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VOLUME 3

COMMITTEE III.1

ULTIMATE STRENGTH

COMMITTEE MANDATE

Concern for the ductile behavior of ships and offshore structures and their structural components under ultimate conditions. Attention shall be given to the influence of fabrication imperfections and in-service damage and degradation on reserve strength. Uncertainties in strength models for design shall be highlighted.

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1 DISCUSSION

1.1 Official Discussion by Paul Frieze

1.1.1 Introduction

The main sections of the report are:

1. Introduction
2. Fundamentals for Ultimate Limit State-Based Design and Safety Assessment
3. Rules and Guidelines
4. Definition of Parameters and their Uncertainties
5. Recent Advances
6. Benchmark Studies.

My report will address each section in turn, with varying degrees of attention to each.

1.1.2 Section 1. Introduction

Figure 1 of the report provides a very useful introduction to the various physical hazards to which ships and offshore structures are exposed and which can lead to nonlinear response. It is clear that some of these are beyond the control of the designer and/or operator, e.g. the low temperatures associated with arctic operations, cryogenic cargo conditions, but some are almost directly under the control of at least the operator if not the designer, e.g. impact loads from collisions or groundings, or age-related degradation, because these fall directly into the category of human factors.

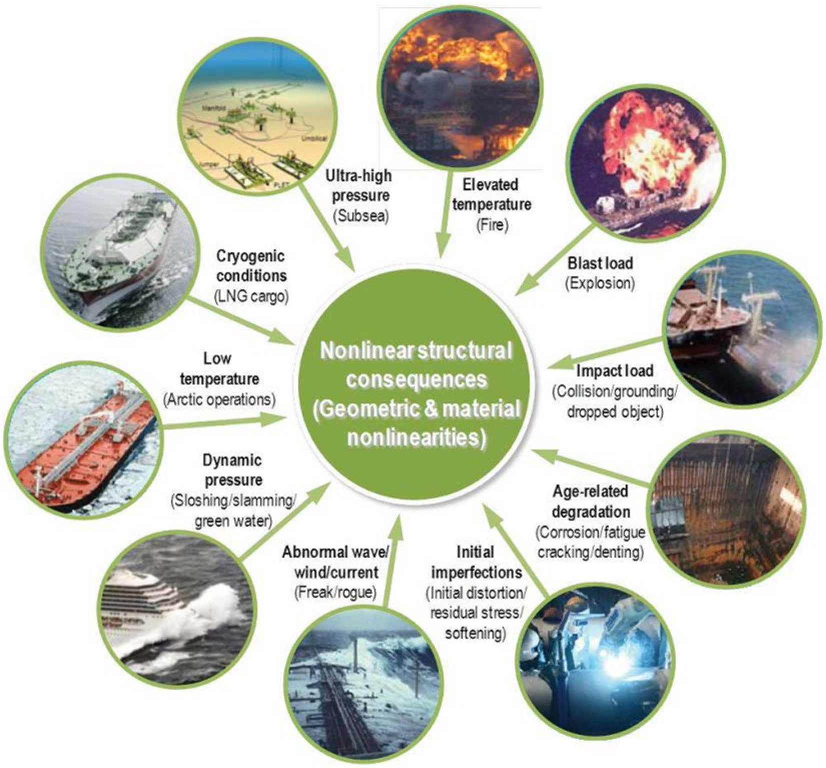

Figure 1: Figure 1 of Report (Paik, 2011)

As highlighted in an article by Paik (2012), Chairman of Committee III.1, human factors contribute some 80% to the cause of accidents which manifests itself as loading on ship and offshore structures. The human factors role is particularly important to recognize and deal with but it is not the subject of this committee's mandate so will not be considered further here.

1.1.3 Section 2. Fundamentals for Ultimate Limit State-Based Design and Safety Assessment

This section addresses, in particular, types of limit states and structural design formats. In the latter, both the partial factor and probabilistic formats are spelt out in some detail via Equations (3) to (11). However, these are all very standard equations which perhaps did not need repeating here but, instead, an appropriate reference to a suitable text book should have been made. Notwithstanding, it does provide an opportunity to comment appropriately on some of the parameters contained in these equations.

Consider Equation (3), which is:

$$C_d = C_k/\gamma_C \; ; \; D_d = \gamma_D D_k$$

This contains two parameters, C_k and D_k, which are described as characteristic values. In the terminology of International Standards, a characteristic value is defined as "value assigned to a basic variable associated with a prescribed probability of not being violated by unfavourable values during some reference period". While this might be the aim when initially determining such parameters, in the Discusser's experience particularly in connection with resistance parameters, such values are invariably not "associated with a prescribed probability". For example, Table 1 presents the modelling uncertainty parameters for the tubular member strength formulations contained in ISO 19902 Fixed steel offshore structures in terms of mean and standard deviation (sd). ISO 19902 assumes that strength formulations represent the 5% fractile which, for an infinite population is the mean minus 1.645 standard deviations. Applying this formula to the listed mean and standard deviation values leads to the numbers listed in the last column which should have a value of unity for consistency with the definition of characteristic value: clearly this is not the case.

There are a number of reasons for this departure from the prescribed requirement, such as:

Table 1: Modelling Uncertainty Parameters for ISO 19902 Tubular Members

Loading condition	Mean	sd	Char. value
Tension*	1.10	0.088	0.955
Local (compression) buckling	1.065	0.072	0.946
Column (compression) buckling	1.046	0.041	0.979
Flexure	1.109	0.094	0.954
Hydrostatic pressure	1.142	0.142	0.909
Tension and bending	-	-	-
Local (compression) buckling & bending	1.246	0.083	1.109
Column (compression) buckling & bending	1.030	0.084	0.891
Tension and hydrostatic pressure	1.075	0.105	0.902
Local (compression) buckling, bending & pressure	1.199	0.161	0.935
Column (compression) buckling, bending & pressure	1.197	0.109	1.018

*Based on API RP-2A LRFD Determined Values

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- As test data are added (or subtracted in a more up-to-date screening process), even if the original equation represented the proper characteristic value, changes in the test database will lead to changes in the modelling uncertainty parameters and, therefore, the characteristic value;
- When analytical models are used as the basis of strength formulation, and may be relatively accurate, the introduction of a factor (around unity) just to achieve the prescribed fractile does not necessarily seem logical;
- Some strength formulations were originally derived as lower bounds to test data and have been retained in their original format or only slightly modified form so will never match the required fractile;
- Some formulations are retained in preference to developing new equations because of their long-standing use.

Consider Equation (5) which is:

$$\eta = C_d/D_d = C_k/(\gamma_C \gamma_D D_k)$$

The parameter η is defined as a Structural Adequacy parameter. It is the ratio of Factored Strength to Factored Demand (Loading). If we take the inverse of this, i.e. the ratio of Factored Demand to Factored Strength, this is the ratio commonly used by Structural Engineers as the Utilization Ratio, i.e. the measure used when undertakings structural design checks, the upper limit for acceptability being unity.

1.1.4 Section 3. Rules and Guidelines

This section is completely devoted to Rules and Guidelines of relevance to ship structures with no reference at all to the topic which has equal weighting, not only in the Committee's Mandate but also in the name of the Congress, namely, Offshore Structures. Exactly the same issue arises in relation to the 2009 and the 2006 reports by this same committee although the latter does devote some space to jack-ups and to typical offshore space frame testing and analysis but not, however, anything on the standards. Perhaps there are good reasons for the lack of reference in which case it is hoped the Report would have indicated these accordingly. One obvious excuse is that none of the Committee members has any experience or exposure to offshore structures. On the other hand, all offshore standards, being international, are in the public domain so their titles and scope at least can be appreciated without the need to purchase the standard.

Given this lack of reference to offshore structures standards, it is useful to summarize these to ensure the wider audience is at least aware of their existence. Table 2 is the complete list of ISO offshore structures standards, the ISO 19900 Series as it is commonly referred to.

It can be appreciated that the top level document is ISO 19900, followed by the 19901 Series of Standards which sets out the provisions for the technologies underlying the structure-specific standards ISO 19902 to 19904. Whilst the same information can be applied to jack-ups (ISO 19905-1), they have evolved different practices for some of the main underlying technologies, particularly foundations, so it offers different approaches to these than specified in the 19901 Series. The standard on Arctic structures primarily addresses loading on these units and other cold-weather operating issues and says nothing about structural design which is the responsibility of the structure-specific documents 19902 to 19904.

Table 2: ISO 19900 Series of Standards and their Status

ISO Number	Title	Published	Status
19900	General requirements	2002	2nd Edition in preparation
19901-1	Metocean	2005	2nd Edition in preparation
19901-2	Seismic	2004	Work beginning on 2nd Edition
19901-3	Topsides	2010	None planned
19901-4	Geotechnical and foundation design considerations	2003	Work beginning on 2nd Edition
19901-5	Weight engineering	2003	2nd Edition in preparation
19901-6	Marine operations	2009	Corrigenda due late 2012, otherwise none planned
19901-7	Stationkeeping	2005	2nd Edition due late 2012
19901-8	Marine soil investigations	-	Due for publication 2013 with addition of Geotechnical site investigations in 2014
19902	Fixed steel structures	2007	Amendment due 2012
19903	Fixed concrete structures	2006	None planned
19904-1	Floating structures: Monohulls, semisubmersibles and spars	2006	2nd Edition under consideration
19905-1	Site-specific assessment of jack-ups	2012	None planned
19905-2	Commentary on 19905-1	2012	None planned
19905-3	Site-specific assessment of mobile offshore drilling units	-	In preparation, publication due 2014
19906	Arctic structures	2010	None planned

In Section 3.1, IACS, reference is made to the fact that harmonized CSR for tankers and bulk carriers is under development: it would be helpful to know who is carrying out this work.

Section 3.2 Classification Societies, the allocation of space to the various Societies is not well balanced with some 3.5 pages devoted to ABS, 2 pages each to Bureau Veritas and DNV but only one paragraph each to Germanischer Lloyd and Registro Italiano Navale. However, not one word on Lloyd's Register or ClassNK Rules. Perhaps it might have been more appropriate to have tried to include all the Class Rules but in a tabular format so that, firstly, all of the components addressed in the various Rules could be systematically listed and, secondly, the coverage in each set of Rules could be directly compared. Perhaps of more help to the reader would be a comparison between the various strength formulations in the different Rules, to highlight any differences and/or similarities.

At the top of page 296, when discussing compactness of Individual Structural Members, the definition of "noncompact" appears to be wrong because normally allowance for buckling is required for "slender" members, "noncompact" members being those in which yield can be achieved but not any plastic hinge capacity because of the possible occurrence of elasto-plastic local buckling.

On page 301, the 3^{rd} bullet in the first set of bullets refers to "panel ring buckling" in which "longitudinal stiffeners act as nodal lines" – this only occurs if longitudinal stiffeners are present which is not always the case.

On this same page, the description of "flexural buckling" (1^{st} bullet of 2^{nd} set of bullets), it is not quite correct because the failure is actually buckling in the direction of the larger slenderness ratio, i.e. effective length / radius of gyration.

Just before leaving this section, it is just worth recording that the ISO standard referred to in subsection 3.3, ISO (2007), which is ISO 18072-1 Ships and marine technology - ship structures - Part 1: General requirements for their limit state assessment, was withdrawn after seven years of work following the cancellation of work on ISO 18072-2 Requirements for their ultimate limit state assessment. This is particularly unfortunate because the Offshore Industry considered ISO 18072-1 to be a fundamentally sound document.

1.1.5 Section 4. Definition of Parameters and their Uncertainties

Section 4.1 Introduction

At the end of this section, it is noted "that large/full-scale experimental data focusing on such practical aspects are rather limited, especially on aspects concerning hull girder strength". It seems to me possible that, because of their age, some very relevant test from the 1970s may have been overlooked when this view was expressed. A substantial number of stiffened steel ship-type cross-sections were tested as part of a major research programme into the ultimate and post-ultimate strength of stiffened steel box girders, precipitated by the collapse, primarily during construction, of four such box girders in the late 1960s. Most of this testing was in the UK but related tests were performed in Europe and Australia.

The main set of tests was performed at Imperial College, London, by Dowling *et al.* (1973), Dowling *et al.* (1977) and Lamas *et al.* (1983). Table 3 summarizes the pertinent features, in imperial units. The geometry was such that failure was precipitated by both plate and stiffener failure, and even cross-frame instability. Some of the models were subjected to pure bending (Figure 2) and some to combinations of bending and shear (Figure 3).

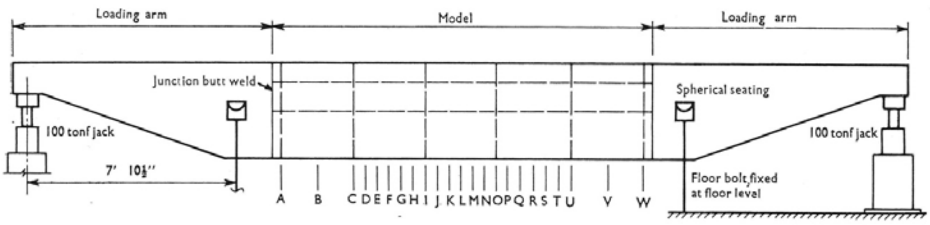

Figure 2: Figure 1b of Dowling *et al.* (1973) showing pure bending test set-up

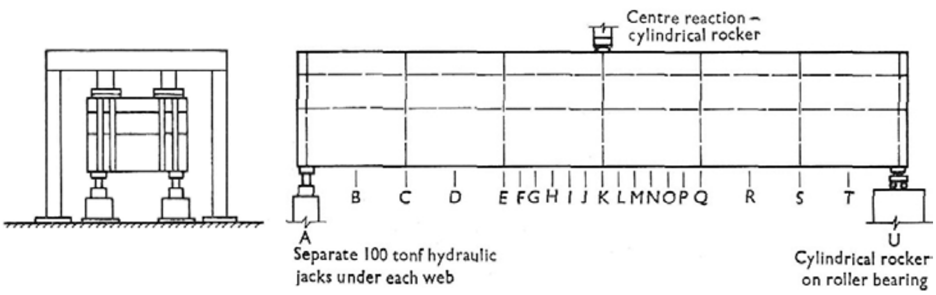

Figure 3: Figure 1a of Dowling *et al.* (1973) showing bending plus shear test set-up

Extensive initial geometrical imperfection and welding residual stress measurements were made with typical results presented in Figures 4 and 5, respectively.

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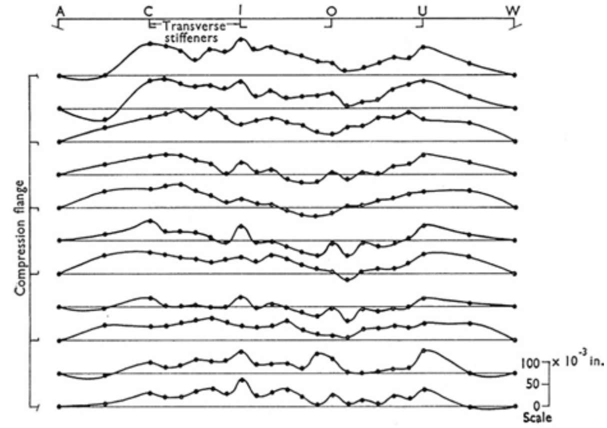

Figure 4: Figure 2 of Dowling *et al.* (1973) showing initial longitudinal profiles of Model 2 compression flange

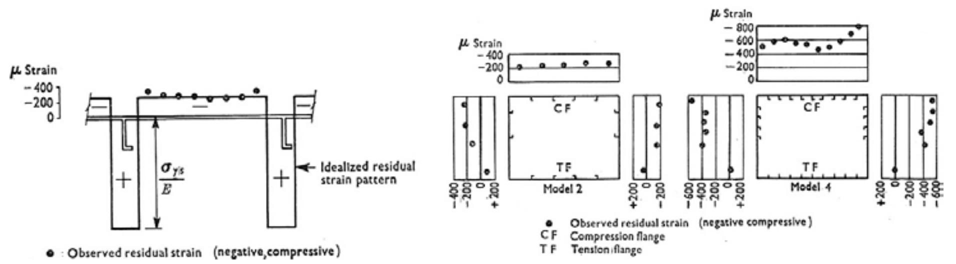

Figure 5: Figures 5a and 5b of Dowling *et al.* (1973) showing welding residual strains in compression flanges of Models 2 and 4

Some 500 strain gauges were fixed to each model to enable the growth of strain with loading to be carefully monitored whilst simultaneously, deflections were measured using the same transducer rig as deployed for measuring the initial shape – see Figure 6. Careful written records of the development of plate and stiffener buckling were made so the sequence could be mapped and numerous post-test photographs taken so as to highlight these buckling modes – see Figure 7.

1.1.6 Section 4.3 Modelling Uncertainties

Several papers are reviewed but only one measure of modelling uncertainty is reported. Considering the Mandate of this Committee states "Uncertainties in strength models for design shall be highlighted", the lack of reported values is felt to be a major omission.

Section 4.5 Conclusions on Practical Aspects in Ultimate Strength Assessment

An area not addressed in the Report, perhaps because its inclusion is borderline to the Committee's activities, concerns the residual strength of vessels that have suffered significant yielding and buckling as a result of grounding, incorrect cargo loading or large wave forces. In ultimate strength terms, the vessel hull girder is post-ultimate strength, i.e. on the falling path of the load-deflection plot and potentially involving gross strains. At sea, such vessels may be subject to salvage but what is the residual strength of the hull; can it sustain the forces associated with retrieval and towing to a safe have? It is not difficult to imagine that, practically, any procedure to analyze

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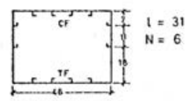
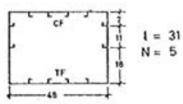
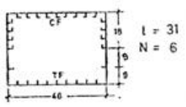
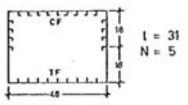
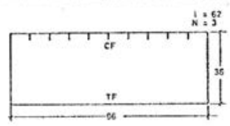
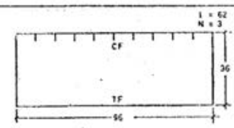
Table 3: Table 1 of Dowling *et al.* (1977) listing geometrical and material details

Model No.	Cross-section of model dimensions, in	Component sizes and material properties: Component	Nominal size, in	t*, in	σ_0 tonf/sq.in	E tonf/sq.in
1		CF	3/16	0.195	16.0	13000
		TF	3/16	0.195	16.0	13000
		W	1/8	0.133	17.7	13900
		LS	2 × 5/8 × 3/16 L	-	21.3	13000
		TS	3 × 2 × 1/4 L	-	20.3	12600
		D	1/4	-	16.5	12900
2		CF	3/16	0.192	19.3	13500
		TF	3/16	0.192	19.3	13500
		W	1/8	0.133	13.7	14000
		LS	2 × 5/8 × 3/16 L	-	17.9	12400
		TS	3 × 2 × 1/4 L	-	20.1	12700
3		CF	3/16	0.198	14.3	13400
		TF	3/16	0.195	14.0	13500
		W	3/16	0.196	18.2	13900
		LS(CF),LS(W)	2 × 5/8 × 3/16 L	-	18.6	12900
		LS(TF),LS(W)	2 × 1/4 Plate	-	19.7	13400
		TS	4 × 2½ × 1/4 L	-	19.7	13000
		D	1/4	0.258	19.4	13500
4		CF	3/16	0.198	14.3	13400
		TF	3/16	0.195	14.0	13500
		W	3/16	0.196	18.2	13900
		LS(CF)LS(W)	2 × 5/8 × 3/16 L	-	18.6	12900
		LS(TF)	2 × 1/4 Flat	-	19.7	12900
		TS	4 × 2½ × 1/4 L	-	19.7	13400
9		CF	3/16	0.192	21.6	13300
		TF	1/4	0.268	20.4	13900
		W	1/2	0.500	18.0	13500
		LS	2¾ × 5/16 Flat	0.312	18.5	13300
		TS	5 × 3 × 3/8 L	-	18.7	13200
10		CF	3/16	0.194	21.7	13400
		TF	1/4	0.242	22.0	13700
		W	1/2	0.500	18.0	13500
		LS	2¾ × 5/16 Flat	0.312	18.5	13300
		TS	5 × 3 × 3/8 L	-	18.7	13200

TF Tension flange; CF Compression flange; LS(CF) Longitudinal stiffener on compression flange
W Web; LS Longitudinal stiffener; LS(TF) Longitudinal stiffener on tension flange
D Diaphragm; TS Transverse stiffener; LS(W) Longitudinal stiffener on web

N Number of bays along span of model
t* Measured thickness

such a damaged hull would be simplified in nature. Does the Committee have any views on the matter?

One of the conclusions in this section is that "The available experimental data that can be used as target values for the calibration of structural models is very limited, which makes it almost impossible to estimate the related uncertainties." Given that the data on girder strength described above is only a part of what one suspects is quite a large database of information highly relevant to the ultimate strength of hull girders and the uncertainties associated therewith, I find it difficult to agree with this conclusion although it is acknowledged that the full set of necessary data does not necessarily reside in one institution.

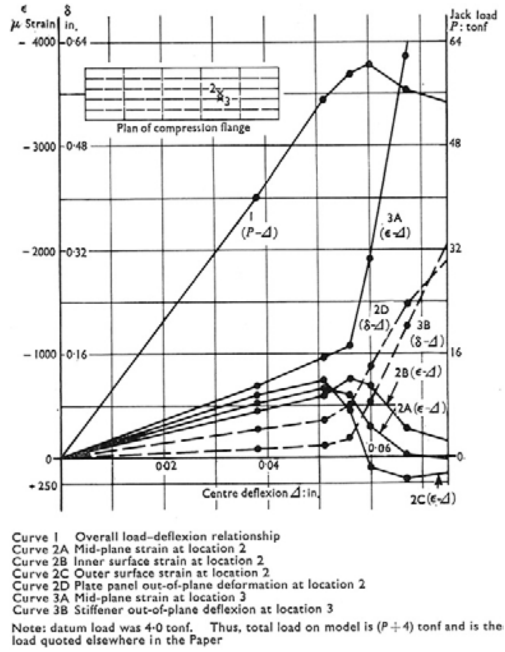


Figure 6: Figures 10 of Dowling *et al.* (1973) showing growth of deflections and strains with load for Model 2

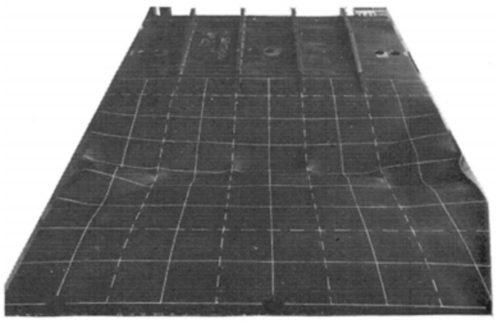


Figure 7: Figures 11 of Dowling *et al.* (1973) showing the post-test buckled shape of Model 2

1.1.7 Section 5. Recent Advances

This is divided into two main subsections, Components and Systems. Under Components, on this occasion, both components of ships and offshore structures are covered and, in keeping with the Mandate, subsections are devoted to (a) Influence of Fabrication-Related Initial Imperfections, and (b) Influence of In-Service Damage.

Section 5.1 Components

On page 309, contributions on curved plates are discussed. Previously, curved plates for marine application have generally been as a subset of complete stiffened cylinders, as covered, for example by DNV-RP-C202 Buckling Strength of Shells. However, the curved plates discussed here appear to be isolated which, if this is the case, will not experience the hoop stress patterns associated with complete cylinders. It would be particularly interesting to see the difference between these findings and the strengths implicit in the DNV-RP-C202. Is it possible the Committee could include such comparison in its reply to this Discussion?

In Subsection 5.1.2 Stiffened Panels, it is instructive to examine the comparisons presented in the paper by Frieze *et al.* (2011) in a little more detail than presented in the Committee Report. Figures 8 and 9 are Figures 7 and 26 of this particular reference. The relevant results in the figures from the point of view of this discussion are those of ALPS/ULSAP and PAFA-SPS. Both are based on ostensibly identical equations yet, whilst in some cases they coincide exactly, in others they do not. They should, of course, always coincide but, unfortunately, the full set of equations on which ALPS/ULSAP is based are subject to copyright and so cannot be replicated exactly. The conclusion at the time is still relevant, i.e. "Thus, if the formulations are to be used more widely, particularly as they are extremely efficient compared with corresponding nonlinear FEA, then further dissemination of their details is necessary in order for users to gain the necessary confidence that they can be used for dealing with this very challenging topic, i.e. the ultimate strength of plates and stiffened panels."

Whilst this whole section seems fairly thorough, it is challenging to gain much appreciation of the papers covered because of the lack of figures or tables that present key findings from the considered papers. Whilst appreciating figures and tables take up space which is often at a premium, the adage that "a figure speaks a thousand words" is nearly always true so the next incarnation of the Committee is encouraged to give more space to the inclusion of figures, in particular, and tables, when appropriate, in its report. The following is hopefully an example of how figures aid the interpretation of findings compared with the approach adopted in the Report.

Consider the last paper addressed in Subsection 5.1.3 Shells, by Pan *et al.* (2010), which deals with the nonlinear analysis of titanium alloy spherical pressure hulls, the Committee Report states "based on their numerical result, the sensitivity of the ultimate strength to critical arc length, thickness to radius ratio, and structural imperfections were studied". One gains nothing from this. Compare that with the information that one can interpret from Figure 10 such as:

- the critical location of an inward deformation is slenderness dependent (although this is not a major influence) so, with inspections in mind, it is clearly far more

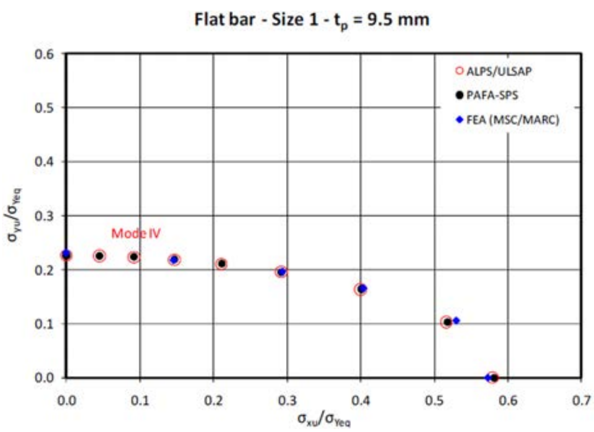


Figure 8: Figures 7 of Frieze *et al.* (2011) comparing ultimate strength interaction relationships between biaxial compressive loads for flat-bar stiffened plate

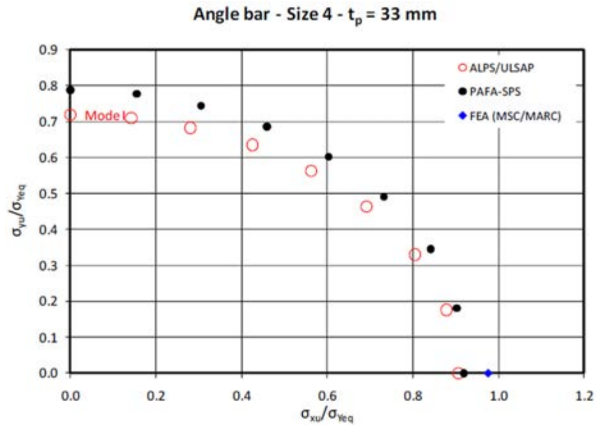


Figure 9: Figures 26 of Frieze *et al.* (2011) comparing ultimate strength interaction relationships between biaxial compressive loads for angle-bar stiffened plate

important to check out-of-sphericity near the top of a hemisphere than anywhere else;

- the same deformation located remotely from the pole can lead to strengths some four times the minimum value, and thus highlights the imperfection sensitivity of these structures;
- viewed another way, a small deformation near the pole could lead to the same reduction as a large deformation remote from the pole.

Another example of where a figure would have been most useful is in relation to the last paper reviewed in Subsection 5.1.5 Tubular Members and Joints. Here the topic is the new IIW (International Institute of Welding) strength formulations for circular hollow section joints, i.e. tubular joints. The review concludes "Detailed comparisons of the new IIW strength formulae to those of API RP2A were provided by Wardenier *et al.* (2009)". How is one supposed to gain my benefit from this review. An engineer, presumably, has spent time tracking down this paper, reading it and preparing this view but no one has gained. Are the new IIW formulae better or worse than the API equivalents. We have no idea from this review, but because I have been heavily involved in the writing, editing and publishing ISO standards for Offshore Structures particularly fixed steel structures which have drawn heavily on API Recommended Practices, I was keen to know if some improvements on the API formulae were available.

The general conclusion was that "the capacities of the new IIW (2008) design equations for CHS joints are between the predictions of the previous IIW (1989) or CIDECT (1991) recommendations and those of the API (2007)". Delving further, it appears that the strength formulations are based on extensive non-linear finite element analyses which give lower bounds to test results. Compared with the finite element analysis results, the new strength formulations give means for the main tubular joint strength parameters between 1.00 and 1.03 with corresponding COVs ranging from 4.2 to 6.8%. Clearly the new IIW formulations are accurate and thus are an improvement on the API equations but it is disappointing that such information is not included in the Committee Report.

In Subsection 5.1.6 Influence of Fabrication-Related Initial Imperfections, the second paragraph states: "Focusing on welded stiffened panels that are mainly subject to axial compression, the welding deformations are normally difficult to obtain from numerical

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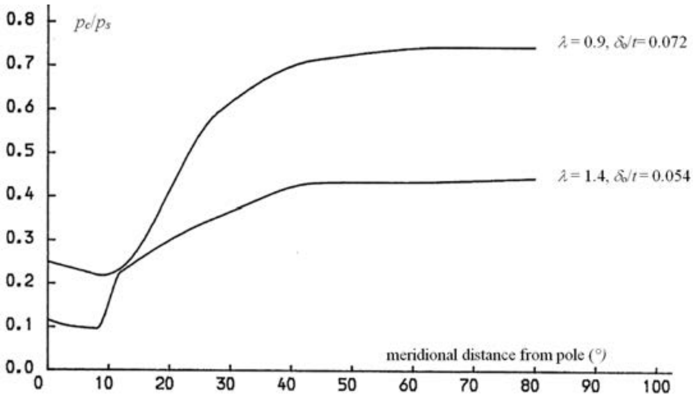

Figure 10: Figures 3 of Shao and Frieze (1989) showing hemisphere pressure sensitivity to initial deformation location as function of hemisphere slenderness and relative initial deformation magnitude

FE-analyses because the complete assembly and fabrication process and possibly the change in shape during overload under operation must be simulated. One option is to measure out-of-plane deformations during the fabrication and during service."

It then goes on to examine three ways in which such imperfections might be estimated in the absence of actual measurements. A major problem in adopting initial imperfections to represent both initial imperfection and welding residual stress effects is that, in the absence of welding stresses in the analysis, the adopted imperfections might be unrealistic. In one analysis conducted by the Discusser, independently derived geometrical imperfections and welding residual stresses for a stiffened plate were input into a nonlinear analysis and the plate buckled. It was not possible to achieve equilibrium with the given initial imperfections and the residual stresses in the absence of buckling indicating that the measurements were not compatible, i.e. they had been separately measured from different stiffened plates.

The conclusion from the paper by Gannon *et al.* (2011) that "only considering fabrication imperfections" and ignoring welding residuals stresses produced "an overly optimistic hull girder strength", apart from being a positive but perhaps not altogether unexpected finding, is also interesting because a study by Birkemoe at the University of Toronto many years ago on a tubular damaged by indenting and subject to axial compression to quantify residual strength, found that the omission of the damage-induced residual stresses in a non-linear simulation of the experiment, led to a significant underestimate of strength, in complete contrast to the present circumstances relating to an intact structure.

In discussing the Influence of In-Service Damage in Subsection 5.1.7, paragraph 4 refers to a paper by Paik (2009) in which the effects of crack location on strength are discussed, reference is made to "longitudinal-inside" and "longitudinal-end" cracks - unfortunately, this is fairly meaningless without a suitable figure to illustrate the location and orientation of such cracks.

On page 303, reference is made to Wang *et al.* (2009) and again on page 323. Naturally, one thinks this refers to the same paper but, no, because the initial of Wang in the first citation is G whilst that of the second is F. One clearly has to be careful using the adopted reference format to ensure the references are in fact uniquely cited because exactly the same problem occurs again with the surname Xu.

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Section 5.2 Systems

In the Subsection 5.2.2 Other Marine Structures, two studies on semi-submersibles are reviewed, one on an intact structure and the other on a damaged structure. They are particularly welcome because of the general lack of papers in the public domain dealing with this structural form. This dearth of papers on semi-submersibles became apparent to this Discusser in a recent review of RSR (reserve strength ratio = ultimate pushover strength / 100 year design return period loading) and probability of failure values of offshore floating structures designed to ISO 19904-1 Floating offshore structures: Monohulls, semi-submersibles and spars.

1.1.8 Section 6. Benchmark Studies

This section provides some very interesting reading. Some of the details have been excluded presumably in order to maximise the number of figures presented. Thankfully, the details will be available via another publication.

Section 6.1 Candidate Methods

Added interest arises from the use of different nonlinear FEA software systems to effect the analyses and, even more appealing, is the use of the same FEA software by different institutions to conduct the same analyses. The importance of this second point was brought home by jacket pushover benchmarking findings reported by Nichols *et al.* (1994) in which users of the same nonlinear analysis software showed a greater variation in results compared with variations between different software packages.

1.1.9 Section 6.3 Modelling Techniques

The first set of results presented addresses the issue of the most appropriate model to adopt for stiffened plate analysis - should it be a single span or a multi-span configuration. The results indicate that it is plate and stiffener geometry dependent. However, in both of the cases presented, the multi-span model generates the lower strength.

Single span models have frequently been used in the past in both stiffened plate and stiffened shell physical tests. In the case of stiffened plates, it is not normally practical to adopt fixed ended conditions because of the difficulty in generating the necessary end flexural/torsional stiffness, thus simply supported ends are the norm. However, the achievement of simply supported end conditions is particularly challenging because initial fabrication effects render the determination of the effective neutral axis difficult: the axial load must be applied concentrically to the ends of the model in order to avoid introducing any end moments. One way to do this in practice is to apply trial positions of the axial load until extreme fibre strains measured at mid span are the same.

Because of the difficulties associated with single span models, biases in the results derived from such tests can occur. Consider the following results for axially compressed cylinders which, based on the strength formulations developed by Cho and Frieze (1988), produced the modelling uncertainty parameter results shown in Figure 11. Two sets are shown, those for single bay tests (described in the figure as "unstiffened cylinder" and those for multi-bay tests ("ring-stiffened cylindrical shell"). The single bay results are seen to be skew with respect to the multi-bay values, reflected in the corresponding modelling uncertainty parameter COVs of 26.8% and 11.3%, respectively.

Because of the biases associated with single-span analyses, I feel the Committee should be more forthright in its recommendation that only these multi-span analyses should be used in practice, for both numerical and experimental studies, particularly in the light of some of the results presented in Figure 23.

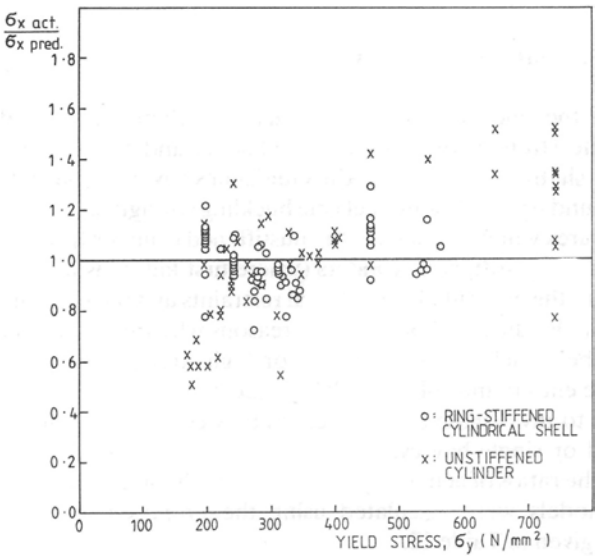

Figure 11: Figure 7 of Cho and Frieze (1988) comparing single and multi-bay axially compressed cylinders

Figures 13 to 15 illustrate some of the meshes used in the numerical analyses. Clearly they differ between the various institutions. Mesh convergence studies are essential even for elastic nonlinear analysis but even more so for elasto-plastic buckling analysis. Can we hope to see such details in the independent publication because the mesh refinement adopted for the stiffeners does seem inadequate.

1.1.10 Section 6.4 Results and Observations

Section 6.4.1 Plates

The results in Figure 16 are particularly encouraging in demonstrating that sophisticated analytical methods such as ALPS/ULSAP and PULS can give strength predictions very similar to those of nonlinear numerical analysis. Clearly some interesting buckling modes are occurring for panels dominated by longitudinal axial compression. Perhaps these modes could be included in the figure to aid understanding.

The results in Figure 17 confirm that the modes of initial geometrical imperfections are important in influencing strength particularly under longitudinal axial compression. It emphasizes the importance when generating strength values for design of ensuring that the initial imperfections adopted for the analysis are appropriate.

Section 6.4.2 Stiffened Panels

In Figure 19, it would be helpful to indicate just what is the changing parameter in each of the series marked Size 1, Size 2, etc: is it possibly plate slenderness β?

In Figure 18 and some other following figures, the controlling buckling modes as identified via ALPS/ULSAP are listed. This information is most helpful for giving insight to structural behaviour and which of course is available from any finite element analysis although one has the impression that, unfortunately, such information is not normally presented.

Figure 23 and some subsequent figures present results which are of some concern. The ABAQUS results in Figure 23 (a) appear to be the consequence of using single rather than multi-span stiffened plate models and adds weight to the comment made earlier on this issue. On the other hand, the reason advanced for the discrepancy in the BV results is less obvious because it is not clear whether it was the results of this study that found the BV method was "not applicable for some ranges of stiffener dimensions" or whether the results were generated by someone unaware of the limitations.

When considering the effects of pressure in Figures 29 and 30, can the Committee clarify whether the ALPS/ULSAP results have been generated for the pressure applied to the plate-side or to the stiffener-side because this is most likely to affect the buckling mode for some combinations of compression and pressure.

In Figure 32, it appears that the average level of welding residual stress has more impact on strength than the severe level. Can the Committee offer an explanation for this?

Section 6.4.3 Hull Girders

The Committee notes the considerable scatter in results obtained for hull girders subjected to sagging and hogging moments and attributes some reasons for this. Where numerical analysis has been used, it seems the limitation of analyzing only one bay between transverse frames could also contribute because this means that the analyses have exactly the same problem as raised earlier in connection with stiffened plates, namely, that single bay models are not adequate for representing compressed stiffened plates.

1.1.11 Conclusion

The Committee is to be congratulated on its report. The challenge of such a geographically diverse team completing this task is recognized, and where the discusser has been critical, it is primarily in an attempt to extract more useful findings from this extensive work, and to hopefully help the next generation of this Committee make the most of its opportunity.

1.1.12 References

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1.2 Floor Discussions

1.2.1 Andrea Ungaro

Regarding chapter 5.1.3, and specifically the overview of current design practices for submarine pressure hulls, it is pointed out that the accuracy of conventional Submarine Design Formulae (SDF) for predicting pressure hull collapse is close to that obtained by nonlinear numerical models, which implies that the latter are not strictly necessary in the design phase unless a better representation of the geometric imperfections is used.

However, typical SDF do not take into account the effect of internal structures (tanks, decks, foundations, etc.) which, while having a mostly local (but potentially very significant) effect on stresses, can influence the failure behaviour of the whole compartment by significantly changing its deformed shape and instability mode shape.

At the same time, even computationally simple axial-symmetric numerical models can offer interesting information on the local stress and deformation close to transition areas (cone/cylinder, cylinder/end-cap), where a different scantling is often necessary and where SDF typically offer lower precision.

Therein, in its inherent flexibility, and in the possibility of accounting for a damaged structure, lie the main advantages of FE techniques in the design of pressure hulls.

Among the list of the non-linear factors in chapter 2.2, the "follower force" effect, that is the change of direction of the applied loads and pressure forces due to large structural displacements, is not listed. This effect can be considered implicit in the geometric non-linearities, however it would be proper to mention it separately in point d), loads.

1.2.2 Shengming Zhang

Regarding hull girder ultimate strength, the current mostly used methods included in the CSR, only longitudinal stress is considered. How important are other stress components such as transverse stress, shear stress and lateral pressure? Should we include all components in design assessment? Should the residual stress effects on ultimate strength assessment be included? Why?

1.2.3 Daisuke Yanagihara

In the benchmark of the unstiffened and stiffened plates, the comparison with CSR is only a few cases. Particularly, there is no comparison with the CSR-B which is the rule for bulk carriers. Does the committee have a clear reason for this?

In the benchmark, the FE analyses were almost performed applying the initial deflection of the buckling mode with $0.1ß^2t$ amplitude. I think that this deflection is very large and not realistic. But these FEA results are used as the reference values to verify the prediction method. Of course, I understand that the lower limit is necessary to provide the safety of the prediction. However, I think that the investigation on the model uncertainty of the prediction method is also the purpose of the benchmark. From this point of view, the average condition of the initial deflection should be considered, and the FEA results under the average condition should be used as the reference value for the comparison. Could you show the committee's view about this problem, that is, what should be used as the reference value in the benchmark?

1.2.4 Weicheng Cui

I like the way of Committee's representation of the ultimate strength problem as a function of several important parameters, in this case, eight aspects of factors (a – h), first I wish the committee chairman to confirm whether I can optimistically say that when eight aspects of factors are clearly described for a particular situation, then the current state-of-the-art method can predict the ultimate strength within 10% of error?

If that is the case, the future emphasis of this committee should be directed to the descriptions of these damage states such as fatigue cracking, corrosion, residual stresses, etc. and in particular the determination of human factors are extremely difficult to quantify their effect on ultimate strength. Do you have any suggestion on how to treat those problems, especially the human factors?

If the 10% of error cannot cover some of the problems, can you give some examples where the ultimate strength of the given structure cannot be predicted within that accuracy requirement?

1.2.5 Philippe Rigo

Let me first thanks the ISSC committee III.1 and his chairman Jeom K. Paik for their brilliant report and attractive presentation in Rostock.

My comments concern the need to integrate the assessment of ultimate strength (specifically the hull girder bending moments) within the optimisation procedure of ship structure (scantling).

In Rostock, the chairman of committee III.1 concluded his excellent presentation saying that, to his knowledge, ultimate strength has not yet been integrated, at industrial level, in the ship structure optimisation loop.

So it is my pleasure to highlight the fact that the LBR5 software (see references below) is an ship structure optimisation package, dedicated to early design, which target least weight and least cost optimisation (multi objective approach), and which is used since 2005 at industrial level by STX France (St Nazaire shipyard) for the design of their large cruise vessels and previously by ALSTOM for gas carriers. LBR5 considers as active constraints of the optimisation process the ultimate strength of each stiffened panel (bottom, decks, side shells, ..) and also the hull girder ultimate bending moments (using the simplified analytical method of JK Paik within the optimisation loop, and a progressive collapse module (PROCOL) as post-analysis (for validation)).

Running structural optimisation (ship scantling) is only meaningful at the conceptual design stage or at initial design stage. Later, there is no more room for significant changes in the structure. So, the challenge to include ultimate strength assessment of hull girder and its components (stiffened panels) within the optimisation process relates to the lack of detailed data to perform advanced ultimate strength analysis (as non linear FEA). The scantling details of the structure are not yet fixed; it is therefore challenging to make a FE model (too high uncertainties on the real geometry). In addition there is also a high uncertainty concerning the imperfection levels (deformation, residual stress) as details about the welding technology and assembling scheme are unknown.

So, there is an urgent need for researches to develop structural optimisation tools including ultimate strength capabilities that are integrated with design and production tools used at initial design stage (CAD, scantling tool, block splitting, ...).

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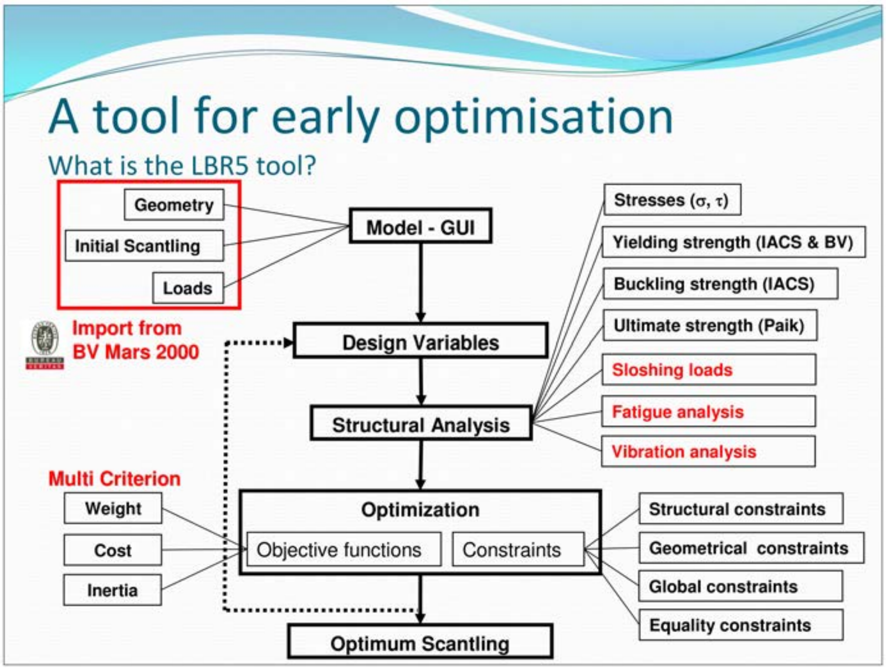

Figure 12: LBR5 Integration in Optimisation Process

1.2.6 References

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2 REPLY BY THE COMMITTEE

The Committee thanks official and floor discussers for their valuable comments and discussions related to our report. In the following, we respond to their remarks.

2.1 Reply to Official Discussion

Accidents are the result of a long chain of human error which is due to a lack of knowledge and engineering disciplines at various stages, including engineering and

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design, construction and operation. To prevent accidents, human error should be eliminated. Human error can be reduced by taking advantage of engineering disciplines in accordance with human factors engineering principles.

Our Committee deals with a key engineering and design disciplines for ships and offshore structures, and it is hoped that the uncertainty characterization of influencing parameters and the development of more refined ULS methods will help to reduce catastrophic failures of ships and offshore structures.

Two types of design format are usually applied in ensuring that a structure has an adequate degree of safety and reliability against ULS, namely partial safety factor design format and probabilistic design format in which the uncertainties are characterized.

In the offshore industry, substantial efforts have been devoted to the development of international standard guidelines associated with limit state assessment of offshore structures, and to extensive applications of such standards and guidelines to industry practices.

Residual strength of ships after significant yielding or buckling is treated by classification societies, e.g., Bureau Veritas (BV 2010), providing a service ERS-S which is an emergency response service corresponding to damage longitudinal strength and damage stability analyses. The structural model is generally very simplified, just removing damaged area from initial or intact model. The main investigations are focused on the additional load due to unexpected flooding. The aim is to determine the allowable still water bending moment and the allowable sea states. A more refined structural analysis would require a good knowledge on the actual state of the structure. Just to obtain accurate information on the actual structural integrity in emergency condition is a primary issue.

In the last decade, the shipbuilding industry has also tended to implement ultimate limit states principles into rules by IACS or classes, but such an effort is far from the level of the offshore industry. For example, 'critical buckling strength' of structural components determined by elastic buckling strength with a simple plasticity correction is regarded as an ultimate limit state, but this technique is not always true and is irrelevant in some cases.

Furthermore, neither international standards nor standard guidelines for limit state assessment of ship structures do exist. Large scale or full scale experimental studies are very lacking, especially in the sense highlighted by the Official Discusser that the limited available experimental data are not shared among involved parties. Moreover, often testing procedures and measurements are not comprehensively documented. Comparison and merging of such data, indeed very expensive to obtain, will be very beneficial and fruitful. The Committee agrees with the official discusser that there are still a lot of technical issues to be resolved.

2.2 Reply to Floor and Written Discussions

2.2.1 Andrea Ungaro

It is challenging to take into account the effects of all influencing parameters such as geometric imperfections and internal structures, among others, within a set of submarine design formulae. In this case, nonlinear finite element methods will be useful as far as their modeling techniques are adequate. Chapter 2.2 lists up the factors affecting the structural nonlinearities. The order or pattern of applied loading, e.g., lateral pressure or out-of-plane loading followed by in-plane loading, can cause different responses as well, and this issue can be classified into the quasi-static load case.

2.2.2 Shengming Zhang

Ship hull girders are subject to combined hull girder loads which include not only vertical bending but also horizontal bending, shearing forces and torsional moments. Even though vertical bending moments are predominant component of hull girder loads, the effect of other load components on ultimate strength cannot be disregarded.

Welding causes geometric imperfections and residual stresses. In welded steel ship structures, it is known that the welding residual stresses can be released by cyclic applications of hull girder actions, i.e., hogging and sagging. In this case, remaining amount of welding induced residual stresses may be small and thus its effect on ultimate strength may also be small. However, this aspect is still uncertain and further studies are recommended to characterize the release of welding residual stresses by cyclic hull girder actions. It is important to realize that the welding residual stresses can reduce the ultimate strength and that its characteristics should be identified for robust design of ships and offshore structures.

2.2.3 Daisuke Yanagihara

The benchmark studies of the Committee have included stiffened panels of both tankers and bulk carriers with class rules, CSR, ULSAP, PULS and nonlinear FEA. Because of the page limits of the Committee Report, only the summary of the results was included. The conclusions of the studies obtained from the stiffened panels of tankers or bulkers are similar.

The geometrical imperfections in stiffened panels induced by welding include plate initial deflection, column type initial distortion of stiffeners and sideways initial distortion of stiffeners. We agree with Dr. Yanagihara that it will be better to consider an average level of initial imperfections in the benchmark studies. In this regard, we adopted the average level of plate initial deflection as $w_0 = 0.1\beta^2 t$, where β = plate slenderness ratio and t = plate thickness. According to Smith et al. (1988), it is noted that the maximum amplitude of the initial deflection of steel ship plates may be given as follows:

$$w_0 = \begin{cases} 0.025\beta^2 t & \text{for slight level} \\ 0.1\beta^2 t & \text{for average level} \\ 0.3\beta^2 t & \text{for severe level} \end{cases}$$

The effect of the initial deflection shape is also significant. The maximum initial deflection indicated in the above equation may actually not be the buckling mode of the plate, but rather it must be equivalent to a “hungry horse’s back shape”. We agree with Dr. Yanagihara that the uncertainties due to the shape of initial distortions needs to be further investigated.

2.2.4 Weicheng Cui

The Committee believes with a certainty that the clear characterization of all the eight aspects is very challenging and further studies are required. For some specific cases, however, we have various refined methods that are able to predict the ultimate strength within 10% error. As previously discussed in Section 3.1, human error is due to a lack of knowledge with uncertainties. Although it is theoretically impossible to totally eliminate human error, we could reduce human error to some extent by taking advantage of advanced engineering disciplines.

2.2.5 Philippe Rigo

The Committee thanks Prof. Rigo for sharing with us on the effort for developing full optimization of merchant ship hull structures. We absolutely agree with him that we will have to urgently develop structural optimisation tools including ultimate strength capabilities that are integrated with design and production tools used at initial design stage. This effort will eventually help to save design times, adjust structural scantlings for too strong and/or too weak members, improve structural safety, reduce structural weight and building cost, improve operational efficiency, and reduce CO_2 emission.

2.3 Reference

BV (2010). Emergency Response Service (ERS), Rule Note NR 556 DT R00 E, January 2010.