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Structural Design of Naval Vessels: Recent Developments and Emerging Challenges

ABSTRACT

This paper presents an overview of current naval structural design procedures and challenges, as well as areas for future exploration. Unique features of the design, production, and operation of naval ship structures are reviewed. Then a two-task breakdown of the structural design process into achieving fitness-for-purpose, and achieving higher design goals is presented. While these tasks are not independent, past developments have tended to focus more heavily on one task or the other. The current state-of-the-art and recent developments such as goal-based standards, classification of naval vessels, and complexity estimation are reviewed. Novel structural configurations such as the advanced double-hull design are reviewed as part of the focus on design for production. Significant opportunities for future development in terms of regulatory approaches, design frameworks, optimization, and design approaches are presented.

INTRODUCTION

Designing the structural system is one of the fundamental tasks of any overall warship design process. Advances in analysis capability, modeling, and information processing have significantly changed what is possible in the realm of structural design. However, to fully realize the capability of these recent advances requires attention not only to the new individual capabilities but also to the overall structural design process. This paper presents an overview of the naval structural design problem and current areas of challenge. This includes the role of structural design in the overall ship design process, a review of historical approaches, and the current approach. Potential future challenges and opportunities resulting from both increased engineering capability as well as changing external influences on the design process are also covered. The aim of this work is to be a state-of-the-art summary highlighting the major developments, not a comprehensive review paper of past or current approaches.

In the remainder of this paper, the unique aspects of naval platform design which impact the structural system design are briefly recapped. Then a two-task perspective on structural design is introduced - the first task focuses on achieving basic fitness-for-purposes, and the second task focuses the achievement of a higher-level design goal. Approaches for fitness-for-purpose, including criteria development are then reviewed. Approaches for addressing the second task, including design for least weight, design for producability, and design for lifecycle performance are presented. The paper closes with a discussion of future challenges for the navy structural design community.

Unique Nature of Naval Platform Design

The overall naval ship and submarine design problem has long been identified as a unique engineering design challenge by many authors (e.g. [1]). While space does not permit a comprehensive overview of the extensive body of work on this topic here, a few of the more challenging design aspects that have direct impact on the structural design process will be highlighted here. Naval platforms are large, complex, engineering products marked by protracted development processes. The structural system often comprises the majority of the vessel's lightweight [2], hence setting and sticking to structural weight targets early in the design process is critical to maintaining a converged design. However, at the early stages of design, structural loads and structural response calculations are necessarily only approximate. This situation where decisions have to be made before complete information is available has been noted by many authors [3, 4]. Recent approaches such as set-based design [3] seek to delay decisions until higher-quality information is available. However as will be discussed later, implementation of these advanced de-

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sign methodologies for structural systems is still in its infancy.

Further complicating the naval vessel structural design challenge, naval vessels are constructed without resort to complete prototype structural testing. Additionally, they are constructed within existing shipbuilding facilities. The lack of prototype testing and custom assembly procedures requires extensive use of simulation tools in design. It also requires careful attention to details of connections, transitions, foundations and other local structures to avoid localized fatigue and deformation issues in service. As complete prototype testing is not feasible, it is also common to discover some structural problems in service. Keane [2] provides some recent examples of this on the FFG-7, CG-52, and DDG-51 classes. Again, this differs from the aerospace and land vehicle world. These industries feature smaller absolute product size and production runs in hundreds or thousands of vehicles; a situation that makes extensive prototype testing and invasive assembly facility modifications cost-effective. When comparing structural design and production techniques across industries, these differences are important to remember.

Naval platforms are also used differently than aerospace and ground platforms, a difference reflected in their concept of operations, or CONOPS. In reviewing the *Virginia* class submarine program, it was noted that the patrol duration for a submarine is normally about 2,000 hours, while recent aircraft and land-based vehicles do not have patrol durations exceeding 24 hours [5]. Similarly, as growing demands and shrinking fleet size impact the surface force, vessel deployments of 9 to 11 months have been noted in the past year [6, 7]. During such deployments, facilities are normally not available for significant structural repairs. Such lengthy deployments places a premium on robust and dependable structural systems that require minimum inspection and maintenance over periods of three to twelve months of service.

In this manner, naval platforms also differ from commercial marine vessels. For example in the commercial high-speed ferry market frequent structural maintenance intervention can be tolerated as the vessels are normally never far from their harbor base. Naval vessels have also long been designed to resist combat loads and damage. The commercial marine industry had not explored incorporating accidental limit states such as collision and grounding into structural design procedures until the last two decades. The impact of such considerations on target structural reliability and local structural details can be considerable. For example, naval structural criteria traditionally require that all longitudinal structure be fully continuous, while commercial practice allows intercostal structure with adequate alignment. Similarly naval practice has traditionally required the use of only symmetric stiffening profiles to maximize structural performance under extreme load, while commercial practice has moved towards asymmetric offset bulb shapes. Such structural detailing decisions are often extensively optimized for producability and structural fatigue concerns and woven into standard shipyard detail design and production practice. Thus, moving from one approach to the other is not a trivial matter for either a new design or adapting a proven design.

Naval Structural Design Process

Fundamentally, the structural design procedure involves two related, but distinct, tasks. The first of these is to ensure that the structure is fit-for-purpose - *i.e.* with an acceptably low probability of failure the structure will carry all loads imposed upon it during the ships' operation. The second is that the structural design achieves some optimality between a series of higher-level goals selected by the designer. These goals may include a particular military capability, minimum weight, minimum build cost, ease of maintenance, etc. While in practice some design approaches blend these tasks into a single methodology without distinction, it is argued that both tasks must be present in any complete design framework. The first task, that of ensuring fitness-for-purpose is normally achieved through analyzing the loads and response of the structure, and comparing the results to established criteria that are specified but not necessarily under the control of the designer. However, requiring fitness-for-purpose does not uniquely define a resulting structural system. Generally, there are many possible structural configurations that would achieve fitness-for-purpose for a given design. Thus, some sort of criteria must be applied to uniquely define the resulting structural system. The second task represents the designer's intent and objectives. By definition it is directly under the control of the designer.

The role of this "second task" in the overall design process has varied greatly over time. In the early half of the twentieth century, the need to armor vessels against enemy shells, provide torpedo protection schemes against contact-fused weapons, and design within rigid displacement limits of the Washington and London naval treaties made the structural system a primary visible component of a vessel's war fighting capabilities. In the cold war era, the explicit connection between the structural system capabilities and the overall platform capabilities weakened somewhat. For example, in reviewing the design of LHD-1, Hackett mentions the structural design only in passing in terms of avoiding problems with cracking and vibration in the island [8]. In a similar review of the DD-963 class, Rains et al. omits any discussion of the structural system [9]. In a detailed discussion of the design procedure behind the DD-963 classes, Leopold et al. [10] makes it clear that the primary concern from the structural design was weight and producability concerns. Discussing the structural design process, Leopold et al. noted that "...a fast and precise response is required because of the design implications of weight and price".

Therefore during much of the cold war, the structural component of design was primarily seen as a large weight group that must be estimated accurately to achieve a satisfactory design. Otherwise the role of structure in the design process had become somewhat decoupled from the discussion of the platforms capabilities. More recently, with the applications of novel materials, such as the composite deck house on the DDG-1000 class, the tie between the structural system and unique military capabilities is becoming stronger again. When talking about structural design procedures and prominence in the overall design process, it is important to assess the primacy of this "second task" in the mind of the naval architects.

CURRENT STATE-OF-THE-ART

Fitness for Purpose

Although the first and second tasks reviewed above are inherently linked throughout the design process, the analysis tools used for each can often be separated. In this section, the tools and approaches used to assess fitness for purpose will be reviewed. In order to use structural engineering analysis to assess designs for fitness-for-purpose, some sort of acceptance criteria is required. The development and maintenance of such criteria is a critical component of any structural design capability within an institution such at the U.S. Navy. This section explores existing approaches to criteria development and the current U.S. Navy approach. Additionally, recent advances in criteria development including reliability-based criteria, goal-based standards, and the use of commercial classification societies are covered.

An overview of the types of techniques commonly used in current naval structural design was recently presented at the 2009 International Ship and Offshore Structures Congress (ISSC), and is presented below in Figure 1. This figure depicts three main types of linked analysis that are typically used during the structural design process. While the details of any particular design process are likely to be unique, this figure gives a high-level overview of the types of fitness-for-purpose assessments currently in use today.

In the uppermost stage, closed-form rule expressions are initially used to synthesize an acceptable structure. Such rule-based analysis can be automated as part of a wider design synthesis procedure. Examples of such automation in the U.S. Navy design community are the "Design Program Ship Structures" [12] and its forerunner, the SSDP [13]. Automating this process necessarily involves combining fitness-for-purposes assessment with some sort of higher-level objective to select a single design from all the feasible designs. The middle stage consists of linear finite element analysis of the initially-synthesized ship structure, allowing higher-fidelity resolution of structural responses in the complete ship structure. Feedback loops connect the second stage to the first stage, as the finite element analysis may reveal problematic areas that require a different structural concept or detail to resolve. The final stage consists of specialized analysis, including weapons effects such as UNDEX resistance, to validate that the structure is acceptable for naval-specific purposes. Again, if shortcomings are identified, the design is modified and the first two levels of analysis repeated to demonstrate that the resulting design meets all fitness-for-purpose requirements.

When examined in isolation as in Figure 1, the structural design process appears relatively straightforward. However, this structural design process is only part of a larger design process. Early in the design process the overall weight and space reservations for the structural system are identified. These estimates then become targets that the structural designer must seek to hit throughout the rest of the design process. Typically, this is done before any structural analysis beyond the first-stage rule analysis has been completed. Thus, the naval architects working on the structural system become increasingly constrained. As higher-fidelity engineering simulation results become available, they may have neither the weight or spatial freedom to adjust the structural system as desired.

An additional complication is that the various stages of structural analysis may be performed by different people in different organizations. For example in the U.S. Navy,

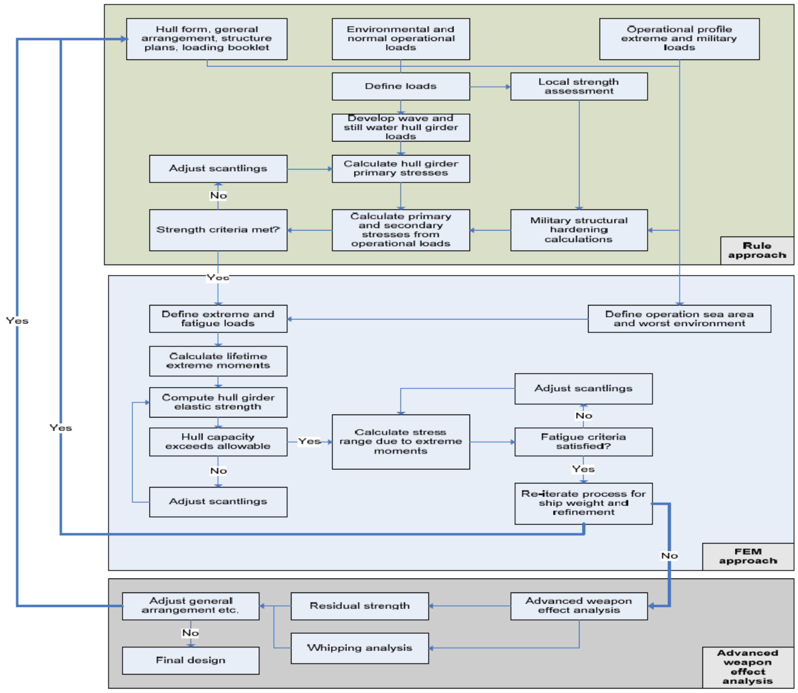


Figure 1: Overview of Naval Ship Structural Design Process after [11]

the early design stage may be carried out in-house by NAVSEA. This is typically done as part of the development of requirements and the initial conceptual design, using DPSS alone or as part of an overall synthesis code such as ASSET. The winning contracting team may then lead the development of the global finite element analysis of the vessel. Specialist codes for weapons effects, survivability, and ultimate strength may be carried out by engineers at NSWCCD who are familiar with these codes. This "over-the-wall" design process can further complicate late-stage adjustments to the structural system. Coordination between each phase in the design process requires extensive data transfer for each structural option to be considered.

The last two decades have seen focused efforts to address these challenges in structural design. The commercial classification societies have developed increasingly complex software packages to automate the first two stages of design, and allow automatic transfer of data between them. Examples include ABS' SafeHull system or DNV's Nauticus. Such packages can accelerate the usage of finite element tools in the design process and can improve coordination between the shipyard and the classification team approving the design. Keane [2] proposed an Integrated Structural Design Environment (ISDE) to be considered as part of the DoD High Performance Computing Modernization Project CREATE-SHIPS. The ISDE intends to reduce data transfer and model generation time, as well as allowing higher-fidelity tools to be applied earlier in the structural design process. Such a toolset could significantly improve the implementation of the process shown in Figure 1. However, challenges such as providing the necessary level of design detail to run advanced analysis tools, and the requirements for both skilled engineers and time to interpret the results of high-performance tools must be addressed.

Historical Criteria Development

Given the difficulty in directly simulating every possible combination of loading a vessel may encounter in its life, structural design methods have historically been developed using a semi-empirical framework. In such an approach, a range of common load cases are applied via accepted analysis techniques, and experienced-calibrated acceptance criteria are used to assess the results. The impact of this approach on design is that it ties together set load-prediction methods, analysis methods, and acceptance criteria into a fixed design approach. In the 1960s, Mr. Malcolm Dick of Gibbs & Cox, Inc. presented this relation in a triangular graphic, an approach then followed by Dr. Sielski [14] and shown below in Figure 2. The placement of material and fabrication at the center of the triangle indicates that a common, consistent set of material and fabrication standards must also be maintained. However, many individual structural criteria will not explicitly address these factors. In this picture, the acceptance criteria is shown as allowable stress, but in principle any other criteria (ultimate collapse stress, probability of failure) may be used.

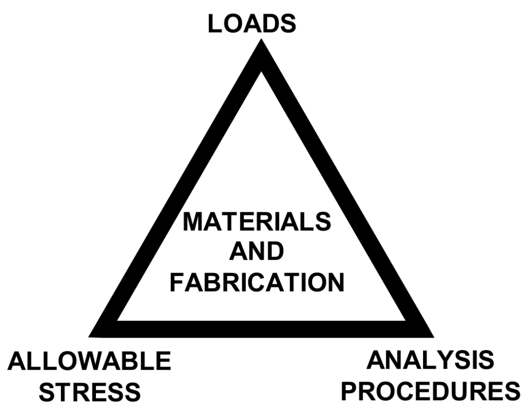


Figure 2: Criteria and Methods Relationship after [14]

Many existing design approaches, including most commercial classification society rules or guides and existing U.S. Navy design criteria implicitly follow the approach shown in Figure 2. When a new analysis method, structural material, fabrication method, or structural concept is introduced the criteria's maintainers must adjust the other legs of the triangle to account for the new method. Often, this is done via bench marking the new approach against the existing methods on proven structures, and adjusting the acceptance criteria to maintain a consistent level of safety. Simply switching out one portion of the triangle for an improved method without adjustment is unlikely to lead to a consistent level of safety. Only the complete triangle - load analysis methods, structural analysis methods, and allowable stresses (or other criteria) has been validated by previous experience, not the individual components.

U.S. Navy Traditional Fitness-for-Purpose Criteria

Before the advent of the combined Navy/American Bureau of Shipping *Naval Vessel Rules*, the fitness-for-purpose criteria of the U.S. Navy was largely captured in a series of specification (most recently handbooks) and design data sheets, DDS. The DDS are similar to those used by NAVSEA for intact stability, electrical load analysis and other technical disciplines of ship design. At the present time DDS 100-4, DDS 100-6, and MIL-HDBK-519 define the majority of the traditional Navy rule-based acceptance criteria, which form the upper box in Figure 1. These documents are supplemented by a large number of additional DDS for specific local structures (masts, shaft struts etc.) or specialized military structural requirements.

In the traditional rule-based approach, the loads on the structure are divided into gravity-based loads, sea loads from the ocean environment, operational loads from the ship's equipment, and combat loads [15]. During the early stages of design, sea loads for global hull girder bending have been estimated by placing the hullform on a wave profile with a wave height equal to $1.1\sqrt{LBP(ft)}$ where LBP is the length between perpendiculars. The resulting bending moment is calculated by integrating the weight and buoyancy distribution along the vessel [14]. To this bending moment, the stillwater bending moment can be added, and a resulting nominal design bending moment arrived at. This can be converted into a nominal bending stress through the section modulus at each transverse structural location along the length of the vessel.

However, as noted by Sielski [14], the derived bending moment is *not* the extreme bending moment likely to be seen in service. In the context of Figure 2, the resulting load must be compared to empirically-developed allowable stress values. Traditionally, these have been 3.5 tons per square inch (tsi) for aluminum vessels [14], and 8.5 tsi for mild-steel monohulls, 9.5 tsi for higher-strength steel monohulls, and 10.5 - 11.5 tsi for HY-80, 100 and other extremely high-yield steels. [16]. A 0.5 to 1.0 tsi margin may be associated with these numbers depending on vessel type for future growth.

The purpose of these empirical stress limits is multi-fold. Historically, ships designed by this combination of approximate load analysis and strength limits have proven acceptable in service. Furthermore, by limiting the overall stress range in the ship they limit the potential for fatigue cracking in service. However, this purpose of the criteria is not explicit. It implicitly assumes traditional structural connection details as the quality and stress concentration factor of these details also impact the rate of fatigue damage. This assumption furthermore requires that the service life, operational tempo, and operational environment of the proposed vessel will be the same as the previous vessels used to determine the tsi limit in the paragraph above. If any of these factors differ significantly, the in-service fatigue damage rate will also differ.

A desire to be able to apply more refined loading estimates has lead to the development of several probabilistic loading approaches. By developing regression-based response amplitude operators for a wide range of vessels, semi-empirical slamming and whipping response functions Sikora [16, 17] developed a rapid means of estimating both extreme hull girder bending stresses as well as likely global fatigue damage spectra. This approach provides a much more customized load forecast, however, it does require additional data about expected operational profiles and wave environments. As an intermediate step, regression fits to long-term loading data for design loads have also been proposed [18], generally following the form:

$$BM = C_1 \left(L^{2.5} B\right)^{C_2} \tag{1}$$

Where L and B are the length and beam of the ship, and C_1 and C_2 are coefficients depending on ship type, operational life, and exposure environment.

The principles of this more customized stress range approach have been formalized into a U.S. Navy structural fatigue design procedure in NSWCCD report NSWCCD-65-TR-2000/25 [18]. This methodology adopts a S-N fatigue approach using a nominal stress range approach to the fatigue design of structural connections and details. The report provides both damage-index based and reliability-based analysis procedures for specific fatigue details. The fatigue strength of local details is based on the American Association of State Highway and Transportation Officials (AASHTO) bridge fatigue design guidance. The AASHTO approach ranks groups of typical structural connections and details in seven fatigue categories, A though E' based on their fatigue resistance. This standard was selected as the large welded connections present in bridges were felt to be most similar to the connections in ships.

As applying the full design procedures presented in [18] directly can still be too time-consuming for early stage design, the procedure was bench marked against 12 existing ships. Assuming traditional service lives, and a North-Atlantic operational environment, a two-stage rapid fatigue design procedure was developed. Initially, the hull-girder bending stress from the design load in (1), are limited to fall below certain values depending on ship type, lifespan, expected local structural detail quality, and operational environment. Then, target stress concentration factors are established for structural details at different locations in the hull girder. This approach allows for a rapid assessment of a proposed design against existing designs in terms of resistance to structural fatigue cracks. It also provides explicit target stress concentration factor guidance for the detailed structural design stage.

While global bending moments and structural fatigue have been the focus of much recent development in the U.S. Navy structures community, the Navy has long also developed first-principles approaches to secondary and tertiary structure fitness-for-purpose criteria. Limiting allowable stresses are set based on a fraction of yield, ultimate, or collapse loads predicted for grillage, columns and other structural components. A combination of expected loads and the estimated global hull-girder bending loads are then applied, and the resulting stresses assessed against these allowable-stress criteria. The criteria also varies by severity of the failure mode and likelihood of experiencing the design load. For example, Sielski [14] outlines the Navy's local plating pressure design criteria. Sielski notes that the allowable set varies, with shell plating designed for no set under operational sea load, while watertight bulkheads that are only expected to carry load in a damage scenario can be designed to allow more extensive permanent set of the plating.

Beyond the initial rule-based design which forms the upper box in Figure 1, the U.S. Navy has used finite element analysis in conjunction with traditional allowable stress levels to further refine the structural response as more details are known. Such models can more accurately predict local secondary loading and fatigue loads accounting for hull girder shear lag, openings, and changes in hull-girder section and other effects difficult to include in rule-based approaches. However, the time and effort required to build a global finite element model of the ship normally means that such models are used for later-stage design verification. Thus, a current challenge is to more effectively incorporate them into the preliminary design stages where different structural concepts may be explored and structural weight targets assigned.

Similarly, advanced simulations are often applied to study shock response and the survivability of the proposed design. Recent work within the DoD-sponsored CREATE program has focused on extending both the fidelity of such predictions with the objective of replacing full-scale trials, and allowing these advanced simulations to be applied earlier in the design process [19]. Similarly to finite element analysis, a key challenge in this undertaking is generating the detailed design data such simulations require without waiting for the design to be fully mature, and achieving reasonable processing times. This would allow earlier application of these simulations in the design process where there is still flexibility to incorporate the lessons learned from the simulation into the structural system.

Recent Developments in Fitness-for-Purpose Criteria In the last 15 years, there have been at least three major developments in naval fitness-for-purpose criteria that have attempted to extend and refine the approach of Figure 2. These are reliability-based design, goal-based standards, and partnerships with classification societies to implement naval ship classification rules. At the present time, each of these is a work-in-progress with ongoing refinement. Each of these development will be reviewed in turn.

A desire to improve the quality and consistency of such criteria in the 1970s and 1980s lead to the development of a number of reliability-based approaches for structural design criteria. In reliability approaches, a target probability of violating a fitness-for-purpose threshold, or limit state, is formally identified. Then, the probability of such a violation occurring for the structure under consideration is estimated to ensure it is less than the target. A number of different approaches, ranging from direct reliability analysis of each design to more simplified methods have been employed. One of the most successful techniques to date has been the Load and Resistance Factor Design (LRFD) approach. This approach decomposes each structural criteria into the following format:

$$\phi R \geq \sum_{i=1}^{n} \gamma_i L_i \tag{2}$$

Where the ϕ and γ terms are partial safety factors applied to the strength or resistance, R of the structure and the various load effects, L_i acting on the structure. The maintainers of the code calibrate these partial safety factors so that a defensible and consistent reliability and risk level is achieved for each criteria. Once complete, an LRFD code is as easy to use as a conventional structural rule code, as the partial safety factors appear as fixed constants to the end users. By assigning individual safety factors to each load component and resistance component, it is possible to achieve much more granular control over the criteria. In a marine demonstration of LRFD design, Mansour, Wirsching, White and Ayyub [20] note that reliability-based design can result in a more efficiently-balanced design, a more rigorous treatment of uncertainties, and a code which is easier to update or extend to novel ship types. However, developing a LRFD code represents a significant engineering undertaking, even if an existing, workable design code is available to benchmark against.

Many industries have adopted LRFD-based codes, including the American Institute of Steel Construction and the U.S. Aluminum Association's in their *Aluminum Design Manual*. The current Eurocodes also use a similar partial-safety factor approach. Efforts to develop LRFD design codes for naval structures have been made, including several example studies [20, 15], culminating in a special issue of *Naval Engineers Journal* in 2002 that outlined a prototype LRFD code for U.S. Navy ship structures [21]. Further adoption of this prototype code seems to have stalled within the U.S. Navy. Application of LRFD outside of the U.S. Navy is continuing in the marine industry, for example the recent *Common Structural Rules* for oil tankers issues by the International Association of Classification Societies (IACS) includes LRFD for some criteria.

Another recent area of progress in criteria development has been the emergence of goal-based standards [22]. In a goal-based approach, the higher-level goals of the design criteria are explicitly stated and documented. A central objective of goal-based standards is to allow innovative design solutions and a more rapid response to emerging technologies [22]. By explicitly stating the high-level goals of the design criteria, assessing equivalence for novel designs or analysis methods is theoretically improved over the traditional approach of Figure 2. In the traditional approach, the exact reasoning behind different prescriptive criteria and acceptance limits may become lost over time.

The development of goal-based standards has been largely pioneered by the commercial marine industry. However, NATO has recently been involved in the development of a goal-based standard for naval vessels, ANEP 77 [23]. This code is being further promoted by a group of European Navies and classification societies, the International Naval Safety Association (`http://navalshipcode.org`). ANEP 77 uses a pyramid approach as shown in Figure 3, defining aims, goals, functional areas, performance requirements, verification methods, and justification for naval vessel design codes. It covers structural systems and other design disciplines such as stability and fire safety, but not military-specific systems. The code has a single aim, namely to protect life onboard naval vessels to a standard not less than that on merchant vessels. Each major section of the code has a goal which is then sub-divided into functional areas, specific performance requirements, and then either prescriptive or performance-based verification methods are specified to assess if a ship complies with the code.

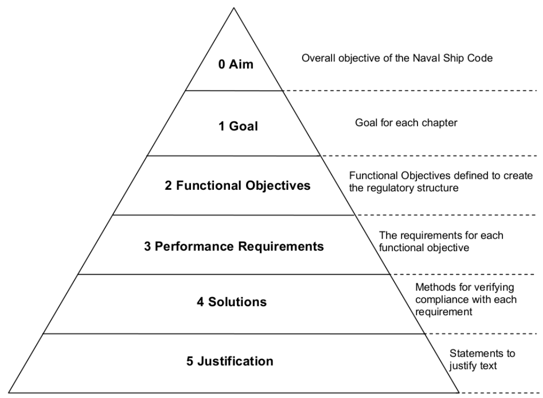


Figure 3: Goal Based Approach in ANEP-77 after [23]

It is not the aim of goal-based standards to have the designing naval architect constantly working with high-level goals. Rather the organization responsible for developing approval criteria may then develop acceptance criteria, including prescriptive regulations, to achieve the code's goals. ANEP-77 does not contain any prescriptive structural regulations noting that it "is written as a 'standard for the selection of standards' rather than a standard for direct application in a design office or construction/repair facility. As a consequence, the primary target audience for this Chapter is the Naval Administration and its Recognised Organisations."(Chapter II, [23]). Thus, the progress in goal-based standards is primarily relevant to NAVSEA and the maintainers of the Navy's structural criteria, as a potential topic for future criteria refinement and documentation. This situation is shown graphically in Figure 4 which was presented with discussion in [11].

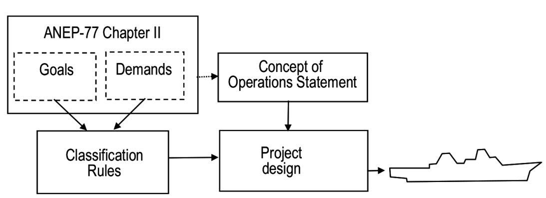


Figure 4: Relationship between ANEP-77 and Design Process after [11]

A final recent development in fitness-for-purpose criteria is the emergence of a large role for classification societies in developing criteria and classing naval vessels. In the 1990s, with declining defense budgets and shipbuilding programs, Navies worldwide began to assess if maintaining a full in-house criteria-developing authority was necessary, or if a more economical partnership with commercial classification societies would make more sense [24]. Within the U.S. Navy, extensive use of commercial fitness-for-purpose approval was proposed for the arsenal ship program in the 1990s [25]. This was followed by a formal partnership with the American Bureau of Shipping. In turn, this led to the creation of the *Naval Vessel Rules* which have been used in support of the LCS and DDG-1000 programs. In the approach adopted by ABS and the U.S. Navy, the Navy retains final technical authority for the ruleset but gains ABS's assistance in rule development and design review. In addition to supporting initial design efforts, naval authority - classification society cooperation extends to through-life service support [26]. Here, similar to criteria and analysis tools development, the goal is to make naval extensions to the lifecycle inspection and forecasting techniques originally developed by class for commercial ships. The Navy's relationship with ABS continues to evolve, and the extent to which future ships will be built to and remain in class is not currently clear.

These developments in the U.S. have been paralleled by similar developments around the globe. At this point in time, most IACS classification societies also offer naval classifications, including Lloyd's Register, DNV, and GL. Recent ISSC reports have compared a number of these rulesets, including both the relationship between the classification society and the Navy, as well as comparison of rule requirements for a the structure of a conventional destroyer-like midship section [11]. These comparisons clearly reveal that the exact role of classification societies in naval vessel fitness-for-purpose criteria is developing, and certainly is not homogeneous nation-to-nation at the current time.

Broader Design Considerations

While the structural design of every vessel must achieve fitness-for-purpose as the "first task" of the structural design, this requirement is not precise enough to uniquely define a structure. Thus, the naval architect must further specify the design objective of the structural system to arrive at a unique solution. This is the "second task" spoken of in the introduction. Eminent naval vessel designers Andrews [1] and Keane [2] have both noted that each complex naval ship design process is inherently a one-off activity. Therefore, each program will develop its own design process and design objectives.

This unique nature of each design process is further reflected in the recent "design-for-X" framework of general ship design, and recent commercial activities to design structures for risk, performance in accidents, and societal expectations. However, in the naval structural community, three common themes have emerged for this "second task", design for minimum weight, design for production, and design for lifecycle performance. Major developments in each of these areas will be reviewed in turn.

As specifying an objective for this "second task" can uniquely define an optimal structural solution, the use of formal optimization becomes possible for structural design. Reviewing the developments in structural optimization would require an entire paper itself, as marine techniques heavily overlap with techniques from other structural disciplines. In this work reference is made to the triennial International Ship and Offshore Structures Congress reports of Committee IV.2, which provide a comprehensive review of recent developments in optimization. Providing efficient optimization frameworks, which can support turn-around times suitable for all stages of design remains a challenge. These needs will be further discussed in the future challenges section.

Design for Minimum Weight

Design for minimum weight is perhaps the longest-running "second task" objective for naval structural engineers. As the structure is often the largest component of a naval vessel's lightweight, minimizing structural weight can have significant impacts on platform size, speed, and lifecycle cost. The current U.S. Navy design program ship structures (DPSS) uses minimum weight as its objective [12]. Reduced structural weight can reduce the resistance of the vessel allowing for smaller main engines and lower fuel storage requirements for the same speed and range requirements. Such compounding effects can significantly reduce the size and cost of some vessels [27]. Additionally, as the largest weight group, removing weight from the structural system can become a design objective when the design has consumed its weight and VCG margins for other reasons. Staiman provides a detailed account of the struggles of the CG-47/52 programs with reducing weight, and the taking tons off sensibly (TOTS) program used to further reduce the structural weight of these vessels to free up weight margin for other purposes [28].

Recent events have led to some re-examination of an intense focus on weight minimization as a suitable "second task" objective for naval structures. As structures become more weight-optimized, both production cost and lifecycle maintenance costs can quickly grow. Thin, lightweight structures are difficult to weld, often requiring extensive and costly efforts to remove initial structural distortion from welding residual stresses. Corrosion and structural fatigue are also more common in lightweight structures as any design margin above the minimum strength requirements has been removed. Ships that have been extensively weight-optimized have also suffered from in-service failures. This includes extensive structural modifications that were required for both the FFG-7 and CG-47/52 vessels. Therefore, most marine structural design approaches today attempt to balance weight concerns with production and operating cost objectives.

Design for Production

Designing the structure for reduced production cost and rapid assembly times has received extensive attention. Design-for-production in ship structures can be done successfully at many different levels in the same design. In considering design-for-production concepts for military vessels, the relative cost and cost impacts of the structural system must be assessed. Given the extensive outfitting, high installed propulsion power, and expensive combat systems, the initial cost of the structure of a warship is a fairly small percentage of the overall acquisition cost. Recent precise figures are difficult to come by, in 1984 Nappi et al. [29] estimated the fraction of initial cost directly related to the vessel's structure at 15% for a 4,000 ton vessel. In 1986 Chalmers similarly estimated 10% for British warships. Thus, even large savings in structural production cost is unlikely to significant impact the vessel's acquisition cost.

However, the structure of a naval vessel often significantly impacts the outfitting cost and complexity of the vessel. Both Nappi et al. [29] and Beach [30] presented nominal breakdowns for frigate and destroyer-sized hullforms, and these are reproduced in Tables 1 and 2 respectively.

Functional Work Group	Assumed % of total man-hours
Welding	7%
Electrical	13%
Pipefitting	9%
Shipfitting	10%
Outside Machinist	4%
Sheetmetal	3%
Painting and Blasting	5%
Ship Assembly and Support	29%
Integration and Engineering	20%

Table 1: Assumed Effort Breakdown for Frigate-Sized Vessel after [29]

Functional Work Group	Assumed % of total man-hours
Hull	28.3%
Electrical	23.4%
Pipefitting	15.6%
Joiner and Insulation	6.2%
Ventilation	6.1%
Paint	9.4%
Manufacturing Services	3.5%
Machine Shop Services	1.0%
Outside Machinist	2.7%
Test and Trials	1.8%
Ship's Management	1.0%
Lifts	0.4%
Other	7%

Table 2: Assumed Effort Breakdown for Destroyer Vessel after [30]

Much of the construction effort in a Navy ship goes into outfit installation of items such as pipe, electrical, and ventilation components. Additionally, painting of this complex outfit is also time-consuming, and it requires extensive integration engineering. Thus, a structure that would be simpler to outfit may offer significant cost savings beyond what is saved on the structure itself. Notably, the data in the more recent Table 2 shows more effort in electrical than the data in the earlier Table 1. This indicates that the potential payoff of easier-to-outfit structures is likely growing as ships become more complex. This increasing complexity of outfit has been noted elsewhere [31].

Recognizing the downstream construction impact of complex ship structures, the U.S. Navy has actively researched structural systems designed to ease outfitting and integration. In 1984. Nappi et al. [29] proposed a novel "no frames" concept for structural design, where intermediate transverse frames between bulkheads were removed. Longitudinal members increased in strength to compensate. The resulting structure is significantly less complex topologically, and therefore is easier to outfit. Extensive studies on this concept for a frigate and destroyer hullform are presented in [29]. An offshoot of this concept, the advanced double hull (ADH) concept was further developed in 1990s. In ADH, the deeper longitudinal members are confined to a double-hull region of the structure for further outfitting complexity reductions. In addition to reduced construction costs, fatigue performance and survivability were also increased by this concept. A comparison of the conventional single-hull and ADH structural concepts and impact on outfitting is shown in Figure 5. Several advanced double hull studies have been released into the public domain [32, 33, 30]. While a relatively extreme example, the ADH studies show what is possible when the structural system is designed to meet a unique and challenging broader design objective.

Design for production approaches can also be used to reduce the initial cost of traditional ship structures. Early in the design process, the influence of hullform complexity on structural production costs can be assessed. By limiting curvature to where it is hydrodynamically necessary, the complexity of the shell structure can be reduced. Bunch et al. [34] review the development of the notional build strategy for the LPD-17, which included hull form modifications such as the insertion of a small amount of parallel midbody, maximizing flat plate and single-curvature surfaces, and the use of straight frames above the waterline. Recently, Temple and Collette [35] explored the trade space between hullform shape complexity and estimated average operational resistance for variants on the DTMB 5415 destroyer hullform and a containership. The commercial marine industry has also investigated early-design stage complexity metrics. Caprace and Rigo [36] extended the concept of complexity to include assembly and material choice complexity as well as surface shape complexity. They formed a composite metric that allows the complexity of both the outer shell structure and the internal structure to be visualized during the early stages of design. An example application of this approach to a large passenger ship is shown below in Figure 6.

The approach of Caprace and Rigo bridges down to the next level of granularity in design-for-production, namely using the complete structural definition to estimate assembly effort and assembly cost. In general, such studies have shown that increasing plate thickness and stiffener spacing can reduce the construction cost of the structure, though the gains may not be large and there is an associated weight penalty. Chalmers [37] presented a plot of the labor, material, and total cost of a warship grillage structure based on the algorithms of the mid-1980s U.K. GODDESS design system. This figure is reproduced below as Figure 7. As both material cost and labor cost vary over time, and material choices are under the control of the designer, such approaches have continued to receive attention for build cost estimation and minimization. Rahman and Caldwell [38] introduced a component-wise build cost estimation approach. A similar approach was also developed in the U.S. known as the

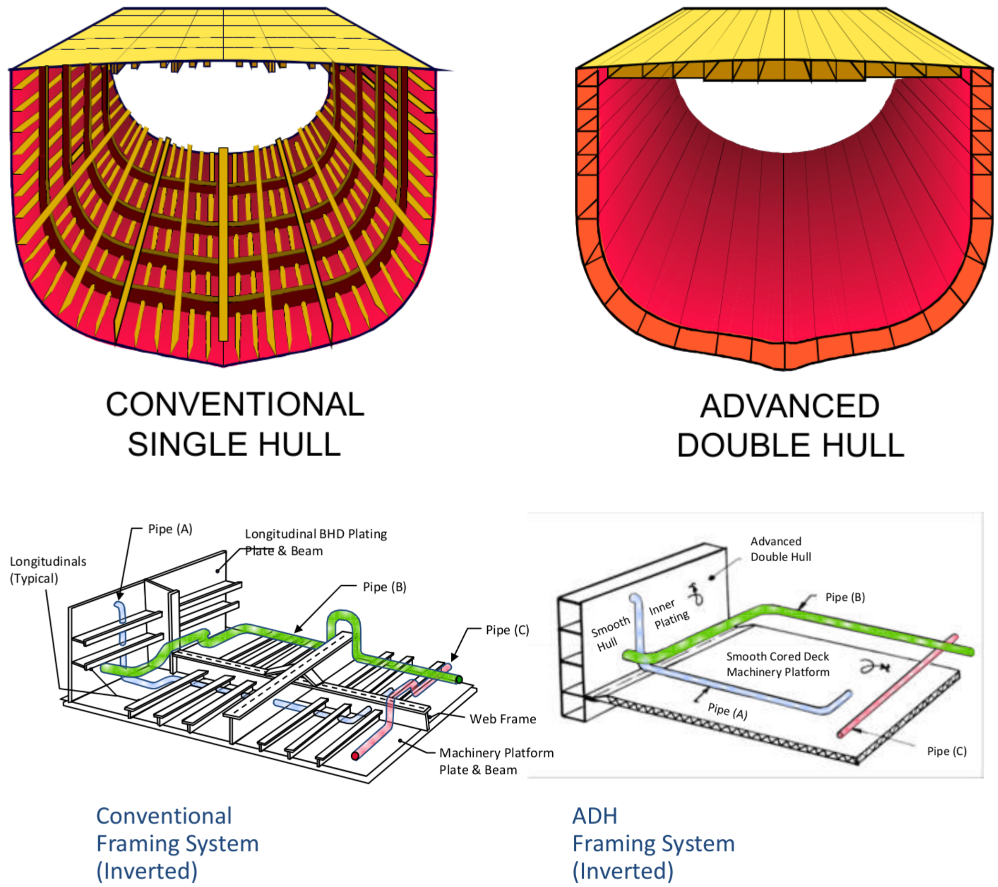


Figure 5: Comparison of Single-Hull and ADH Hullform and Impact on Outfitting after [30]

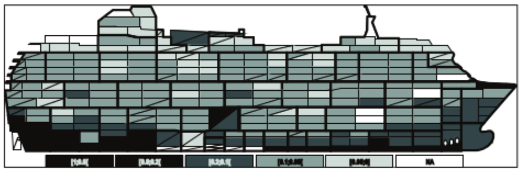
Product-Oriented Design And Construction Cost Model (PODAC) [39]. These approaches have been extended in to more complex optimization techniques for least-initial cost designs [40]. Recent extensions to model production processes in specific shipyards [41] and more complex optimization environments [42] have also been reported.

Design for Lifecycle Performance

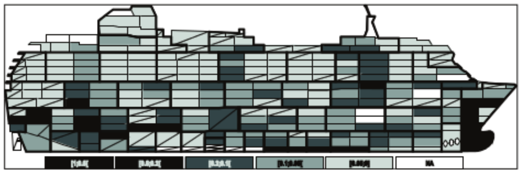
It is possible to extend the approach of considering production cost in structural design to include other aspects of lifecycle cost, such as steel renewal, fatigue cracking and other failure mechanisms. However, at the current time structural lifecycle models are relatively rare in the marine industry for surface or subsea platforms. Several authors [43, 44, 45] have studied the structure of individual transverse vessel cross-sections. These approaches attempt to predict time-varying reliability of the structural system using simplified hull girder ultimate strength models with time-varying corrosion and fatigue models. Typically only the longitudinally effective material is considered.

To date, these approaches do not address wider design integration, but predict lifecycle risk over time for a given design solution. With such a model, the impact of pre-scheduled inspection and repairs can be assessed, and the lifetime of the structure before a critical reliability threshold is violated can be determined. It is also possible to cost-optimize inspections to maintain a minimum fitness-for-purpose threshold. These reliability approaches have been recently extended to include varying operational profiles, the concepts of structural redundancy, and limited updating based on in-service measurements by Frangopol and his research team [46, 47].

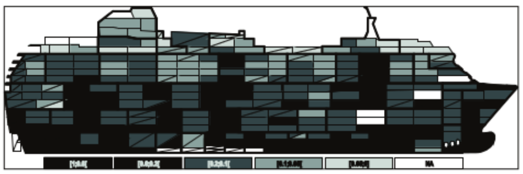
If lifecycle performance is the goal, compared to lifecycle cost, the problem becomes substantially more complex as performance covers a wide range of cost, reliability, and performance concerns. Hess [48] linked structural reliability analysis with conventional operation availability, capability, and dependability (Ao, Co,



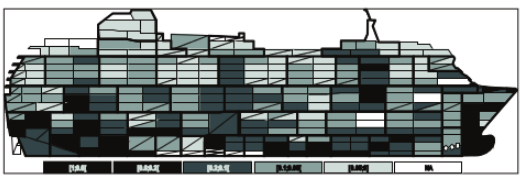
(a) 3D shape complexity



(b) Assembly complexity



(c) Material complexity



(d) Global complexity

Figure 6: Shape, Assembly, and Material Complexity after [36]

Do) metrics to provide some lifecycle guidance when assessing structures. Some initial exploration of the trade space between build cost, maintenance downtime, and repair costs for commercial vessels has recently been presented as part of a design-oriented optimization study [49]. Collette [50] explored the impact of structural design decisions on the mission fatigue reliability of a naval platform with a simplified analysis. However, these recent studies have primarily highlighted the complexity of the lifecycle performance predictions, and the lack of mature design frameworks and tools to tackle this topic for new naval structures.

FUTURE CHALLENGES

Design of ship structures is a challenging component of naval architecture. While the recent past has seen substantial progress in many areas of structural design, future technology developments and budgetary challenges will call for further improvements. Potential areas for future investigation based on the topics covered in this paper are outlined below.

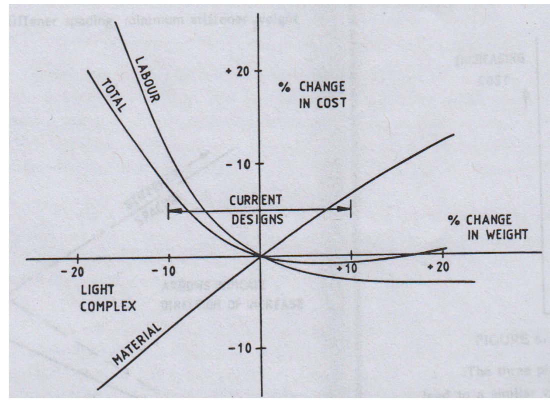


Figure 7: Warship Grillage Structures of Constant Strength - Weight and Cost after [37]

Continued support and updating of the U.S. Navy's structural fitness-for-purpose criteria is clearly required. As classification societies and other code bodies move towards LRFD codes and goal-based standards, the potential benefits of these methods must be examined and what role, if any, they are to play in future standards decided. Additionally, two major developments may further drive changes to design standards.

First, a number of academic research efforts for efficient computational methods to determine phase-resolve specific wave group encounters that lead to extreme load events are reaching maturity [51, 52]. This leads to growing potential to design structures based on specific wave encounters resulting in even higher fidelity than the spectral-based probability methods used today. However such analysis will require formal fitness-for-purpose criteria to be developed, as well as efficient computational approaches to make such simulations practical in design. Additionally, such methods are likely to only be practical after an initial structure and vessel is synthesized, so updating preliminary design methods with the findings and experience from these refined techniques will also be valuable.

Second, the current rapid growth in structural health monitoring systems is putting increased demand on fitness-for-purpose assessments of in-service platforms. As such actually-measured loads and response generally do not follow the design-stage assumptions inherent in Figure 2, there is a growing need for criteria for this purpose. Recent reliability-based methods based on civil engineering approaches by Frangopol's research team (e.g. [46]) are one potential approach to this problem. However, the availability of such monitoring data also makes it attractive to continue to update and refine design-stage criteria, so some sort of a unified framework may also be attractive.

Exploration of set-based design for structural design. The U.S. Navy design community is experimenting with set-based design as a required element of future platform design programs in the early phases of design [3]. While the general principles of set-based design are well known, the application of this technique to structural disciplines, and the types of supporting tools and criteria required have not been explored. If set-based methods are to be used to their full effectiveness, the structural community should develop design methods capable of exploiting this new technique.

Exploration of lifecycle performance frameworks. Building off the lifecycle reliability work, more general lifecycle performance frameworks are possible. In such approaches, structural capability, reliability, and costing can be investigated for a range of different operational profiles and service lives. However, fundamental work is still needed to develop reasonable frameworks for quantifying such trade-offs during design, and reasonable uncertainty approaches for the different aspects of this problem.

Improved computational support for high-fidelity design methods. While initial design studies are likely to be done with approximate methods for some time, there is a strong advantage to be gained by earlier access to high-fidelity simulation. Recent developments in compartment-based collapse methods, non-linear finite element analysis and advanced fatigue prediction techniques all require additional design data and computational effort compared to existing methodologies. Further exploration of efficient techniques to lower the computational time and manual pre- and post-processing time of high-fidelity methods - such as that outlined by Keane [2] as a potential CREATE-program extension - are worth exploring. Areas of design such as fatigue, where the predicted life varies with the third or forth power of applied stress range, would benefit from earlier availability of higher-fidelity load and stress analysis. Recent developments of methods for predicting specific wave encounters that lead to extreme loads are also likely to demand an efficient system of high-fidelity simulation if they are to be used in practical design work.

Improved optimization methods for marine structures. Unlike strict analysis, design often revolves around discovering what is possible and attempting to define the trade space between competing objectives. Efficient optimization approaches, for both single-objective and multi-objective problems are required so that efficient decision support methods can be developed. Recent experience from Europe on the FP-6 IMPROVE integrated project (`http://www.anast-eu.ulg.ac.be/summary.html`) have indicated that combining structural optimization with early-stage arrangement decisions can lead to significant cost savings for complex vessels. However, attempting to merge optimization, high-fidelity analysis, and early-stage design with significant information uncertainty is a challenging task. Thus, improved methods for uncertainty-aware optimization such as reliability-based optimization or robust optimization, and computationally-efficient methods such as surrogate modeling and variable fidelity optimization would be beneficial. The lessons from IMPROVE also point to the need for efficient coupling of data and tools, similar to the CREATE extension proposed by Keane that was discussed above.

CONCLUSIONS

Designing the structural system is one of the major challenges in marine design. Naval ships and submarines are unique in their design process, lack of full-scale prototype for testing, and operating environment. These factors significantly influence both the goals and approaches of marine structural design. Structural design can be viewed as being composed of two related tasks - that of achieving fitness-for-purpose, and that of achieving higher design goals such as minimum weight or production cost. Approaches to both tasks are under active development, with new concepts in regulatory approaches, complexity estimation, and lifecycle performance being actively developed. Significant opportunities have also been highlighted in these areas for future development. As analysis capability and platform design demands continue to grow, the approach to structural design must growth as well.

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