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New Directions in Ship Structural Regulations

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Abstract

A recent review of ship structural regulations (Ship Structures Committee Project 1444) was aimed at clarifying best practice in regulations. The review focused on the hull girder and bottom structure. The majority of rules reviewed are formulated in terms of elastic stresses. It was expected that the review would be able to identify implicit as well as explicit factors of safety in either the load or strength formulations or both. However, no such factors of safety against yielding were found. While this was initially surprising, it leads to an interesting and useful insight into the question of why ships are able to operate safely. The best explanation is that ships, especially new ships, rely on small levels of plastic deformation to create a significant strength reserve, easily capable of withstanding not only the design loads, but overload conditions as well. Ductility is thus a crucially important material property for keeping ships safe. The complexity of plastic response raises the question of how best to reflect this issue in rules. This is especially important when considering the safety of aging ships. The issues of coating design, corrosion and fatigue deserve to be reexamined with a view to the effects of the plastic behavior during ageing.

Keywords

Ship design; Ship structures; Regulations; Plastic response; Classification.

Nomenclature

B :	beam [m]
Cb :	block coefficient [-]
f_1 :	material factor [-]
H :	height [m]
kw :	function of frame geometry [-]
Lbp :	length between perpendiculars [m]
p :	pressure [kPa]
p_C :	pressure causing 3 hinge plate collapse [MPa]
p_{dp} :	dynamic pressure [kPa]
p_{EH} :	pressure to cause edge hinges in plate [MPa]
p_Y :	pressure to cause plate yield [MPa]
s :	frame spacing [m, mm]
T :	draft [m]
t :	thickness [mm]
t_k :	corrosion addition [mm]
Zpns:	normalized plastic modulus [-]
σ :	stress (design) [MPa]
σ_x:	longitudinal stress
σ_y:	lateral stress
σ_{VM}:	von-Mises equivalent stress

Introduction

A review of various ship structural regulations has been conducted as part of a Ship Structures Committee project (Kendrick, Daley and Pavic 2006). The review has shown that while ship structural rules can appear to be complex, they are based on quite simple structural mechanics. It was not a surprise to find that the rules are formulated with simple combined elastic stresses. On the other hand, it was surprising to find that the combined stresses appear to exceed the yield stress. This led to the realization that ship rules, being based on real world experience (strong empirical evidence), reflect an intrinsic plastic capacity that ships have. At deformations that are too small to observe, ship structures can exceed yield and be perfectly safe. The ductility of modern steel ships is implicitly providing a substantial 'factor of safety'. The rational next step is to have the rules explicitly recognize this capability and reflect this behavior in the rules we use to design the structure. This will result in better ship designs, with improved safety and economy, a win-win outcome for everyone.

Background

The desire to develop more rational approaches to ship structural design is not new. The foreword to 'A Guide for the Analysis of Ship Structures' published in 1960, starts:

> "It has been the dream of every ship designer to rise above the conventional empirical methods of

> structural design and create a ship structural design based on rational methods."

In order to understand the need for a unified and rational approach to ship structure design, it is necessary to review the history and nature of current methods, and of alternatives to these.

"Traditional" Ship Structural Design Standards

The origins of most current commercial and naval ship structural design approaches can be found in the work of a number of mid-19th century pioneers, including Rankine, Smith and Reed. They developed methods of estimating hull girder bending loads due to waves, and also developed response criteria for bending and shear. Early iron-framed ships tended to have wooden decks and hulls, meaning that buckling did not become an issue. Formal approaches to buckling date from the 1940s to 1960s. Material property issues (notch toughness, weldability) started to be addressed systematically within the same timeframe, partly through the early work of the SSC on fatigue and fracture. One hundred and fifty years of research and development, cross-fertilized by efforts in other engineering disciplines have been incorporated in commercial and naval ship design standards in somewhat different ways.

Most commercial ships are constructed under the Rules of a Classification Society, such as the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Lloyds Register (LR), Bureau Veritas (BV), Germanischer Lloyd (GL), etc. These and other classification societies developed, starting in the 19th Century, in order to meet the growing needs of both governments and commercial interests to ensure that ships were adequately reliable and safe. Initially, they largely focused on national interests and fleets (or imperial, in the case of LR and BV); and most were wholly or partly government controlled. More recently, the market for ship classification services has become international in nature (in most cases) and so the classification societies have become more independent of national ties. However, most classification societies retain strong links with maritime administrations in their home countries.

In keeping with their origins, classification society rules developed in some level of isolation from each other for many years, meaning that (for example) ABS, DNV and LR requirements for different areas of design were presented in very different ways and could lead to significantly different outcomes in terms of scantlings. As technologies developed (new ship types, faster operating speeds, replacement of rivets by welding), rules governing their use were introduced into the various Rules, extending their scope.

Advances in analytical methodologies have also been incorporated as they have been developed. For example, prior to the work of Rankine and others noted above, LR's rule scantlings were proportional only to displacement, which led to decreasing factors of safety for larger ships. Subsequently, the rules were modified to incorporate a more systematic treatment of wave bending. Similarly, local strength and stability rule requirements were initially based on successful past practice and "rules of thumb"; and modified as the state-of-the-art expanded. However, some of the historical features were retained, making the rule systems a mixed bag of analytical and prescriptive requirements.

The differences in Rules systems, and organizational issues that influenced their application, led to differences in outcomes in terms of safety and reliability. Accordingly, a group of the leading Classification Societies formed the International Association of Classification Societies (IACS) in 1968.

Recent Structural Standards Development

As noted previously, some recent convergence in classification society rule systems has been generated by IACS. IACS can trace its origins back to the International Load Line Convention of 1930 and its recommendations. The Convention recommended collaboration between classification societies to secure "as much uniformity as possible in the application of the standards of strength upon which freeboard is based…". Milestones towards achieving this included the formation in 1948 of the International Maritime Consultative Organization (now IMO), by the United Nations, and major conferences of the leading classification societies in 1939, 1955, and 1968. The last of these led to the formation of IACS, which has since developed more than 200 Unified Requirements (URs) and many Unified Interpretations and Recommendations of rule requirements. The first UR dealing with structural strength unified the classification societies' approaches to maximum wave bending moment, almost 100 years after Rankine's first theoretical model.

IACS was given consultative status with IMO, and works closely with IMO (though with frequent tensions) to address structural and other safety issues through the development of new URs and by other mechanisms. Two notable models can be cited. Under the High-Speed Craft Code, IMO has left structural requirements at a very broad and performance-based level. The responsibility for the development of appropriate rules was left to the classification societies, each of which has developed its own approach. Conversely, in the new Guidelines for Ships Operating in Arctic Waters (Polar Code) IMO has specifically referenced new IACS URs for structural and mechanical design. Representatives of the national administrations and of the classification societies have been involved in the development of both the Guidelines and the URs.

Other important developments within the last decade have included the move towards the use of numerical analysis (FEA) to optimize scantlings, and the development of automated systems (ABS Safehull, DnV Nauticus, etc.) to generate and check most structural components. To some extent, these have led to less standardization amongst class, although in principle all structures should still comply with the intent of the relevant URs. The classification societies' various software packages (e.g SafeHull from ABS) simplify the work of the average ship structural designer. However, by capturing many important issues into software that tends to be used as a 'black-box', these developments do not encourage insight into the structural issues involved. The use of FEA also carries risk for the unwary and for the occasional user, and classification society guidance notes are an imperfect substitute for training and experience.

In parallel with these 'organizational' changes to standards and to their implementation, the ship rule systems have continued to incorporate some of the developments in the technical state-of-the-art.

Another recent development is the increased involvement of national and international standards organizations (ASTM, CSA, ISO) in the development of structural standards for ships and offshore structures. To date, these have gained only limited acceptance in the shipping community, but they represent increased competition for traditional rule systems.

The two key technical aspects that are to be found in recent developments are the treatment of the mechanics of structures (load and strength models) and the treatment of uncertainty (probability models, risk reduction strategies). Both developments are aimed at inserting more rational understanding into the process of specifying structural requirements.

Load and Resistance Factor Design (LRFD)

LRFD (Load and Resistance Factor Design) is a relatively recent development, although it has been employed in some standards for a few decades. In certain areas, notably related to buildings, bridges and offshore structures, it is common to use LRFD. The approach attempts to achieve a consistent risk level for all comparable structures by employing calibrated partial safety factors. Various parameters affecting the design, both load and strength related measures, are individually factored to reflect both the level of uncertainty and the consequences of failure, which may range from loss of serviceability to catastrophic collapse. The approach relies on several assumptions about the nature of risk and failure, many of which are reasonable when thinking of the types of hazards (wind, seismic) that a static building will face. The approach implicitly assumes that failure is a consequence of an uncertain load exceeding an uncertain strength, which is a very simplistic model of an accident. The approach does not attempt to model complex (nonlinear) paths to failure, including feedback and interdependence, gross errors or any but the simplest of human errors. LRFD has not been implemented in ship structural design, at least partly due to concerns about its suitability.

LRFD is often implemented along with concepts from Limit States (LS) design. LS design attempts to look beyond the intact behavior, and establish the limits, both from a safety and operational perspective, so that the design point(s) reflect the boundary of unacceptable behavior. Traditional elastic design, on the other hand, tended to focus on a design point far below a level where actual negative consequences arose. When combined, LRFD and LS design purport to both properly balance risk and reflect, to all concerned, the actual capability limits of the structure. Together, this is intended to clarify and communicate the realistic structural risks. There are ship structural rules that have employed LS design, without LRFD. Two notable examples include the new IACS Unified Requirements for Polar Ships, and the Russian Registry Rules for Ice Class Vessels. In both cases the rules contain checks for post-yield limit states, but do not include load or resistance factors, as are typically included in LRFD codes.

Formal Safety Assessment (FSA)

Formal Safety Assessment (FSA) is a recent development in the area of structural standards. FSA is actually more of a standards development approach than a design standard. The International Maritime Organization (IMO) has led the development of this concept. They describe it as "a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks."

The IMO, and others, are evaluating FSA as a method to comparatively evaluate the components in proposed new regulations or to compare standards. FSA allows for a cost-risk-benefit comparison to be made between the various technical and other issues, including human factors. The FSA approach is based on the recognition that many risks arise from multiple causes (i.e. from system behavior) and can be mitigated in a variety of ways. This view leads to the approach of allowing safety to be based on the most cost effective risk control option (RCO) rather than on some standard, prescribed, one-size-fits-all approach. This is especially beneficial for innovative designs, where the standard approach to reducing risk may not be optimal.

FSA is largely a development out of the UK, developed partly in response to the Piper Alpha offshore platform disaster of 1988, where 167 people lost their lives. FSA is being applied to the IMO rule-making process.

FSA offers much promise. The complexity of risk assessment technology itself is probably the major obstacle standing in the way of wider use of the FSA approach.

Performance Based Standards

In recent years, there has been a strong trend towards what is generally referred to as performance-based standards (PBS). These standards describe a context and safety targets that they expect the design to meet, and then leave it to the proponent to achieve the targets in any manner they wish. CSA S471 is one example of this approach. In PBS, there are no specific loads or strength levels prescribed. The designers are expected to demonstrate the achievement of a target level of safety by an analysis of the loads and strength. In effect, the proponent is asked to both develop a design standard for their own structure and evaluate it against a risk criterion.

This approach is very popular in certain industries, especially the offshore oil and gas industry, as it enables them to examine a variety of structural and system concepts (gravity based platforms, semi-submersibles, tension-leg platforms, ship shape FPSOs, and others) on a more consistent basis.

The obvious drawback with this approach is the divergence of designs and the possibility for divergence in safety attainment when each project group develops an essential custom design standard. In reality, for most aspects of a design, the proponents will have neither the resources nor the time to develop a complete standard from scratch, and will instead apply existing standards as demonstration that requirements have been met.

Discussion of Structural Standards Development

Taken as a whole, there has been a piecemeal approach to structural design standards. As technical developments occur (models of various structural behaviors, risk methodologies), they have been incorporated into structural standards. Individuals and rule committees have framed their own rules with an emphasis on certain load/strength/failure models, coupled with some risk avoidance strategy (explicit or implicit). It is hardly surprising that various standards are different, even quite different. More, rather than fewer, concepts are available to those who develop structural standards. In the absence of a binding philosophy of structural behavior, there will continue to be divergence along the way to improved standards.

It must be appreciated that all current standards “work”. Any of the current commercial ship design approaches can be used to produce structural designs that function with adequate reliability over a 20+ year life expectancy, unless subjected to poor maintenance, human operational error, or deliberate damage. Changes to standards are, therefore, resisted by all those who have invested time and effort in them as developers and users. The rationale for change must be presented well, and its benefits have to outweigh its costs.

Experienced designers recognize that structural behavior can be very complex. Despite this, it is necessary to use simple, practical approaches in design standards, to avoid adding to the problem through overly-complex rules that are difficult to apply and more so to check and audit. Stress is the primary load-effect that standards focus on, partly because it is so readily calculated. The main concerns are material yielding, buckling and fatigue. All of these are local behaviors, and all are used as surrogates for actual structural failure. A structure is a system, comprised of elements, which in turn are built from materials.

As an example, yielding can be considered. Yielding is a material level ‘failure’, very common, usually very localized, and usually producing no observable effect. It can be quite irrelevant. The important issue is the behavior and failure of the structural system, even at the level of the structural components. Ship structures are especially redundant structures, quite unlike most civil structures and buildings. Ship structures are exposed to some of the harshest loading regimes, yet are usually capable of tolerating extensive material and component failure, prior to actual structural collapse. An essential deficiency of all traditional structural standards has been the failure to consider the structural redundancy (path to failure) and identify weaknesses in the system. Areas of weakness are normally defined as those parts that will first yield or fail. However, far more important is the ability of the structure to withstand these and subsequent local/material failures and redistribute the load. The real weaknesses are a lack of secondary load paths. It is often assumed, wrongly, that initial strength is a valid indicator for ultimate strength, but it is certainly far simpler to assess. There is a need to focus on ways of creating robust structures, much as we use subdivision to create adequate damage stability.

As another example, consider frames under lateral loads. When designed properly, frames can exhibit not only sufficient initial strength, but substantial reserve strength, due to the secondary load path created by axial stresses in the plate and frame. In effect, it is possible to create a ductile structure analogous to a ductile material. If we instead use current design standards that emphasize elastic section modulus, we risk creating a ‘brittle’ structure, even when built from ductile materials

In the case of fatigue and buckling, it is again necessary to stand back from consideration of the initial effects, and examine whether there is sufficient reserve (secondary load paths). When there is no such reserve, there is the structural equivalent of a subdivision plan that cannot tolerate even one compartment flooding.

The above discussion talks only about structural response, and indicated some gaps. Similar gaps exist in our knowledge of loads. The complexity of ship structures, the complexity of the loads that arise in a marine environment, and the dominating influence of human factors in any risk assessment for vessels, all present daunting challenges.

Classification Society Rules

The DNV Rules for Ships (DNV, 1998) are typical of individual society rules. They will be used for illustration of several points that are common to may classification societies’ rules. The discussion presented below is summarized from Daley, Kendrick and Pavic (2007). The analysis examines the combined design stresses on the bottom structure. The aim is to dissect the design requirements to see how they work, and if and where the rules contain a factor of safety. The factor of safety is seldom explicit, so each term is examined to see if there are implicit reserves, equivalent to a factor of safety. The plating requirements are first examined. Then the combined stresses are presented.

Plating Requirements

The DNV plate formula for shell thickness is given by;

$$t = \frac{15.8 \cdot s \cdot \sqrt{p}}{\sqrt{\sigma}} + t_k \qquad (1)$$

The equation is essentially a plate response equation, inverted to become a thickness design equation. When converted to an equation with consistent units (t and s in mm, and p and σ, in MPa), it becomes;

$$t = .5 \cdot s \sqrt{\frac{p}{\sigma}} + t_k \qquad (2)$$

Converted to a capacity equation (ignoring the corrosion addition);

$$p = 4 \cdot \sigma \cdot \left(\frac{t}{s}\right)^2 \qquad (3)$$

The standard plate capacity equation, giving the pressure to cause yielding, (see Table 1) has a constant of 2.25, rather than 4. Clearly the DNV equation assumes a response beyond yield. The standard load and deflection equations for a long plate with a uniform load, and fixed at the edges are given in Table 1. As well, Fig. 1 shows a sketch of the three conditions. If the plate design equation were to have been based on yield, the constant, in the units used by DNV, would have been 21.1 instead of 15.8.

Eq. 2 underestimates the stress that will occur when the pressure p is applied. This must be considered when combined elastic stresses are examined. Is it reasonable to think of the plate being partially plastic, and then to combine stresses in an elastic manner?

Table 1. Plate response equations.

Behavior	Load	Deflection
Yield	$p_Y = 2.25 \cdot \sigma \left(\frac{t}{s}\right)^2$	$\delta_Y = \frac{1}{384} \frac{p_Y s^4}{D}$
Edge hinge	$p_{EH} = 3.375 \cdot \sigma \left(\frac{t}{s}\right)^2$	$\delta_{EH} = \frac{1}{384} \frac{p_{EH} s^4}{D}$
Collapse	$p_C = 4.5 \cdot \sigma \left(\frac{t}{s}\right)^2$	$\delta_C = \frac{2}{384} \frac{p_C s^4}{D}$

Based on the above, it can be concluded that the plate design equation implies some yielding, close to nominal 3 hinge collapse. This appears at first to be non-conservative, but when added to other factors, is a reasonable statement of plate capability. These other factors that will tend to raise the plate capacity are;

- real plates will have finite aspect ratio (i.e. length to breadth of less than 6), and will tend to be stronger than long plates (this aspect may add 5-10% to the strength)
- actual yield strength tends to be above specified values (this aspect adds an uncertain amount, though often significant)
- stress redistribution and strain hardening while hinges begin to form will tend to add capability in the post yield region. (this adds approximately 50% to the plate strength)
- membrane effects will tend to help, though only at very large deflections.

As well, there are factors that tend to reduce plate capacity. These include;

- aging effects (fatigue, corrosion)
- poor workmanship and random flaws
- non-uniform load patterns

As a result of the above factors, it is most likely that a plate designed with Eq. 1 would yield, but would not have started to show visible permanent deformation.

From the above, it is concluded that the 15.8 constant in Eq. 1 may well be quite adequate, but does certainly not include a factor of safety against yielding. On the contrary, it represents a condition in which the plate has yielded, though with very small permanent deflection.

Continuing to the other terms in Eq. 1, the design pressure (for bottom plating near midships) is given by

$$p = 10 \cdot T + p_{dp} \qquad (4)$$

The constant 10 is the weight density of seawater (in kN/m^3). In other words the design pressure is just the static head at the design draft, plus some dynamic increase. The equation for p_{dp} is somewhat complex, but typically adds only about 20% to the static head. As such, the design pressure does not appear to include any factor of safety. It is perfectly plausible that a typical plate panel will experience the design pressure on a regular basis, even when the ship is in the undamaged condition. Damage may well lead to deeper drafts. There does not appear to be any allowance for other types of loads, or uncertainties, contained in the pressure term.

Next, the allowable plate bending stress σ is examined. Mild steel is assumed (yield strength of 235 MPa), so that the material factor f_1 is 1.0. The allowable plate bending stress (see Kendrick, Daley and Pavic 2006, or Daley Kendrick and Pavic, 2007) for a transverse plate is 55 MPa and for a longitudinal plate is 120 MPa. To see whether the allowable stress contains a factor of safety, it will be necessary to check the combined plate/frame/hull girder stresses.

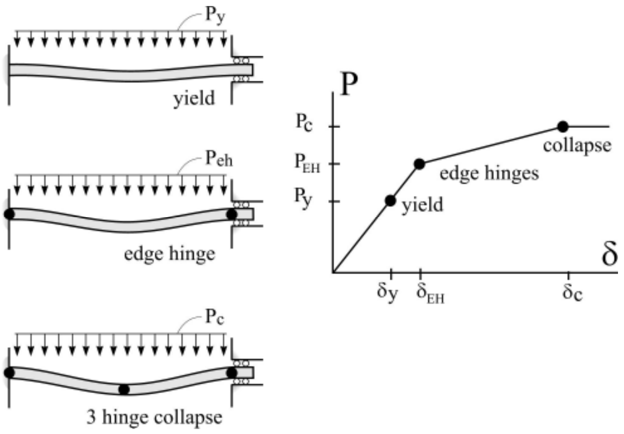

Fig 1. Plate behavior diagram

Combined Stress Results

In the DNV plating formula, the allowable stress formula depends on the type of framing, longitudinal or transverse. The reason for this has to do with combined stresses and is illustrated in Fig. 2. For location 1, the maximum plate bending stresses are aligned with the hull girder stresses and at right angles with the frame bending stresses. For location 2 the maximum frame bending stresses are aligned with the hull girder stresses and at right angles with the main plate bending stresses. At both locations 1 and 2, the frame bending stress is assumed to be 1/8 of the design value This is because the moment at the center of the frame is half of the end values, and the modulus on the shell plate side is assumed to be 1/4 of the flange side value. In the case of the plate, there is always a Poisson's ratio effect producing a biaxial stress state. The Poisson's effect gives a 30% stress of the same sign in the other direction (i.e., in the along frame direction).

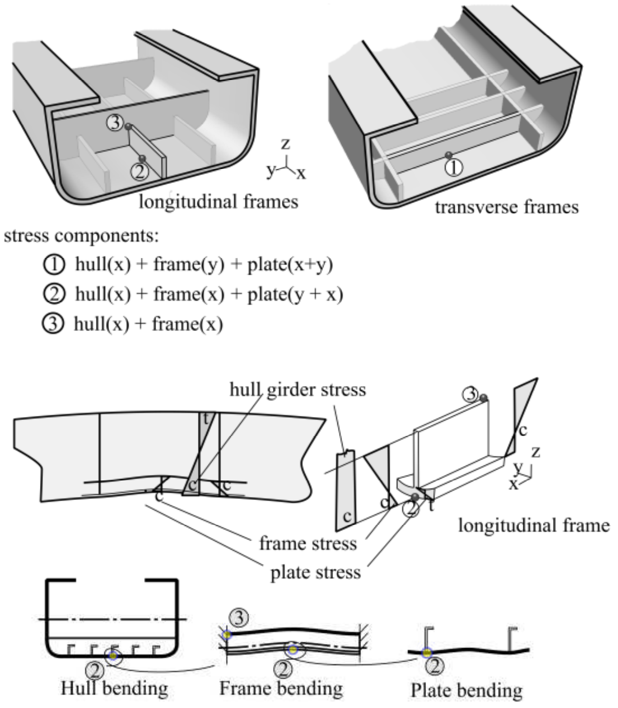

Fig 2: Stress Locations (Transverse and Longitudinal)

The combination of stresses for locations 1, 2 and 3 (in Fig 2) are shown in Table 2. Comparable values from the DNV rules, the Joint Bulker (JBR), Joint Tanker (JTR) rules and the Bureau Veritas (BV) rules are given. The details of these calculations are shown in Kendrick, Daley and Pavic (2006), and Daley Kendrick and Pavic, (2007). From the sum of the local and hull girder stresses x and y direction stresses, the von-Mises equivalent stress is also calculated;

$$\sigma_{VM} = \sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2} \tag{5}$$

The combined stresses are all close to yield, with the average being slightly above yield (at 246 MPa or 5% above yield). Note that the numerical constant in the plate equations (the 15.8 value) does not actually represent the proper relationship between loads and elastic stresses. The actual plate bending stresses are higher by 1.78x (=$(21.1/15.8)^2$). Table 2 includes this adjustment in the von-Mises stresses.

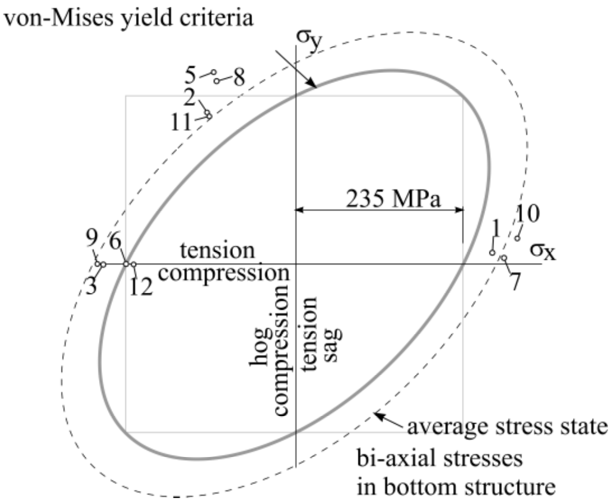

Figure 3: Von-Mises Stresses (12 cases in Table 2).

The basic plate equation (the constants) is non-conservative against yield. The plate pressures are not very high, meaning that one might be able to actually measure these pressures in a field trial in rough weather. The allowable stresses, while individually well below yield, are such that the combined stresses (plate+ frame + hull) are generally at or above the yield stress. One can only conclude that if the design loads were to occur, the structure would certainly begin to yield. Kendrick, Daley and Pavic (2006) discuss the hull girder design bending moment, and conclude that it does not contain a sufficient factor of safety to change this conclusion.

Table 2: Combined Stresses at the Locations Shown in Figures 2 and 3 for DNV, JBR, JTR and BV

Rule Set	Case	Location	Hull Girder Stress [MPa] (note 1, 2)	Plate Stress [MPa]	Ordinary Frame Stresses [MPa]	Combined Stresses [MPa]	VM Total Stress [MPa]
DNV	1	1	175 (x-t)	97 (x-t), 29 (y-t)	~ 16 (y-c)	273 (x-t), 13 (y-t)	266
	2	2	175 (x-c)	64 (x-t), 213 (y-t)	~ 12 (x-c)	123 (x-c), 213 (y-t)	295
	3	3	175 (x-c)		95 (x-c)	270(x-c)	270
JTR	4	1	Not Permitted				
	5	2	190 (x-c)	81(x-t), 270(y-t)	~ 6 (x-c)	114(x-c), 270(y-t)	343
	6	3	190 (x-c)		45 (x-c)	235(x-c)	235
JBP	7	1	175 (x-t)	117(x-t), 35(y-t)	~ 26.5 (y-c)	292(x-t), 9(y-t)	288
	8	2	175 (x-c)	77(x-t), 258(y-t)	~ 13 (x-c)	110(x-c), 258(y-t)	328
	9	3	175 (x-c)		103 (x-c)	279(x-c)	279
BV	10	1	175 (x-t)	135 (x-t), 41 (y-t)	~ 7 (y-c)	310(x-t), 34(y-t)	295
	11	2	175 (x-c)	62 (x-t), 208 (y-t)	~ 7 (x-c)	120(x-c), 208(y-t)	287
	12	3	175 (x-c)		53 (x-c)	228(x-c)	228

Note 1: It is assumed that section modulus at the locations considered (Z_B for the bottom) are the design values.
Note 2: The stress direction (x for longitudinal dir'n, y for transverse dir'n) and the sense (c-compression, t- tension) are indicated. The worst combinations are assumed.

Plastic Behavior

The above analysis of various rules suggests that the combined stresses on a bottom panel tend to exceed yield. The design loads and the strength formulations do not contain any significant factor of safety that would prevent yielding. Many people know that ships contain residual stress from construction, and so will likely experience local plasticity during 'shakedown' as the self-equilibrating residual stresses are redistributed. However, few people in the field would expect that yielding would occur due to normal sea loads. This somewhat surprising result is not, in fact, in conflict with the experience that ships are safe when built to the various above mentioned rules. The reason is that the local plating and framing has considerable plastic capacity and reserve to resist the local hydrostatic pressures. This will be examined in the following section.

Elasto-Plastic Response of a Bottom Grillage

To examine the design of a simple bottom grillage, a 3-frame (3x4 bay) stiffened panel has been designed. The basic design satisfies Germanischer Lloyd's rules. (GL 2006). This was taken to represent another typical example of classification society rules. A 50,000 tonne deadweight bulk carrier was chosen as the vessel. The vessel properties are:

- Length - Lbp: 218.5m
- Breadth - B: 32.24 m
- Height - H: 20m
- Draft - T: 14.5m
- Block - Cb: .75

With these properties, the design bottom panel is as shown in Fig. 4. The hull hog bending stress at the design condition is 126 MPa. The design lateral pressure on the outer shell is 210 kPa. The finite element analysis examined the ability of the grillage to resist lateral load. Fig. 5 shows the deflection at the center of the frame plotted for each load level. The two curves show the influence of the hull bending stress. Up to the design pressure, the hull stress has almost no influence on the response. For higher lateral pressures the presence of the hull stress increases the deflection of the grillage. Nevertheless, the grillage can withstand twice the design pressure with only 2mm of permanent deflection. This level of deflection is very minor.

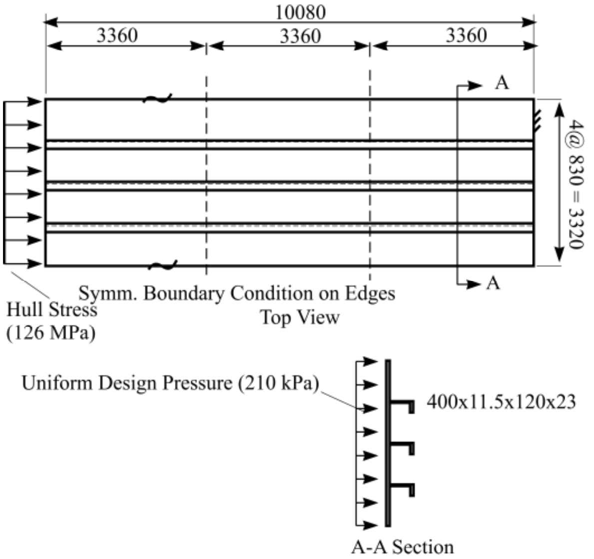

Fig 4: Grillage for Stress Analysis

The analysis showed that at the design pressure, while the peak stress exceeds yield, there is only a very small zone of plastic strain, and the deflections are too small to be seen. Further, the structure can withstand two or even three times the local design pressure without any visibly significant deformation.

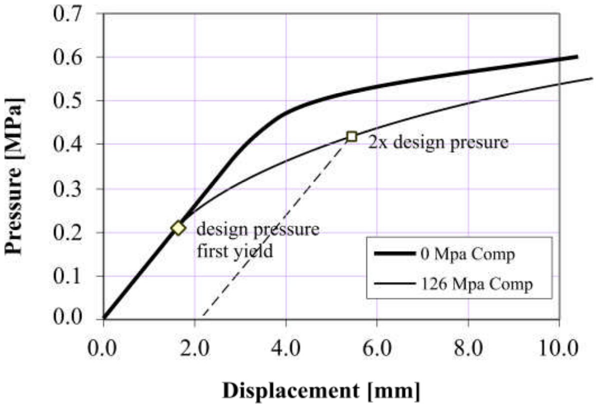

Fig 5: Load vs. Lateral Deflection of the Grillage

Elasto-Plastic Response of Transverse Frames

While the above analysis has shown that plastic capacity can provide a significant contribution to strength, it is important to recognize that there are still no simple design equations that can predict the full plastic behavior of ship frames. In the IACS Polar Rules (IACS 2006), the frame design equations are formulated using energy methods and the assumption of rigid plastic behavior. Eq. (6) expresses 3-hinge strength of the frame and should be the onset of large deformations. A full explanation is given by Daley (2002).

$$P_{3h} = \frac{(2-kw)+kw\cdot\sqrt{1-48\cdot Zpns\cdot(1-kw)}}{12\cdot Zpns\cdot kw^2+1}\cdot\frac{Zp\cdot\sigma_y\cdot 4}{\left[S\cdot b\cdot L\cdot\left(1-\frac{b}{2\cdot L}\right)\right]} \quad (6)$$

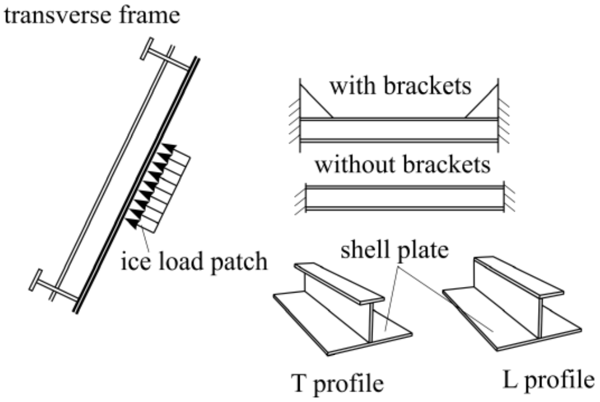

Fig 6. Sketch of transverse frame geometry.

In order to compare a variety of frames, a set of transverse frame finite element models have been created and analyzed. Fig. 6 shows the type of frame and load. Fig. 7 shows the load vs. deflection plots for nine example frames. The frame dimensions and geometry are given in the figure index. For example, the designation L2400nb_W8/309_P20_F16/95 means an ‘L’ frame, with 2400mm span, a web of 309x8mm and a flange of 95x16mm. All frames were spaced at 400mm and had a yield strength of 315MPa, and a post-yield modulus of 500 MPa. The loads have been normalized by the nominal plastic capacity as given by Eq. (6). It is clear from Fig. 7 that while Eq.6 may well predict the ‘collapse’ strength (i.e. the load causing the onset of large deformations) to within 10%,the various frames behave quite differently. Some frames exhibit a substantial reserve capacity, while others ‘collapse’ completely at relatively small deflections. These differing behaviors are not accounted for in any design standards, and yet these differing behaviors would have an important influence on the consequences of overloads. Thus these differing behaviors have an influence on safety that is not captured in design standards.

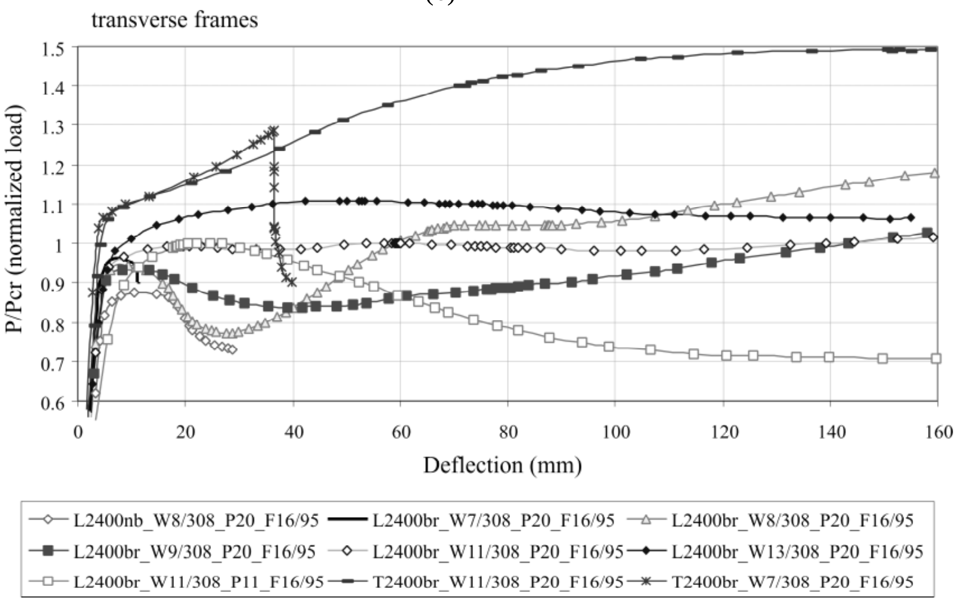

Fig 7: Response analysis of various frames.

Discussion

These results show that both the plating and framing can have significant post-yield capacity without significant deflections. This reserve provides a significant factor of safety, in contrast with the lack of nominal safety factors. However, this result raises a number of questions. Class rules are based on a linear-elastic idealization of structural response, but appear to rely on plastic behavior to ensure safety and serviceability. It is also shown that there is variability in the ultimate capacity and plastic reserve for different configurations, something not accounted for in current rule approaches. Local structure is designed to meet requirements for elastic section modulus. Unfortunately, elastic section modulus (the 2nd moment of area) does not reflect plastic capacity. Even the concept of the plastic section modulus is too simple to reflect the capacity accurately. In effect, the wrong measures are being optimized. There is a significant opportunity for improvement in both safety and cost of ship structures.

Conclusions

The paper has presented several findings. One is that classification society rules do not appear to have any significant factor of safety against yield at the design point. A second key point is that there is a significant strength reserve, and thus a factor of safety to be found in the plastic capacity of the shell structure. Consequently, it becomes clear that while classification society rules generally result in quite safe structures, different notionally equivalent structures can have quite different capacities, and thus different true factors of safety. The latest developments (e.g. Common Structural Rules) have added considerable complexity to the formulations, but do not appear to have addressed the points being raised here. The new requirements are still based on the traditional elastic section properties, and so are still encouraging the optimization of the wrong measures.

The plastic reserve is, at least for new construction with proper steel, quite significant and comes with little cost. How to optimize this is still not clear. Unlike elastic response, there is no one measure (such as section modulus) that predicts behavior. This is because plastic behavior is nonlinear and so superposition does not hold. Each structure requires a full nonlinear analysis. A method of assessing and comparing behaviors is needed. A measure, based on the full plastic capacity, would encourage better proportions and more effective steel. This is a direction that could give structures that are both safer and less expensive, and would serve everyone’s interests.

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