FRAMING DESIGN IN THE UNIFIED REQUIREMENTS FOR POLAR CLASS SHIPS

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Recent work directed by the International Association of Classification Societies (IACS) to produce Unified Requirements for Polar Class ships has included significant advances in the treatment of limit states for framing. This has been based on the principle that plastic design will allow a better balance of strength and ensure safety margins against ultimate collapse under accidental overloads.

The design formulations that have been developed have taken the plastic design methodologies of the current Canadian and Russian rules as their starting point. They have been developed significantly further for the IACS URs, incorporating more rigorous treatments of combined bending and shear, a range of possible load locations, and direct consideration of section shapes. The result is a set of analytical formulae that have been tested by extensive FEA, both to confirm that the deflections under design loads are within shipbuilding and operational tolerances, and that the strength reserves under overloads are acceptable. Extensive validation against service experience has also been undertaken, to ensure that the results are in line with physical data.

This paper describes the development of the formulae, the validation exercises undertaken, and how the approach can be used to develop efficient structural designs.

INTRODUCTION

The International Association of Classification Societies (IACS) is preparing a set of Unified Requirements for Polar Ship construction that is intended to replace the member societies' current Rules and to provide alternatives to national systems such as the Canadian Arctic Shipping Pollution Prevention Regulations and standards.

This document describes how the framing requirements in Unified Requirements have been developed. It explains how the principles for design and analysis were established, how design cases were identified, and how systems of equations describing these were formulated and compared with predictions from finite element models. Examples illustrating results are presented, illustrating trends with polar class, frame spacing and span. Other examples also show how well balanced certain existing designs would be against the new criteria.

The full derivations of many of the UR equations are quite complex. They are presented in annexes to the background report [1]. A number of documents [3-9] are noted as references. Many of these were produced during the UR development process. They provide more details of the rationale behind the selection of the methods and assumptions presented here.

PLASTIC DESIGN CRITERIA

The framing requirements are based on plastic response criteria. Operating practice for ice class ships is such that occasional local deformation (denting) has tended to be an acceptable consequence of ice

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operations, if this does not compromise the overall strength or watertight integrity of the ship. Given this, plastic design can help ensure a better balance of material distribution to resist design and extreme loads. This is particularly important because extreme ice loads can be considerably in excess of design values. This is more likely for ice loads than (for example) for wave loadings. The use of plastic methods ensures a considerable strength reserve, which may or may not be the case with elastic design.

In addition, plastic design methods are more applicable to damage analysis, which will allow the assumptions in the URs to be tested against experience and refined in future as necessary.

Acceptable Limit States

The selection of structural design criteria for plastic design is more challenging than in elastic design. In the latter, onset of yield is relatively easy to predict, giving a simple criterion for design. In plastic design, there are many possible limit states ranging from yield through to final rupture.

The design limit states used in the UR proposals are idealized plastic collapse onset mechanisms. The simplified mechanisms include assumptions that will have the effect of limiting both deflection and strain under the design load. The reasons for this are that the assumed mechanisms ignore the beneficial effects of membrane stresses and strain hardening. Consequently, the real structure can be expected to have a substantial reserve beyond the design condition. More precisely then, the design limit states represent a condition of substantial plastic stress, prior to the development of large plastic strains and deformations.

The limit states used in the UR can be derived using analytical energy methods, which balance external and internal work under certain loading and response mechanisms, as described below. Such methods cannot provide deflection or strain predictions. Finite element methods have been used to 'calibrate' these aspects of the design criteria and procedures, and ensure that a considerable plastic reserve remains.

The energy methods utilized in deriving the URs take account of the following possible energy-absorbing mechanisms:

- a 3-hinge collapse under a central load;
- a combined shear/bending collapse under and end load;
- a pure shear hinge collapse;

Other mechanisms were also investigated, to ensure that this set does provide a solution at, or close to, the lower bound for collapse for a wide range of configurations.

Figure 1 illustrates the 3-hinge collapse of a typical frame and Figure 2 shows the associated FE analysis.

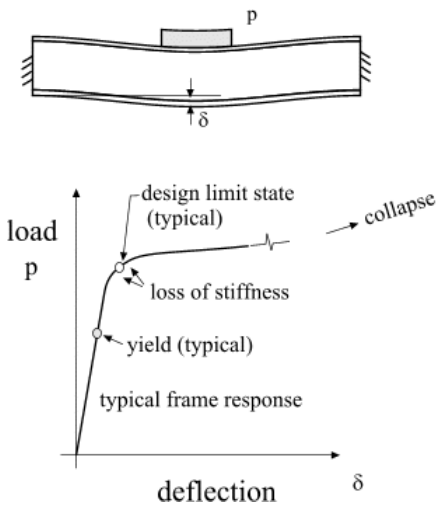

Figure 1: Typical Load Deflection Curve for a Frame Showing the Design Point

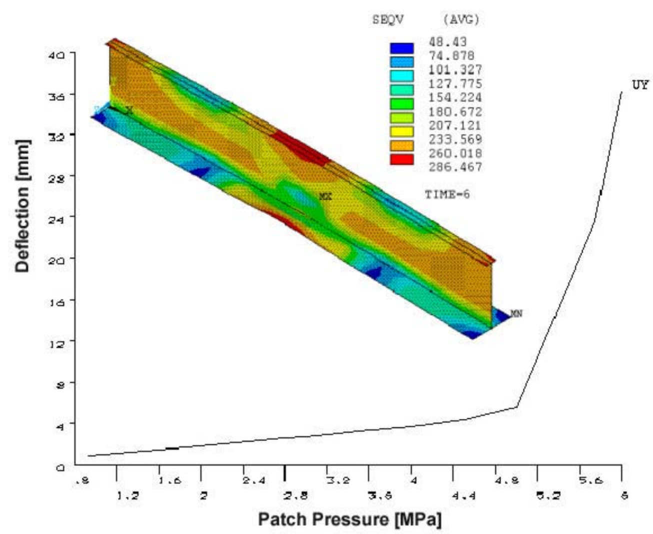

Figure 2: Load vs. Deflection and State of Stress for a Typical Ice Frame

DESIGN CASES AND MECHANISMS

Assumptions

All of the structural design requirements are based on the UR load model, described in [2]. This model assumes a uniform rectangular load patch of constant intensity. This is a considerable simplification of actual ice load distributions, and a number of adjustments are made to the load before it is applied to the structure to account for various characteristics and orientation. The load is assumed to be applied to an ice-strengthened area of the hull, with a magnitude and distribution determined by polar class (PC 1-7, with 1 being the highest class), hull area (bow, midbody, etc.) and hull shape (in some hull areas only). Within the ice-strengthened areas, it is assumed (and required) that stiffeners terminate in a manner that provides full fixity. Intersections with deep members, decks, bulkheads etc are to be designed to provide the same restraint.

The basic design equations assume that frame members have uniform cross-sections along their length (see below for treatment of brackets). It is also assumed that all structure has the same material properties, e.g., yield strength is identical for plating and framing. When this is not the case, section properties need to be adjusted as appropriate.

A final assumption used in many of the calculations is that the position of the plastic neutral axis of a frame cannot move inside the attached plate, although the equal area axis (nominally the same thing) will frequently be within the plate. Stress/strain compatibility makes a locus within the plate impossible in practical terms. The neutral axis is permitted to be above the plate.

Bending and Shear Interaction

In most structures, elements support a combination of bending and shear loads and associated stresses. A frame carrying shear load will have less bending capacity than one in pure bending; likewise when bending stresses are present full shear capacity is no longer available.

The current UR proposals treat bending and shear interaction more rigorously than any existing rules or standards, by taking into account actual section shape in the calculation procedure. This can be represented by equation 1 where M_o is section-dependent, and greater than or equal to zero.

(1) $$\left(\frac{M - M_o}{M_p - M_o}\right)^2 + \left(\frac{T}{T_{ult}}\right)^2 = 1$$

Bending moment, M, and Shear, T have actual and ultimate values as indicated.

Reviewing this equation and the curve that can be used to represent it (Figure 3), it can be seen that at full shear any section with $Mo > 0$ will have some reserve bending capacity.

The full plastic section modulus *Zp* is defined as the sum of contributions from the web *Zw* and flange *Zf*;

(2) $$Zp = Zf + Zw$$

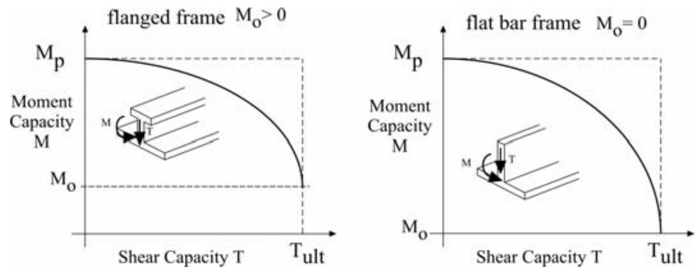

Figure 3: Bending/Shear Interaction Diagrams

For any value of shear, there is a minimum web area *Ao*, that would be just enough to carry *T*. The actual web area *Aw* must be greater or equal to *Ao*. As the level of shear increases, the bending contribution of the web is reduced, until at the maximum shear (T_{ult}) the contribution of the web is zero (as it is fully yielded in shear). Thus, the moment *M* lies within the range M_o to M_p. The moments and shear forces are related to section properties with the usual relationships;

(3) $$M_p = Zp\ \sigma_{yield},\ M_o = Zf\ \sigma_{yield},\ M = Zpr\ \sigma_{yield},\ T = Ao\ \tau_{yield},\ T_{ult} = Aw\ \tau_{yield}$$

The 'reduced' modulus *Zpr* will lie somewhere between the full and minimum values, depending on the level of shear;

(4) $$Zpr = Zf + Zw[1-(Ao/Aw)^2]^{0.5}$$

Equation (4) is used for hinges that contain significant shear.

Limit States

Three primary limit states are considered in the URs. These are illustrated in Figure 4. All three result in the formation of a collapse mechanism. 4(a) shows a 3-hinge mechanism that will form under a centered load. 4(b) shows an asymmetric shear collapse mechanism under an edge load. Finally, 4(c) shows a web collapse under a central load. Each of these mechanisms can be solved with energy methods (limit equilibrium), in which the external work done by the ice load is equated to the plastic work done in the hinges and shear panels. The detailed derivations can be found in the annexes of [1]. The dominant mechanism is the one with the lowest load capacity that depends on the section shape, the load length and the load intensity.

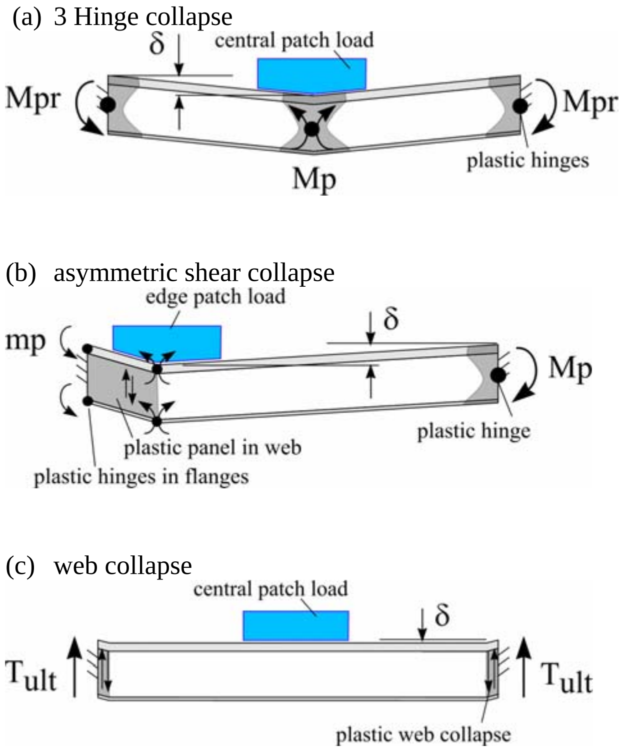

Figure 4: The 3 Limit States Considered for Frames

Limit state equations

All of the rule formulae are derived by equation internal and external work. For the web collapse (4.c) the energy equation is:

(5) $$P \cdot b \cdot S = 2 \cdot A \cdot \frac{\sigma_y}{\sqrt{3}}$$

where *P* is the load patch pressure, *b* is the load length along the frame, *S* is the frame spacing and σ_y is the yield strength. Thus, the minimum web area *Ao*, required to carry the load in pure shear is:

(6) $$Ao = \frac{1}{2} P \cdot b \cdot S \cdot \frac{\sqrt{3}}{\sigma_y}$$

For the 3-hinge collapse case (4.a) the energy balance equation is:

(7) $$(P \cdot b \cdot S)\left(1 - \frac{b}{2 \cdot L}\right) = 4 \cdot \frac{\sigma_y}{L} \cdot (Zp + Zpr)$$

where Zp is the full plastic modulus, Zpr is the reduced plastic modulus and kw is a correction term;

(8) $$Zp = Af \cdot \left(\frac{tf}{2} + hw + \frac{tp}{2}\right) + Aw \cdot \left(\frac{hw}{2} + \frac{tp}{2}\right)$$

(9) $$Zpr = Zp \cdot \left[1 - kw \cdot \left[1 - \sqrt{1 - \left(\frac{Ao}{Aw}\right)^2}\right]\right]$$

(10) $$kw = \frac{1}{1 + 2 \cdot \frac{Af}{Aw}}$$

In the above formulae, *L* is the frame span, *Aw* and *Af* are the cross-sectional areas of the web and flange, *hw*, *tf*, *tp* are the web height, flange thickness and shell plate thickness, respectively. Equation (7) can be re-arranged to give the capacity for 3-hinge collapse;

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

where

(12) $$Zpns = \left[\frac{Zp}{Aw \cdot L \cdot \left(1 - \frac{b}{2 \cdot L}\right)}\right]^2$$

Equation (11) can be used directly in comparisons with finite element model results or experiments, for example, in Figure 5. As can be seen, Equation (11) shows a frame capacity that is just below the ‘knuckle’ in the response curve over a wide range of frame configurations. This equates to plastic strains of fractions of a percent and to very small residual deflections. These are all desired characteristics for the design point, and thus this capacity equation is considered to offer a valid basis for the required UR formulations.

The rule requirement for section modulus is also found from equations (7, 8, 9);

(13)

$$Zp = \frac{P \cdot b \cdot S \cdot L}{4 \cdot \sigma_y}\left(1 - \frac{b}{2 \cdot L}\right) \cdot \frac{1}{2 + kw \cdot \left[\sqrt{1 - \left(\frac{Ao}{Aw}\right)^2} - 1\right]}$$

Equation (13) shows that the required section modulus and shear area are interdependent, as would be expected from the discussion above. This approach is more rigorous and consistent with actual structural behaviour than those of any current system.

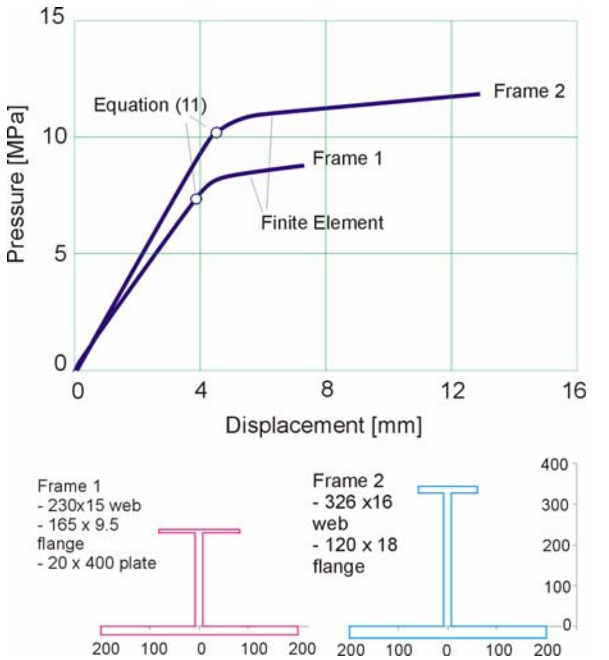

Figure 5: Energy Solution (Eqn 11) and FE Responses for 3-Hinge Collapse

For the asymmetric shear collapse case (4.b) the energy balance equation is:

(14) $$(P \cdot b \cdot S)\left(1 - \frac{b}{2 \cdot L}\right) = \sigma_y \cdot \left[\frac{Aw}{\sqrt{3}} + \frac{Zp}{L} \cdot fz\right]$$

where fz can be approximated as:

(15) $$fz = 1.1 + 5.75 \cdot kz^{.7}$$

and kz is the ratio of the combined flange moduli to the total section modulus:

(16) $$kz = \frac{zp}{Zp}$$

Equation (14) can be re-arranged to give the capacity for asymmetric shear collapse;

(17)

$$P_{asym} = \frac{\sigma_y}{b \cdot S\left(1 - \frac{b}{2 \cdot L}\right)} \cdot \left[\frac{Aw}{\sqrt{3}} + \frac{Zp}{L} \cdot (1.1 + 5.75 \cdot kz^{.7})\right]$$

Figure 6 shows the capacities predicted by equations (17) for the same two frames used to illustrate the 3-hinge response.

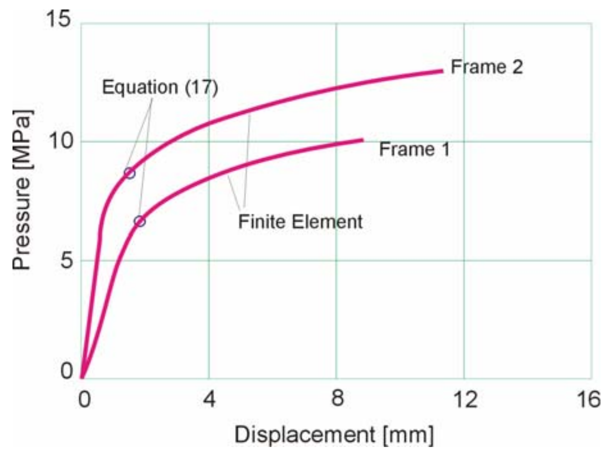

Figure 6: Energy Solution (Eqn 17) and FE Responses for Asymmetrical Shear

The rule requirement for section modulus is also found from equation (14);

(18)

$$Zp = \frac{P \cdot b \cdot S}{\sigma_y \cdot (1.1 + 5.75 \cdot kz^{.7})}\left(1 - \frac{b}{2 \cdot L}\right) \cdot L \cdot \left[1 - \frac{Aw}{2 \cdot Ao\left(1 - \frac{b}{2 \cdot L}\right)}\right]$$

where *Ao* is given in (6).

Equations 18 and 13 govern the asymmetrical and symmetrical load capacities respectively. Both show that shear area and section modulus are interdependent, and require iteration to yield an optimal design. A satisfactory frame must satisfy equations (6), (13) and (18).

FINITE ELEMENT ANALYSIS COMPARISONS

Several FE analyses have been undertaken to validate the rule equations. The set shown here in Table 1 and the example in Figures 7 are in the bow of a notional 30,000 tonne ship, and are approximately matched to the design loads for each of the seven classes. The P_3h and P_asym entries give the calculated capacity values for the symmetrical (central) and asymmetrical (end) load cases respectively. Case C4a was a variant on C4, with a lower load height on a longer frame, with the 3 hinge mechanism dominating.

Depending on the frame, the asymmetrical shear load/deflection curve may be above the 3-hinge (symmetrical) curve, or the two may cross to give a region where a given load will give larger deflections for the asymmetrical case. For the case shown in Figure 7, the 3-hinge mechanism is the important one. In other frames (e.g., C5) the shear response will give the lower capacity and will govern.

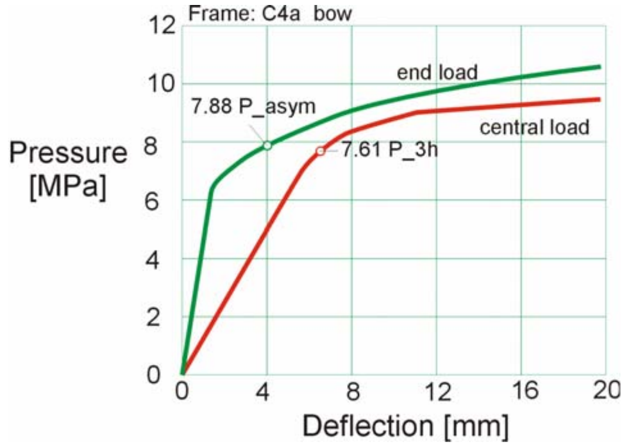

Figure 7: Load-Deflection Curves for Frame C4a

Table 1: Parameters of Frames for FE Validation.
Case: 30kT ship, Bow

var \class	C1	C2	C3	C4	C4a	C5	C6	C7
b [mm]	1220	1180	1120	1060	960	1010	1110	1000
hw [mm]	620.8	547.3	511.8	484.1	409.9	444.3	411.6	345.3
tw [mm]	37.5	37.8	21.1	15.8	21.6	13	11.3	10.2
wf [mm]	187.3	138.8	147.8	142.3	108.1	142.8	124.1	143.2
tf [mm]	31.8	31.9	27.5	22.9	21.6	22.1	20.3	19.9
tp [mm]	37.5	30.8	26.4	22.6	21.6	20.0	17.4	15.7
S [mm]	350	350	350	350	350	350	350	350
L [mm]	2500	2500	2500	2500	3250	2500	2500	2500
σ_y [MPa]	355	355	355	355	355	355	355	355
τ_y [MPa]	205	205	205	205	205	205	205	205
P_asym [MPa]	20.94	18.00	10.48	7.79	7.88	6.21	4.56	3.83
P_3h [MPa]	22.32	19.47	10.55	7.98	7.61	6.44	4.72	4.04

SUMMARY AND CONCLUSIONS

This paper has presented the rationale and equations for the use of plastic design for framing in the IACS Unified Requirements for Polar Ships. Stress, strain and deflection levels are all important considerations, and all are kept within acceptable limits by the analytical representations of the design point in the draft UR. This has been checked by extensive numerical analysis of frames that comply with the proposed requirements. Large factors of safety against ultimate failure are also assured by additional stability criteria.

Checks have been undertaken to ensure that the proposed requirements are not excessively complex, and that they can be used to develop practical design solutions. Comparisons with existing ships` scantlings show expected trends.

Potential users of these requirements, and other interested parties, are encouraged to use and comment on this system of equations.

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