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OFFSHORE STRUCTURES CONGRESS

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## COMMITTEE III.1
# ULTIMATE STRENGTH

## COMMITTEE MANDATE

Concern for the ductile behaviour 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. Consideration shall be given to the practical application of methods.

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# 1. DISCUSSION

## *1.1 Official Discussion by Tetsuya Yao*

### *1.1.1 Introduction*

It is very nice to mention about the history of design criterion in INTRODUCTION. It is very important to know history from which we can learn something useful. Explanations regarding the role of GBS by IMO and CSR by IACS are also nice and timely.

### *1.1.2 Fundamentals*

*1) Design for ultimate strength*

Attention is focused mainly on the ultimate hull girder strength, and various factors by which the ultimate strength is affected are discussed. As the fundamental design criterion,

$$\gamma_S M_S + \gamma_W M_W \leq \frac{M_U}{\gamma_R}$$

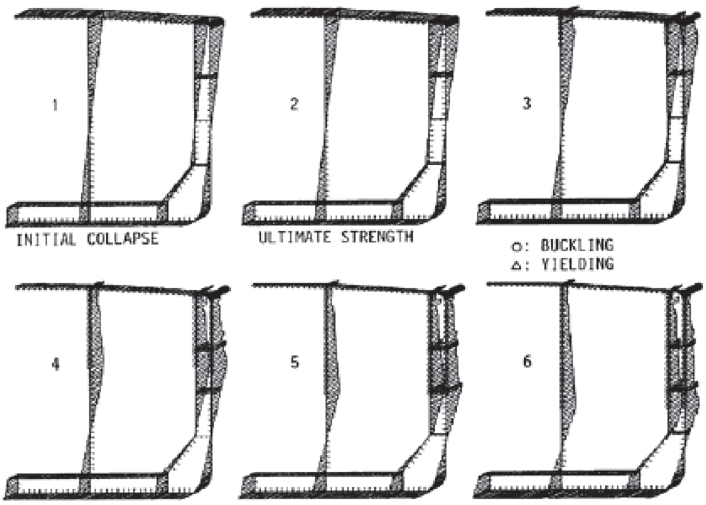
is shown including partial safety factors. Probabilistic approach using reliability index:

$$\beta = \frac{\mu_D - \mu_C}{\sqrt{\sigma_D^2 - \sigma_C^2}}$$

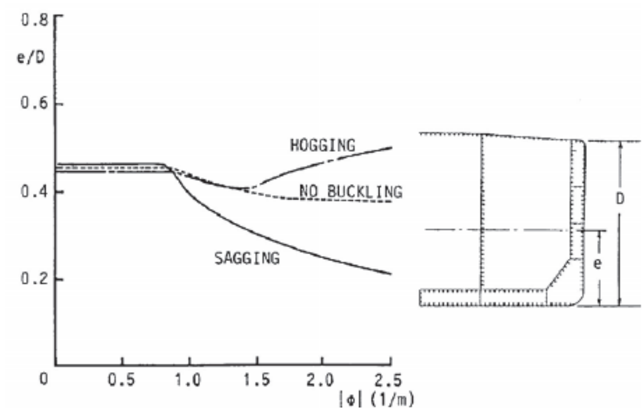
is also introduced as a recent trend.

*2) General characteristics of ultimate strength*

I completely agree that both magnitude and shape are important when the influence of initial deflection is considered, as the report says. In many cases, initial deflection of a buckling mode is considered, but the meaning of this mode should be carefully considered.




(a) Change in stress distribution during progressive collapse




(b) Shift of neutral axis in cross-section

Figure 1.1 Progressive collapse behaviour of cross-section (double-hull oil tanker) [1].

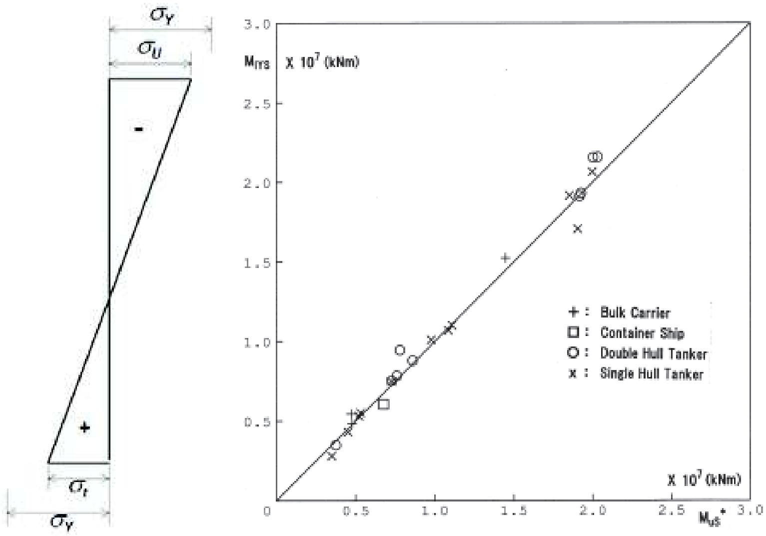
The sentence: “A constrained plate structure under in-plane compression gradually increases after elastic buckling and reaches ultimate strength when it yields due to bending moment caused by lateral deflection.” in the fifth paragraph of Section 2.2 is not understandable. What does “constrained” imply?

As for the collapse behaviour of hull girder in sagging, it is described that “*Under the sagging moment, the hull girder can endure excessive bending moment after the strength deck reaches ultimate strength by redistributing the stress and sharing the load with other members. It then reaches ultimate strength when the stress of bottom structure achieves yield stress in tension.*” In general, this is not true since after the strength deck has been collapsed by buckling, stress in the collapse region start to decrease as indicated in Figure 1.1 [1], and the location of the neutral axis of the cross-section continues to move downwards. Because of this, even if the curvature of the cross-section increases, the tensile strain at the bottom does not increase up to yielding strain owing to the downwards movement of neutral axis. So, as described in the sentence following the above sentence, “*But in this case, the deck structure cannot maintain its resistance after reaching ultimate strength in compression.*” is correct. Therefore, bottom does not reach its yielding strength in tension under the sagging condition. Only the deck collapses in compression by buckling.

### *1.1.3 Assessment Procedure for Ultimate Strength*

#### *1) Empirical and analytical method*

With the same reason explained in 1.1.2, assumption of stress distribution at the ultimate strength in sagging is not correct. That is, after the strength deck has attained its ultimate strength in compression due to buckling collapse, stress in the buckled region starts to decrease and the neutral axis continues to move down as indicated in Figure 1.1. Because of this, stress in the bottom does not reach the yield stress in tension. So, at the ultimate strength in sagging, the stress distribution in the cross-section is not as that indicated in Figure 1.2 of the report. The stress distribution in Figure 1.2 (a) may give the better estimation of the ultimate hull girder strength in sagging, see Figure 1.2 (b) [2].




(a) Assumed stress distribution (b) Accuracy of estimated ultimate hull girder strength [2]

Figure 1.2 Assumed stress distribution in sagging at ultimate strength and estimated ultimate hull girder strength.

It is described that the method on the basis of assumed stress distribution gives comparable ultimate hull girder strength compared to those obtained by other calculation methods. This seems to indicate that the assumed stress distribution method is a good method to predict the ultimate hull girder strength. However, in some cases, for example in sagging condition, or may be in alternative heavy load condition of bulk carrier, the assumed stress distribution in the cross-section at the hull girder ultimate strength is quite different from actual stress distribution. Nevertheless, if good estimation is obtained, something must be wrong, and the errors by different causes may cancel each other. The possible causes of errors could be:

1. wrong assumption in stress distribution at the ultimate strength; which may come from;
2. wrong estimation in capacity reduction in the structural members beyond their ultimate strength;
3. shift of neutral axis of the hull girder cross-section during progressive collapse;
4. which may cause elastic unloading of structural members after they have collapsed.

These should be always kept in mind when a simple prediction method is developed.

I agree with the possibility of extended application of Smith's method. The original Smith's method assumes that a plane cross-section has to be plain during progressive collapse and the individual elements follow the stress-strain relationships considering buckling and yielding which are derived prior to performing progressive collapse analysis. Therefore, if such assumptions can be modified in due manner, application limit of Smith's method can be removed.

It is interesting to know that simple formulas are introduced to estimate the influence of damage on the ultimate hull girder strength. However, the application limit should also be specified, since these formulas may cover only the analysed vessels and not all the cases.

At the beginning, the damaged region has been removed and the progressive collapse analysis was performed. This may result in the underestimation of the ultimate strength of damaged hull girder. Therefore, it is interesting that load-shortening curves are derived analytically for stiffened panel models with dent damage. The research dealing with the influence of cracking is also interesting.

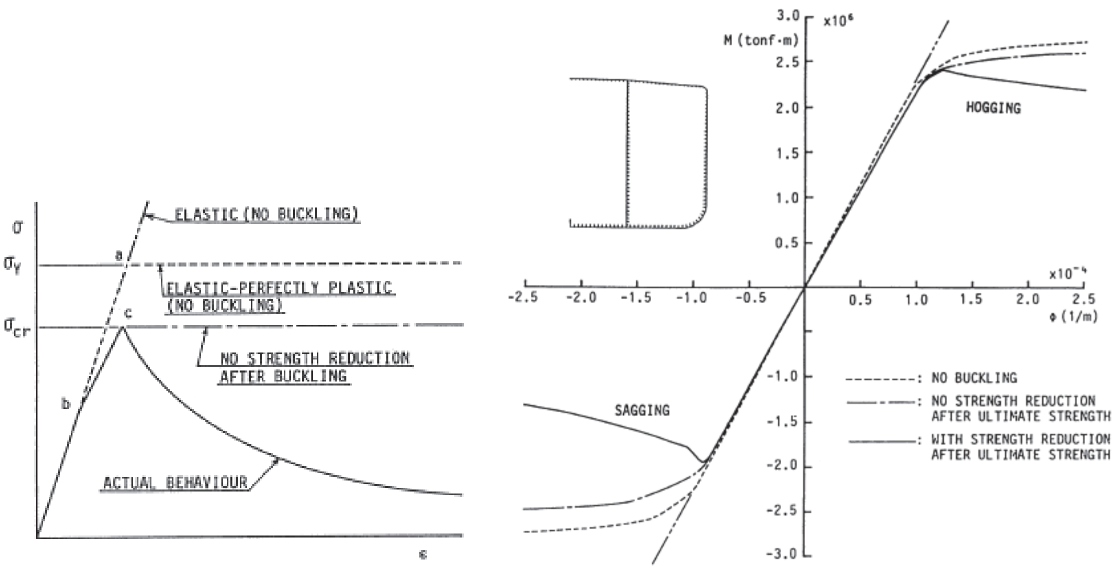
It is known from literature survey that empirical formulas or semi-analytical methods were proposed to estimate the ultimate strength of plates and stiffened plates with damages.

### *2) Numerical methods*

It is nice that categorization is indicated for calculation methods to simulate progressive collapse behaviour of a ship's hull girder and to evaluate its ultimate strength. They ate:

a. Direct method
b. Smith's method
c. Nonlinear Finite Element Method (FEM)
d. Idealised Structural Unit Method (ISUM)

and explanation and literature survey performed for each are interesting and useful.




(a) Behaviour of element (b) Behaviour of hull girder

Figure 1.3 Influence of Element behaviour on global behaviour (by Smith's method) [3].

Regarding nonlinear FEM, nearly 30 research papers are referred. In some papers, calculated results are compared with test results using simple box girders modelling a ship's hull girder. A ship's hull girder may be too huge to construct its scale model even if it is a small model.

Figure 1.3 indicate how the post-ultimate strength behaviour of individual structural member affects the global collapse behaviour of a hull girder [3]. As for the ISUM elements, it has now become possible to estimate relatively accurate ultimate strength. However, what is more important is how accurately the ISUM element can simulate the capacity reduction beyond the ultimate strength in individual ISUM element.

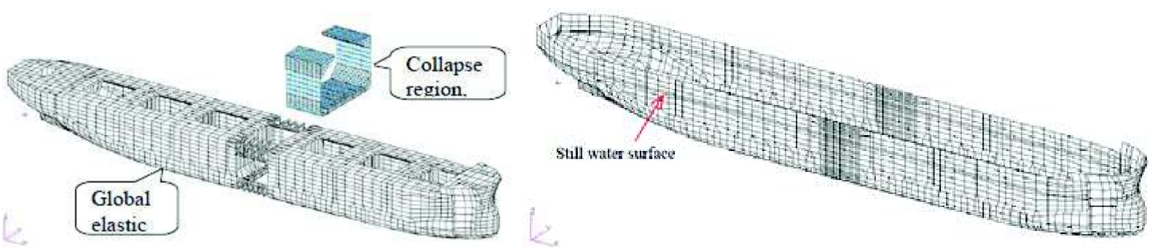
ISUM analysis is usually performed to simulate progressive collapse behaviour of, for example, a ship's hull girder. In this case, structural members collapse one by one, and the capacity of each member beyond its ultimate strength largely affect the progressive collapse behaviour and the ultimate strength of a whole structure as indicated in Figure 1.3. So, when an ISUM analysis is performed, characteristics of ISUM element, both the ultimate strength and the post-ultimate strength behaviour have to be carefully examined before performing progressive collapse analysis. Without this, the calculated results cannot be properly assessed.

It is nice to have an overview of ISUM introducing old papers. On the other hand, new papers are very few. It is also described in 3.2.4 that "… *most of the collapse analyses neglect the time dependent mass and inertia effects and* … ." I wonder why the important papers dealing with this subject are missing [4, 5, 6]. These papers deal with development of a total system to simulate progressive collapse behaviour of a ship's hull girder in an extremely rough sea.

Of course it is very important to know the ultimate hull girder strength itself as the maximum capacity of the hull girder that it can sustain. At the same time, it is important to know what shall happen if the wave load higher than the capacity acts on a ship's hull girder. This question was raised by Prof. Lehmann as an official discusser to the Report of Committee III.1 in ISSC 2006 [7]. A joint research project was launched in 2008 responding to Prof. Lehman's question among Tsuneishi Shipbuilding Co., Ltd., Osaka University and Hiroshima University and later National Maritime Research Institute.

The aim of the research project was to develop a total system to simulate progressive collapse behaviour of a ship's hull girder in an extremely rough sea. In the total system developed through this project,

1. A full ship model is used.
2. Three dimensional singularity distribution method is applied to obtain time history of pressure distribution on ship's surface.
3. For the pressure calculation, the same surface mesh is used with that for progressive collapse analysis, see Figure 1.4.
4. Progressive collapse analysis is performed with mixed model of FEM and ISUM elements. Only the region which may collapse is modelled with ISUM element, and the remaining region with elastic FEM elements with course meshing.
5. There are two phases, which are Phase 1 and Phase 2.
6. In Phase 1, time history of pressure distribution is firstly calculated performing motion/load analysis assuming that a hull girder is rigid. Then, progressive collapse analysis is performed applying the pressure distribution with time history. Analysis is performed until stable solution can not be obtained.
7. In Phase 2, displacements are divided into rigid body motion components and elastoplastic components, see Figure 1.5. Equation of motion is in terms of rigid body components and equilibrium equation in terms of elastoplastic components. Two equations are solved alternately reflecting the calculated results each other.




(a) Model for progressive collapse analysis (b) Model for motion/load analysis

Figure 1.4 Two models for total system analysis [4].

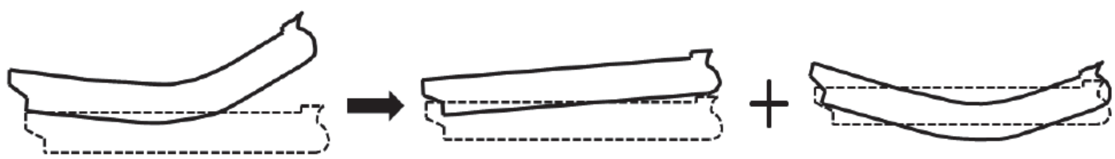


Figure 1.5 Decomposition of displacements (rigid body motion and elastoplastic components) [5].

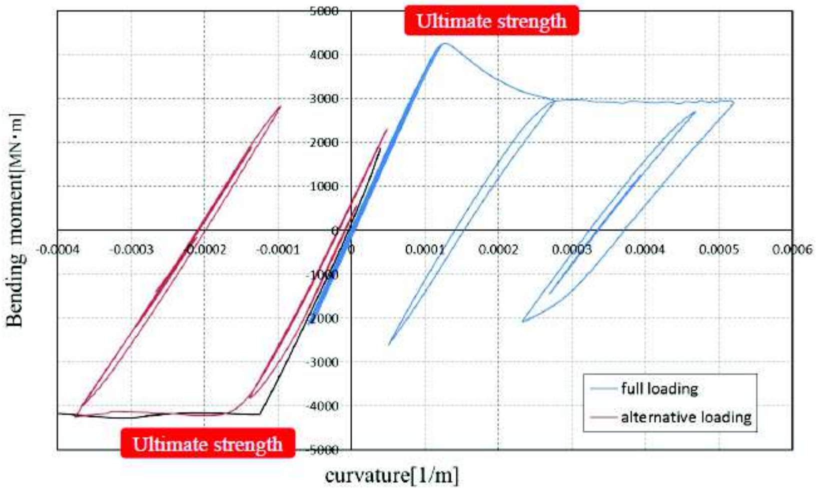



Figure 1.6 Repeated progressive collapse behaviour of bulk carrier in extreme sea [6].

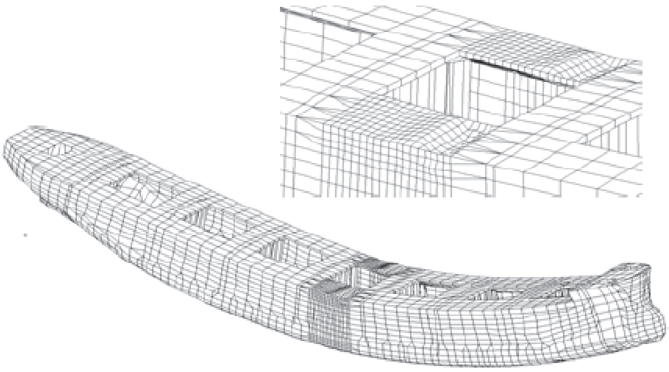


Figure 1.7 Sagging collapse mode in homogeneous loading condition [6].

Bending moment-curvature relationships in sagging under homogeneous loading condition and in hogging under alternative heavy loading condition are indicated in Figure 1.6 and the collapse mode in sagging in Figure 1.7. It is seen that progressive collapse behaviour under repeated extreme loads is well simulated.

### *3) Experimental methods*

More than 30 papers are reviewed related to collapse tests on plates and stiffened plates as well as box girders modelling a ship's hull girder. It is described that experimental data can be used as target values for calibration of progressive collapse behaviour of structural models.

### *4) Reliability assessment*

Research is continuously performed for the strength assessment of ship structures on the basis of reliability analysis. Topics on damage indices for grounding and collision, their influence on residual strength as well as reliability of a fixed offshore platform against seismic loads are interesting.

### *5) Rules and regulations*

It is very nice that the report includes this section at the timing that Goal-Based New Ship Construction Standards (GBS) and Harmonised Common Structural Rules (H-CSR) have come into effect. The report describes the history of GBS and H-CSR, which helps to understand why GBS and H-CSR appeared.

In general, scantlings determined by H-CSR are in many cases too conservative, that is structural members are oversized. This may be because, as described in the committee report, safer scantling is adopted among CSRs for bulk carriers and oil tankers in harmonisation when theoretical background is not clear. This should be revised urgently aiming at more rational design, and more researches have to be conducted for this.

### *1.1.4 Ultimate Strength of Various Structures*

#### *1) Tubular members and joints*

It is described that the subject of recent researches on tubular members are mostly focused on how to strengthen the tubular members. There exist two method, which are to use fiber reinforced polymers and the other to use steel-concrete composite structure. Altogether 42 papers are referred for the researches on strength of tubular members and joints.

#### *2) Steel plates and stiffened plates*

Plates and stiffened plates are the most fundamental structural members especially in ship structure. Because of this, researches on buckling/ultimate strength of plates and stiffened plates have been actively conducted during the last three years also. Altogether 46 papers are introduced, which deal with analytical formulations for ultimate strength of stiffened panels; uniaxial compression; multiple load effects; panels with openings, cut-outs, or rapture damage; welding effects; in-service degradation; experimental testing; and optimization. I agree that future works indicated in the report are important, especially a better treatment of complex load patterns in progressive collapse type methodologies. I also agree what is written in the report that the ultimate strength formulas in H-CSR have to be carefully examined.

#### *3) Shells*

12 research papers are introduced in which buckling/ultimate strength issues are investigated after a brief introduction of state of the art of the research in this field. The research on strength of ring stiffened cylinder under external pressure, collapse tests on 47 models of submarine pressure hulls and buckling strength of deep-sea pipelines are interesting.

#### *4) Ship structures*

It is reported that the research works conducted during the last three years are mainly on the validation of the ultimate strength formulas in H-CSR. This is very important. Many of the papers deal with progressive collapse analyses on a ship's hull girder. In the report, as a fundamental, Smith's method is briefly explained before introducing research results.

#### *5) Offshore structures*

Research papers dealing with strength of offshore structures are not so many compared to ship structures. Nevertheless, 10 papers are referred which deal with different subject. Recently, supply boats are getting larger and the bow structure has been changed. Because of this, it is pointed out and I agree that existing rules have to be revised on the basis of the recent research results.

#### *6) Composite structures*

To analyse progressive collapse behaviour of composite structure, it is necessary to introduce the criteria of breaking. It is also necessary to introduce degradation model which can simulate damage progression from the start of failure until the ultimate failure. These are quite different from steel structures and essential when composite structure is considered. Many of the research works are on developing such degradation model. Experimental work is very important to validate the degradation model. Degradation of material due to exposure in sea water and/or under high temperature is also an important issue in composite material.

#### *7) Aluminium structures*

Aluminium structures are lighter compared to steel structures. The main problem of aluminium structure is the lower strength in the region of head affected zone in welding. In case of aluminium stiffened plates, stiffeners of a different shape can be used, for example, a hat-type, which has two webs and a flange. Stiffened panel can be produced also by extrusion. By this, a hat-type stiffener can be provided. There is no softening problem in this structure.

At the moment, use of aluminium for ship structure is limited. However, the use of aluminium shall increase to build high speed vessels in a near future. In this case, the researches have to be performed to investigate into alloy components, material nonlinearity, welding problems especially material softening, initial deflection and welding residual stress as well as aluminium honeycomb and sandwich structures

### *1.1.5 Benchmark Study*

#### *1) Smaller box girder*

Size of the model seems appropriate and this may be the reason why eleven members among seventeen contributed to the benchmark study. It is known that:

1. Scatter in the evaluated ultimate strength is rather small. On the other hand, some differences are observed in the capacity reduction beyond the ultimate strength.
2. Nevertheless, it can be said that performing progressive collapse analysis has now become no more special if the size of structure is not so large.
3. It is a very nice way to indicate the results of benchmark calculation with mean numerical and mean plus/minus standard deviation curves.
4. Measured ultimate strength is relatively higher than the calculated results applying nonlinear FEM. Several seasons are indicated why large difference is observed. For example, difference in existing and assumed initial imperfections as well as difference in loading conditions are indicated.
5. On the other hand, nonlinear FEM analysis using solid elements gives relatively higher ultimate strength and higher elastic flexural stiffness comparative to the measured results. The reason for this is not explained.
6. Smith's method also gives higher ultimate strength compared to nonlinear FEM. This is partly because of the use of hard corner elements. Of course the average stress-average strain relationships are the main factor which affect the calculated ultimate strength. However, the area and the number of hard corner elements also affects the ultimate strength as described in the report. It is recommended to examine by the FEM analyses if hard corners actually exist by plotting stress distribution in the girder cross-section in bending.
7. Influences of magnitude and shape of initial deflection, material model parameters and plate thickness are also examined, but they may not be the cause of difference in the measured and calculated ultimate strength. However, the plate thickness of the model may not differ so much from 4 mm.
8. Although it was not examined, the influence of welding residual stress should also be examined. In general, high welding residual stresses are produced in a small-sized girder models with several longitudinal stiffeners [8]. The compressive residual stress may reduce buckling and the ultimate strength of local panel between longitudinal stiffeners. On the other hand, the tensile residual stress near the longitudinal stiffener may increase the buckling and the ultimate strength when a collapse takes place in an overall mode.

#### *2) Three hold model of hull girder*

Participants to this benchmark study are four. This may be partly because, as described in the report, stable solution cannot be obtained when an analysed structure becomes huge. Cape size bulk carrier which was used in the Special Task Committee VI.2 is again used. It is timely and nice to examine the influence of local bending of double bottom on the ultimate hull girder strength in hogging through benchmark calculation. Back data for H-SCR to define the reduction ratio, $\gamma_{DB}$ = 1.25, in case of an alternative heavy loading condition in bulk carriers is obtained by this benchmark calculation.

### *1.1.6 Conclusion and Recommendation*

The contents of the report is well summarised and recommendations for the future works are informative. What are important among them are:

1. Collapse tests using larger test models are expected, of which results can be used to verify new calculation methods and/or calculated results.
2. There still exist unclear issues in H-CSR rules, and in some cases structures are over-sized. For such issues of which technical background is not clear, urgent researches are expected to start.
3. It is very important to clarify the capacity of the ultimate strength by nonlinear progressive collapse analysis applying forced displacements or forced rotations. However, at the same time as Prof. Lehmann pointed out nine years ago [7], it is very important to apply actual loads (distributed pressure) and see what shall happen in the structure exposed to severe loads from the safety viewpoints. Such study has already started and has to be further developed.

### 1.1.7 Acknowledgement

At the end, the report covers wide range related to the ultimate strength of marine structures within limited pages. The answers to the committee mandate are fundamentally indicated. We should appreciate the members for their excellent works and thank them with laud applauses.

### 1.1.8 References


[1] Yao, T., Fujikubo, M., Kondo, K. and Nagahama, S.: "Progressive Collapse Behaviour of Double Hull Tanker Under Longitudinal Bending," Proc. Fourth Int. Offshore and Polar Engineering Conference, Vol. IV, Osaka (1994), pp. 570–577.

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[6] Fujikubo, M., Goto, M., Iijima, K., Pei, Z. and Yao, T.: Motion/Collapse Analysis of a Ship's Hull Girder in Waves Using Idealized Structural Unit Method," Proc. Int. Conf. on Safety and Reliability of Ship, Offshore & Subsea Structures, Glasgow, UK (2014).

[7] Lehmann, E.: Official Discussion on Report of Committee III.1: Ultimate Strength, Proc. ISC 2006, Vol. 3 (2006), pp. 121–131.

[8] Dow, R.S.: Testing and Analysis of a 1/3-scale Welded Steel Frigate Model, Proc. Int. Conf on Advances in Marine Structures, ARE, Dunfirmline, UK (1991), pp. 749–773.


## 1.2 Floor and Written Discussions

### 1.2.1 Tetsuo Okada (Yokohama National University)

Thank you for the excellent report on ultimate strength.

I have two questions on the verification of double bottom factor stipulated in the Harmonized CSR. Firstly, I think that appropriate considerations on the simultaneous combination of loads is important for rational investigation. To my understanding, in case of the deepest draft condition when the lateral load is maximum, hogging still water bending moment is typically not maximum. Therefore, if the double bottom factor $\gamma_{DB}$ of 1.25 was verified to be quite appropriate in case of the combination of maximum hogging bending moment and maximum lateral load, application of $\gamma_{DB} = 1.25$ may be too conservative if it is applied to the condition with maximum hogging still water bending moment. I would like to know the committee's view on how to combine longitudinal bending moment and lateral load, considering their simultaneity.

Second point is the location within the ship where the effect of the lateral load is critical. I think that the location where the effect of the lateral load is critical is limited, while the location where the effect of the longitudinal bending moment is critical is throughout the hold in the midship region. Therefore, if the double bottom factor of 1.25 is applied throughout the hold, it may result in too conservative design. I would also appreciate the committee's view on this point.

### 1.2.2 Robert A. Sielski (Consultant, USA)

The principal difference between the calculation of the ultimate strength of a stiffened panel in compression and the ultimate strength of a grillage, such as the box girder that the committee evaluated is the presence of transverse frames to support the longitudinal stiffeners. If the transverse frames are sufficiently rigid, the stiffeners will have the strength of a single panel, and analysis with the strength method is valid. However, if the transverse frames are not sufficiently rigid, the strength of the longitudinal stiffeners is reduced.

The literature that the committee has reviewed does not investigate the minimum required rigidity of transverse frames.

There are several conflicting requirements that have been developed in the past, and some classification societies have requirements based on the deflection under transverse loads, not ultimate strength under compression.

Can the committee explain why they found no recent research on the required stiffness of transverse frames and if they think such work is needed?

### *1.2.3 Marco Gaiotti (University of Genoa)*

My question to ISSC Committee on ultimate strength can be summarized in the following:

"During the presentation a degradation model for composite materials was mentioned, in order to account for ultimate and post-ultimate response of composites.

I wish I knew how such degradation model is intended, considering the brittle behavior of composites".

### *1.2.4 Wolfgang Fricke (Hamburg University of Technology)*

The Committee, which has produced an excellent report, covers the ultimate strength of structures made of different materials, namely steel, aluminium and composites. What is missing are glass structures applied to an increasing extent in cruise vessels and megayachts. However, several accidents occurred in recent years calling for better understanding of the structural behavior of glass windows and surrounding structures. This is an important issue for the ship's safety. Some investigations regarding the ultimate strength under quasi-static and dynamic loads have already been performed and published [1]. I recommend to include this subject in the work of the next Committee.

[1] Fricke, W.; Gerlach, B. and Guiard, M.: Experimental and numerical investigation on the load carrying behaviour of large ship windows. Proc. 33rd Int. Conf. on Ocean, Offshore and Arctic Engng. OMAE2014-23803, ASME 2014.

### *1.2.5 Ling Zhu (Wuhan University of Technology)*

The committee is congratulated for providing a comprehensive report covering various issues concerning the challenging topic of ultimate strength. I have two issues which are raised to the committee for comments.

Firstly, most of ultimate strength work in the report is on the traditional topic of bending-only condition, including the benchmark buckling strength studies. No doubt this is a fundamental part of ultimate strength. Against the background of many realistic cases/incidents which showed the significant importance of combined loads, particularly the appearance of torsion loadings, for instance, larger container ships or twin-hull vessels in oblique sea condition. The total stress in these cases could be dominant. I would like to have the view from the committee on the future development on this aspect.

Secondly, it is good to see many numerical simulations carried out and software packages developed. I would like to stress the importance of experimental work to be in partnership with the fast-growing numerical ones. It is well-known that many rule/regulations were driven by major accidents, which are the real full scale experiments, albeit, the most expensive ones. Many organisations around the world have various testing facilities doing same or different types of experiments. I would like to have the committee's view on the possibility of using experimental facilities available worldwide, by some sort of joint projects.

### *1.2.6 Saad Bahey Eldeen (Port Said University)*

**Experimental methods**

Corrosion degradation is one of the most important ageing parameters to be included in the strength assessment. The preparation of the corroded specimens is a huge mission from time and cost point of view. The history of the unique corrosion test may be recognized, where three corrosion tests for large scale box girders, representing a mid-ship section of single hull tanker have been performed by Domzalicki et al. (2009).The step forward to study of ultimate strength of real corroded box girders has been performed by Saad-Eldeen et al. (2010, 2011b, 2011a, 2013b), where three experimental tests have been conducted for three corroded box girders, with different corrosion degradation levels. The box girder was subjected to four-point loading resulting in a uniform bending moment along the specimen.

**In service degradation**

We need to stress that, most of the experimental tests reported are based on new built specimens as plates, stiffened panels and box girders, which considering only the strength at zero service life. These specimens are not capable of representing the in service behaviour of the structural components, due to different failure modes that may occur.

To account for this issue, Saad-Eldeen et al. (2012a), et al. [25], analysed the structural behaviour of real structural elements, where the initial and post-collapse plate deflections, based on measurement records of the experimental tests of three corroded box girders subjected to pure vertical bending loading.

The effect of initial imperfections and real corrosion degradation on the final post-collapse deformation shape has been investigated and a relationship between different loading responses, shape of initial imperfections and plate slenderness has been derived. Analysing initial imperfections, plate slenderness and final post-collapse deformations, a slenderness criterion has been established to predict the post-collapse deformation shape.

**Corrosion**

Additional analysis, considered by SNAME as a significant paper, regarding corrosion-dependent ultimate strength assessment of aged box girders based on experimental results has been performed by Saad-Eldeen et al. (2012b). The effect of corrosion degradation on the residual stresses during the service life has been analysed, and regression equations for predicting the remaining residual stresses along the service life were developed. A corrosion-dependent moment–curvature relationship has been established, accounting for the changes in geometrical and material properties of the tested steel box girders.

**Reviews and applications**

The review and applications may be divided in two parts; one for intact structures and the other one for aged structures. Because the methodology of dealing with the corrosion degradation is different, starting from the corrosion simulation (average or real node thicknesses) and the stress-strain material models. In this field, Saad-Eldeen et al. (2012d, 2012e, 2012f, 2013a, 2014) performed a series of FE analysis for ultimate strength of corroded box girders. Two models of corrosion degradation have been adopted, one is an average general corrosion thickness reduction, and the other is the real thickness of the corroded plates. New stress-strain models have been developed, accounting for the effect of corrosion degradation on the mechanical properties and the residual stresses. The comparison showed a good agreement with the experimental results and supported the choice of the newly developed stress-strain relationships for corroded structures

The report misses the opportunity to add a section related to material property degradation for steel structures

In this section, the results of ultimate strength tests of corroded structures and direct tensile tests of corroded specimens can be the base for new material models for aged structures. These models can be implemented to any software to account for the mechanical properties changes as a result of corrosion. Saad-Eldeen et al. (2012c) presented an experimental study on the effect of corrosion degradation on the ultimate strength of corroded steel box girders, tested in direct contact with sea water. The effect of corrosion degradation on the ultimate strength of the box girder was analysed, and dissipated energy, compliance, ductility and elastic limit are verified and discussed. A significant reduction in the stiffness, stress-strain relationship and elastic modulus was observed. A relationship based on the experimental observations has been developed to calculate the equivalent Young's modulus of corroded structures as a function of the total reduction of the cross sectional area by Saad-Eldeen et al. (2013a).

Garbatov et al. (2014a) performed tensile strength tests on small scale corroded specimens. The specimens were cut from a box girder that was corroded in real sea water conditions. As a result of the tensile tests the mechanical properties of the specimens are determined; modulus of elasticity, yield stress, tensile strength, resilience, fracture toughness and total uniform elongation. An equivalent stress-strain curve of corroded steel plates as a function of the corrosion degree of degradation was developed based on the regression equations.

The findings presented in the above mentioned papers may influence significantly the strength assessment of corroded structures, as changes of material properties due to aging effects are normally ignored in the currently used procedures.

Very similar output has been also seen in fatigue test of corroded specimens done by Garbatov et al. (2014b).

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### *1.2.7 George Wang (ABS)*

<u>Benchmarking tests</u>

Recall Prof. Yao led the 2000 ISSC Committee on ultimate strength. They compared predictions using different approaches by different institutes. Their comparative study has become a classic cooperative work. I am pleased to know that this current committee has also performed a series of benchmark study, summarized in Section 5.

When I review Figures 24, 25, 26, 28, 31, 32, 33, 34, 35, I feel uncomfortable. The differences between calculations and tests are extremely big. Would like to hear the Committee's view about these differences.

<u>What is Hull Girder Ultimate Strength?</u>

The latest IACS CSR Rules has the following definition:

"The ultimate bending moment capacities of a hull girder transverse section, in hogging and sagging conditions, are defined as the maximum values of the curve of bending moment capacity versus the curvature $\chi$ of the transverse section considered."

The implied assumption is that a hull girder under bending behaves like a beam. This may be true when calculating hull girder ultimate bending capacity under sagging.

Under a hogging condition, the IACS-adopted calculation approach overestimates the sagging ultimate strength of a bulk carrier at its empty hold. Therefore, IACS introduces a factor to adjust. While I am glad to note that this Committee capture the research reports on this discrepancy in Smith-type method, I would expect the Committee to make a suggestion on make fundamental improvement to our current state-of-art technology. An adjustment factor is no more than a quick fix. We are not close to solving the disadvantages of our state of art technology.

## 2 REPLY BY COMMITTEE

### *2.1 Reply to the Official Discusser Emeritus Prof. Tetsuya Yao (Osaka University, Japan)*

First of all, this committee would like to express our thanks to Prof. Yao for his kind evaluation, precise comments, and discussions on the Committee III.1 Report. The committee will try to reply to the comments and discussions. For easy cross reference, the comments and discussions were arranged in subsections. The committee will try to reply to the comments and discussions.

#### *2.1.1 Introduction*

The committee thanks for Prof. Yao's discussion and agree his comments.

#### *2.1.2 Fundamentals*

The committee thanks for Prof. Yao's discussion and agree his comments.

The following expressions are used in our report.

It is important to take into account the post buckling strength of stiffened structure in order to estimate accurately the hull girder ultimate strength under sagging condition. The hull girder reaches its ultimate strength just after the time when the deck reaches its ultimate strength.

I should think that the section of general bulk carrier and oil tanker will reach to the ultimate strength in sagging condition when the collapse by buckling in deck part takes place.

Figure 1 (Figure 2 in committee report) shows the assumed stress distribution at ultimate strength according to simplified method by Paik et al. This distribution is however incorrect for ordinarily designed bulk carriers and oil tankers as the hull girder collapses before the stress at bottom reaches the yield stress.

If the scantling of stiffeners in deck and in its neighbourhood is not consistent, stiffener buckling failure will not take place at the same time. In this sense, for estimating the hull girder ultimate strength accurately under sagging condition, I should think that it is important to take into account the post buckling behavior of deck part.

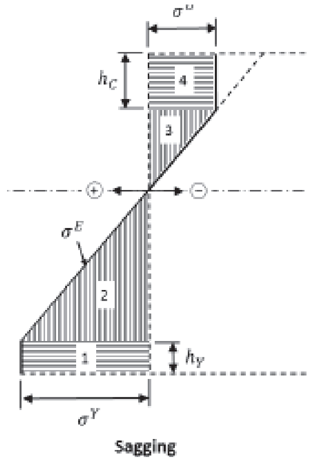


Figure.1 Assumed stress distribution at ultimate strength in sagging in a simplified method

#### *2.1.3 Assessment Procedure for Ultimate Strength*

#### *1) Empirical and analytical method*

The committee thanks for Prof. Yao's discussion and agree his comments.

### *2) Numerical methods*

Thanks for providing useful comments and showing recent researches.

As Prof. Yao has stated, it is important to know what shall happened if the wave load higher than the capacity acts on a ship's hull girder. Using a full ship model and ISUM elements, the behavior under wave load were calculated dynamically in suggested references.

As for the dynamic effect on the ultimate strength, I would like to point out the paper investigated by Iijima et al. (2011). In this paper, the dynamic effect on the ultimate strength was investigated analytically, and some results are validated against experimental results. As future work, systematic assessment of the effect of dynamic loading on ultimate strength is desired to be investigated.

Kazuhiro Iijima, Kazuhiro, Kimura, Weijum Xu, Masahiko Fujikubo, 2011. Hydroelasto-plasticity approach to predicting the post-ultimate strength behavior of a ship's hull girder in wav. *Journal of Marine Science and Technology*, 16, 379–389.

### *3) Experimental methods*

The committee thanks for Prof. Yao's discussion and agree his comments.

### *4) Reliability assessment*

The committee thanks for Prof. Yao's discussion and agree his comments.

### *5) Rules and regulations*

The committee thanks for Prof. Yao's discussion and agree his comments.

## *2.1.4 Ultimate strength of Various Structures*

The committee thanks for Prof. Yao's discussion and agree his comments.

## *2.1.5 Benchmark Study*

### *1) Smaller box girder*

The committee thanks for Prof. Yao's discussion.

As for the effect of residual stresses, we will continue to investigate and we will present our findings in a paper of the Marine Structures Journal.

As for the effect of imperfection, the effect of lateral buckling mode imperfection on the ultimate strength was found to be dominant in this model. Panel buckling mode and torsional buckling mode imperfections were found to have a small effect. This is because the stiffeners in the model were relatively small and were attached to a relatively thick plate. Then, the stiffened panel firstly buckled with lateral buckling mode of stiffener. If the plate buckling takes place first, the effect of plate buckling mode imperfection becomes dominant.

As for the yield stress, the value of yield stress used in our calculation is different from the original paper. It is because that the exact value was obtained from the supplier.

As for the difference in loading conditions, the following is considered to be one of the reasons.

The friction at loading and supporting points will produce the moment (see Figure 2). This moment has opposite direction to the moment produced by vertical forces. Then, in the experiment, the ultimate strength of box girder model must be evaluated by reducing this additional moment by friction. This friction effect will be 8–10% (see Table 1 and Figure 3), and imperfection effect will be 5–10% (see Table 8 in committee report).

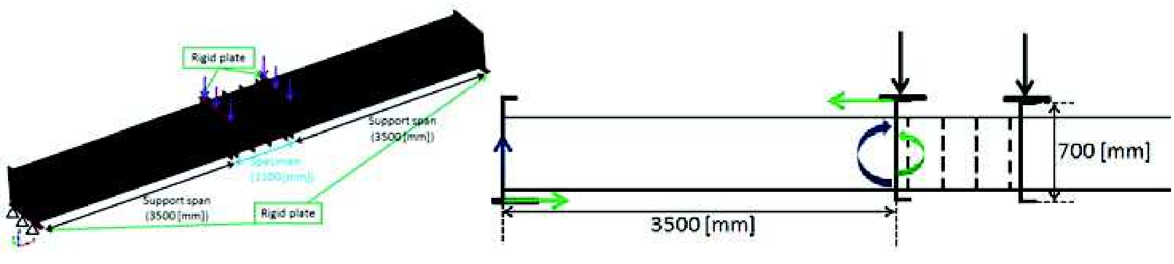


Figure 2 The schematic view for explanation of added bending moment induced by friction forces.

Table.1 The effect of friction at loading and supporting point on bending moment.

| Friction | Maximum Z-force $F_z$ [N] | Bending moment by $F_z$ [MN・m] | Maximum X-force $F_x$ [N] | Bending moment by $F_x$ [MN・m] | Maximum applied moment at mid-span of specimen [MN・m] |
|---|---|---|---|---|---|
| Without | $2.83\times10^5$ | 0.99 | 0 | 0 | 0.99 |
| With | $3.13\times10^5$ | 1.09 | $1.17\times10^5$ | -0.08 | 1.01 |

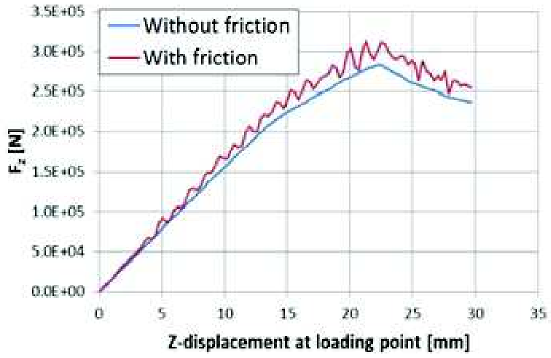


Figure 3 The comparison of calculated load displacement curves between with/without friction forces.

The official discusser had also commented that Nonlinear FEM analysis using solid elements gives relatively higher ultimate strength and higher elastic flexural stiffness comparative to the measured results and the reason for this is not explained.

We should think that one possible reason is that enough number of elements are not used in solid model. When the half size of solid elements is used, the ultimate strength is reduced about 8%. We are planning to check using finer mesh, but have not yet finished.

The official discusser had also commented that Smith's method also gives higher ultimate strength compared to nonlinear FEM. This is partly because of the use of hard corner elements. Of course the average stress-average strain relationships are the main factor which affects the calculated ultimate. It is recommended to examine by the FEM analyses if hard corners actually exist by plotting stress distribution in the girder cross-section in bending.

The committee thanks for Prof. Yao's discussion.

From our experience of calculations for the actual Bulk Carrier, the results of Smith's method gives the ultimate strength between FEA results without imperfection and with imperfection of buckling mode, as shown in table 13 in our report. But, for the box girder model, Smith's method gives higher ultimate strength compared to nonlinear FEA with imperfection.

This is partly because of the use of hard corner elements. I should think that this is mainly because of the difference of the average stress-average strain relationships assumed in CSR and FEA.

In this box girder model, the size of stiffener is considerably small and the attached plate is relatively thick, compared to actual ship structure. Therefore, the rigidity of stiffener is much smaller than $\gamma_{min}$. In this case, the ultimate strength obtained from the average stress-average strain relationships of stiffened panel in CSR gives much higher than FE result (see Figure 4).

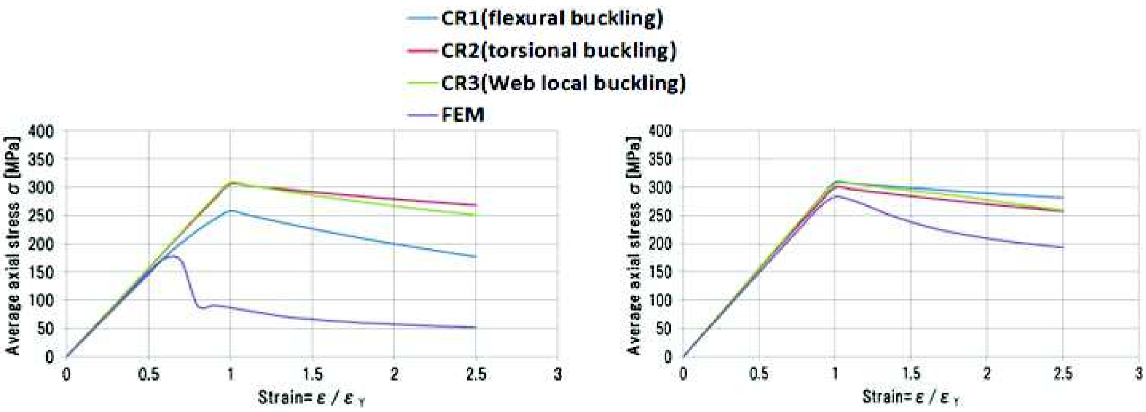


Figure 4 Comparison of CSR and FEM in stress-average strain relationships of stiffened panel

*2) Three hold model for hull girder*

The committee thanks for Prof. Yao's discussion and agree his comments.

### *2.1.6 Conclusion and Recommendation*

The committee thanks for Prof. Yao's discussion and agree his comments.

One last time, we will appreciate deeply to Prof. Yao for taking much time and providing us many useful comments. I would like to express our thank him deeply.

## ***2.2 Reply to the Floor and Written Discussers***

### *2.2.1 Reply to Prof. Tetsuo Okada (Japan)*

As Prof. Okada had pointed, the hogging still water bending moment may be typically not maximum when the lateral load is maximum. From this point of view, the classification society must define the double bottom factor $\gamma_{DB}$ under various loading condition to precisely estimate the hull girder ultimate strength under the lateral load because the still water bending moment is not unique for various loading conditions. And, the ship building company must verify the ultimate strength under many loading conditions if IACS defines the double bottom factor $\gamma_{DB}$ in this way. But, it doesn't seem to be realistic.

Therefore, we should think that it is reasonable to estimate and verify the double bottom factor $\gamma_{DB}$ when the lateral load is maximum as for the somewhat safety side estimation.

In CSR-H, the hull girder ultimate strength is required to be assessed though the cargo area and machinery space. As Prof. Okada had pointed, it may be too conservative if the double bottom factor of 1.25 is applied throughout the hold because the location where the effect of the lateral load is critical is limited. However, the hull girder ultimate strength is usually not critical in aft and fore part of ships. Therefore, we should thank that it may not result in too conservative design.

### *2.2.2 Reply to Dr. Robert A. Sielski (USA)*

The classification rules, such as CSR-H, have the scantling requirements of net section modulus and net shear area for designing the primary support member, such as transverse flame.

This means that these requirements based on allowable stress under transverse loads not ultimate strength under compression.

Up to now, the committee have not found recent researches on the required stiffness of transverse frames.

Although the bending stiffness of transverse frame seems to be large enough to prevent the overall buckling mode in ordinary ships of bulk carrier and oil tanker, we will recommend to investigate requirement of the minimum bending rigidity of transverse frames. It is because there is a possibility that the ship structure with light transverse flame will be adopted especially in high speed ship to reduce the hull weight.

Otherwise, the hull girder ultimate strength including the overall buckling mode of stiffener must be checked utilizing the compartment level collapse analysis, such as "Procoll" developed by Benson.

### *2.2.3 Reply to Prof. Marco Gaiotti (Italy)*

Due to the limitation of presentation time, a degradation model for composite materials could not be explained in detail. The composite material, such as GFRP and CFRP, fails in brittle under tensile load, but the failure mode is more complex under compression. The possible and typical failure modes under compression are matrix failure, fibre breaking, and shearing failure. Moreover, after the lateral impact loading, the delamination between layers will take place and it results the buckling of layer under compression. After these failures, the degradation of rigidity will take place.

Several numerical methodologies exist to represent this degradation, but the two most commonly used approaches are the total discount method and the limited discount method. In the total discount method the strength and stiffness of a failed ply are reduced to zero by altering the material properties of the Finite Element model. This approach tends to underestimate the ultimate strength as it does not take in to account that the residual stiffness of the failed ply. The total discount method is easy to apply and has low computational requirements however its accuracy is low and, as already mention, leads to conservative estimations of the final load (Anyfantis and Tsouvalis, 2012).

The limited discount method works by introducing a stiffness and strength reduction as function of the failure mode. For fibre failure, the longitudinal stiffness and strength properties are degraded, whilst for matrix failure the transverse stiffness and strength are reduced (Cheung et al., 1995). Continuum damage models can be used to better estimate the reduction in stiffness and progressive damage of a laminate (Ribeiro et al., 2013). In this model, complicated damage evolution laws predict the damage accumulation during loading.

As for the more detail of degradation model of composite material, please see Figure 15 in the committee report and the research report by Yang et al. (2011), which was referred in the committee report.

### *2.2.4 Reply to Prof. Wolfgang Fricke (Germany)*

The committee thanks for Prof. Fricke's comments and introduction of a reference.

We had not stated the glass structures, but as Prof. Fricke said it is supposed to be important for in cruise vessels and mega-yachts. We hope that this subject will be included in the work of the next Committee.

### *2.2.5 Reply to Prof. Ling Zhu (China)*

I agree that the hull girder ultimate strength under torsional moment is one of the topics to investigate. We hope that this subject will be included in the work of the next Committee. At that time, the coupling effect of bending moments and torsional moment must be considered by taking account of the different of phase between them.

As you stated, the joint project by using experimental facilities available worldwide is meaningful, if the adequate target is found.

### *2.2.6 Reply to Prof. Saad Bahey Eldeen (Egypt)*

The committee thanks for Prof. Eldeen's offered information and his comments.

As you pointed out, the effect of corrosion on the ultimate strength is one of important items to be treated in our report. In previous ISSC report, the property of aged materials was surveyed in ISSC2009 committee report V.1 (Damage Assessment after Accidental Events) with using 2 pages and ISSC2012 committee report III.1（Ultimate Strength）with using 1 page. The assigned pages in this report are totally one page, and some of your papers had been referred (see section 3.3, 4.2.7 and 4.4.3). There is a limitation of pages in the committee report and therefore we could not refer all of literatures. Please understand this situation.

The followings are comments from our committee to your researches.

The expression of material property degradation for steel structures is not adequate and the expression of *apparent* material property degradation is recommended. The mechanical property will not change excluding oxidized region. Even when the reduction of rigidity and yield stress are recognized in the tensile test of corroded specimen, the yielding takes place earlier due to the stress concentration at the vicinity of corrosion parts and it results the reduction of apparent Young's modulus and yield stress in megascopic.

Moreover, the tensile test was performed to evaluate the equivalent Young's modulus of corroded structures in referred paper, but it is doubtful to be able to apply in the case of compressive loading. In compressive loading, the buckling will take place and the bending rigidity is more important than membrane rigidity in this case. The equivalent Young's modulus in bending is possible to be different from that of tensile loading because the degradation will take place in the vicinity of plate surface.

We hope that the effect of corrosion on the ultimate strength will be discussed more in the work of the next Committee.

### *2.2.7 Reply to George Wang (Singapore)*

For the first question, please see the answer to O.D. (sec. 2.1.5).

As for the effect of lateral loading on hull girder ultimate strength under hogging condition, it was confirmed by FEA for a certain bulk carrier with/without lateral loading that the double bottom factor, $\gamma_{db}$, is adequate. Where, the double bottom factor, $\gamma_{db}$, was introduced in CSR-H in order to consider the decrease of hull girder ultimate capacity by the stresses due to double bottom deformations. For several kinds of bulk carrier, the same results were obtained. Therefore, this factor seems to be applicable for bulk carrier. However, it must be confirmed whether this double bottom factor can be applicable for other kinds of ships such as a container ship.

Instead of double bottom factor, the new approach for estimating double hull girder ultimate strength with directly considering the effect of lateral loading is desired to be developed. For instance, the effect of lateral pressure and bi-axial compression is desired to be included in stress-strain relations of stiffened panel members in smith's method.