14th INTERNATIONAL SHIP AND
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NAGASAKI, JAPAN

VOLUME 3

DISCUSSION ON THE REPORT OF

SPECIAL TASK COMMITTEE VI.2

ULTIMATE HULL GIRDER STRENGTH

MANDATE

Evaluate and develop procedures for estimating the ultimate strength of ship hull girders. Due consideration shall be given to relevant load combinations, including overall bending, torsion and shear as well as local pressure loads. The influence of fabrication imperfections, corrosion and in-service damage on the strength shall be discussed. The procedures shall be assessed by comparison with model tests and more refined calculation methods. Recommendations for ultimate strength assessment methods shall be given.

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Prof. H. Ohtsubo

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MEMBERS

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KEYWORDS

Ultimate hull girder strength, longitudinal bending, buckling/plastic collapse, benchmark calculations, structural design, combined loads, initial imperfection, corrosion damage, in-service damage, average stress-average strain relationship.

CONTENTS

Dowling (1997), and on numerical results for panels subjected to local and inplane loading, Jackson and Frieze (1981), has demonstrated that these are far from straight. This is not altogether surprising because, unless one has perfect elastic buckling, elasto-plastic buckling soon dictates the growth of a limited number of buckles in adjacent panels that rarely align perfectly. The large transverse membrane stresses that arise around the peak of these buckles will clearly tend to pull in the panel edge locally. Where significant shear stresses are present, particularly when shear buckling occurs, this results in an even greater tendency for the panel edge to distort inplane, Dean and Dowling. Is the Committee aware whether this phenomenon has been examined since the only way I could deal with it when examining local lateral loading, Jackson and Frieze, was to use an assembly of 9 panels around the panel of interest? It is of course possible that the developers of ISUM may be better placed to deal with the question, in which case I trust the question will be redirected accordingly.

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2 REPLY BY COMMITTEE

2.1 Reply to Official Discusser

The committee is grateful to the official discusser, Prof. Ueda, for his excellent discussions, which are not only valuable but also very informative regarding the future direction of nonlinear structural analysis methods including ISUM.

The committee completely agrees with the discusser on what is written in "1.1.2.1 Advances in Ultimate Strength Analysis." It is sure that the methods of analysis have been developed in accordance with the developments in computer hardware and with advances in our understanding of buckling/plastic collapse behaviour of structures.

The committee also agrees with the discusser on his opinion that the approximate methods can be grouped into two: (1) Empirical formulation and (2) Theoretical approximation. However, regarding the grouping of Smith's method, the committee's opinion differs from the discusser. Smith's method itself is outside of this grouping, but the average stress-average strain relationships used in the analysis applying Smith's method should be grouped into the above two categories. Some being based on empirical formulation, but some are based on theoretical approximation taking into account of stiffener tripping as well as overall buckling as a continuous stiffened panel.

The committee also considers that any approximate method belonging to category (2) would be more accurate since the possibility of missing or omitting possible failure modes should be rare. In this sense, the most fundamental items which should be included in the ultimate hull girder strength analysis are:

(1) local panel buckling
(2) overall buckling as a stiffened panel after local buckling
(3) tripping of stiffeners
(4) localisation of plastic deformation and resulting elastic unloading in the post-ultimate strength range
(5) influence of initial deflection and welding residual stress
(6) influence of lateral pressure
(7) influence of transverse thrust and additionally:
(8) influence of horizontal bending moment acting on hull girder
(9) influence of vertical shear force acting on hull girder
(10) influence of torsional moment acting on hull girder

If large structural elements are employed, for example when an orthogonally stiffened panel between two transverse bulkheads is regarded as one element, items (3) and (4) have to be considered in the element level formulation.

In the above mentioned items, the committee considers that items (2), (3) and (4) cannot be ignored when calculating the ultimate hull girder strength. The committee realises that some simplified methods satisfy these conditions, but presently no ISUM satisfies these especially items (3) and (4) although item (3) may be satisfied by an empirical manner. That is, even in the present ISUM, some of the very important phenomena for the ultimate hull girder strength analysis are not yet implemented in the simplification process, and they can not be reproduced. At least, Masaoka's ISUM clearly indicates this, since the strength reduction beyond the ultimate hull girder strength is very slight in the moment-curvature relationships in Figure 4.7 of the report.

In "1.1.2.3 Prospective Methods of Analysis with Sophisticated Elements," the discusser seems to consider only the ISUM as a sophisticated element. However, the committee considers that some elements used in Smith's method can also be very sophisticated and can account for the influences of various factors.

In Section 1.1.3 of the discussion, as the discusser pointed out, the committee did not distinguish the ISUM of the first and the second generations. As far as the committee understands, ISUM used by Dr. Chen probably belongs to the first generation, and ISUM used by Dr. Masaoka the second generation. However, the committee presumes that above mentioned items (3) and (4) are not accounted in either ISUM.

It is generally known that ISUM is a simple but efficient method to analyse buckling/plastic collapse behaviour of structures. On the other hand, people who can understand ISUM at a detailed level are very few. The reason for this is, as the discusser who is known as father of ISUM says in "1.1.3.2.1 First Generation," because that "the idealization needs tremendous efforts to observe complicated phenomena, to extract essential points, to express them in mathematical forms and to develop some theories for incremental stiffness matrices. This is quite tedious intelligent work."

ISUM is, with no doubt, an excellent method, and the committee do hope that more sophisticated elements which can account for the above mentioned items (3) and (4) may come out in a near future, and the ultimate hull girder strength analysis can be performed applying the new ISUM.

In concluding the committee's comments on Section 1.1.3 of the discussion, the committee would like to commend Prof. Ueda for preparing Section 1.1.3, which is an excellent lecture note about ISUM.

Regarding the first part of Section 1.1.4 of the discussion, the committee is in complete agreement with the discusser on his opinion regarding the results of experiment. The results of experiment can be untypical of real structures because of scantling and other problems. However, if all the initial conditions of an experiment are known including the initial imperfections due to welding, the experiment could be an appropriate measure to examine the accuracy of the theoretical analysis. This point is especially important for ISUM, since ISUM is usually used to analyse large parts of the structure, and this structure could be too large to get correlations with the exact collapse load by performing FEM analysis. From this point of view, performing experiments on large structure is important although it may not represent the collapse behaviour of real structures.

The statement in 4.2 of the report, which reads, "*It is seen that initial yielding strength and initial buckling strength by the different methods are almost the same although few exceptions exist. This implies that the modelling applying different methods is fundamentally correct,*" only implies that the representation of the cross-section from raw data is correct.

The committee agrees with the discusser on his opinion that Smith's method has been developed for the special purpose strength analysis and that ISUM has more general purpose applications. However, the committee considers that the discusser has some misunderstanding regarding the Smith's method.

Of course, in the Smith's method, the analysis is simplified to one-dimensional one. However, this is a simplification of the hull girder behaviour, and the collapse behaviours of structural members, such as local panel buckling, overall buckling as a continuous stiffened panel between transverse frames and the tripping of stiffeners, which are the most dominating factors when the hull girder collapses, are accounted for accurately.

Many facts observed from jackknifing casualties (JMT 1977, Rutherford and Caldwell 1980, JMT 1997), experiments (Dow 1991, Yao *et al.* 2000) and FEM analyses (JMT 1997, JSRA 2000) indicate that buckling/plastic collapse of deck or bottom at one frame space dominates the ultimate hull girder strength. Smith's method using sophisticated average stress-average strain relationships can represent such collapse mode. On the other hand, stiffened plate between two transverse bulkheads is often considered as one element in the present ISUM analysis. In this case, the displacement function of the ISUM element should be the one which can represent concentration of the plastic deformation at one frame space to simulate the actual collapse behaviour. Another point which should be considered in ISUM is to develop curved stiffened plate element which may be necessary for the analysis on some types of ships with large curved part.

The discusser asks if the ship structure is not sufficiently safe against longitudinal bending. It has been said that a ship structure is a highly indeterminate structure, which may imply that collapse of one structural member does not result in the collapse of the whole structure. However, the deck and the bottom plates have in many cases same thickness across the full width and are stiffened by equally spaced stiffeners of the same size. In this case, under vertical bending, the whole deck or bottom structure collapses at the same time, which leads to the jackknifing collapse of the hull girder.

Because of this, the committee considers that the initial yielding strength of the deck plate and the buckling strength of the bottom plate can be the candidates of a simple measure of the ultimate hull girder strength under the sagging and the hogging conditions, respectively.

As for the comment in Section 1.1.5 of the discussion, load carrying capacity beyond the ultimate hull girder strength can be estimated if the progressive collapse analysis is performed applying Smith's method or ISUM. Regarding the carrying capacity itself, the committee is quite pessimistic. As mentioned above, the ultimate strength of a hull girder is attained at a certain cross-section, and beyond this point, the bending moment at this cross-section decreases with the increase of plastic deformation at this cross-section. This means that the bending moment decreases also at the remaining cross-sections. That is, elastic unloading takes place at the remaining cross-sections. If this collapse takes place in a calm sea as in the case of *Energy Concentration*, the ship will remain afloat. However, if the collapse occurs in a rough sea, where large cyclic loads can easily initiate low cycle fatigue cracks from the buckled area, the ship may be broken into two as in the case of *Nakhodka* and many other lost vessels.

In concluding the committee's reply to Prof. Ueda, the committee has to say that ISUM is a potential method of simple but efficient and sophisticate structural analysis. Applying ISUM, strength of a ship's hull subjected to any general combined loading can be analysed. However, more sophisticated and advanced elements have to be developed to get more rational results. As mentioned above, regarding the ultimate hull girder strength analysis, tripping of stiffeners and concentration of the plastic deformation at one cross-section beyond the ultimate strength have to be accounted when the element characteristics are formulated. On the other hand, Smith's method is also a powerful method for ultimate hull girder strength analysis. For this method, introduction of the influences of various factors are necessary to get more practical results.

2.2 *Reply to Floor and Written Discussers*

2.2.1 *Reply to Prof. J.K. Paik and Prof. O.F. Hughes*

The committee would like to answer to the questions one by one.

(1) The Committee would like to thank the discussers for pointing out the misprinting in the report. Calculation was of course performed using $w_{0max} = 0.1\ (b/t_p\sqrt{\sigma_{Yp}/E}\ )^2 \times t_p$.

(2) The committee agrees with the discussers' comment that depending on initial conditions, loading and collapse modes, alternative model should be used to investigate grillage collapse between two transverse bulkheads. However, according to the results of FEM analyses (JMT 1997, JSRA 2000) and experiments (Dow 1991, Yao *et al.* 2000), buckling collapse of deck or bottom plating in one frame space dominates the collapse of the hull girder. So, the committee considers that, in case of ordinary merchant ships, it is usually adequate if the collapse in one frame space can be simulated. At the same time, the committee would like to mention that, even if one tank between two transverse bulkheads is analysed, local collapse in one frame space has to be simulated to get rational results.

(3 a) The committee agrees with the discussers on their opinion regarding the effects of shear force and horizontal bending moment on the ultimate hull girder strength.

(3 b) The committee could not refer to the paper dealing with the influence of torsional moment on the ultimate hull girder strength to appear in 2000 when preparing the committee report.

(3 c) The committee introduced the results of analysis regarding the influence of thickness reduction (JSRA 2000). In this analysis, uniform corrosion was assumed. The discussers insist that such an assumption is less meaningful. However, the committee disagrees with the discussers' opinion. The committee considers that such assumption produces the ultimate hull girder strength on the safe side,

and the objective of this analysis was just to evaluate conservative ultimate hull girder strength to provide technical background data for a new proposal at IMO. The assumption regarding the corrosion damage has to be made according to the objective of the analyses.

(3 d) The committee realises the importance of considering the influence of cracks located in the tension side of hull girder bending. For the existing cracks, it can be easily accounted in the simplified method such as Smith's method. However, for the crack which newly initiates or starts to propagate, careful consideration is necessary. More exactly saying, the condition for crack initiation and propagation should be as exact as possible when the rapture phenomenon is simulated. The committee recognises that one of the discussers predicted in his paper (Paik 1994) the strength of 1/3-scale steel welded frigate model introducing the influence of rapture in the tension side of bending. Very good agreement was obtained in the post-ultimate strength range between the calculated and measured moment-curvature relationships. However, no rapture was present according to the comment of Dr. Dow, one of the committee members, who conducted this experiment.

(3e) Regarding the effect of lateral pressure on the ultimate hull girder strength, the committee is sorry not to have had time to introduce the results of the discussers' paper to appear in the journal in 2000, and thank them for their information.

(4) Table 8.1 was produced as a result of significant amount of discussion by the committee members. The table and its scores represent the accumulated knowledge of the committee members, and in the committee's opinion, this table is a fair reflection of the relative merits of alternative methods. If this disagrees with the discussers' opinion, then we must agree to differ.

The committee recognises that Prof. Paik has worked with the ISUM for a long time. The committee realises that ISUM is very good at representing the effect of combined loads on stiffened panel, but this can also be accommodated by other methods such as the beam-column approach. On the other hand, as was mentioned in the reply to Prof. Ueda, the committee does not consider that the present ISUM is an appropriate method of analysis since it cannot deal with the localization of plastic deformation in the post-ultimate strength range and the stiffener tripping in an explicit manner. That is, the present ISUM has various functions, but does not have sufficient functions for the ultimate hull girder strength analysis. This is the reason of the low score of the present ISUM by the committee.

Again, the committee still thinks that Table 8.1 is a fair reflection of the relative merits of alternative methods of ultimate hull girder strength analysis, including the score allocated to the ISUM.

At the end, the committee agrees with the discussers on their opinion that the closed form solution is useful for the reliability analysis, and such formulation should also be developed besides the methods of progressive collapse analyseis.

2.2.2 *Reply to Prof. H.-H. Sun*

The discusser states that the ultimate hull girder strength for Case (2) is higher than that of Case (1) for single hull VLCC. However, this is only Masaoka's result in sagging applying ISUM, and the reason is not clear.

Regarding the initial deflection in panels for Case (2), the coefficient, η, in Eqn. 4.1 is not given in the report. It is given in Table D1.

It should be noticed that there is mistyping in Eqn. 4.2. The committee is sorry for this, and the correct expression is:

$$w_{0max} = 0.1\ (b/t_p\sqrt{\sigma_{Yp}/E}\ )^2 \times t_p \tag{4.2}$$

The committee welcomes to see the results of calculation on five vessels used for benchmark calculations in the committee report, and would like to thank the discusser for presenting his results.

The committee considers that the discusser's recent work on the time variation reliability and sensitivity studies for some types of vessels is very important, and is very interesting. Unsteady propagation of a fatigue crack shall become critical when the safety of aged vessels is assessed as the discusser says. It is quite easy to construct a calculation procedure to take into account this phenomenon in the progressive collapse analysis. However, careful consideration is necessary regarding the condition for the start of unstable crack propagation from a fatigue crack.

TABLE D1

COEFFICIENTS OF EFFECTIVE INITIAL DEFLECTION

aspect ratio	η	buckling/collapse mode
$a/b < 1.2$	1.0000	$m = 1$
$1.2 \le a/b < 2.2$	0.0481	$m = 2$
$2.2 \le a/b < 3.6$	0.3321	$m = 3$
$3.6 \le a/b < 4.2$	0.0344	$m = 4$
$4.2 \le a/b < 5.6$	0.2017	$m = 5$
$5.6 \le a/b < 6.2$	0.0261	$m = 6$
$6.2 \le a/b < 7.6$	0.1275	$m = 7$
$7.6 \le a/b < 8.2$	0.0210	$m = 8$
$8.2 \le a/b < 9.6$	0.0835	$m = 9$
$9.6 \le a/b < 10.2$	0.0176	$m = 10$
$10.2 \le a/b < 11.6$	0.0645	$m = 11$
$11.6 \le a/b < 12.2$	0.0157	$m = 12$
$12.2 \le a/b < 13.6$	0.0410	$m = 13$
$13.6 \le a/b < 14.2$	0.0146	$m = 14$
$2n + 0.2 \le a/b2n + 1.6 <$	0.0340	$m = 2n+1$
$2n + 1.6 \le a/b2n + 2.2 <$	0.0143	$m = 2n+2$

$n \ge 7$

2.2.3 *Reply to Mr. T. Quesnel*

The committee agrees with the discusser that nowadays the difficulty in assessing the ultimate hull girder strength of passenger vessels having many decks and including various openings has not yet been raised particularly at the preliminary design stage. For detailed analysis, only three-dimensional FEM analysis of the full ship can be considered as a reliable direct analysis approach. Unfortunately, such analysis is not affordable for standard design offices and shipyards, and particularly at the early design stage.

The committee recommends using the classic progressive collapse analysis known as the Smith's Approach which is based on calculated "average stress – average strain curves" of stiffened elements. ISUM method of the 2nd generation could be, in the future, an alternative solution.

Of course the committee is aware that for passenger ships the vertical stress distribution is not linear (as assumed by the Smith's Approach). The long superstructure and the large openings in the side shells and in the decks induce this non-linear distribution.

Based on the present situation, the committee believes that new specific studies are required to quantify the real stress distribution in the cross-section and to assess its effect on the ultimate hull girder strength. The next ISSC III.1 committee is hoped to continue surveying this problem.

2.2.4 *Reply to Dr. Y. Pu*

The definition of t_p is the thickness of all the panels including deck, bottom, inner bottom and side shell plating in this sensitivity analysis. Of course as the discusser points out, the ultimate hull girder strength is sensitive to the thickness of deck plating under the sagging condition, and to the thickness of bottom plating under the hogging condition. Regarding the thickness of the stiffener, t_s, the thickness of both web and flange of all the stiffeners is considered.

The sensitivity analysis is performed applying the computer code, HULLST, using average stress-average strain relationships of elements calculated in HULLST. This implies that the variation of the ultimate hull girder strength (M_u) owing to differences in applied methods does not appear in the calculated results. Coefficient of variation (C.O.V.) of the ultimate hull girder strength applying different methods is given in Table 7.2. If this variation is also included, C.O.V of M_u can be greater than 10% as the discusser points out.

Regarding the last question related to the sensitivity of the ultimate hull girder strength with respect to the panel thickness in case of the double hull VLCC, some error was found in the calculation. The committee has to apologise for this mistake and thank Dr. Pu for his indication. Corrected Table 6.2 is given below.

TABLE 6.2 (corrected)

NORMALISED SENSITIVITYES ULTIMATE HULL GIRDER STRENGTH

variables	Double Hull VLCC		Container Ship		Bulk Carrier		*Energy Concen.*	
	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging
t_p	1.1622	0.8841	0.8972	1.1366	1.1297	1.0096	1.0880	0.7943
t_s	0.2638	0.3438	0.2387	0.1847	0.3159	0.2486	0.3678	0.3615
σ_{MS}	-	-	-	-	-	-	0.00646	0.01545
σ_{HT32}	0.7836	0.8450	0.3038	0.6036	0.01578	0.3300	0.7248	0.9134
σ_{HT36}	0.01687	0.03834	0.4296	0.2412	0.1023	0.2205	-	-
σ_{HT40}	-	-	-	-	0.5848	0.2784	-	-
σ_{rc}	-0.04922	-0.04738	-0.02149	0.003143	-0.03705	-0.02123	-0.03157	-0.01097
w_{p0}	-0.01272	-0.01548	0.01882	-0.02356	-0.01440	-0.00798	-0.02816	-0.000751
w_{s0}	-0.02125	-0.01604	-0.02209	-0.00666	-0.06975	-0.02156	-0.00980	-0.00283
v_{s0}	0.000259	0.00141	0.000085	-0.0000024	0.000162	-0.001440	0.000079	-0.00237

t_p: thickness of plates
t_s: thickness of stiffeners
σ_{MS}: yielding stress of Mild Steel
σ_{HT32}: yielding stress of HT32
σ_{HT36}: yielding stress of HT36
σ_{HT40}: yielding stress of HT40
σ_{rc}: compressive residual stress in panel)
w_{p0}: initial deflection in panels
w_{s0}: initial deflection in stiffeners (flexural buckling mode)
v_{s0}: initial deflection in stiffeners (tripping mode)

2.2.5 *Reply to Dr. P.A. Frieze*

The 'empirical formulation' defined by the committee is the formulation based on the measured results of experiments and/or calculated results of theoretical analyses.

Regarding the influence of inplane boundary condition on the buckling/plastic collapse behaviour of structural members, the committee is aware of this fact. This influence may play an important role when a stiffened panel has relatively small number of stiffeners such as the compresion flanges of the test girder tested by Dowling *et al.* (1973). On the contrary, in case of a deck plate or a bottom plate of ships with number of stiffeners, only the panel adjacent to the side shell plating or side coaming provided along opening is affected by the inplane boundary condition, and most of the local panels between stiffeners are considered to behave keeping their edges almost straight. This is the background of the boundary conditioin which was imposed on the stiffened panel for benchmark calculation in Chapter 3.

At the end, the committee thanks Prof. Ueda, Prof. Paik, Prof. Hughes, Prof. Sun, Mr. Quesnel, Dr. Pu and Dr. Frieze for their submission of interesting and valuable on-line discussions.

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