1.

3.1.2 Structural Analysis Process against Operational Loads

In addition to the conventional load assessments associated with environmental conditions, increased bending moments are usually derived for the enhanced strength assessment for extreme conditions. Similarly reduced bending moments are calculated for the residual scantling assessment as a damaged ship will not be expected to survive in the same environment as one without damage. The damage for the residual strength assessment is normally taken either from the military load assessments or specified grounding and collision damages. Both the extreme strength and residual strength bending moments are compared to the capability of the structure derived using an ultimate strength type analysis.

Acceleration factors are calculated for each area of the ship so that the structure can be optimized. This may be particularly useful for large point loads from aircraft and vehicles. Non-linear finite element analysis is commonly used for assessing structural strength especially for extreme loads and weapon effects.

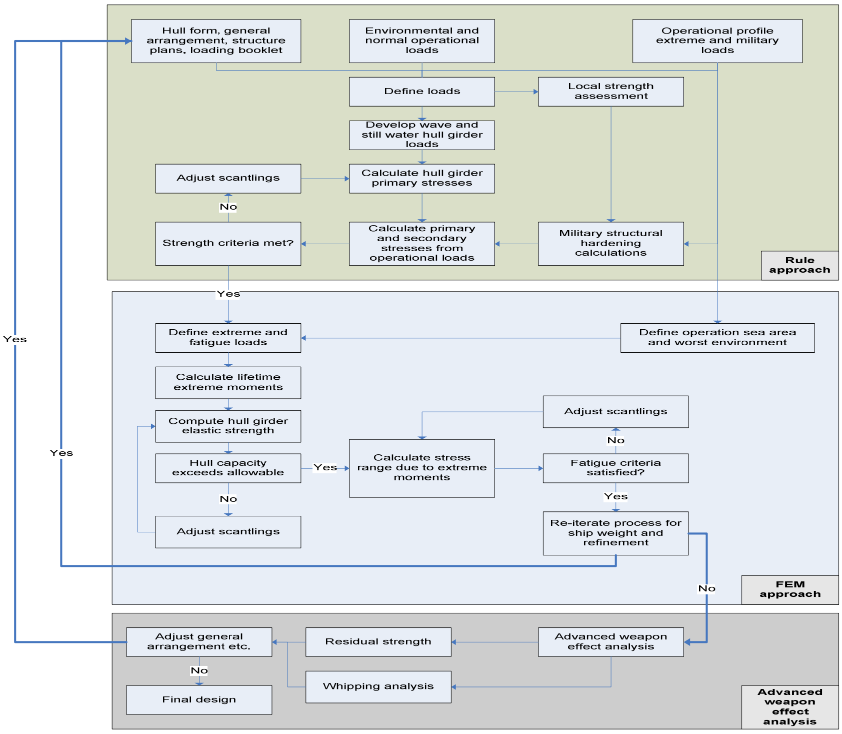

Figure 3.1: Structural analysis process

3.2 *Operational Considerations*

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 naval vessels must be capable of withstanding design defined sea states, without any decrease in their fighting ability or aviation support activities. The second is 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 include the following: above water attack, primarily internal and external blast; underwater explosions, shock and whipping; and fragmentation and residual strength.

While most of the class rules cater for the above in terms of design and construction, class societies tend to treat the "classification" of naval ships differently between peace and war time operations due to practical difficulties encountered in keeping up the normal survey requirements in order to maintain class.

3.2.1 American Bureau of Shipping (ABS)

Classification of naval vessels to the ABS Naval Vessel Rules is intended to remain in place for the vessels for which classification has been obtained under all operational considerations – both during peacetime and during actual combatant operations. Operation of the vessel outside of the safe operating envelope may be necessary and guidance is given in the appendix to class on steps which should be taken if such operation becomes necessary. In essence, the classification process is established to provide a structured, consistent risk assessment tool for the operational commander as well as the navy.

3.2.2 Det Norske Veritas (DNV)

In general, the DNV Rules address the "material state" of the ship, and do not differentiate between "peace" and "war". It is considered that the operation of the ship is the responsibility of the navy. This means that the DNV certificate confirms how the ship was designed, and what operating conditions it was designed for. It is up to the navy to go beyond these limits in a critical situation. The main assumption in the DNV naval rules is that the ship may suffer damages (weapon damage) beyond those caused by normal accidents. The rules contain some assumptions to reflect the main assumption and it is also reflected in the certification of machinery equipment. The rule assumptions are similar as for civilian ships with respect to environmental conditions. It is expected that if stricter assumptions are to be applied, these are specified by the navy. In some cases, the operational limits are specified explicitly by the navy, and the vessels are classed based on this.

3.2.3 Germanischer Lloyd (GL)

Under conditions which make maintaining class difficult (e.g., war or war-like situations), GL will have to be informed accordingly. GL will decide whether the certificate will have to be returned and class suspended or withdrawn. This decision will be based on the risk involved for GL personnel. Where only special equipment and installations are concerned, the corresponding notation will be withdrawn and the certificate amended accordingly.

3.2.4 Lloyd's Register (LR)

Military distinction notations are awarded by LR to provide added protection for military operations. LR requires demonstration of the capability of the ship to withstand specified hostile military action without loss of capability. It is the responsibility of the navy or designer to specify and quantify the weapon performance and scenarios to be studied. A military distinction notation is awarded by LR on the basis that the assessment presented has been conducted in accordance with agreed procedures and the ship constructed in a manner that reflects the design requirements. LR is to be informed of any incident of the ship sustaining damage. Such ships are to be made available for survey thereafter at the earliest possible opportunity. Class survey requirement will normally be suspended at the time of hostility where the normal classification process cannot be operated.

3.2.5 Bureau Veritas (BV)

BV Rules state that Class assigned to a naval ship reflects the discretionary opinion of BV that the ship, for declared conditions of use and within the relevant time frame and complies with the Rules applicable at the time the service is rendered. Class requirements can be temporarily suspended under emergency conditions declared by the navy such as war, terrorist attack, etc.

3.2.6 Korean Register (KR)

For the time being, KR rules do not define the interface between naval operations in peace and at war. Only naval operation in peace is dealt with by KR Rules. However, if the interface should be considered, a significant impact on the rule philosophy will be expected.

3.3 Structural Appraisal Process for Rule Compliance

The appraisal process for rule compliance for naval ships is broadly similar to that of merchant ships as shown in Figure 3.2. This usually means that class societies require the submittal of a complete set of structural drawings including general arrangements, loading booklets, stability documentation, etc. In addition to this, a submittal of loads and special conditions that apply to the vessel is required. Approval is generally based on an individual society's own rules and calculations. Some societies such as LR, DNV, BV and GL provided rules software for designers and builders to perform their rule calculations. Direct calculations using finite element analysis are normally required by the rules and all details are required to be submitted for approval.

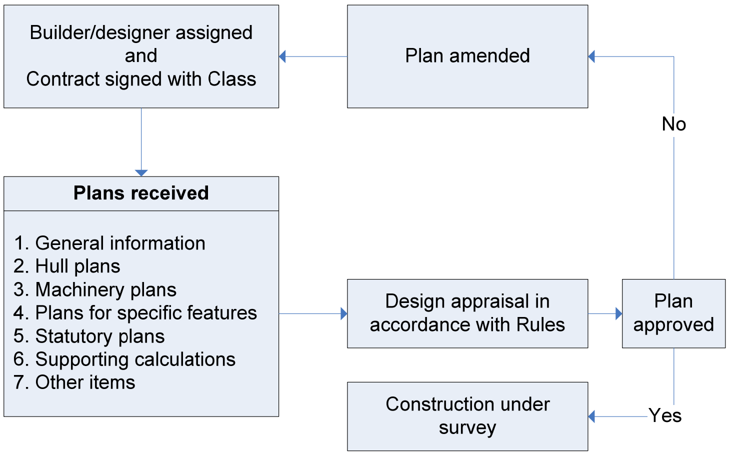

Figure 3.2: Structural appraisal process for rule compliance

3.3.1 Submittal Requirements

The submittal requirement for naval ships is similar to that of merchant ships and they can be broadly categorized under the following:

- **General information and arrangement plans:** these include general arrangement plan, deck plan, technical specifications, loading booklet, lines plan and material specification.
- **Hull structure and ship equipment plans:** these include mid-ship section, aft and fore end sections, bottom structure, engine room structure, shell expansion, decks, superstructures and deck houses, bulkheads, tank arrangement, rudders and associated items, and equipment details.
- **Safety plans and documentation:** these include closing appliances, stability booklet (both intact and damage), ammunition storage, fire safety and life saving appliances, etc.
- **Military features plans:** these include gun seating, lifts, landing decks, citadels, etc.
- **Special features:** these include ice strengthening, etc.
- **Supporting calculations and documentation:** these include loading assumptions for environmental loads, military loads, fatigue loads and their associated structural calculations such as whipping response and residual strength analyses.

Some of the information and documentation that are classified may not be submitted unless special arrangements are made to ensure secrecy.

4. THE ROLE OF NAVAL STRUCTURAL RESEARCH AND DEVELOPMENT IN CLASSIFICATION SOCIETIES

For most Classification Societies (CS), research on naval ship architecture (and all the more so on naval ship structure) is not performed in a specific technical department. In most cases research in this domain is managed in a R&D department in charge of all the topics covered by the CS.

Global R&D department means also that its position is never included in the department in charge of the rules but in a separate branch. Even if this independence from the rules department, is quasi systematic, there is a strong relationship between those two departments. In general, rules are not to be approved by the R&D department but it is the most important adviser, not only for improvement in the rules but also to initiate rules and criteria.

The research for naval ship structure is initiated and performed in the same way as research for ships in general. This research is mainly performed internally (external companies are seldom used). The direction for research in naval ship structure (and for naval ships in general) stems from the involvement of the Navies. Generally CS have contacts only with the navy of their countries but there are some exceptions. In the case of a strong cooperation between her country's CS and its Navy the role of the Navy is to initiate and to finance projects.

The main role of the R&D department is to initiate projects that aim at improving rules. The trigger of a rule's improvement can come from R&D as from any customer (navies in this case) but in the naval ship domain (where the customer is unique) the role of R&D department is particularly essential. R&D department is often the main link between the technical department of the Navy and the CS. Actually a key feature of Navies (versus civil ship-owner) is that Navies (or ministry of defence) have a strong technical department who are in charge of the regulation of the naval ships and who, in some cases in the past, had the national authority to establish internal rules.

5. APPROACHES TO NAVAL SHIP FATIGUE DESIGN LIFE

Design for fatigue crack initiation life was briefly mentioned in the 2006 Committee V.5 report and has been addressed in the literature for commercial ships for many years. This report takes a brief look at how fatigue crack initiation and crack growth is handled by Class for naval ships and cites some relevant literature addressing improvements to fatigue life prediction.

While catastrophic failure due to fatigue has not occurred recently in naval vessels, fatigue crack management does pose one of the primary maintenance issues for warships, which are of lightweight construction and often have to operate in severe sea loading conditions.

5.1 Class NSR and Navy Approaches to Fatigue Design

Class Naval Rules differ in approach to fatigue design. Some follow their commercial practice rules while some have slightly or very different rules for Naval vessels. In some cases full spectral fatigue assessment, using first principles sea load and structural response modelling, is required, while in others a maximum stress level approach based on past experience is used. Sielski *et al* (2001) summarize commercial and naval fatigue design practice pointing out the need to allow more flexibility in approach to meet the differences in operational profiles for naval vessels. While included and described in some naval rules, a full spectral fatigue analysis using first principles is still a considerable undertaking and example cases are quite rare. Honrubia *et al* (2004) present a detailed first principles approach to fatigue calculation for a Spanish frigate.

The material fatigue characteristics are also represented differently, with some codes using a family of curves to represent fatigue resistance of different types of details in a nominal stress approach, while others have a single curve relying on stress intensity factors of high stress areas to be determined through a hot-spot analysis method. SN curves from the Civil engineering field such as the UK Department of Energy curves and the American Association of State Highway Officials bridge code are commonly employed for steel ship structures. Czyryca *et al* (2003) give a good discussion of the qualification of steels for naval use and the testing of structural details to meet fatigue design requirements.

Reliability methods are not yet widely used but are allowed in some cases. Sieve *et al* (2000) discusses the LRFD approach being developed for the USN but not yet fully incorporated into naval vessel rules. The reference describes an approach of developing a calibrated maximum stress limit through spectral analysis and reliability methods for a variety of warship types.

5.2 Operational Profiles, Load Types and Design Life for Naval Vessels

The primary difference highlighted between commercial and naval fatigue design is the operational profile with naval ships usually seeing less time at sea but a more varied and often more severe operating environment. However, time at sea varies considerably amongst naval rules with the USN using a figure of 35% usage and the Bureau Veritas naval rules using a value of 80%. This in itself can cause a significant difference in calculated fatigue lives for different codes. Most codes allow a user defined operational profile but this is not often easy to determine. Guszvany *et al* (2006) study the importance of including a realistic operational profile for fatigue life design.

Fatigue life varies from a minimum of 20 years to a maximum of 40 years with most codes allowing the means to undertake fatigue assessment for longer lives via the operational profile. The effect of a corrosion margin on stress levels needs to be considered for longer lives.

For the most part, fatigue calculations are limited to cyclical linear wave induced bending loads, although most recognize the important influence that slamming, whipping and severe sea loads can have on fatigue life. A rigorous means to include these loads in design calculations have not yet been developed, however Bureau Veritas includes a correction coefficient for vessels with bow flare and the USN uses a formula derived from model test data to account for slamming and whipping effects. Bridges *et al* (2006) take an initial look at the effects of operating in ice on fatigue of ship hulls.

5.3 Crack Management Philosophies for Naval Vessels

As mentioned above, fatigue cracks often occur in naval vessels, and have been dealt with in the past through inspection, monitoring and management. Cracks are not always repaired immediately upon detection, which is generally the practice used in commercial vessels. In general Class does not allow ships to operate with known fatigue cracks although Lloyds Register and the UK MOD are undertaking a pilot project to allow naval ships to maintain their crack management approach while keeping ships in class. Grabovac (2003) and Guzsvany and Grabovac (2006) describe the successful Royal Australian Navy approach to managing fatigue crack initiation and growth using carbon fiber patches.

The Ship Structure Committee has a strong naval and coast guard emphasis and continues to sponsor research on a variety of fatigue topics including Dexter *et al* (2004) who look at propagation of cracks in stiffened panels along the plate and through the stiffener. Shield *et al* (2005) look at methods of non-destructively determining remaining fatigue life in connections based on detection of existing cracks and Kendrick (2004) looks at available data on fabrication tolerances in comparison to assumptions made in fatigue design standards.

5.4 Recommendations for Future Work

A survey of Class societies indicated three main areas for future work. A practical method of quantifying the effects of slamming and whipping on fatigue life is a subject in need of work for naval and commercial vessels. The increased use of aluminum has reinvigorated research efforts in understanding fatigue performance of various types of aluminum and in methods to help improve the fatigue life of aluminum ships. More work on approaches to managing cracks in warships within class is also a topic of interest.

This brief review of fatigue design and analysis for naval vessels has shown that significant diversity in approach exists and that perhaps design for fatigue is given less attention than other failure mechanisms. The considerable effort required for a rigorous fatigue assessment is prohibitive. Work to improve efficiency would help promote fatigue to the mainstream of the ship design process.

6. SHIP COMMON PRODUCT MODELS

6.1 Background

A naval ship must function dependably and with stealth in a wide variety of operating conditions over the lifetime of the ship. To do so a number of structural integrity and operational parameters must be met. In order to ensure that naval vessels are operating within acceptable parameters, a number of structural life-cycle management (LCM) analysis tools must be utilized. Some of which are used to assess the structural integrity of the ship, while others are used to evaluate the ability of the ship to operate with stealth. Each tool has its own input data requirements, for instance, assessing fatigue crack initiation and growth requires extremely fine descriptions of the crack sites that may require description of connection details, including weld profiles. On the other hand, most signature prediction and management tools do not require the same level of detail. For example, the acoustic electric field signature tools employed usually require only a coarse description of the wetted portion of a ship hull and some pertinent underwater appendages, although above water Radar Cross-Section tools can require a very detailed representation of microstructure which is not normally present in a CAD model.

Due to the different modeling requirements of the various LCM tools, a great deal of effort and expense can be incurred in developing suitable models for each tool, even though the same ship is being described for each type of analysis.

While data requirements between the various analytical tools vary, all LCM analysis tools depend on a similar geometric description of the ship. In all cases the basic ship geometry is the same. The differences are only in the level of detail, the portion of the ship to be modeled and the data format. A typical Ship Product Model (SPM) database should contain most, if not all, of the geometric data required by LCM analytical tools.

6.2 Current Developments

Current developments being carried out are addressing the development of interfaces between Design Tools and the ship model data required by current ship structural LCM analysis tools, the ultimate goal of this effort is to develop a link that can bridge the gap between these analysis tools and the data stored in a SPM database (see Figure 6.1).
The main advantage of such a system is that the SPMs that are delivered as part of new builds, or developed for existing naval vessels, can be readily incorporated into an improved and more efficient LCM program that takes advantage of recent technology advances. This should significantly reduce the time and cost of using LCM analytical tools.

There are still a significant number of development challenges to be met before this can be achieved.

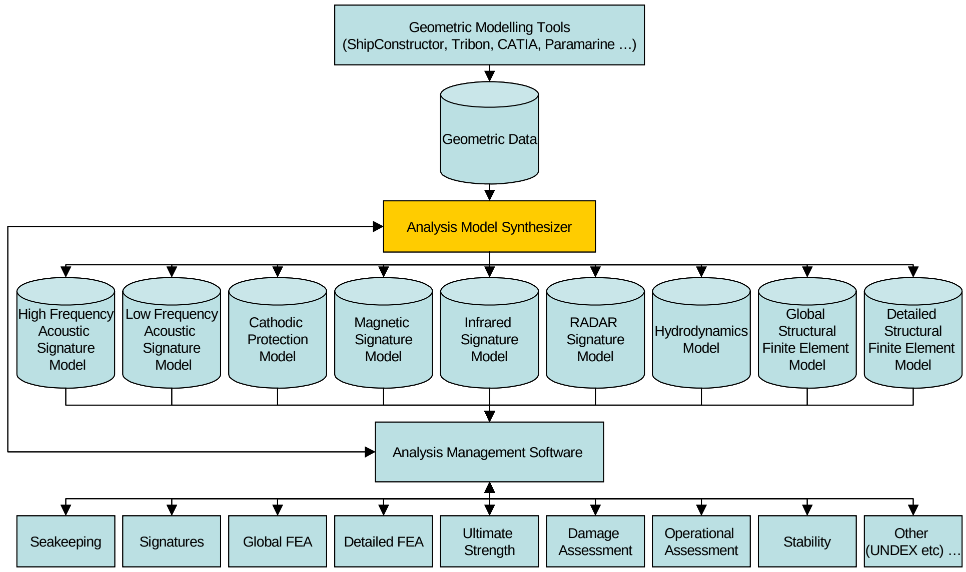

Figure 6.1: Integrated Toolset

6.3 Ship Product Management Systems

The tools and techniques used to design ship structures have evolved over the last forty years, from producing blueprints on the drafting board to the digital design of today. As computer technology became more powerful and less expensive, computer-aided-design (CAD) systems have evolved to support the design of complex products. CAD and other related tools empower designers and engineers to create innovative products more quickly and efficiently.

In order to manage the large amounts of data being produced by CAD systems, software providers have developed systems, often referred to as ship product model (SPM) management systems. These systems help engineers manage their evolving designs, and share them with their colleagues within organizations.

As these SPM management systems have grown in sophistication it has been recognized that these systems can be used, not just to design their products, but also to manage the product data over the entire lifecycle from concept through deployment. Some CAD/SPM systems and their capabilities are shown in Table 6.1.

Table 6.1
SPM Software

Stage	Basic Design			Global Analysis			Detailed Design	Other Interfaces	
Software	Hullform	Basic Design	Stability	Power	Sea-keeping	FEA	Detailed Design	Strength	Sig-natures
ARL - Shipconstructor	X	X					X		
Autoship Systems - Autoship	X		X	X			X		
Aveva - Tribon	X	X	X		X		X		
Dassault - Catia		X				X	X		
Defcar Engineering - Defcar	X	X	X				X		
Formation - Maxsurf	ARL	ARL	X	X	X		ARL		
GRC - Paramarine	X	X	X	X		?	X	X	X
Napa OY - NAPA	X	X	X	X					
Proteus - Flagship	X	X	GHS	Navcad	X	X	ARL		
Sea Solution	X	X	X				X		
Sener Group - Foran	X	X					X		

6.4 Ship Product Management Systems and Lifecycle Management (LCM) Tools Links

Developing links between SPM databases and LCM analysis tools undoubtedly reduces the effort currently required to perform structural assessments of naval vessels. However, in order to develop this link, issues related to CAD interoperability, or the ability to share a CAD model across different applications, must be addressed. Hidden errors and anomalies in the originating CAD data representation, as well as translation issues, often result in numerous problems and frustrations for the downstream users. While the emergence of standards such as STEP has helped reduce some of these problems, true interoperability is still far from reality.

6.4.1 Model Interface Requirements

The main areas which need to be considered when discussing SPM tools for warships are the following:

- Structural Models
  - Global and local FE Models
  - Underwater and above water explosions
  - Fluid-Structure Interactions
- Hydrodynamic Models
  - Prediction of Seakeeping, powering and loads.
- Radar Signature Modeling
- Infrared Signature Modeling
- Electric/Magnetic Signature Modeling
- Cathodic Protection Modeling
- Acoustic Signatures
  - Low and High Frequency
- Shock and Blast Vulnerability Modeling

Each of these models has its own specific requirements from a modeling/geometric point of view. Some of which are listed below:

Global Structural FEA
- Details of Ship Geometry
- Plate Thicknesses and stiffener scantlings
- Mass distribution/vessel weight curve in all operating conditions
- Material properties

Detailed FEA Model
- Same as Global FEA, plus;
- Connection details, etc.

Hydrodynamic Models
- Detailed description of the ship's wetted hull form
- Detailed description of submerged appendages
- Hull surface roughness parameters
- Propeller geometric data
- Total Mass Distribution and radius of gyration of lumped masses

RADAR Signature
- Detailed description of above water geometry
- Including imperfections and micro-geometry

Infrared Signature
- Above water geometry
- Heat sources, etc.

Electro-Magnetic Signature
- Geometry description of wetted hull and submerged appendages

- Paint Quality and damage
- Polarization curves for materials
- Description of cathodic protection system

Magnetic Signature Modeling

- Description of all major ship components made from ferrous materials
- Induced and permanent magnetic properties
- Description of major fixed magnetic fields
- Major electrical circuitry which will produce external magnetic fields

Cathodic Protection

- Similar to Underwater Electric Potential Analysis

Low and High Frequency Acoustic Signature

- The surface mesh to be generated is dependant on frequencies to be looked at, i.e., lower frequencies coarser mesh, higher frequencies finer mesh.

Above and Underwater Explosion Analysis

- Similar to global and local FE Analysis
- Including Fluid/structure interaction effects

6.4.2 STEP Protocols

Another key topic in co-design from designer's perspective is how to bridge the multitude of models required supporting a complex design circumstances at multidisciplinary system tools. STEP, or "Standard for the Exchange of Product model data," (ISO 10303) has been developed using rigorous data modeling disciplines and formal methodologies and each model receives a thorough international review. The tool has been expanded and adopted in some shipbuilding design software. STEP Application Protocols (APs) covering 80-90% of ship product definition data (e.g., molded surfaces, structure, piping, HVAC) are developed, tested, and ready for implementation. XML format specifications conforming to STEP APs are becoming more available for use. STEPml is based on robust, internationally standardized data models from ISO 10303 (STEP). STEPml takes the data models from STEP and publishes them as XML specifications, which brings together the rich semantics of STEP and the widespread adoption of XML technology. Additional STEP APs are in various stages of development, ISO publishing, prototype translator development and testing. It would be a major advantage if we were to ensure product model data meets ISO/STEP requirements.

The ship STEP standards should be a key element of any strategy for review of shipbuilder designs and certification of naval ships. Presently, ship definition information of interest to Naval Authorities is contained in numerous different IPDE systems, rather than attempt to interface each of the analysis software applications to numerous different systems and keep all of them up to date.

6.5 Major Software Developments

6.5.1 US Developments (LEAPS)

A major part of NAVSEA and the U.S. marine industry thrust in the development of links between SPM's and LCM tools has been in the development of the LEAPS software. NAVSEA is investing in development and implementation of the Leading Edge Architecture for Prototyping Systems (LEAPS) shown in Figure 6.2.

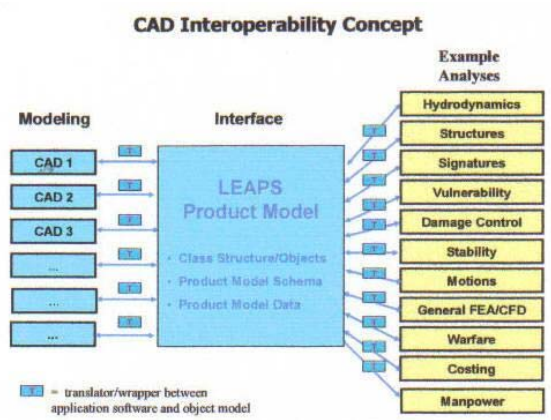

Figure 6.2: Leading Edge Architecture for Prototyping Systems (LEAPS)

The result of a decade of development and testing, LEAPS was initiated as an Innovation Cell by the Carderock Division of NSWC. Using STEP-based interfaces, LEAPS will act as a "Rosetta Stone" allowing LCM analysis software to access definition data from multiple sources through a single interface. LEAPS will also facilitate the exchange of analysis results between programs and will serve a significant configuration management role.

NAVSEA and NSRP with their CAD interoperability strategy for LEAPS and STEP AP's are amongst those leading the warship design community toward an integrated, collaborative warship design environment. This strategy represents a significant shift in the strategic focus of computer aided warship design beyond the Navy toward the "virtual corporation" including U.S. shipbuilders and their vendors. Thus, continues the evolution toward building capabilities that extend throughout the process of warship development with a primary focus on the bridge between ship design and shipbuilding.

6.5.2 UK Developments (PARAMARINE)

PARAMARINE is so named because it provides the capability of parametric design for marine vehicles and systems. It is an object-oriented package written for the Windows operating system*. PARAMARINE incorporates many features to expedite the creation of analysis data and to validate this data in the context of the analysis including automatic damage case generation for probabilistic damage analysis, MARPOL hypothetical outflow, and carpet plot generation. It is capable of performing stability analysis from the earliest concept through to in-service safety certification.

Using a solid model definition, analyses such as stability become very straightforward and take full advantage of the inter-connectivity (data configuration wiring) of PARAMARINE. Uniquely, the PARAMARINE stability specification meets the latest UK MoD requirements for Military and International / National Regulations, covering Loadline requirements, intact stability, deterministic and probabilistic damage.

For stability analysis objects are "wired" together such that any changes in the geometry or weight definition will propagate and be used in the analysis, ensuring the integrity of the design analysis. Full intact and damaged stability analysis can be carried out against naval, commercial or user defined standards. Analyses include Limiting KG curves, Hydrostatics, Cross-flooding, Damage Cases, Grounding and Fluid Restrictions.

PARAMARINE forms part of a software environment designed to facilitate design iterations via a data "bus" utilising ISO (STEP) / Industry (IGES, DXF, Parasolid Transmit) / NATO standards. Other emerging Military standards (ANEPS) can be supported under the MerIT infrastructure.

These abilities provide inter-operability between software products which support configuration-management. Such a process is aimed at providing support for Smart Procurement and Smart Product Models. In this context a Smart Product Model is a data structure capable of relating requirements and design solution to allow Modeling and Simulation (M&S) test evaluation as well as conventional regulatory analysis. MerIT software integration provides ‘Design to In-service’ continuity including operator training, design review and In-service operator guidance.

Current Interfaces within PARAMARINE to LCM software applications include the following:

- Warship Stability
- Longitudinal Strength
- Powering Analysis
- Ship Above Water Vulnerability
- RADAR Cross-section (RCS)
- Seakeeping/Manoeuvring
- Finite Element Analysis

Specialist analysis from third party products are integrated with PARAMARINE through the MerIT infrastructure including the analysis of Radar Cross-section, Shock and Manoeuvring. Additions will be made to this range of integrated expert tools from time to time. The low cost, ease of use and integration of these powerful tools brings first-pass analyses into the domain of the inexpert user. Confidence in the results obtained increases with use and by comparison with vastly more expensive methods. Where reiterative evaluation is required there are significant cost savings. These synthesis tools are particularly applicable to military (naval) loads.

6.6 Achieve an Integrated Design and Production Enterprise (IDPE).

Product development, however, has to encompass much more than the standard drafting and 3-D modeling tools at the center of CAD for the past 20 years. All designs require engineering analysis tools that can keep up with the fast pace of warship design. While these tools have improved engineering productivity, they must be more fully integrated with production engineering in order to optimize the whole development process and make it more efficient. To achieve the next level of product development competitiveness, enterprises must have a more comprehensive strategy.

One of the major Recommendations that are included in the May 2005 US Office of the Secretary of Defense (OSD) Report on the Global Shipbuilding Industrial Base Benchmarking Study emphasizes:

> "The Navy and industry should reduce construction costs for years to come by applying state-of-the-art practices in design producibility that will facilitate a move to 21st century manufacturing processes."

The Report also emphasizes the overall importance of the Design Engineering/Production Engineering (DE/PE) recommendation. This thrust area represents almost 60 percent of the funding proposed for collaborative shipyard remedies. The largest investment in the DE/PE thrust area is Design for Production followed closely by Enable Enterprise Interoperability of Design and Production Data. The relatively large initial investment in these initiatives would likely have long-term positive impact on a number of new naval ship designs.

7. STRUCTURAL RELATED ASPECTS OF THE ANEP 77 CODE

7.1 Introduction

NATO has initiated work on a common safety standard for naval craft. A first version of the complete code is almost ready, and this paper will highlight the philosophy and practical results of this new code in the area of structural strength.

7.2 Overview of the Philosophy behind the Code

The NATO ANEP-77 Chapter II Structure (2008) is a generic code that defines a number of goals that have to be fulfilled under all operating condition of the vessel. The code is primarily written as a "Standard for the selection of standards" rather than a standard for direct application. The goals are given on a high generic level and it is expected that the more detailed prescriptive requirements will be found in underlying technical standards such as Classification Rules. In practice, the code is aimed to act as calibration and a framework for rule development of Classification Rules for hull strength of naval craft.

Being a generic code, the ANEP-77 Chapter II can be applied for any type of naval craft. The differences between the different ship types are mainly related to various functions and operating conditions of the ship. The code defines three goals that the structure has to meet for all normal operating conditions, and one goal for the damage conditions. The combination of goals and operating conditions defines all the structural requirements for the naval craft.

7.3 Concept of Operations Statement

The Concept of Operations Statement is defined in the ANEP-77 as: "The Owners vision of how the structure of the ship is to be operated and maintained throughout its life". The Concept of Operations Statement is a standard form where the main information of the ship is filled in. This includes the following areas:

- primary and secondary roles of the ship
- main dimensions, speed, payload, emergency loadings
- survivability requirements
- environmental conditions
- human environment
- operating philosophy
- principal standards and authorities
- survey and maintenance and disposal philosophy

The purpose of the Concept of Operations Statement is to provide all information needed for classification and approval of the ship. Based on the combination of role, speed, environmental conditions, etc., one can deduce all the load scenarios for the ship. These are used as basis for the check of the structural strength.

7.4 Goals

The ANEP-77 specifies four goals related to structural strength. These are given in Table 7.1.

Table 7.1
Goals for the hull structural design

	Goal **The structure shall be designed, constructed and maintained to:**
1	Provide weathertight and watertight integrity
2	Carry all loads that may be foreseen
3	Permit embarked persons to carry out their duties safely
4	Protect the embarked persons and essential safety functions in the event of all foreseeable emergencies and accidents at least until the persons have reached a place of safety or the threat has receded.

The Goals relate to the main functions of the ship structure, and one may observe that the goals give a wider scope for the hull structure than is normally found in standards for structural strength. Particularly goals 3 and 4 give functional requirements that go beyond strength. Goal 3 specifies that the structure shall be arranged so the crew can carry out their duties safely. This means in practice that the ship's structure itself is not a hazard. One example may be to avoid sharp corners that may be a hazard for the crew. Goal 4 specifies that a part of the structure shall function as safe haven for the embarked persons in an emergency, at least for a limited time. As a practical implication of this, the safe haven must function for all damages for which the ship is designed.

7.5 Structural Demands

The "demands" define all the design conditions that have to be considered for the ship. The list of demands is generic, and any design condition has to be categorized under one of these demands. (See Table 7.2)

Table 7.2
Demands defined by ANEP-77 Chapter II

	Demands defined by ANEP-77	**Typical load scenario, examples**
Normal Operations	Natural environment	Wind, waves, ice, temperatures, etc.
	Built and man-made environment	Berthing, dry-docking, towing
	Demands limited by capacity	Operation limited by procedures, such as speed limit, loading limit, lifting limit etc.
	Unquantifiable demands	General ruggedness
	access, layout and arrangement	Access to all spaces within the ship, manholes etc.
	Disregarded demands and disregarded capacity	The probability of a load is so low that it can be disregarded in the structural design.
Damage Scenarios	Foreseeable damage	Grounding, flooding, collision, fire, explosion, mal-operation
	Extreme threat damage	Battle damage scenarios that are explicitly specified
	Access, layout and arrangement	Safe passage and safe haven in case of a damage scenario.
	Disregarded demands and disregarded capacity	Damage scenario that may be critical to the ship, but with so low probability that the personal safety is acceptable

7.6 Acceptance Criteria

The combination of all the demands and goals will define all the structural loading conditions that the Naval Ship Code requires for the ship. The Table 7.3 shows all the load conditions that must be included and those which may be excluded.

Table 7.3
Combination of Demands and Goals as specified by the ANEP-77.

	Demands	Goal 1	Goal 2	Goal 3	Goal 4
Normal Operations	Natural environment	Y	Y	Y	NA
	Built and man-made environment	Y	Y	Y	NA
	Demands limited by capacity	Y	Y	Y	NA
	Unquantifiable demands	Y	Y	Y	NA
	Access, layout and arrangement	Y	Y	Y	NA
	Disregarded demands and disregarded capacity	NA	NA	NA	NA
Damage Scenarios	Foreseeable damage	C	C	C	Y
	Extreme threat damage	C	C	C	Y
	Access, layout and arrangement	C	C	C	Y
	Disregarded demands and disregarded capacity	NA	NA	NA	NA

Y = Yes, the goal must be met, NA = Not Applicable
C = the goal may be Compromised (i.e., accept that the ship may receive damage)

7.7 Practical Implications

The systematic approach given in the ANEP-77 makes it possible to put any load scenario into one category or another. Some practical implications of this are as follows:

New areas:
The Code requires the ship structure to provide strength for the crew to carry out normal duties, dry docking, towing, and access for inspection/repair of tanks, etc. This scope is more extensive than other traditional structural codes.

Disregarded loads
Unrealistic load scenarios can be disregarded in the structural design. This may apply to the risk of being hit by a comet from outer space.

Damage scenarios:
The ANEP-77 requires that all "foreseeable damage" scenarios are to be covered by the design. This means all damage scenarios that can be expected based on the operation of the ship. For example, one may expect a severe bottom damage if grounding at high speed. In that case, the foreseeable damage scenario should reflect this, and the ship should be designed accordingly.

Combat damages:
The ANEP-77 does not cover combat damages. However, if a specific combat damage is specified by the Navy/Naval Flag Administration, evacuation routes and safe haven

have to be provided for that scenario.

Own weapons/ammunition under normal operation:
The foundations for weapons are governed by the demand “natural environment” taking into account, the reaction forces of the weapon due to weight, ship acceleration, etc.
The firing of the weapons is covered under “built and man-made environment”, i.e., it is a load condition initiated by the embarked crew.

Explosion of ammunition:
Explosion of own ammunition may give severe damage, or even sink a naval ship. If the probability of own weapon explosion is sufficiently low, it is categorized as “disregarded demand”. To prove this, one has to show that the probability of own weapons exploding and damaging/sinking the ship is sufficiently low to be disregarded.

Ammunition has generally a good tolerance to self-initiated explosion as long as it is not subjected to extreme conditions such as fire, high electromagnetic pulses, etc. The requirement can normally be met by providing safe storage conditions.

7.8 From ANEP-77 to Ship Design via Classification Rules

In a goal-based code such as ANEP-77 there are a number of steps between the code and the actual ship design. The different steps are summarized below and illustrated in Figure 7.1.

Rule Basis:
The demands and goals in the ANEP-77 are used to develop and calibrate Classification Rules. The generic goals in the ANEP-77 are transferred into practical and quantifiable Rule requirements. These requirements are normally written in prescriptive form such as rule formula, description of material quality etc. To justify compliance with the Code, it may have to be proven or justified that the Classification Rules fulfill the ANEP-77.

Ship Specification:
The Navy’s specifications related to the structural strength of the ship are collected in a Concept of Operations Statement.

Ship Design:
The Concept of Operations Statement together with the Classification Rules defines the design requirements for the ship, and it is up to the Designer to come up with the best design within these limitations. The Designer will normally not have to relate to the ANEP-77 at all. The only visible effect of the Code may probably be some new load cases in the Classification Rules.

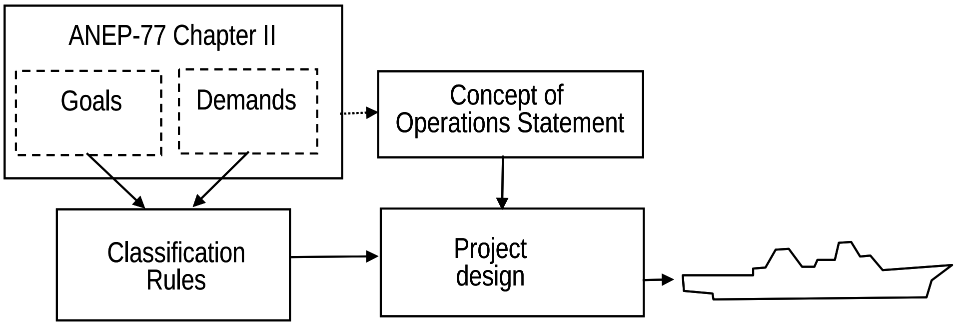

Figure 7.1: Relation between ANEP-77, Classification Rules, and ship design requirements.

7.9 Final Remarks

What has the new ANEP-77 given to naval ship structural strength? The use of the Code may in a longer perspective have the following effects on naval ship structural design:

- Classification Rules will be calibrated to commonly accepted safety objectives.
- The safety goals behind Classification Rules become more transparent.
- A goal-based standard can handle more complex safety scenarios, which is of particular importance for multi-functional naval ships.
- Naval Flag Authorities can refer to an internationally accepted safety standard for their naval ships.

The future will show how well the ANEP-77 is received and used among navies.

8. COMPARISON OF STRENGTH CALCULATIONS FOR EXISTING NAVAL RULES

8.1 Introduction.

Following the recommendation made in the previous ISSC 2006, this Naval Ship Design committee has developed a comparison exercise consisting in the application of several naval rule sets to a test ship structure. At the beginning of the exercise definition, several concerns and uncertainties arose with regards to the usefulness of such a comparison due to the fact that the design of a real whole ship structure depends on criteria coming from different partners like navies, shipyard designers and class rules requirements.

The exercise was then simplified as much as possible and focussed in design basic principles in order to compare just the contribution of the different naval codes recently developed by the classification societies. Thus, the exercise is defined as follows:

a) Optimised strength calculations are developed just for the Hull 5415 midship section longitudinal structure according each one of the available naval class rules. Results for each rule set are compared in order to extract some general trends regarding differences and similarities between rule structural approaches. Further objectives and other comparison parameters are explained in Section 8.2. Hull 5415 test ship is kindly supplied by the US Navy committee member. A description of this test ship is provided in Section 8.3.

b) Scope of calculations are limited to basic principles applied to global longitudinal strength and local strength due to standard operational loads, that is, pressures coming from sea, deck and tank loading. Further considerations inherent to a naval ship design like extra reinforcement needed for weapon effects as well as considerations for general arrangement design or fabrication are not included in this exercise. Other assumptions and parameters used in the calculations are presented in Section 8.4.

c) Results and conclusions presented in Sections 8.5 and 8.6 respectively are not identified with the each corresponding classification society because the interest of the exercise has been focussed in a comparison in general terms of the results obtained for the different rules and not in specific differences between each rule set.

8.2 Objectives and Parameters for the Comparison.

Main objective for this exercise is to compare differences and similarities between the resulting scantlings according to several naval ship classification rules applied to the same test ship. In other words, the intention is to provide a rough idea about how much different a ship design could be if one or other naval class rule is used by the structural designer.

For that, an optimised longitudinal structure is presented in Section 8.5. Minimum structural weight is the specific objective for the optimization process, so calculations have resulted in the minimum possible weight according to each rule set for the longitudinal structural elements in the Hull 5415 midship section.
Relevant parameters that could contribute to a sensible comparison of results are as follows:

- Structural weight.
- Plate and stiffeners scantlings.
- Global longitudinal wave bending moments required by each rule set.
- Design pressures applied for local loading.
- Safety factors inherent in class rules formulations.

8.3 Test Ship for the Strength Calculations.

The notional US Navy Destroyer structural design was kindly supplied to the committee in order to develop the strength calculations in accordance with every classification society rules. This is a simple ship design that reflects traditional US Navy combatant design for use in collaborative research projects with non-US institutions and has been designed based upon the 5415 hull form used in previous international collaborations in the public forum. The development of Hull 5415 preceded the design of the DDG-51. Further details may be found at http://www.dt.navy.mil/hyd/sur-shi-mod/index.html.

The basic dimensions of Hull Form 5415 are as follows:

- Overall Length: 151.18 m
- Length Between Perpendiculars: 466 ft (142.04 m)
- Maximum Beam: 21.15 m
- Beam at Waterline: 20.03 m
- Depth of Hull: 12.74 m
- Design Draft: 6.31 m
- Displacement: 9033 T
- Longitudinal CoG: 72.05 m from FP
- Stillwater bending moment at section 10: 17867 MT·m.

Hull lines as well as main section scantlings are shown in Figures 8.1 and 8.2.

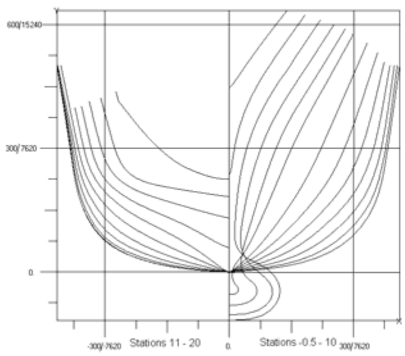

Figure 8.1: Hull 5415 lines.

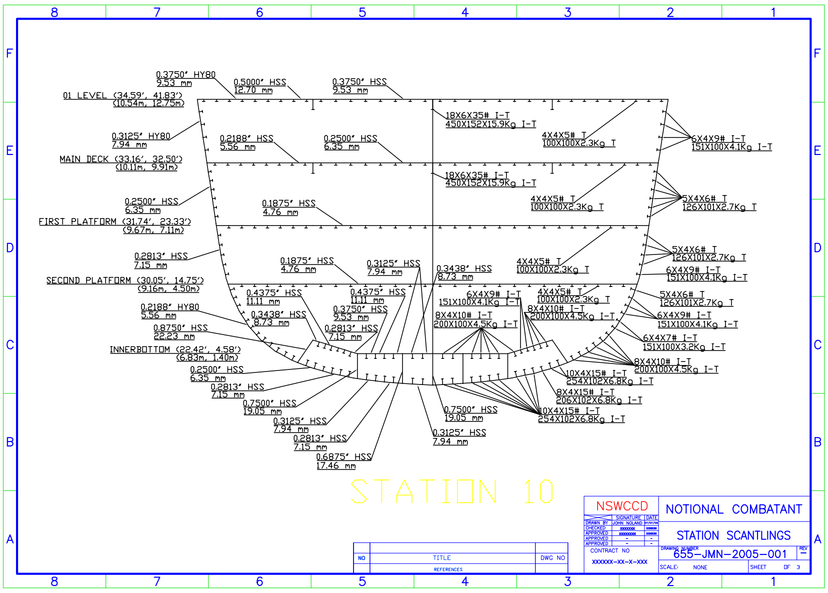

Figure 8.2: Hull 5415 Section 10 longitudinal scantlings.

8.4 Assumptions and Variable Parameters for the Design.

As previously explained, the exercise is defined from the beginning as a pure analytical comparison between the results obtained from the application of the different CCSS formulation for the longitudinal strength of the Hull 5415 main section. This means that a lot of considerations that should be taken into account in real structural design are skipped here since the intention is just to compare basic principles formulation for the longitudinal scantlings. Thus, design parameters driven by cost, life cycle, fabrication and / or operation of the ship are not taken into account for the aim of this exercise.

The following assumptions were defined in order to obtain a consistent and comparable set of results for each one of the optimised designs according to the different Classification Society's rules:

- Cruise speed is 20 kn and maximum speed is 32 kn.
- Material to be used is high tensile steel (355 MPa yielding).
- Web frame spacing is 1905 mm.
- Longitudinal stiffeners shall be T shaped.
- The 6 girders (3 in the 01 level and 3 in the main deck) defined in the existing hull 5415 design shall be maintained with the same scantling and location.

The following uses are defined for each one of the decks and platforms:

- 01 Deck is the weather deck.

- Main deck is supporting operational spaces.
- First and second platform are for accommodation rooms.
- Inner bottom is part of the engine room.

Inner bottom tanks are supposed to be filled with sea water. Corrosion and overflow height shall be defined according to each class rule.

Stillwater bending moment defined for the Hull 5415 section 10 (17867 MT·m) shall be used in the calculations for combination both with hogging and sagging wave bending moments according to each class rule.

The whole main section is considered 100% effective in the contribution to the longitudinal strength. That means, decks are continuous having no openings.

Design criteria are fixed for just ultimate strength including yielding and buckling for plates and stiffeners. Fatigue failure considerations have not been taken into account as criteria for the scantlings.

Variable parameters free to be chosen to obtain an optimised scantling for the longitudinal structure of the Hull 5415 main section are:

- Decks and shell plate thickness.
- Longitudinal Stiffeners T shaped dimensions and spacing.

Some other parameters, such as corrosion allowance or the support condition for longitudinal stiffeners in the web frames, are defined by each class rule.

8.5 Strength Calculations Results.

Six designs obtained as a result of the optimization process carried out according to each one of the class rules are presented in the following tables. Also, significant values and parameters are here presented in order to compare them in the next chapter section.

Results for the whole main section longitudinal structure weight and modulus are presented in Table 8.1. Wave bending moment values to be used in the calculations in accordance to each rule set are also included in the table.

Table 8.1
Whole section resulting data

Classification Society #	1	2	3	4	5	6
Weight of LONGITUDINAL structure for 1.905 m (kg)	16520	21121	19276	15844	18329	19733
HOGGING WAVE BM (KN·m)	4,07E+05	-	4,47E+05	4,26E+05	5,35E+05	4,46E+05
SAGGING WAVE BM (KN·m)	-6,59E+05	-	-7,38E+05	-5,35E+05	-3,21E+05	-7,08E+05
Deck Cross Section Modulus (m^3)	3,56	4,49	4,20	3,53	3,52	5,00
Bottom Cross Section Modulus (m^3)	3,77	4,60	4,14	3,64	3,34	4,93

Detailed scantlings and design parameters are presented for each one of the section longitudinal structural elements. As shown in Figure 8.3, midship section have been divided in 18 parts (named T1 to T18) for decks, shell, inner and outer bottom. Four more parts (named CL, A, B and C) are defined for the double bottom girders.

For each one of these parts, and for each one of the classification rules used, Tables 8.2 to 8.5 presents the following values:

- Design pressure applied to the part.
- Plate thickness.
- T shaped longitudinal stiffener scantling.
- Stiffeners spacing.
- Determining factor for the scantlings (Failure mode driving the design).
- Thickness increments due to corrosion allowance.
- Stiffener section modulus.

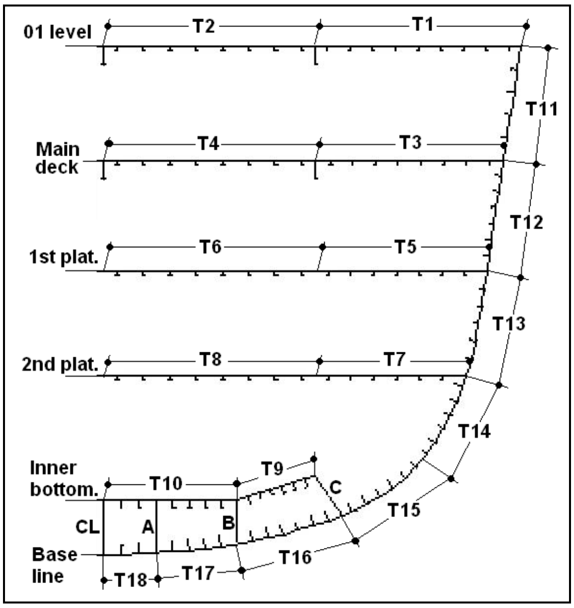

Figure 8.3: Parts for detailed calculations which main section has been divided in.

Table 8.2
Resulting data for each part of the main section

Classification Society #		1	2	3	4	5	6
Part T1: 01 level - side strake.	Design Pressure (KPa)	ps = 10 / pw = 20.67	12	ps = 10 / pw = 17.5	26,1	13,70	18,52
	Plate thickness (mm)	8	10	8,3	8	10	10
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	100*4.4 / 64*6.3	150x5-75x7	174.5x5.8-127.0x8.5	69.65x4.44/ 25x6.35	76.2x2.9-46.8x4.3	140x7 - 120x7
	Stiffener Spacing (mm)	666	700	500	350	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: minimum Z global; stiff.: minimum req.	No smaller member	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	56,13	110	124,24	19	22,70	159,60
Part T2: 01 level - center strake.	Design Pressure (KPa)	ps = 10 / pw = 17.5	12	ps = 10 / pw = 17.5	26,1	13,70	18,52
	Plate thickness (mm)	8	10	8,3	8	8	10
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	100*4.4 / 64*6.3	150x5-75x7	174.5x5.8-127.0x8.5	69.65x4.44/ 25x6.35	76.2x2.9-46.8x4.3	140x6 - 120x6
	Stiffener Spacing (mm)	666	700	500	350	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: minimum Z global; stiff.: minimum req.	No smaller member	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	56,13	110	124,24	19	21,87	138,36
Part T3: Main deck - side strake.	Design Pressure (KPa)	ps = 7.5 / pw = 3.73	12	Unif. distr. load = 7.5	14,9	4,90	7,32
	Plate thickness (mm)	5	8	6	6	6	8
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	80*4.1 / 55*5.7	75x5-75x7	149.9x4.3-100.1x5.5	69.65x4.44/ 25x6.35	76.2x2.9-46.8x4.3	80x4 - 60x4
	Stiffener Spacing (mm)	666	700	500	400	600	650
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: minimum	No smaller member	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	33,89	45	111,53	19	21,04	29,04
Part T4: Main deck - center strake.	Design Pressure (KPa)	ps = 7.5 / pw = 3.73	12	Unif. distr. load = 7.5	14,9	4,90	7,32
	Plate thickness (mm)	5	8	6	6	6	8
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	80*4.1 / 55*5.7	75x5-75x7	149.9x4.3-100.1x5.5	69.65x4.44/ 25x6.35	76.2x2.9-46.8x4.3	80x4 - 60x4
	Stiffener Spacing (mm)	666	700	500	400	600	650
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: minimum	No smaller member	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	33,89	45	111,53	19	21,04	29,02
Part T5: First Platform - side strake.	Design Pressure (KPa)	ps = 5 / pw = 2.48	7	Unif. distr. load = 5.0	5,2	27,45	7,32
	Plate thickness (mm)	5	5	5,3	4	6	3
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	80*4.1 / 55*5.7	75x5-75X7	76.2x4.4-25.4x6.4	69.65x4.44/ 25x6.35	101.6x3.4-57.9x4.8	60x4-40x4
	Stiffener Spacing (mm)	666	700	500	400	600	900
	Determining factor for the scantlings	plate: minimum req.; stiff.: minimum req.	plate buckling	Plates: minimum thick. Req.; Stiff.: minimum web thick. req.	minimum requirements	No smaller member	Plate: min thikness / Stiff: buckling
	Corrosion allowance (mm)	0	0	0	0	-	0
	Stiffener Section modulus (cm3).	33,89	42	20,7	19	37,13	14,35
Part T6: First Platform - center strake.	Design Pressure (KPa)	ps = 5 / pw = 2.48	7	Unif. distr. load = 5.0	5,2	27,45	7,32
	Plate thickness (mm)	5	5	5,3	4	6	3
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	80*4.1 / 55*5.7	75x5-75X7	76.2x4.4-25.4x6.4	69.65x4.44/ 25x6.35	101.6x3.4-57.9x4.8	60x4 - 40x4
	Stiffener Spacing (mm)	666	700	500	400	600	900
	Determining factor for the scantlings	plate: minimum req.; stiff.: minimum req.	plate buckling	Plates: minimum thick. Req.; Stiff.: minimum web thick. req.	minimum requirements	No smaller member	Plate: min thikness / Stiff: buckling
	Corrosion allowance (mm)	0	0	0	0	-	0
	Stiffener Section modulus (cm3).	33,89	42	20,7	19	37,13	14,34

Table 8.3
Resulting data for each part of the main section

Classification Society #		1	2	3	4	5	6
Part T7: Second Platform - side strake.	Design Pressure (KPa)	ps = 5 / pw = 2.48	7	Unif. distr. load = 5.0	5,2	53,04	7,32
	Plate thickness (mm)	5	6	5,8	4	6	5
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	80*4.1 / 55*5.7	75x5-75X7	151.4x5.1-100.8x5.7	69.65x4.44/ 25x6.35	95.1x4.3-100.1x5.2	60x4 - 40x4
	Stiffener Spacing (mm)	666	700	500	400	600	700
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: minimum thick. Req.; Stiff.: minimum web thick. req.	minimum requirements	No smaller member	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	0,5	0	-	0
	Stiffener Section modulus (cm3).	33,89	42	120,99	19	61,20	14,78
Part T8: Second Platform - center strake.	Design Pressure (KPa)	ps = 5 / pw = 2.48	7	Unif. distr. load = 5.0	5,2	53,04	7,32
	Plate thickness (mm)	5	6	5,8	4	6	5
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	80*4.1 / 55*5.7	75x5-75X7	151.4x5.1-100.8x5.7	69.65x4.44/ 25x6.35	95.1x4.3-100.1x5.2	60x5 - 40x5
	Stiffener Spacing (mm)	666	700	500	400	600	700
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: minimum thick. Req.; Stiff.: minimum web thick. req.	minimum requirements	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	0,5	0	-	0
	Stiffener Section modulus (cm3).	33,89	42	120,99	19	61,20	18,27
Part T9: Inner Bottom - side strake.	Design Pressure (KPa)	ps = 50.93 / pw = 13.21	122	ps = 48.73 / pw = 0.0	80,1	111,77	174,22
	Plate thickness (mm)	7	8	8,1	6	8	8
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	124x5-124x8	154.4x6.0-101.8x8.9	104.48x5.08/ 44x9.52	144.4x4.3-100.1x5.4	140x6 -120x6
	Stiffener Spacing (mm)	710	670	500	365	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	pate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local pressure	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1,5	1	-	0
	Stiffener Section modulus (cm3).	234,12	138	128,28	60	107,26	135,60
Part T10: Inner Bottom - center strake.	Design Pressure (KPa)	ps = 47.86 / pw = 9.76	122	ps = 48.73 / pw = 0.0	80,1	111,77	170,44
	Plate thickness (mm)	7	8	8,2	6	8	8
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	124x5-124x8	154.4x6.0-101.8x8.9	104.48x5.08/ 44x9.52	144.4x4.3-100.1x5.4	140x6 - 120x6
	Stiffener Spacing (mm)	666	670	500	350	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	pate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local pressure	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1,5	1	-	0
	Stiffener Section modulus (cm3).	233,42	138	182,72	60	107,26	135,72
Part T11: Shell Strake between 01 level and Main deck.	Design Pressure (KPa)	ps = 0 / pw = 22.66	24	ps = 0.0 / pw = 21.31	17,7	77,45	25,08
	Plate thickness (mm)	7	8	8,1	7	10	7
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	120*4.4 / 64*6.3	99x4.5+99x7	151.4x5.1-100.8x5.7	69.65x4.44/ 25x6.35	120.2x4.8-100.6x5.3	60x4 - 40x4
	Stiffener Spacing (mm)	709	700	500	412	550	350
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	pate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: minimum	Yield	Plate: buckling / Stiff: local pressure
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	69,65	77	123,92	19,5	94,03	15,00
Part T12: Shell Strake between Main deck and First Plat.	Design Pressure (KPa)	ps = 0 / pw = 48.36	29	ps = 0.0 / pw = 36.04	38	77,45	37,53
	Plate thickness (mm)	6	8	5,8	5	8	7
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	100*4.4 / 64*6.3	99x4.5+99x7	100.3x4.3-100.1x5.2	69.65x4.44/ 25x6.35	144.4x4.3-100.1x5.4	80x5 - 60x5
	Stiffener Spacing (mm)	700	700	500	354	550	600
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: minimum thick. req.; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local	Yield	Plate: min thickness / Stiff: local pressure
	Corrosion allowance (mm)	0	0	0,5	0	-	0
	Stiffener Section modulus (cm3).	55,04	77	66,05	19	91,61	35,52

Table 8.4
Resulting data for each part of the main section

Classification Society #		1	2	3	4	5	6
Part T13: Shell Strake between First Plat and Second Plat.	Design Pressure (KPa)	ps = 18.12 / pw = 50.46	56	ps = 13.05 / pw = 41.63	56,1	90,19	154,73
	Plate thickness (mm)	6	10	5,8	5	8	7
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	120*4.4 / 64*6.3	100x10+75X10	100.3x4.3-100.1x5.2	104.48x5.08/ 44x9.52	144.4x4.3- 100.1x5.4	140x5 - 120x5
	Stiffener Spacing (mm)	652	685	500	334	600	500
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff compression	Plates: minimum thick. req.; Stiff.: minimum web thick. req.	plate: minimum; stiff.: local pressure	Yield	Plate: min thickness / Stiff: local pressure
	Corrosion allowance (mm)	0	0	0,5	0	-	0
	Stiffener Section modulus (cm3).	68,83	94	66,3	61,4	91,61	114,43
Part T14: Upper Shell Strake between Second Plat and Inner Bottom.	Design Pressure (KPa)	ps = 40.05 / pw = 40.98	81	ps = 39.57 / pw = 37.04	71	117,65	166,27
	Plate thickness (mm)	7	10	6,6	6	8	7
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	140*4.7 / 73*6.9	150x9-90x14	151.4x5.1-100.8x5.7	104.48x5.08/ 44x9.52	197.9x6.2- 102.1x8.0	140x6 - 120x6
	Stiffener Spacing (mm)	622	710	500	417	600	500
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: minimum; stiff.: local pressure	Yield	Plate: min thickness / Stiff: local pressure
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	99,92	218	122,16	63	156,53	135,67
Part T15: Lower Shell Strake between Second Plat and Inner Bottom.	Design Pressure (KPa)	ps = 53.75 / pw = 34.66	91	ps = 51.38 / pw = 35.17	83,5	122,55	172,39
	Plate thickness (mm)	7	10	7,5	6	10	8
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	140*4.7 / 73*6.9	150x9-90x14	151.4x5.1-100.8x5.7	104.48x5.08/ 44x9.52	197.9x6.2- 102.1x8.0	140x5 - 120x5
	Stiffener Spacing (mm)	622	710	500	417	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local requirements	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1	0	-	0
	Stiffener Section modulus (cm3).	99,92	218	123,32	63	156,53	114,40
Part T16: External Shell Strake at Inner Bottom.	Design Pressure (KPa)	ps = 60.6 / pw = 33.6	103,6	ps = 59.75 / pw = 33.89	86,6	127,45	174,55
	Plate thickness (mm)	9	11	8,1	7	8	10
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x9-90x14	154.4x6.0-101.8x8.9	113.64x6.35/ 63x13.36	246.9x5.8- 101.6x6.9	220x6 - 200x6
	Stiffener Spacing (mm)	672		500	364	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff compression	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local pressure	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1,5	1	-	0
	Stiffener Section modulus (cm3).	237,73	222	181,44	118	156,53	346,66
Part T17: Middle Shell Strake at Inner Bottom.	Design Pressure (KPa)	ps = 62.76 / pw = 33.27	106,7	ps = 62.36 / pw = 33.51	86,6	132,35	173,05
	Plate thickness (mm)	9	11	8,9	7	8	10
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x9-90x14	154.4x6.0-101.8x8.9	113.64x6.35/ 63x13.36	246.9x5.8- 101.6x6.9	280x7 - 260x7
	Stiffener Spacing (mm)	662	700	500	352	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff compression	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local pressure	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1,5	1	-	0
	Stiffener Section modulus (cm3).	236,49	222	183,68	118	156,53	640,79
Part T18: Internal Shell Strake at Inner Bottom.	Design Pressure (KPa)	ps = 63.44 / pw = 33.17	107	ps = 63.28 / pw = 33.37	91	136,28	171,52
	Plate thickness (mm)	9	11	8,1	9	8	11
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x9-90x14	154.4x6.0-101.8x8.9	113.64x6.35/ 63x13.36	246.9x5.8- 101.6x6.9	280x7 - 260x7
	Stiffener Spacing (mm)	666	700	500	352	600	400
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff compression	Plates: buckling; Stiff.: minimum web thick. req.	plate: buckling; stiff.: local pressure	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	1,5	1	-	0
	Stiffener Section modulus (cm3).	237,32	222	181,2	118	156,53	651,25

Table 8.5
Resulting data for each part of the main section

Classification Society #		1	2	3	4	5	6
Part CL: Double Bottom Central Girder.	Design Pressure (KPa)	ps = 61.95 / pw = 16.73	134	ps = 58.11 / pw = 0.0	86	118,14	36,81
	Plate thickness (mm)	12	11	8,7	10	13	5
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x7-150x10	154.4x6.0-101.8x8.9	104.48x5.08/ 44x9.52	-	60x5 - 40x5
	Stiffener Spacing (mm)	700		500		1400	200
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	plate buckling	Plates: buckling; Stiff.: minimum web thick. req.	Buckling: t p =10.04	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	2	1,5	-	0
	Stiffener Section modulus (cm3).	243,12	255	182,64		-	17,43
Part A: Double Bottom Girder.	Design Pressure (KPa)	ps = 61.28 / pw = 16.46	134	ps = 0.0 / pw = 0.0	85,3	117,65	36,81
	Plate thickness (mm)	10	11	8,3	10	13	6
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x7-150x10	154.4x6.0-101.8x8.9	104.48x5.08/ 44x9.52	-	80x6 - 60x6
	Stiffener Spacing (mm)	666	725	500		1350	200
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff. Compression	Plates: buckling; Stiff.: minimum web thick. req.	Buckling; t p = 10.02	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	2	1,5	-	0
	Stiffener Section modulus (cm3).	239,46	255	181,47		-	29,89
Part B: Double Bottom Girder.	Design Pressure (KPa)	ps = 62.19 / pw = 18.8	134	ps = 0.0 / pw = 0.0	84,6	116,18	36,81
	Plate thickness (mm)	9	10	9,8	9	11	6
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x7-100x10	206.0x6.2-102.1x8.0	104.48x5.08/ 44x9.52	-	80x5 - 60x5
	Stiffener Spacing (mm)	558	550	500		1100	200
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff. compression	Plates: buckling; Stiff.: minimum web thick. req.	Buckling; t p = 8.53	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	2	1,5	-	0
	Stiffener Section modulus (cm3).	236,05	180	248,84		-	33,82
Part : Double Bottom Girder.	Design Pressure (KPa)	ps = 55.35 / pw = 15.4	134	ps = 49.26 / pw = 0.0	80,4	112,75	36,81
	Plate thickness (mm)	8	9	6,9	8	9	5
	Stiffner T scantlings (H web x T web - H flange x T flange mm)	160*6.2 / 120*9.8	150x7-100x10	154.4x6.0-101.8x8.9	104.48x5.08/ 44x9.52	-	80x5 - 60x5
	Stiffener Spacing (mm)	592	500	500		900	200
	Determining factor for the scantlings	plate: buckling; stiff.: minimum req.	stiff. compression	Plates: buckling; Stiff.: minimum web thick. req.	Buckling; t p = 7.80	Yield	Plate: buckling / Stiff: buckling
	Corrosion allowance (mm)	0	0	2	1,5	-	0
	Stiffener Section modulus (cm3).	234,53	180	177,8		-	33,10

8.6 *Results Comparison and Conclusions*

8.6.1 Minimum Structural Weight Comparison

Weight for the longitudinal structure presented in Table 8.1 is compared in figure below. Difference between the highest to lowest weight value is about 30% of an average weight for the six class rules considered (about 18500 Kg, highlighted by the dash line in Figure 8.4 below). This difference can be understood as an optimization range available for the ship owner at the time to select a classification society for the vessel.

In other words, variation in weight resulting from optimization approaches is largely a function of inherent conservatism in each of the classification societies and is the ship owner who has to manage how much conservatism shall be used in the design. At the end of the day, the owner should be thoroughly familiar with the design assumptions inherent in the Rule set he has chosen so that he has full awareness of the limits of conservatism which have governed his design flexibility.

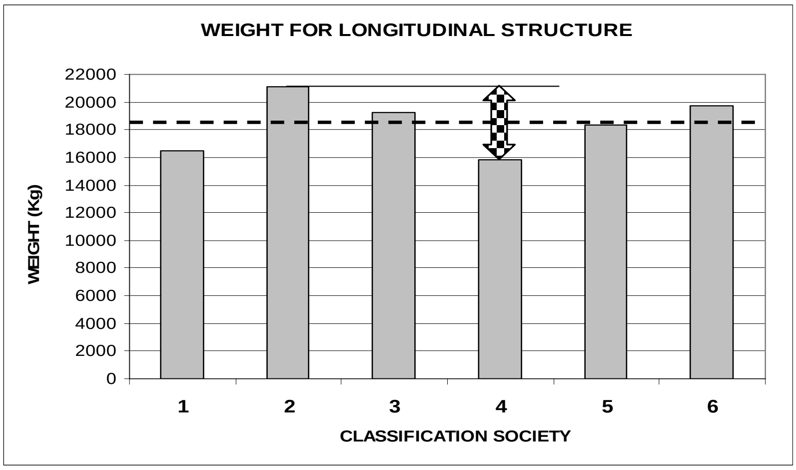

Figure 8.4: Structural weight comparison.

It is also needed to mention that a tiny part of the 30% range (no more than 5%) could be explained by the manual optimization approach used, in which the final and refined value for each minimum structural weight depends on the number of optimization loops carried out.

8.6.2 Vertical Bending Moment Comparison

Figure 8.5 below, shows the vertical bending moment rule values due to wave loadings in hogging and sagging conditions, versus the deterministic computed expected extreme values obtained for HULL 5415. For the deterministic values, the adopted operational profile is such that the ship is considered during all her life in the North Atlantic area, facing pure head waves and with a constant speed, being equal to zero or to 66% of the maximum operational speed (that is, twenty knots in the present case). The annual wave atlases that are taken into account refer to IACS recommendation n°34, and to NATO area A00 respectively. The expected extreme values are defined as the values that have a probability to occur during a 30 years period, with a sailing factor of 80%, equals to 63%.

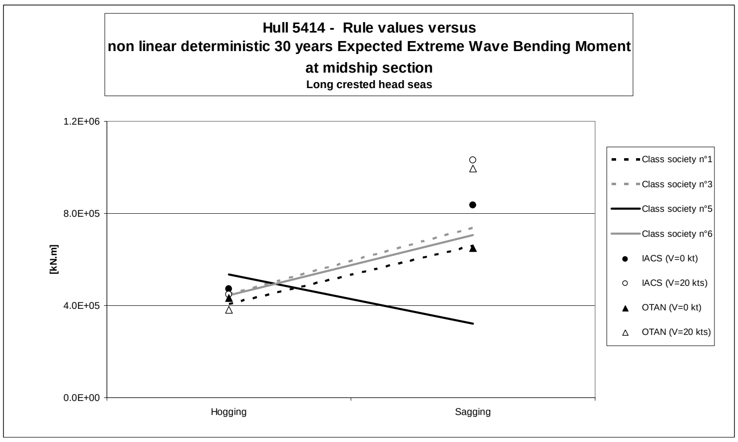

Figure 8.5: Calculated and class societies rule values of the vertical bending moment at the mid-ship section.

Comparison for long term stress assessment is also here presented. When considering a point of the hull, the probability for the normal stress to exceed a given level can be deduced from the bending moment probabilistic law through the local section modulus. The exercise has been made taking into account six different class societies and for two points situated on the centreline at the mid-ship section, the first being located on the strength deck and the second on the bottom shell. The still water component provided from Hull 5415 definition is added to the wave-induced components.

Hence, Figures 8.6 and 8.7 below shows for each class society and at each location, the various probability distributions for the longitudinal hogging and sagging stresses, when the ship is considered to be placed during all her operating life defined by the following parameters:

- 30 years with a sailing factor of 80%
- North Atlantic operation
- Facing long crested head seas
- Speed equals to zero or 20 knots.

The 30-year expected extreme stress, which has a probability of 63% to occur, can be read using the horizontal dashed line corresponding to the probability of the elementary event, in the neighbourhood of 10^8 for such a period.

The raw material limit strength is also represented to compare the above results to a physical limit.

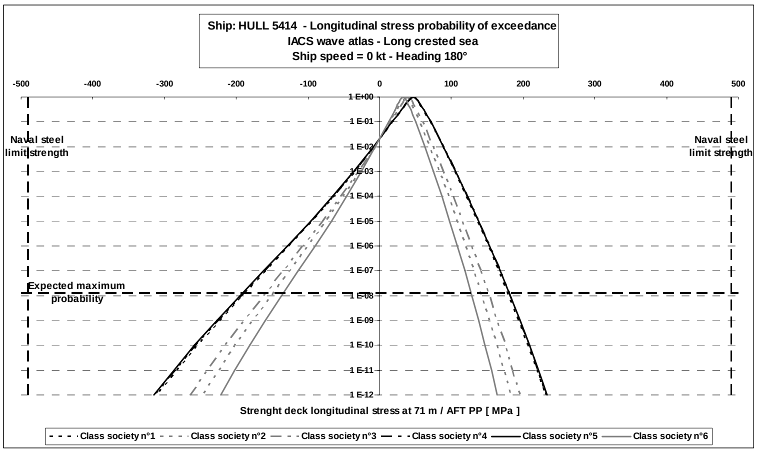

Figure 8.6: Longitudinal stress probability distributions at the strength deck of the Hull 5415 mid-ship section.

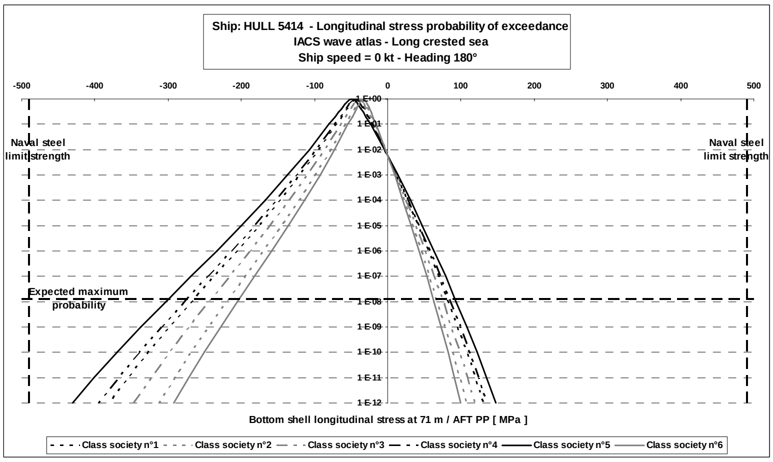

Figure 8.7: Longitudinal stress probability distributions at the bottom shell of the Hull 5415 mid-ship section.

8.6.3 Global Midship Section Properties Comparison.

Midship section properties are compared in the Figure 8.8 by means of the deck and bottom cross section modulus, resulting in a very consistent set of values where nearly similar modulii are obtained for designs according to rules number 1, 3, 4 and 5. Design according to rule number 2 has resulted to be more conservative, while values resulting from design according rule number 6 is representing a design are 40% higher than average modulus due to ultimate strength criteria consideration.

Hull girder strength per unit weight is compared in Figure 8.9 which presents a clear reflection of the effectiveness of material distribution for global bending. The figure shows that all values are quite similar for all the designs. Just the exception is for design according to rule number 6, which shows a higher efficiency due to inherent rule considerations for ultimate strength. On the contrary, the lowest value is for design according to rule number 5 and seems to be a consequence of the application of additional V-lines requirements.

It can be concluded that with the removal of the additional requirements for consideration of ultimate strength and internal deck loading, the results of all the rule sets are remarkably similar and show that each approach reflect sound physical principles.

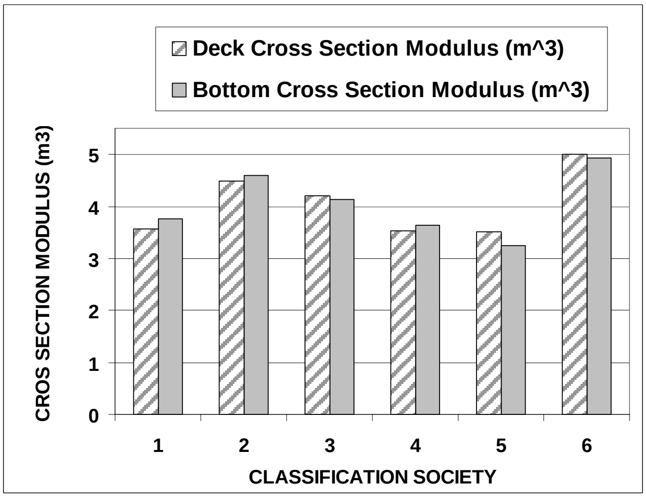

Figure 8.8: Midship section modulus comparison.

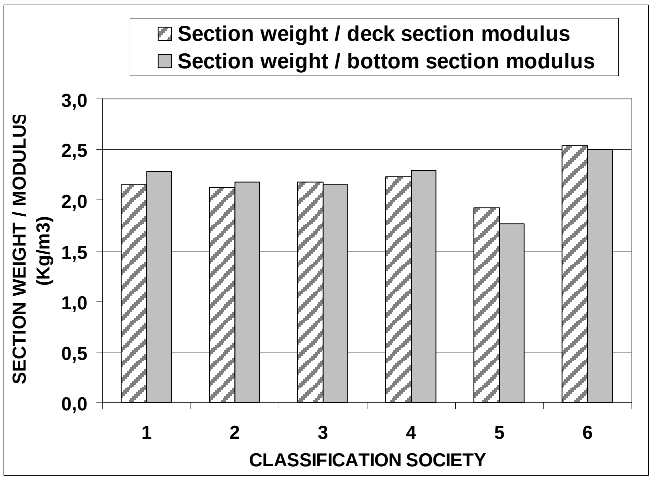

Figure 8.9: Comparison of hull girder strength per unit weight.

8.6.4 *Local Scantlings Comparison.*

Illustrated in the figures in this section (Figure 8.10) is a comparison of stiffeners scantling (by means of the cross section modulus) for each rule set and for each deck and bottom.

Here the comparison shows significant differences between each rule set which make difficult to extract some clear conclusion. These differences are driven by the common effect of several parameters such as:

- Stiffener contribution to global cross section properties
- Design pressures due to local loading
- Combination with adjacent plate thickness as well as stiffener spacing.

One of the most remarkable results here is for some of the rules set which dedicates the stiffeners at 01 level and outer bottom for the contribution to the global cross section properties, while stiffeners at intermediate decks are more dedicated to support local loadings. This behaviour can be observed for rule set number 6 and reflects basic physical principles for global longitudinal strength.

On the other hand, stiffeners at the inner bottom are mainly governed by the design pressure due to tank overflow resulting in a wide range of scantlings between different rule sets.

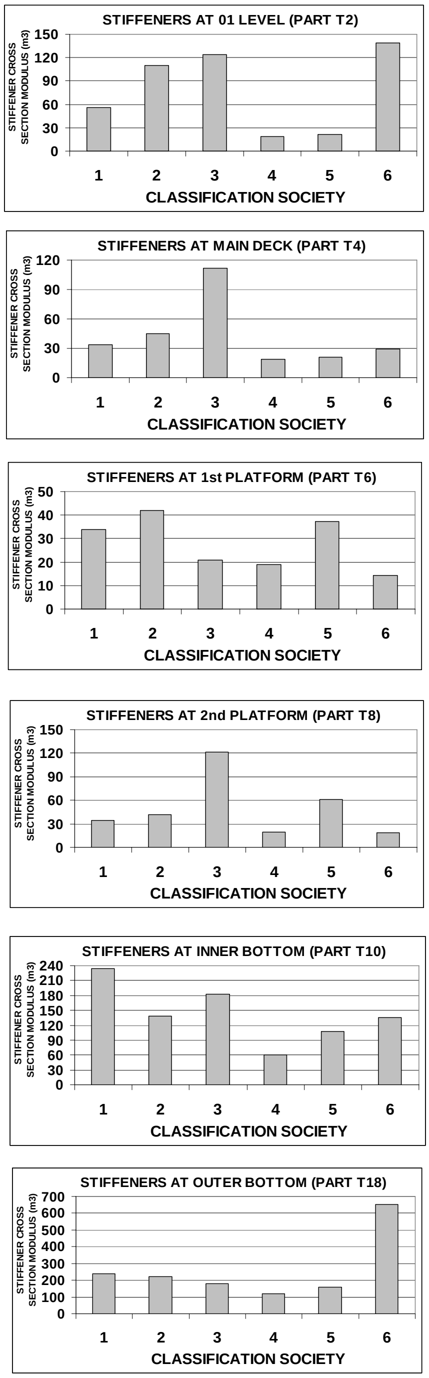

Figure 8.10: Stiffeners s cantlings.

9. CONCLUSIONS

We have continued our exploration into 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 have focused on the move by navies worldwide to partner with classification societies for the development and application of technical baseline criteria including structural design. We have explored in more detail aspects of naval structural design which are of particular concern today including fatigue and overall design integration and optimization. We have found that, even though developing quite independently, approaches by the various classification societies and their naval partners have been remarkably similar. The centerpiece of our work has been the application of a number of existing classification Rule sets to the initial structural design of a common destroyer hull. This exercise clearly pointed out that there are differing structural design philosophies which appear to rest in a range of conservatism which may be attributable to the through life projected employment each navy views as central to its ships' missions. That said, having developed independently, it is remarkable how closely the overall structural capability of each approach remains in the global aspect.

10. RECOMMENDATION

It is recommended that this committee continue concentrating on extension of the actual design study which compared application of several Rule sets to a structure with the goal of addressing the entire hull girder design and optimization. This will allow better insight to just where the approaches differ.

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