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COMMITTEE III.1
ULTIMATE STRENGTH

COMMITTEE MANDATE

Concern for 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 highlightened

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KEYWORDS

Ultimate strength, buckling strength, yielding strength, nonlinear analysis, steel structures, aluminium structures, composite structures, ship structures, offshore structures, initial imperfections, in-service degradation, uncertainties, reliability, static/quasi-static loads

CONTENTS

1. INTRODUCTION

Ultimate strength of structural members and systems is a real measure in strength assessment in a sense that the ultimate strength is the maximum capacity that they can have. No additional load can be carried beyond the ultimate strength. Under general combined loads, buckling and yielding dominate the ultimate strength when compressive stress is dominant, whereas only yielding dominates the ultimate strength when tensile stress is dominant.

It is now common to design structural members and systems so that they do not collapse by buckling or yielding. However, until the middle of 19th century, the design criterion was the breaking strength of the material. This was partly because wrought iron used for ship structures at that time was a brittle material and was week against tensile load just like concrete. Another reason was that buckling phenomenon and its consequence were not well understood, although it had been known that structure may collapse by buckling in the compression side of bending through Fairbairn’s famous collapse test on box girder bridge models in 1845 (Timoshenko, 1953). It was after Bryan (1891) that the panel buckling was theoretically understood and calculated, and that the buckling strength was used as a condition to determine the panel thickness.

From the beginning of the 20th century, it had become common to consider the buckling as a design criterion, and in 21st century it shall be replaced by the ultimate strength. Now is the transition period. The first attempt to evaluate the ultimate strength of ship structure was made by Caldwell (1965). He applied *Rigid Plastic Mechanism Analysis* to evaluate the ultimate hull girder strength. The influence of buckling was considered by reducing the yielding stress of the material at the buckled part.

In 1956, there was a debut paper of the Finite Element Method (FEM; Turner *et al*., 1956). At the beginning, the FEM was only for the analysis of elastic behaviour of structural members and systems. To evaluate the ultimate strength of structural members and systems theoretically, it is necessary to perform structural analysis considering the influences of both buckling and yielding. Such analysis is called elastoplastic large deflection analysis. It was from the early 1970’s that such analysis had become possible to perform applying the FEM. However, it took a decade or two that commercial codes which enable to perform such collapse analysis became commonly used.

It was from the 10th ISSC that benchmark calculation using different nonlinear codes started in this committee (De Oliveira *et al*., 1988). Since then, benchmark calculation has been performed every time. Also this time, benchmark calculation is performed on ultimate longitudinal strength of a passenger ship, see Chapter 14. In other chapters, as previous reports, the literature survey related to buckling/ultimate strength is performed regarding ship and offshore structures. The contents of individual chapters shall be introduced briefly in Chapter 2 in connection with the fundamentals in ultimate strength.

To aim more rational design, it shall be quite natural to consider the ultimate strength as the strength standard instead of buckling strength. Recently, there exist three big movements in the marine society, which are Goal-Based New Ship Construction Standards (GBS) in International Maritime Organisation (IMO), Common Structural Rules (CSR) by International Association of Classification Societies (IACS) and Ultimate Limit State (UL) assessment by International Organisation for Standardisation (ISO). The GBS consists of five tiers as indicated in Figure 1.1. In Tier I, goals are specified for design and construction of new ships. In Tier II, functional requirements are specified to achieve the goals. Tier III is verification of Tier IV, which is an existing framework of regulations, IMO conventions and rules of recognised organisation such as classification societies. CSR are closely related to GBS through Tier IV. What is important is that it is required to evaluate ultimate hull girder strength as well as ultimate strength of plates and stiffened plates in ship structures in CSR. Some important issues related to CSR and GBS shall be explained in Chapters 8 and 10, respectively.

Also in ISO, new standards for limit state assessment of ship structures including buckling/ultimate strength are now coming up. The situation is quite different from that at the previous ISSC. Under such social conditions, the ultimate strength assessment is now becoming a more and more important issue to ensure the safety of ship structures. From this point of view, the role of this committee has also been becoming very important.

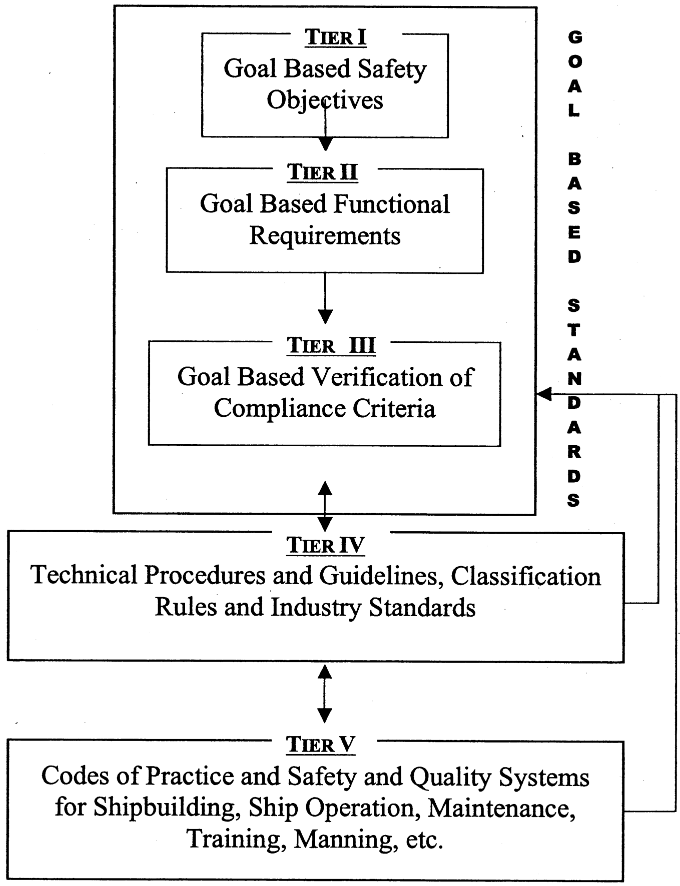


Figure 1.1: Goal-based regulatory framework of five tiers system

2. FUNDAMENTALS

When compressive stress is produced in the structural members such as columns, plates, stiffened plates *etc.* under external/internal loads, buckling shall take place if the compressive stress reaches a certain critical value. In general, lateral deflection rapidly increases after buckling, which reduces axial/in-plane rigidity of the buckled structural members. Due to lateral deflection, bending stress is produced in addition to axial/in-plane stress.

In case of metal structures, this bending stress hastens the occurrence of yielding in combination with the axial/in-pane stress. The rigidity is reduced also by yielding. After the yielded region spreads to some extent, the axial/in-plane rigidity becomes zero and the ultimate strength is attained. Beyond the ultimate strength, capacity starts to decrease rapidly soon after or after a while the ultimate strength has been attained depending on the dimensions of the collapsed structural member and loading conditions.

On the other hand, in case of composite structures, many materials show nonlinear stress-strain relationships and lamina strength may dominate the ultimate strength especially after lateral deflection grows by buckling when the panel has a laminate structure. Such behaviour is quite different from metal structures.

In case of one-dimensional members such as columns, capacity is kept constant and deflection increases after the buckling if the material is elastic. Then, capacity starts to increase with further increase in the deflection. This phenomenon is called ***elastica***. In the actual metal structure, however, yielding takes place soon after the buckling deflection begins to grow, and the capacity starts to decrease. So, the buckling strength is at the same time the ultimate strength in case of one-dimensional members.

It should be noticed that buckling and/or ultimate strength of one-dimensional members is very sensitive to initial distortion. At the same time, in actual structures, both ends are connected to other structural members, and the boundary condition for evaluation of buckling strength has to be carefully considered. The issues related to one-dimensional members and their connections in offshore structures are described in Chapter 7.

In case of metal plates with lower slenderness ratio, yielding starts to take place before buckling occurs. This behaviour is similar to that of columns from the viewpoint that the buckling strength is the same with the ultimate strength. On the other hand, plates with higher slenderness ratio show a little different feature from this. In this case, buckling takes place in an elastic range, and capacity increases after buckling with the increase in lateral deflection although in-plane rigidity is reduced by buckling. This increase in capacity is attributed to the effect of membrane stress produced by large deflection. Then, yielding starts to take place, rigidity gradually decreases and the ultimate strength is attained.

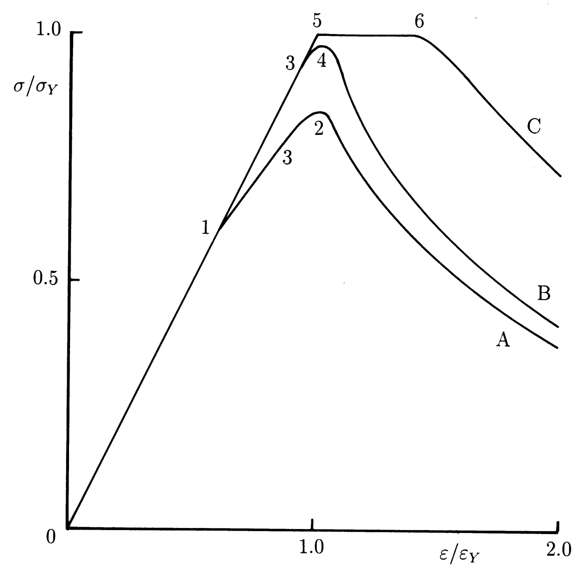


Figure 2.1: Schematic representation of average stress-average strain relationship for stiffened plates under in-plane thrust

Figure 2.1 schematically shows buckling/plastic collapse behaviour of a metal stiffened panel subjected to in-plane thrust in terms of average stress and average strain. When the local panel undergoes elastic buckling, the average stress-average strain relationship follows curve A. In this case, elastic panel buckling takes place at point 1. After this, yielding starts at point 3 and stiffener buckling follows at point 2, where ultimate strength is attained.

When the slenderness ratio of the panel is lower, the average stress-average strain relationship is represented by curve B. In this case, initial yielding starts at point 3, and the ultimate strength at point 4 by stiffener buckling.

When the panel and the stiffener have much lower slenderness ratios, the average stress-average strain relationship follows curve C. In this case, yielding starts at point 5 but no lateral deflection is produced at this moment. At point 6, either panel or stiffener buckles, and the capacity starts to decrease with the increase of lateral deflection in the panel or stiffener.

For other structural members and systems, similar collapse behaviour can be observed under various loading conditions. To simulate such collapse behaviour, empirical, analytical, numerical and experimental methods can be applied. Issues related to these methods are explained in Chapters 3, 4 and 5. At the same time, issues related to buckling collapse behaviour of plates and stiffened plates are explained in Chapter 8 and those related to shells in Chapter 9.

Collapse of metal structures other than buckling is a plastic collapse due to concentrated or distributed lateral loads perpendicular to the axis or plane of the structural members. In this case, plastic hinges or plastic hinge lines are formed due to yielding, and the structure collapses forming a mechanism. Including such collapse, issues related to collapse of structural units or whole structural systems of ships and offshore structures are explained in Chapters 10 and 11, respectively. For aluminium structures, Chapter 13 is provided. Aluminium structures show a little different collapse behaviour from steel structures because of different strain-hardening characteristics and HAZ softening, but the fundamental characteristics in collapse behaviour are almost the same as steel structures.

In any case of metal structures, ultimate strength, which is the maximum capacity that structural members and systems show, is attained after yielding has spread to some extent with and/or without the occurrence of buckling. On the other hand, in case of composite structures, breaking of fibours and/or debonding between layers of the laminated material may dominate the ultimate strength. Issues related to collapse behaviour of composite structures shall be explained in Chapter 12.

At the end, it should be noticed that both the capacity of structures and loads acting on them have statistic characteristics. So, for rational strength assessment to ensure the safety of ship and offshore structures, it is recommended to perform reliability analysis. This issue is explained in Chapter 6.

3. EMPIRICAL AND ANALYTICAL METHODS

For design of marine structures in these days, numerical elastic analyses have been performed using FEM commercial packages. In order to perform the ultimate limit state design, which is already adopted in the common structural rules of IACS, however, nonlinear analyses should be carried out considering material and geometric nonlinearities and initial imperfections. Even for matured structural analysts, nonlinear analyses are still expensive and time-consuming. Therefore, any robust empirical or analytical methods should be developed for structural designers with which the structural analysis process can be simplified and easier to operate.

Traditionally, empirical design formulations have been derived by regression analysis of test data. However, most of design equations are developed based upon numerical parametric study results rather than test data. Any numerical methods even the popular commercial packages employed in the parametric study should be substantiated with relevant test data. Some of design formulations proposed in the open literature, however, were derived omitting the substantiation process.

3.1 Unstiffened and Stiffened Plates

Analytical methods are still welcomed by structural engineers, because of their soundness and physical meanings. For unstiffened and stiffened plates, many kinds of analytical formulations have been proposed to predict their structural behaviour even beyond the ultimate state. Hu and Cui (2003a) developed a simplified analytical method to predict the ultimate strength of unstiffened and stiffened plates based on the combination of elastic large deflection analysis and rigid plastic mechanism analysis. The predictions by the developed method were compared with test data and the design equations of classification society rules. The influences of various factors, such as welding residual stress, transverse stress and lateral pressure were also studied. Hu and Cui (2003b) extended their method for unstiffened plates to deal with combined loadings including longitudinal compression, transverse compression, lateral pressure and edge shear.

Sano *et al.*(2005) proposed a simple model to simulate buckling/plastic collapse behaviour of an ultra-wide rectangular plate subjected to in-plane compression on its wider edges. The buckling and post-buckling strength behaviour are simulated by performing elastic large deflection analysis applying analytical method. On the other hand, post-ultimate strength behaviour is simulated according to the rigid plastic mechanism analysis. Using the proposed method, the average stress-average strain relationship was constructed, which can be applied to transversely stiffened parts of the hull girder when ultimate longitudinal strength analysis is performed with Smith's method.

Byklum *et al.*(2004) derived a computational model for global buckling and postbuckling analysis of stiffened panels subjected to biaxial in-plane compression or tension, shear and lateral pressure. The global buckling model is based on nonlinear plate theory of Marguerre and the local buckling is treated in a separate local model. The two models provide a tool for buckling assessment of stiffened panels. The local and global stresses are combined in an incremental procedure. Ultimate limit state estimates for design were obtained by calculating the stresses at certain critical points, and using the onset of yielding due to membrane stress as the limiting criterion.

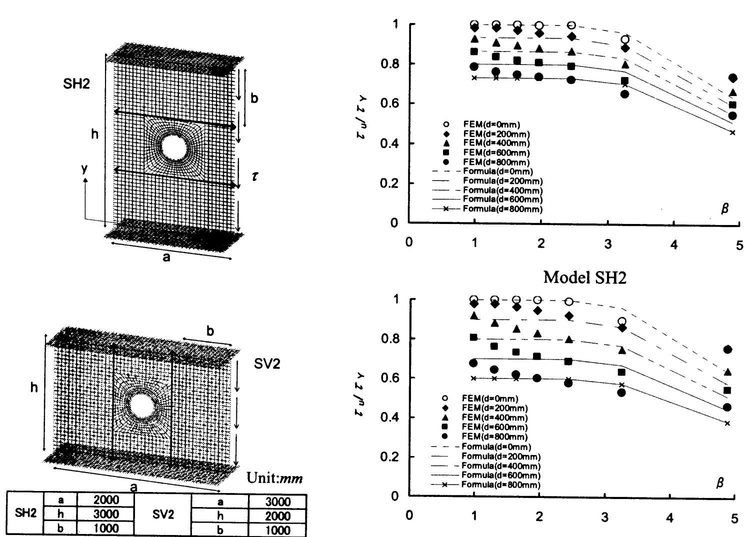


Figure 3.1: Comparison between predicted and calculated ultimate

shear strength of girder web with cutout

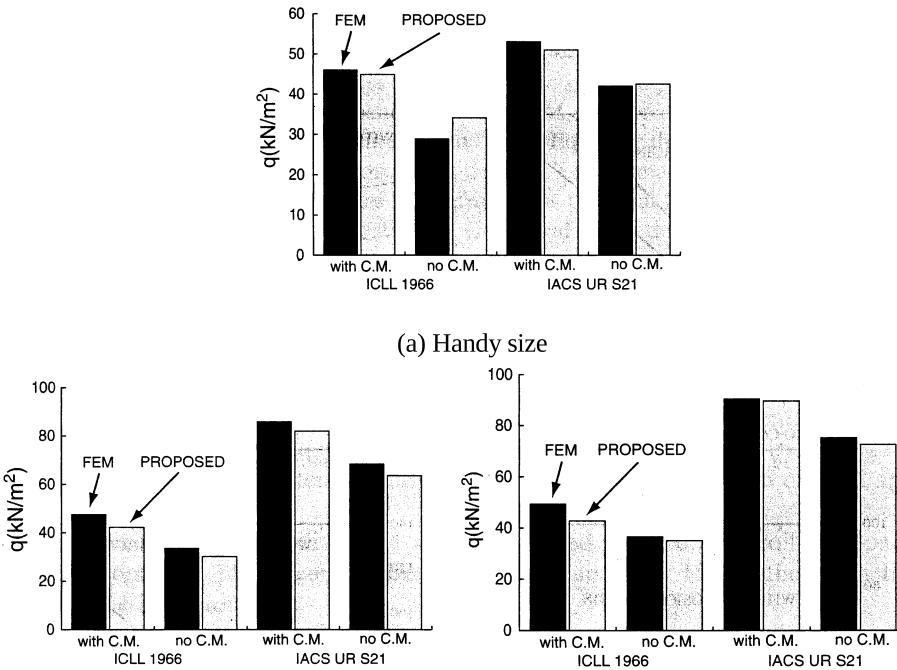
Harada and Fujikubo (2005) performed a series of buckling eigen-value calculations and elastoplastic large deflection analyses by FEM to examine buckling/plastic collapse behaviour of a stiffened web plating with cutout as a part of the ship bottom girder together with those of an isolated plate with cutout. Based on the observations of the FEM calculation results, a set of closed simple formulae were proposed to estimate the elastic buckling and ultimate strength of a stiffened web plating with cutout. The predicted ultimate strength showed good correlations with FEM results, see Figure 3.1.

Zheng and Hu (2005) derived differential equation to analyse tripping of thin-walled stiffeners and solved it with Galerkin's method to get a general eigenvalue problem. A Computer code is developed applying the proposed method to evaluate the tripping strength. After confirming the accuracy of the calculated results with FEM results by MARC, a series of calculation is performed applying axial force, lateral pressure and end moments, respectively. Regression of the calculated results gives out a correlativity formula of the three kinds of applied loads.

Zhang and Tong (2005) summarises currently available techniques of setting up flexural-torsional buckling theory of thin-walled members. They pointed out that all the existing methods introduced a nonlinear load potential in their total potentials, whereas, based on the classical variational principle for stability of a solid structure, no such load potential should be included, of which situation has led to an inconsistency between some widely referenced monographs in buckling theories of beams with mono-symmetrical cross-sections. They provide a new theory for flexural-torsional buckling of thin-walled members on the basis of classical variational principle and the theory for thin-walled shells. No nonlinear load potential is included, but a new term: nonlinear strain energy from transverse stress, which has been neglected in the previous theories of thin-walled members, is introduced. It is found that the proposed theory and the traditional theory gives the same results for most cases encountered in practice.

Some analytical and semi-analytical formulations were performed to evaluate ultimate strength of steel and/or aluminium plates without and with stiffeners subjected to various loads by Paik and Thayamballi (2003), Yanagihara *et al*.(2003), Paik and Duran (2004), Steen *et al*.(2004), Harada *et al*.(2004), Paik *et al*.(2004b), Wang *et al*.(2005), Paik and Lee (2005) and so on. Some of them are introduced in the following chapters with obtained results.

Yao *et al*.(2003) developed a simplified method to evaluate the collapse strength of hatch covers of a folding type and a side sliding type for bulk carriers. The elastic behaviour is simulated by modelling a hatch cover by a both-ends simply supported beam in case of a folding type and by an orthotropic plate with three edges simply supported and one edge free. On the other hand, the plastic strength interaction relationship of the top panel is derived in terms of the pressure load and compressive stress. The influence of local buckling of a top panel is considered introducing effective width after buckling. Collapse pressure is obtained as the pressure at the intersection of elastic and plastic curves. Fugure 3.2 shows the comparison between predicted and calculated collapse pressure.



(a) Handy size

(b) Panamax size

(c) Cape size

Figure 3.2: Comparison of predicted and calculated collapse loads

For the strength assessment, it is very important to predict damages which may affect the strength. Cho and Lee (2004) proposed a simple analytical method to predict the denting damage of stiffened plates under small lateral collision. They assumed that the plate can absorb some portion of the collision energy by the plastic rotation along plastic hinge lines and the membrane plastic tension, and the remaining collision energy can be dissipated by those in the stiffener flanges and the plastic shear deformation of stiffener webs. The proposed method was substantiated with thirty-three test data.

3.2 Tubular Members and Joints

Cho (2005) derived simple empirical design equations for offshore tubular collisions including the relationship between lateral collision force and denting damage, the rate of further deepening of local dent due to curvature increase and the ultimate bending capacity of damaged tubular members. These equations were derived by regression analysis of relevant test data.

To evaluate chord stress in tubular joints, empirical formulas are proposed for various joint types by Qian (2005), Pecknold *et al*.(1998, 2000, 2001), Van der Vegte *et al*.(2003), Liu *et al*.(2004), Burdekin (2001) and so on. Details are described in Chapter 7 together with the descriptions of the proposed formulas.

3.3 Shells

Fukuchi and Okada (2004) presented governing equations for the finite deformation analysis of shell-like lattice structures defined by monoclinic coordinates. The governing equations have been developed applying the method of disturbed small motions to clarify the stability problem of shell-like lattice structures. Calculated results indicate that the complex peninsular shaped instability region are in the excitation force field for arch-lattices under certain loading conditions, and their stability is lost suddenly at a threshold point of dynamic equilibrium from a heteronomous state to an autonomous state of self-sustained motions.

Xiang *et al*.(2005) combined the simple Timoshenko thin shell theory and the more sophisticated Flugge thin shell theory to analyse the elastic buckling behaviour of axially compressed circular cylindrical shells with intermediate ring supports and to examine the sensitivity of the buckling solutions to the different degree of approximations made in shell theories. They divided shell into segments at the locations of the ring supports, and employed the state-space technique to derive the solutions for each shell segment and utilised the domain decomposition method to impose the equilibrium and the compatibility conditions at the interfaces of the shell segments.

Alexandrova and Vila Real (2005) proposed a simplified set of equations for a nonlinear bifurcation problem in thin-walled structures applying the rate formulation on the basis of the classical Hill's approach.

On the basis of the results of FEM calculations as well as simplified methods, empirical formula is derived by Masaoka and Mansour (2004) to estimate the ultimate compressive strength of unstiffened plates. The accuracy of the proposed equations are confirmed through comparison of the calculated results with those by FEM.

4. NUMERICAL METHODS

Numerical methods, such as Finite Element Method (FEM), Mesh-free Method and Idealised Structural Unit Method (ISUM), have been developed as one of the major tools to assess ultimate strength of ships and offshore structures. Instead of generally discussing the recent development in these methods, this chapter is concentrating on the development of these methods for evaluatuion of ultimate strength of marine structural components, such as plates and stiffened plates, and systems.

4.1 Finite Element Method

The techniques in FEM have matured for ultimate strength evaluation of plated structural components. Many researchers have applied FEM to predict ultimate strength of unstiffened plates and stiffened plates, such as, Yanagihara, *et al.*(2003), Harada, *et al.*(2004), Hughes, *et al.*(2004) and Paik, *et al*. (2003a, 2004a, 2005a). In these applications, both geometric and material nonlinearities are considered. It may be said that it is fairly straightforward to use FEM for ultimate strength prediction of plates and stiffened plates.

However, to evaluate ultimate strength of a complicated structure, such as a ship's hull girder, is still a daunting task because large amount of computational time is required. Rapid development in computer capacity may solve this problem in the future. At the moment, it is desirable to further improve computational efficiency in FE nonlinear analysis. Nevertheless, no research work was reported in this aspect in the last three years.

4.2 Mesh-Free Method

As an alternative method to FEM, Mesh-Free Method has been used in many engineering applications. This method is advantageous over FEM in some cases, such as moving boundary problem, crack growth with arbitrary and complicated paths, and phase transformation problems. However, it is more time-consuming than FEM. Peng, *et al.*(2005) have proposed an element-free Galerkin (EFG) method and applied it to static linear analysis of stiffened plates. The results are in good agreement with those of FEM. However, Mesh-Free Method has not yet been applied to collapse analysis of structural members and systems as far as the committee members know.

4.3 Idealised Structural Unit Method (ISUM)

Fujikubo, *et al*.(2003) have introduced a new feature into the existing web element formulation so that the effect of web buckling in bending could be considered. This could improve the accuracy of the method when it is applied to evaluate the strength of double-bottoms of ships. Kaeding, *et al*.(2004) and Fujikubo, *et al*.(2005) have extended the existing ISUM plate element to consider combined uniaxial/bi-axial compression and lateral load, see Figure 4.1. The results are compared favourably with FEM results. Detail of the new ISUM rectangular plate element is explained in detail by Yao (2005a).

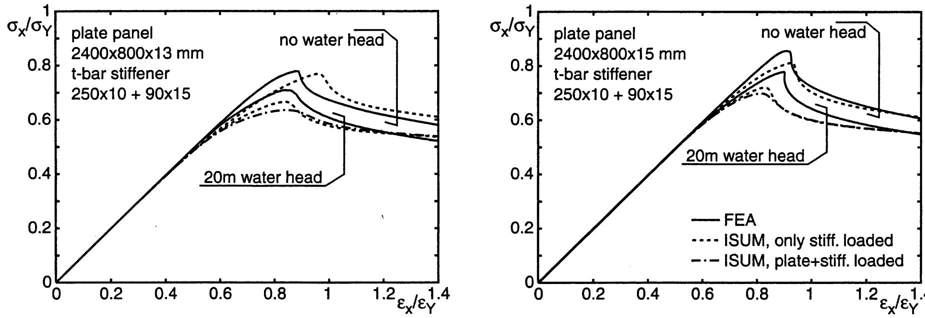


Figure 4.1: Comparison of average stress-average strain relationships of stiffened plates subjected to combined thrust and pressure loads by FEM and ISUM

5. EXPERIMANTAL METHODS

Recently, it has become possible to simulate collapse behaviour of structural members and systems numerically by performing, for example, nonlinear FEM analysis using computers. However, experiments to simulate progressive collapse behaviour of structural members and systems are still important from the viewpoints of:

(1) development and validation of new calculation method;
(2) understanding of collapse behaviour of new structural systems based on new concept.

In such experiments, load-displacement relationships are measured as well as strains and displacements at specified locations to detect buckling or yielding. What has to be noticed is that strains and displacements are in general very large when the load is applied until the test structure completely collapses after attaining its ultimate strength.

In this chapter, development of new experimental techniques for in-service and inspection monitoring as well as above mentioned collapse tests are the main target. Although some important experimental works can be seen during the last three years, for example on stiffened plating (Gordo and Guedes Soares, 2004) and on box girders (Gordo and Guedes Soares, 2005), no new experimental technique has been reported as far as the committee members know.

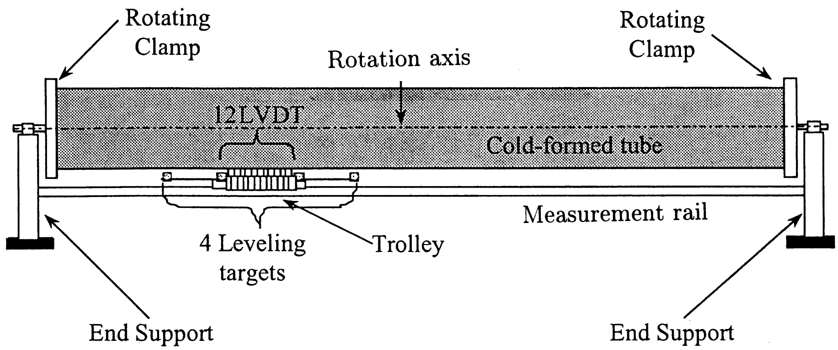


Figure 5.1: Schematic diagram of rig for measurement of initial imperfections

This is not a proposal of new measuring technique in experiments, but a new system is proposed by Pircher and Wheeler (2003) to measure initial imperfections in cylindrical thin-walled members. Their measurement is performed combining Low Boltage Displacement Transducers (LVDTs) and optical levelling to determine the accurate tube geometry. Figure 5.1 shows the measuring system. Numerical method is also presented to process the measured data into three-dimensional imperfection maps along with an algorithm to distinguish between significant imperfection patterns and measurement noise.

6. RELIABILITY

Consideration of the ultimate strength of ship and offshore structures in a decision process requires the comparison of strength predictions to expected loadings. The increasing acceptance and use of structural reliability techniques require the ultimate strength discussion to account for the likely use of strength prediction tools and information in a structural reliability-based process. Reliability-based approaches include approximate, exact, or numerical analyses. Each approach requires the strength expert to probabilistically characterise the basic strength variables (i.e. plate thickness, yield strength, stiffener distortion) in order to account for inherent randomness in the strength prediction, and also requires some estimate of the modelling uncertainty inherent in the model. Characterisation of modelling uncertainty is usually accomplished by comparing the predictive tool results to experimental tests. The resulting characterisations are then available for use in a reliability-based analysis. The development of variability and uncertainty models for ultimate strength prediction, and examples of the use of this information are considered in this chapter.

6.1 Ultimate Strength Modelling Bias and Uncertainties

Ivanov (2002) presents time-dependant, analytic, probabilistic models of areas, moments of inertia, section modulii and thicknesses for selected stiffener profiles for use in determining their sensitivity to corrosion. Hess *et al.*(2002) present probabilistic characterisations of basic strength variables resulting from literature surveys, ship-board measurements and material tests of ship structures to be used in understanding as-built scantlings and distortions. The variability models may be viewed as historical due to the changing nature of material specifications which are highly dependent upon the manufacturer's contract with the shipyard.

6.2 Ultimate Strength Reliability Analysis

Reliability analysis on hull girders against collapse is typically undertaken using simplified, closed form equations or progressive failure models. Downes and Pu (2005) evaluated the reliability of a notional high speed craft against hull girder collapse using both the First Order Reliability Method (FORM) and Monte Carlo simulation with an embedded hull girder ultimate strength code based on Smith's method. Load-shortening curves were from LR.PASS. A sensitivity analysis was also performed, and it was clarified that the location of a structural member influences which basic random variable is dominant. Another approach for predicting the hull girder collapse reliability is proposed by Lua and Hess (2003) where the probability distribution of the hull girder collapse strength modelled by ULTSTR is developed using Monte Carlo simulation. The probability distribution is then approximated by an automated piecewise curve-fit in PULSTR before use in a FORM analysis of the limit state equation for hull girder collapse in a seaway. The number of simulation cycles is greatly reduced from what would be required for Monte Carlo simulation of the limit state function, without a significant reduction in accuracy.

Fang and Das (2005) use Monte Carlo simulation to predict hull girder collapse reliability for intact and damaged ships. The strength predictions are based on the Smith's method which is presented in Fang and Das (2004). The mean hull girder strength is determined using nominal values for the basic strength variables in the strength prediction. The coefficient of variation of the strength prediction is assumed to be 10 percent.

A time-dependant reliability model is presented and exercised by Paik, *et al*.(2003b) for a bulk carrier, a double hull tanker and a FPSO. The reliability model accounts for the effects of fatigue-induced cracking and corrosion. Timelines are presented for each vessel relating the probability of hull girder failure to ship age. Each timeline is heavily dependant upon the modelling assumptions such as severity and location of corrosion or cracking. The effects of various repair schemes on the reliability over time are shown. Qin and Cui (2003) present a discussion on current corrosion models and propose a new model that uses three piece-wise continuous stages to represent the corrosion process.

Das *et al*.(2003) present modelling uncertainty evaluations of strength predictions of ring stiffened shells and ring and stringer stiffened shells for various modes of buckling and various radius to thickness ratio values (range used in offshore structures). Model uncertainty factors in terms of bias and coefficient of variation (COV) are developed by comparing predictions to experimental results found in the literature. Comparisons are made for API BUL 2U and DNV buckling strength of shells models.

6.3 Ultimate Strength Reliability-Based Design and Optimisation

An American Society of Naval Engineers Journal Special Edition on Ship Structural Design was published in 2002 and presented results from a US Navy investigation in the use of Load and Resistance Factor Design (LRFD) rules for ship structural design. Ayyub *et al*.(2002) consider two hull girder ultimate strength models in the rule development: one being elastic-based and the other the US Navy progressive collapse model code ULTSTR. Assakaf *et al*.(2002a, 2002b) present limit state equations and strength models for unstiffened and stiffened panels. The chosen strength models, uncertainty characterisations and partial safety factors found in these papers are for demonstration purposes only and do not necessarily represent accepted US Navy approaches to structural design or analysis.

7. TUBULAR MEMBERS AND JOINTS

7.1 Background

The last decade sees many developments and innovations of tubular connections in the offshore industry. Such applications include the more widespread adoption of thick-walled sections in both offshore and onshore structures, internally or externally reinforced tubular connections, *etc*. Recent research effort also focuses more on the failure assessment of tubular connections with initial defects, since fatigue induced cracks remain as a potential threat for offshore steel platforms in the event of extreme environmental loading. These practical concerns in the industry do not find corresponding theoretical background in the literature or design codes (API, 2000; ISO 19902, 2004). Zhao (2005) points out that the chord stress effect for Circular Hollow Section (CHS) and Rectangular Hollow Section (RHS) joints still remains as an issue to be solved for the upcoming version of the IIW design guidelines. It, therefore, requires a more detailed understanding on the ultimate strength of tubular connections with due emphasis on the larger wall thickness, presence of initial defects, provision of reinforcement, and the effect of chord stresses, for a safe and economical design. The upcoming design API RP 2A (Karsan *et al*., 2005; Pecknold, *et al*., 2005) will include some of the recent development on the ultimate strength of tubular joints.

This chapter summarises the key recent research publications on the ultimate strength of the tubular connections, focusing on the following four aspects: thick-walled joints, joints with initial cracks, effects of chord stresses, and the reinforced joints.

7.2 Thick-Walled Joints

For CHS joints with the chord outer radius to the wall thickness ratio (γ) less than 10, few research publications have been reported in the literature. However, the offshore structures (e.g. jack-up platforms), as well as the onshore structures (e.g. railway bridges), are increasingly using thick-walled pipes with γ ratio as low as 4. The existing design equations in API (2000) or ISO (2004) have been derived from curve-fitting equations based on thin-walled joint database, for which the chord outer radius to the chord wall thickness ratio □ remains greater than 10.

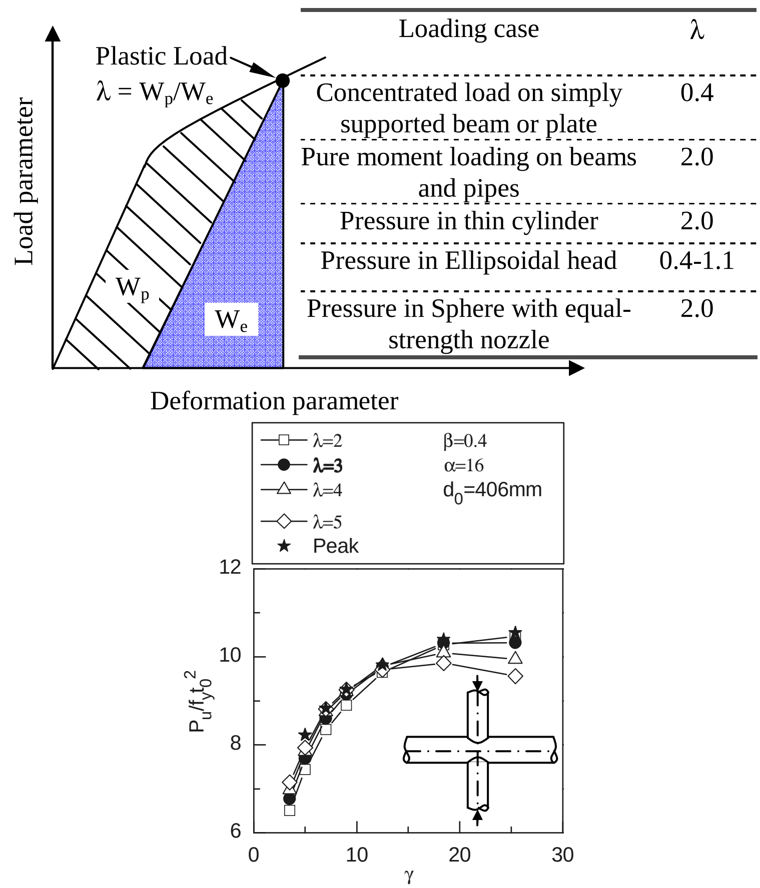


Figure 7.1: New strength definition for CH joint and comparison of the new approach with the peak load definition for X-joints under brace axial compression

In the context of thick-walled joints, which usually exhibits increasing load after the elastic response in the load-deformation curves, a consistent strength definition becomes necessary in providing appropriate comparisons among different joint parameters. Choo *et al.*(2003a, 2003b) propose a new strength definition applicable for both thick-walled and thin-walled joints, based on the plastic limit load approach originally proposed by Gerdeen (1980) for pressure vessels and beams. This strength definition, as illustrated in Figure 7.1, compares the joint strength corresponding to different □ values, of which a larger value corresponds to a larger joint deformation. The plastic limit load approach demonstrates consistent estimations as those using Lu's deformation limit (1994) for thin-walled joints, as reported by Choo *et al.*(2003a).

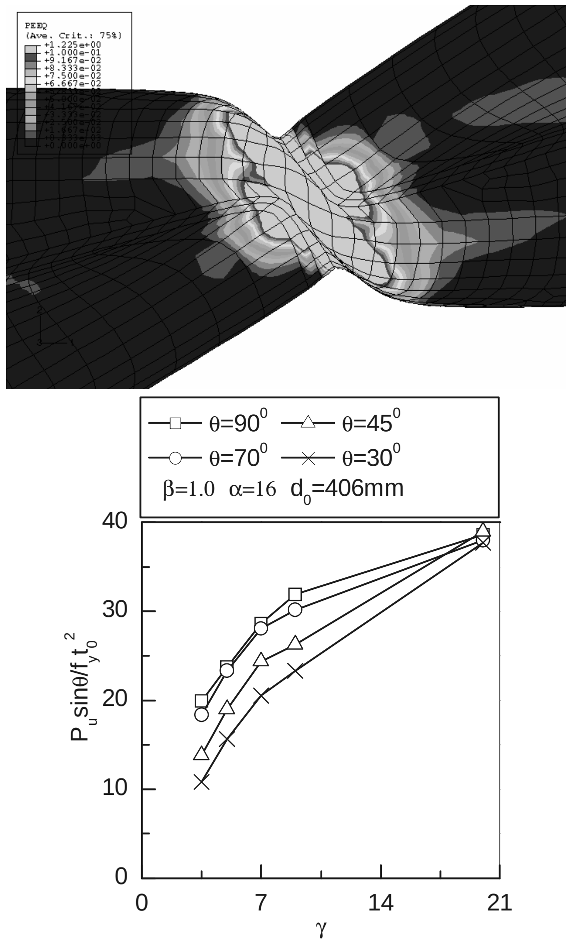


Figure 7.2: Failure modes and non-dimensional strength for X-joins with different brace inclination angle

Choo *et al.*(2004a) investigate the effect of the brace inclination angle on the strength of thick-walled X-joints, with the presence of chord axial stresses. The X-joints with a low brace inclination angle show a different failure mode as compared to X-joints with $\theta = 90^o$, as illustrated in Figure 7.2. The design equations (e.g. API, 2000), which include the effect of the brace angle using a term $\sin\theta$, do not consider the newly identified shearing failure for X-joints with low brace inclination angles. The non-dimensional joint strength for low θ angles is found to be lower than the joints with high θ angles, as shown in Figure 7.2.

Choo *et al.*(2005a) present a finite element study on the static strength of CHS T-joints under the brace axial loads. The numerical analysis considers the effect of the chord length. The 'true' joint strength is derived from the membrane and bending of the chord wall near the brace-chord intersection. To exclude the chord member failure and thus mobilise the 'true' joint strength, an externally applied, compensating moment minimises the equilibrium-induced in-plane bending in the chord near the brace-chord intersection. A regression analysis based on the combined results by Choo *et al.*(2005a) and van der Vegte (1995) leads to a new strength equation for T-joints under compensating moments, as shown in Eqn. 7.1. Consequently, the chord stress function presented by Qian (2005) includes effect of the equilibrium-induced chord bending stresses.

$$\frac{P_u \sin\theta}{f_y t_0^2} = \frac{8.3}{1-0.2\beta}\gamma^{(0.7\beta-0.2)} \tag{7.1}$$

Choo *et al.*(2005b) describe a detailed numerical investigation on the effect of boundary conditions on thick-walled CHS K-joints. This study separates the boundary conditions into three independent groups: the chord load effect, the chord bending effect and the brace end effect. The results from a K-joint integrated in a 2D frame prove that displacement controlled loading shows a more realistic representation of the actual boundary conditions on a K-joint. Qian (2005) summarises the numerical investigation on thick-walled X-, T-, K- and DK-joints performed in the National University of Singapore.

Mashisri and Zhao (2005) review the thickness effect on the strength of welded joints. Schumacher *et al.*(2003) study the fatigue behaviour of the thick-walled CHS joints. Oomens *et al.*(2005) verify the computational procedure of stress intensity factors (SIFs) for thick-walled T-joints. Qian *et al.*(2005a, 2005b) examine the mixity of modes I and II crack opening for a surface crack located near the weld toes in thick-walled X- and K-joints subjected to remote brace tension. A subsequent study (Qian *et al.*, 2005c) focuses on elastic-plastic crack driving force, represented by the *J*-integral, on thick-walled CHS X-joints with an initial surface crack at the mismatched weld toe.

7.3 Effect of Chord Stresses

The chord member of CHS and RHS joints normally experiences loads induced to maintain the equilibrium in the adjacent structure. The strength equation, derived from the joint database where only brace loads exist, can be un-conservative when applied to realistic joints in an offshore platform. The existing chord stress functions in the design codes (API, 2000; CIDECT, 1991; ISO 19902, 2004) neglect the contribution from the tensile chord stresses and the geometric parameters. However, recent researchers (van der Vegte *et al.*, 2001; van der Vegte and Makino, 2001; Pecknold *et al.*, 1998) reveal, from calibrated finite element studies, that the chord stress effect demonstrates a significant dependence on the geometric parameters.

Pecknold *et al.*(1998; 2000; 2001) report an extensive numerical study on the CHS X- and gapped K-joints. They propose a new chord stress function, Q_f, in terms of externally applied chord loads, based on their numerical database consisting of 1500 cases:

$$Q_f = 1.0 + k_1\left[\frac{N}{N_y} - \frac{M}{M_p}\right] - k_2\left[\left(\frac{N}{N_y}\right)^2 + \left(\frac{M}{M_p}\right)^2\right] \tag{7.2}$$

where $M = \sqrt{M_{ipb}^2 + M_{opb}^2}$. The k_1 and k_2 are functions of □ for X-joints and constants for K-joints. Equation 7.2 applies to both compressive and tensile chord stresses, and includes the dependence of the chord stress effect on □. These numerical findings become the basis for the new chord stress functions in the coming edition (22nd edition) of API RP 2A.

Van der Vegte et al.(2001, 2002) present finite element studies on the effect of chord stresses for CHS X- and K-joints. Van der Vegte et al.(2003) summarise the new chord stress function for three different joint types: X-, T- and K-joints.

$$f(n) = \left[1 - |n|^A\right]^{(B + C\beta + D\gamma)/100} \tag{7.3}$$

The new chord stress function is based on the maximum chord stress ratio, n, which includes the equilibrium induced chord stress effects and is consistent with the chord stress function for RHS joints. This new function will become the basis for the new CIDECT chord stress function. For thick-walled joints, Qian (2005) summarises the chord stress functions in consistent with Eqn. 7.3 for four different types of joint configurations: X-, T-, K- and DK-joints. Figure 7.3 plots the comparison of the chord stress function of ISO 19902 (2004) and Van der Vegte (2003) with the FEM results reported by Choo et al.(2006).

For RHS joints, Zhao and Hancock (1993) derive a chord stress function using the yield line theory. Yu (1997) presents a numerical study on the effect of chord stresses on the RHS X- and T-joints subjected to chord axial and moment loads. Liu and Wardenier (1998) report a detailed finite element investigation of the chord stress effect on the RHS K-joints. Liu et al.(2004) summarise the chord stress function for RHS connections, adopting the format of Eqn. 7.3. The chord stress function for an I beam to a RHS chord also follows Eqn. 7.3, while the chord stress function for a longitudinal plate to a RHS chord becomes:

$$f(n) = \left[1 - |n|^A\right]^{(B + F\eta)/100} \tag{7.4}$$

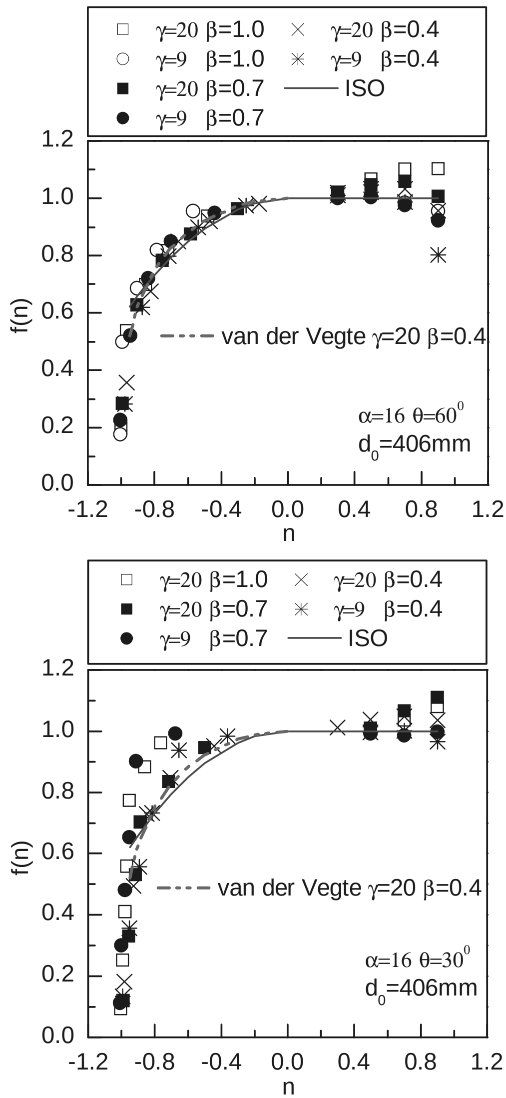


Figure 7.3: Comparison of the chord stress function of ISO 19902 (2004) and Van der Vegete (2003)
With the FEM result reported by Choo *et al*.(2006) for K-joints

7.4 Joints with Initial Cracks

The fatigue induced crack imposes a detrimental threat to offshore platforms under extreme environmental loads. Burdekin (2001) summarises the experimental study on the static strength of cracked tubular connections. The extensive numerical investigations (Burdekin and Frodin, 1987; Cheaitani and Burdekin, 1993) on the static strength of cracked CHS T- and K-joints suggest a reduction factor to be applied on CHS joints with an initial crack:

$$RF = \left[1 - \frac{A_{crack}}{L_{\text{int}} \times t_0}\right] \frac{1}{Q_\beta} \tag{7.5}$$

where A_{crack} denotes the cracked area and L_{int} refers to the intersection length between the brace and the chord. The factor Q_β equals to 1 for $\beta \leq 0.6$, and $\dfrac{0.3}{\beta(1-0.833\beta)}$ for $\beta >$ 0.6. The reduction factor, *RF*, applies to the strength formulation for an intact joint and thus estimates the static strength of a joint with initial defects. The comparison of the reduction factor and the experimental data indicate the conservative nature of Eqn. 7.5.

In order to assess the possible incidence of fracture failure as opposed to plastic collapse failure, many researchers employ a failure assessment diagram (Figure 7.4), of which the procedure is detailed in many design guidelines (R6, 1997; BS 7910, 1999). The vertical axis (K_r in Figure 7.4) of a failure assessment diagram denotes the ratio of the linear-elastic stress intensity factor to the fracture toughness, while the horizontal axis (L_r in Figure 7.4) describes the ratio of the applied load to the plastic collapse load of a cracked joint at the yield strength. Zerbst *et al.*(2002a) present a detailed experimental study on the behaviour of a CHS T-joint with an initial surface crack near the toe of welds at the saddle point, subjected to remote tension at the brace tip.

Subsequent studies (Marshall and Ainsworth, 2002; Burdekin, 2002; Zerbst *et al.*, 2002b; Schindler, *et al.*, 2002; Zerbst and Miyata, 2002) apply different failure assessment methods to the T-joint and lead to the following conclusions. That is, the inclusion of residual stresses contributes to the value of stress intensity factors, without affecting the magnitude of the limit load. For the range of crack depths investigated (9 mm < a < 11 mm), the limit load does not depend on the initial defect size. The numerical computation of the T-joint indicates that the ductile tearing occurs first at the two ends of the surface flaw (with $a/c \approx$ 0.43), rather than at the deepest point of the crack at □ = 0.5□see Figure 7.4. Generally, the R6, BS 7910 and the ETM 97/1 approaches, which require a detailed calculation of the SIFs, show close predictions of the limit loads for cracked T-joints. The WES-2805 (1997), which does not require an accurate computation of the SIFs, indicates conservative estimations of the limit loads for cracked joints.

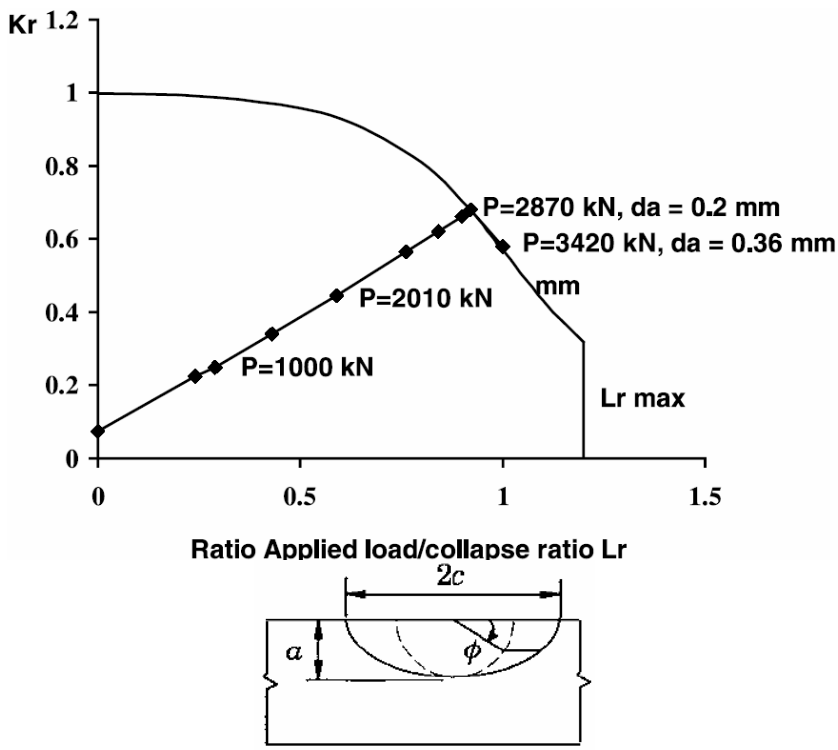


Figure 7.4: Failure assessment diagram and a surface crack configuration

For joints fabricated using high strength steels, Talei-Faz *et al.*(2004) demonstrate, through nine tests on CHS Y- and T-joint, that the presence of cracks does not reduce significantly the joint strength.

7.5 Reinforced Joints

Joint reinforcement can adopt the form of an internal stiffener such as the ring stiffener (Figure 7.5), and an external stiffener such as doubler or collar plates (Figure 7.6). Lee and Llewelyn-Parry (2005) find that the ring stiffener does not affect the ductility of the tubular joint, and the effectiveness of a stiffener depends primarily on the geometric parameters (□ and □, as well as the location of the stiffener. Thandavamoorthy (2003) reports an experimental comparison between ultimate strength of the ring stiffened T-/Y- joints and the unstiffened joints. The strength of the ring stiffened T-joints increases to almost twice as that of the un-reinforced joint with the same dimension. The failure mechanism of the ring stiffened joint becomes chord bending, instead of ovalising and punching shear as observed in un-stiffened joints.

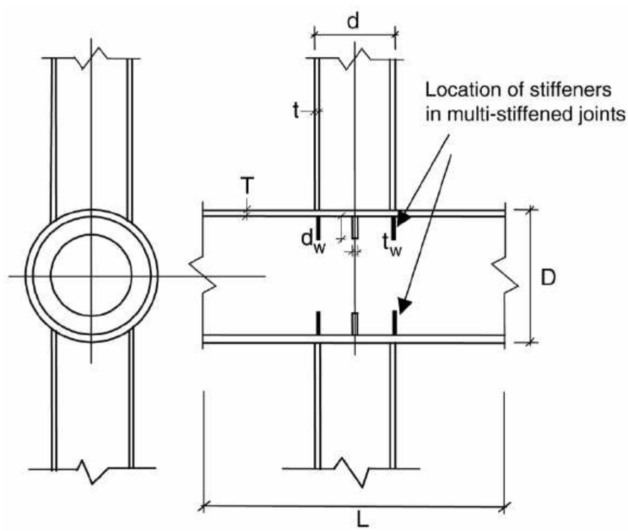


Figure 7.5: Ring stiffened CH X-Joint

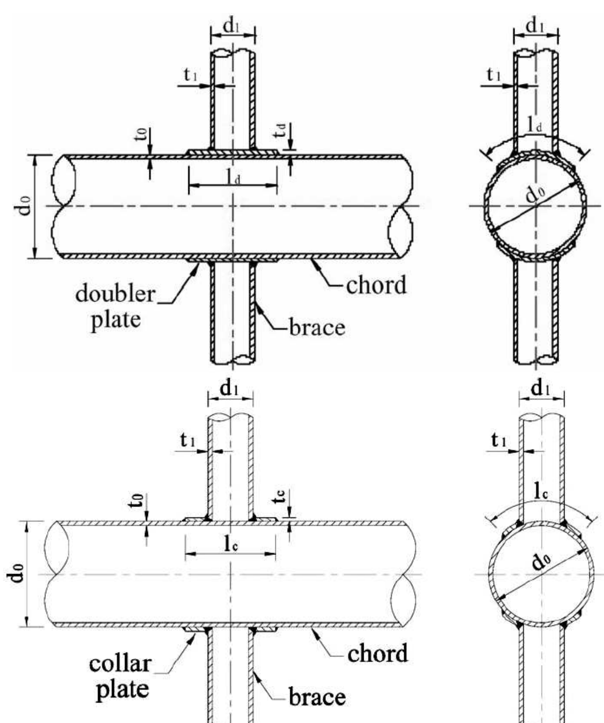


Figure 7.6: Doubler and collar reinforced CH X-joint

Choo *et al*.(1998) report the experimental and numerical study on doubler and collar plate reinforced T-joints. Subsequently, Choo *et al*.(2005b) and Van der Vegte *et al*.(2005) report on the extensive comparisons between the experimental and numerical results for plate-reinforced T-joints. Choo et al.(2004b, 2004c) present a detailed, calibrated finite element study on collar- and doubler-reinforced X-joints under brace in-plane bending. The collar plate reinforced proves to be more efficient than the doubler plate, with a more significant strength enhancement for the same length and thickness.

8. PLATES AND STIFFENED PLATES

Ultimate strength of plates and stiffened plates is the most fundamental strength for marine structures, and a great deal of progress has been achieved in the past decades. There are a variety of methods and computer codes available for the ultimate strength analysis of plates and stiffened plates, ranging from simple analytical formulas to complicated numerical methods. The analysis costs typically increase with the level of detail modelling and the fidelity of the analysis procedure used. Therefore, the studies on ultimate strength of plates and stiffened plates have been and shall continue to be a large area of active researches in marine structures.

8.1 Unstiffened Plates

The studies on the ultimate strength of plated structures have continued over several decades and significant progress has been achieved. However, there are some aspects of this subject unresolved and interested in. In recent years, the research efforts in the ultimate strength of plated structures are devoted to:

- development of analytical formulas,
- development of simplified methods,
- assessment of effects of initial imperfections,
- assessment of effects of fatigue cracks.

Hu and Cui (2003a, 2003b) have carried out a comparative study between simplified analytical method and design formulas for ultimate strength of unstiffened and stiffened plates. The simplified analytical method is developed based on the combination of elastic large deflection analysis and rigid plastic mechanism analysis. Paik and Thayamballi (2003) and Paik and Lee (2005) have presented a semi-analytical method for the elastoplastic large deflection analysis of unstiffened plates and stiffened plates under typical loads until the ultimate strength is reached. The effect of initial imperfections is accounted for in the calculations. Shariat *et al*.(2005) perform the studies on the buckling behaviour of functionally graded rectangular plates with geometrical imperfections.

The initial imperfections in forms of initial distortion and welding residual stress are inevitable in marine structures due to the limits of fabrication technology. They have very significant effects on the ultimate strength of plates and stiffened plates and should be accounted in the ultimate strength evaluation of marine structures. An energy measure is suggested by Sadovsky *et al*.(2005) to provide an integral measure of the degree of initial deflections according to the comparison between the energy measure and the commonly employed amplitude to thickness ratio. The effects of initial deflections on the collapse strength of thin rectangular plates in longitudinal compression are analysed by using measured data of distortions.

EI-Sawy *et al*.(2004) present the curves representing both elastic and elastoplastic buckling stresses versus the slenderness ratio of perforated plate for different grades of steel according to a series of finite element analysis results. The results show that the critical buckling stress for perforated plates always decreases as the plate slenderness ratio and/or hole size increases. It is recommended to avoid to punch the hole near the plate edge.

In addition to initial imperfections, the fatigue cracks have an important effect on the ultimate strength of marine structures and should be accounted in residual strength evaluation of aged ship hull. A systematic investigation is carried out by Hu and Cui (2003c) on the effects of the crack damage on the residual strength by using finite element method. The regression formulas are provided for the residual strength evaluation of the damaged plates and stiffened plates.

Brighenti (2005) has carried out the theoretical and numerical studies on the elastic buckling of cracked thin-plates under tension or compression. A series of finite element analysis is performed to evaluate elastic buckling strength of rectangular thin-plates with various cracks under tension and compression and a simple approximate theoretical model is proposed to explain and predict the buckling phenomena in cracked plates subjected to tensile load.

Paik *et al*.(2005c) have performed an experimental and numerical study on the ultimate strength of cracked steel plate elements subjected to uni-axial compressive or tensile loads. The ultimate strength reduction characteristics of plate elements due to cracking damage are investigated with varying size and location of the cracking damage. A theoretical model for prediction of the ultimate strength of cracked plate elements under uni-axial compression or tension is developed based on the experimental and numerical results.

Kumar and Paik (2004) deal with the estimation of buckling loads of plates with cracking damages. The hierarchical trigonometric functions are used to define the displacement function of the cracked plate. The buckling loads of plates with various types of cracks, such as an edge crack and a central crack are calculated under the in-plane compressive load and/or shear load.

8.2 Stiffened Plates

Simplified methods are very important in ultimate strength assessment of plates and stiffened plates not only to provide initial guidance in the early stage of design but also to evaluate results obtained from time-consuming numerical simulations. Consequently significant attention is paid to develop rational, robust and simplified methods for ultimate strength evaluation of plates and stiffened plates. The current topics of interest related to plated structures are:

- simplified method,
- idealised structural unit method (ISUM),
- effects of initial imperfections,
- sensitivity analysis.

Byklum *et al.*(2004) have derived a computational model for global buckling and postbuckling analysis of stiffened panels. Deflections are assumed in the form of trigonometric function series and local and global stresses are combined in an incremental procedure. Ultimate limit state estimates for design are obtained by calculating the stresses at certain critical points, and using the onset of yielding due to membrane stress as the limiting criterion.

Zhang *et al.*(2003) present a new solution of the elastic buckling and post-buckling behaviour of imperfect stiffened plates based on the large deflection theory. The tangential stresses of the stiffeners are neglected and nonlinear membrane forces of the stiffeners are taken into account in the discretely stiffened plate model. The deflection as well as the initial imperfection and stress distribution of the plates are represented by Fourier series. The analytical expression of buckling of the stiffener is obtained by using the differential equations and boundary conditions.

A simplified method is proposed by Yanagihara *et al.*(2003) and Harada *et al.*(2004) to estimate ultimate strength of a continuous stiffened plate under combined uni/bi-axial thrust and lateral pressure on the basis of the results of a series of nonlinear finite element analysis. Three collapse modes are considered in a simplified method, which are stiffener-induced failure, plate-induced failure and hinge-induced failure. The accuracy of the proposed method is examined through comparison of the calculated results with FEM results, see Figure 8.1. The numerical results show that the ultimate strength of a continuous stiffened plate under transverse thrust is significantly higher than that of a continuous unstiffened plate simply-supported along stiffener lines because of a stiffener's torsional stiffness.

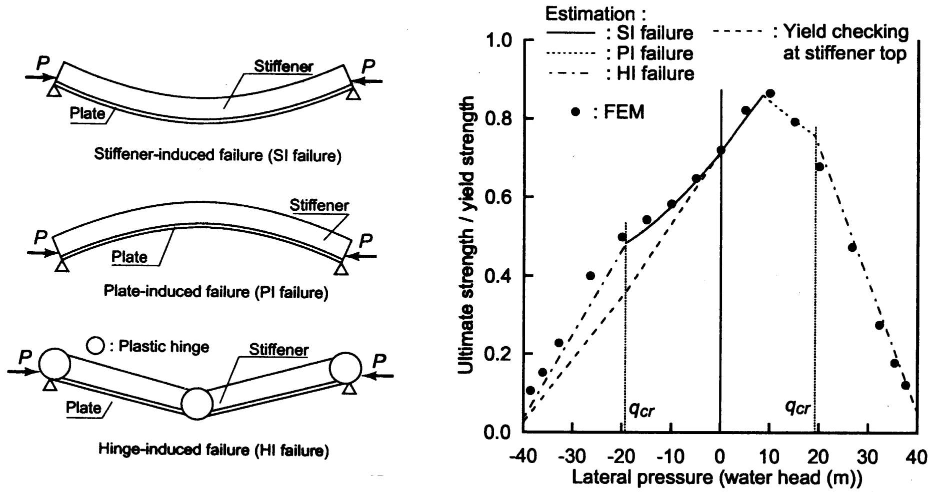
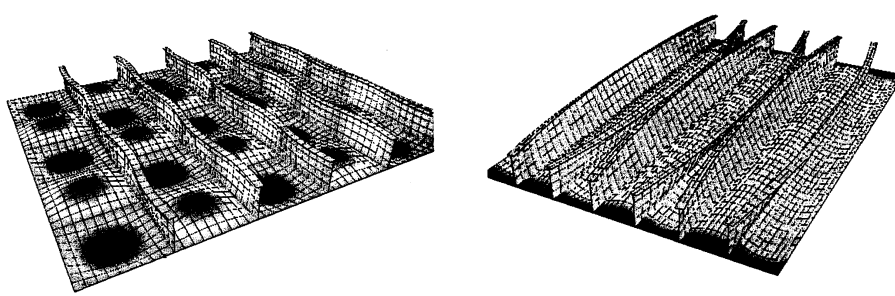


Figure 8.1: Failure modes and comparison of estimated ultimate strength with that by FEM



(a) Longitudinal thrust (b) Transverse thrust

Figure 8.2: Buckling modes of stiffened plate subjected to thrust load

Advanced nonlinear buckling models of thin-walled stiffened panels are developed (Byklum and Amdahl, 2002; Steen *et al.*, 2004) based on the elastic large deflection plate theory of Marguerre and von Karman. The models cover geometrical proportions of plates and stiffeners typically used in ship hulls and offshore constructions. Figure 8.2 shows the calculated buckling modes of stiffened plates under longitudinal and transverse thrust, respectively. Improved expressions are developed by Hughes *et al.*(2004) for elastic local plate buckling and overall panel buckling of uni-axially compressed panels with T-bar stiffeners. The expressions are validated with fifty-five ABAQUS eigenvalue buckling analyses of a wide range of typical panel geometries.

The ISUM provides an efficient method to evaluate the load carrying capacity of large structural system. It can be used to simulate both stiffener collapse and plate panel collapse and evaluate the ultimate strength at the structural system level by employing particular definitions of elements. Fujikubo and Kaeding (2002) have developed a new simplified model for collapse analysis of stiffened plates in the framework of ISUM by employing accurate shape functions. The proposed stiffened plate model consists of ISUM plate elements and beam-column elements. Combination of plate and beam-column elements allows for both local buckling of the plate panel and overall buckling of the stiffened plate.

Kaeding *et al.*(2004) present the state-of-the-art in ISUM modelling and extend the formulation to include lateral pressure. Two shape functions have been investigated for unstiffened double-span/double-bay models. The combined models of present ISUM plate elements and beam-column elements are employed to analyses the ultimate strength of stiffened plates under bi-axial compression and lateral pressure and good agreements are observed between the results by the IUM and the FEM analyses, see Figure 8.3. Paik and Thayamballi (2003) present a summary of their ISUM theory and its application to nonlinear analysis of steel plated structures. Some important concepts for development of various ISUM elements are discussed.

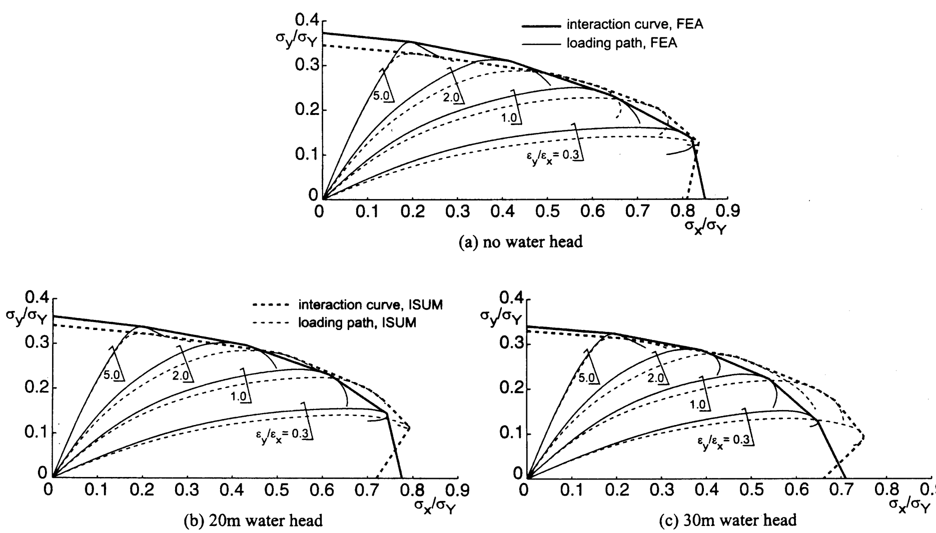
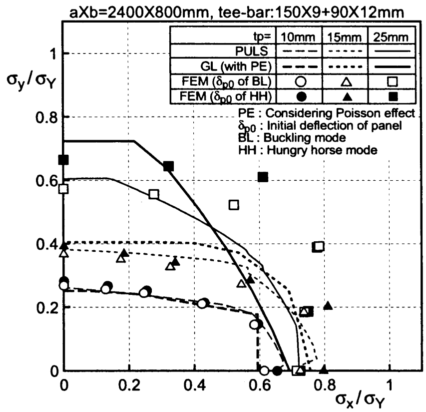


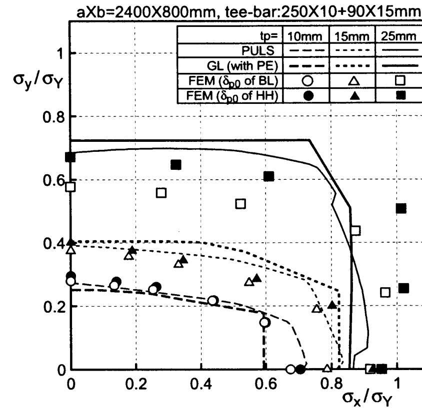
Figure 8.3: Comparison of loading path and ultimate strength interaction relationships of continuous stiffened plate subjected to combined bi-axial thrust and lateral pressure (ISUM and FEM) (plate: 2,400 x 800 x 15 mm; tee-bar stiffener: 250x10+90x15 mm)

8.3 *Ultimate Strength of Stiffened Plates in Common Structural Rules*

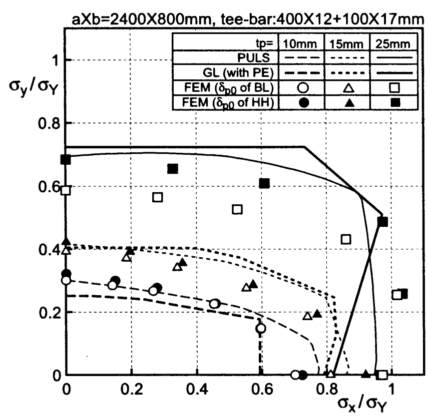
Japan Society of Naval Architects and Ocean Engineers has established a technical committee to study on the Common Structural Rules for Double Hull Oil Tankers (JTP) and Bulk Carriers (JBP) proposed by IACS (2005). The committee report consists of three parts, which are camparative studies on (1) buckling and ultimate strength of plates and stiffened plates, (2) ultimate hull girder strength and (3) fatigue strength. Regarding the buckling and ultimate strength of plates and stiffeed plates, Fujikubo (2005) performed a series of calculations applying JTP and JBP methods as well as FEM. Figure 8.4 shows the comparison among the calculated ultimate strength by JTP method, JBP method and FEM.



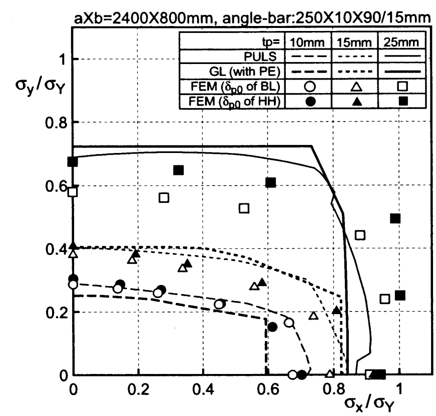
(a) tee-bar type1, a/b=3



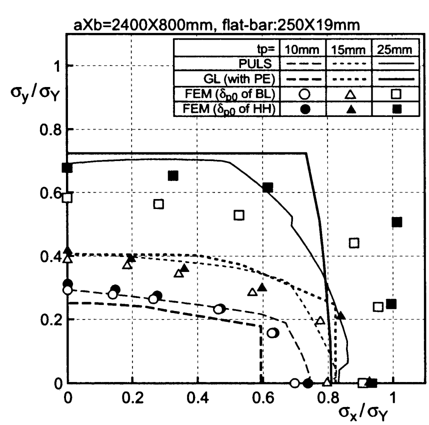
(b) tee-bar type2, a/b=3



(c) tee-bar type3, a/b=3



(d) angle-bar type2, a/b=3



(e) flat-bar type2, a/b=3

Figure 8.4: Ultimate strength interaction relationships of stiffened plate under bi-axial thrust(Comparison among PULS, GL and FEM)

In the JTP method, the computer code, PULS, is applied which is on the basis of the research by Steen *et al*.(2004). On the other hand, in JBP method, the formulae developed by German Lloyd (GL) is applied. The calculated results for stiffened plates subjected to bi-axial thrust are plotted in Figure 8.4 in terms of ultimate strength interaction curves. It has been concluded that:

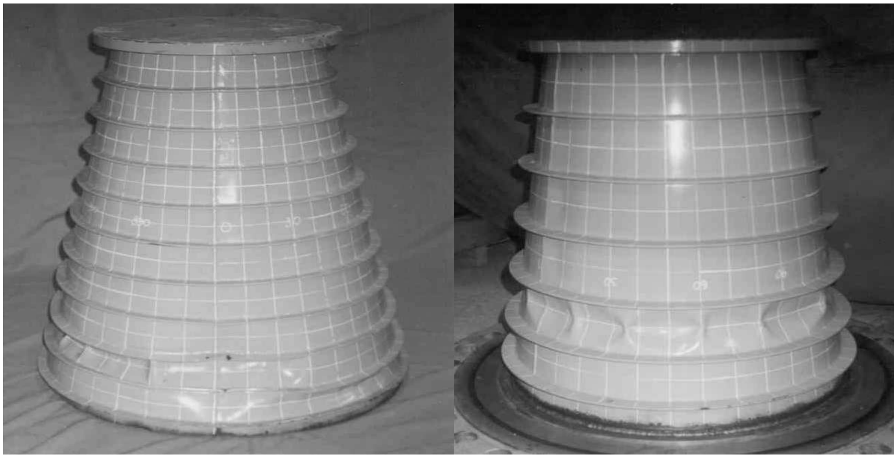
(1) The ultimate strength interaction relationships obtained by PULS, GL and FEM are in good correlations with each other.
(2) PULS and GL tend to overestimate the ultimate strength of a thick plate when transverse thrust is dominant, whereas underestimate the ultimate strength when longitudinal thrust is dominent.
(3) PULS can not correctly simulate the lateral-torsional buckling behaviour of stiffeners with large web height, and overestimate the ultimate strength in this case.
(4) The Poisson-effect correction in GL has a significant influence on the predicted ultimate strength although the physical background and guideline for its application are expected to be more clarified.

9. SHELLS

9.1 Cylinders and Conical Shells

Das *et al*.(2003) provide ultimate strength design formulations for ring stiffened and ring/stringer stiffened cylinders under various loading like axial compression, radial pressure and combined loading. Comparisons are made with screened test data, which have realistic imperfections and various radius to thickness ratio values in the range generally used in offshore structures. This research is to provide statistical data of model uncertainty factors in terms of bias and coefficient of variation (COV) for a reliability analysis as mentioned in Chapter 6.

Unlike ring-stiffened cylinders, the test results of stiffened conical shells are difficult to find in the open literatures. Cho and So (2003) reported hydrostatic test results on four ring-stiffened conical shells together with those on six ring-stiffened cylinders. Among four conical shells, three were collapsed by inter-frame failure, but the other was by overall failure. As can be seen in Figure 9.1, the collapsed shapes of stiffened conical shells are quite similar to those of ring-stiffened cylinders. Comparison of their ultimate strength with those predicted by relevant design codes showed reasonable agreements.



(a) Inter-frame collapse (b) Overall collapse

Figure 9.1: Collapse modes of ring-stiffened conical shells subjected to hydrostatic pressure

Underwater explosion tests were performed by Hung *et al*.(2005) on one unstiffened and two ring-stiffened cylinders of a small scale. In the tests, the deformed shapes were captured by a high-speed video recorder. The dynamic structural analysis of the test models was also performed using FEM together with USA code to take into account the fluid-structure interaction effects. They discussed the problems experienced in the underwater explosion tests.

9.2 Unstiffened and Stiffened Curved Plates

Recently, structural behaviours of unstiffened and stiffened curved plates were numerically investigated subjected to axial compression or combined with hydrostatic pressure. Maeno *et al*.(2003, 2004) performed a series of elastoplastic large deflection analyses to investigate buckling/plastic collapse behaviour of ship's bilge strakes which are unstiffened curved plates under axial compression (Figure 9.2). Based upon the analysis results, a simple formula is derived to calculate buckling/ultimate strength and to simulate average stress-average strain relationship of the bilge structure under uniaxial compression. It is found that the bilge structure with a conventional shape and size reaches the ultimate strength by yielding before buckling. Therefore the hard corner elements could be used for bilge part in the ultimate hull girder strength evaluation by the Smith's method and the effects of buckling of bilge part should be accounted beyond the ultimate strength.

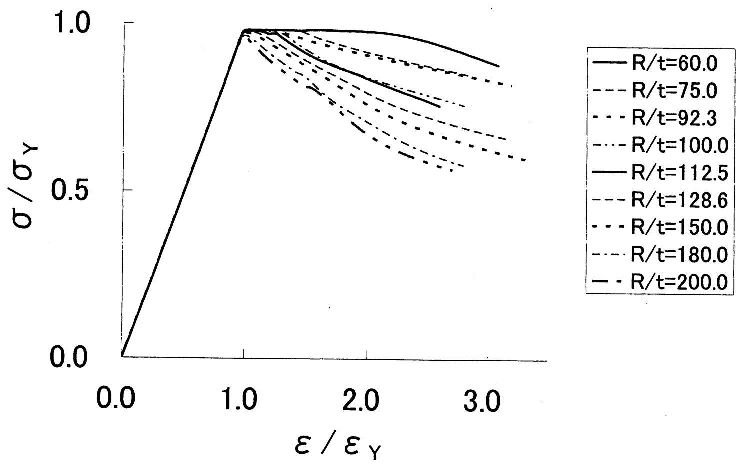


Figure 9.2: Average stress-average strain relationships of bilge circle under thrust

Yumura *et al.*(2005) investigated buckling/plastic collapse behaviour of cylindrically curved plates under axial thrust. They, firstly, performed a series of elastic eigenvalue analysis changing curvature of a curved plate to clarify the fundamentals in its elastic buckling behaviour. Then, giving a small initial deflection of a buckling mode, a series of elastic large deflection analysis is performed to investigate the characteristics of post-buckling behaviour of a curved plate. Finally, a series of elastoplastic large deflection analysis was performed to clarify the buckling/plastic collapse behaviour of cylindrically curved plates.

Unlike other ship types, container ships have bilge strakes having large radius of curvature, which should be stiffened with longitudinal stiffeners. In shipyards, however, those stiffened curved plates are designed using formulations for flat stiffened plates. Park *et al.*(2005) performed non-linear FEM analyses using a commercial code for stiffened curved plates changing the curvature and spacing of stiffeners. In the analyses, initial shape imperfection and residual stresses were considered and combined axial compression and hydrostatic pressure loads were applied.

9.3 Effects of Imperfections

It is well known that shell structures are imperfection sensitive. Various aspects of the effects of imperfections were investigated on the structural behaviour of shell structures. Khamlichi (2004) investigated the effect of localised axisymmetric initial imperfections on the critical load of elastic cylindrical shells subjected to axial compression. The obtained results showed that the critical load varies very much with the geometrical parameters of the localised defect. Reduction of the critical load due to the localised defect was found to reach a level which may be down to a half of that predicted by general distributed defects.

The progress of non-linear FEM allows it nowadays to simulate the load-bearing behaviour of steel shells taking geometric and material nonlinearities as well as imperfections into account. However, simulation of initial shape imperfections in the analysis models is still a difficult task for structural engineers. For the basic buckling case of uniform external pressure, Schneider and Brede (2005) investigated the equivalent geometric imperfections which have to be applied in the numerical analysis to achieve the experimentally determined buckling resistances. They proposed the amplitude and width of the equivalent shape imperfections.

In fabrication of small scale test models following the procedures similar to those of actual structures, it is difficult to simulate the amplitude and pattern of the imperfections. Teng and Lin (2005) developed a technique for the fabrication of small models of large steel cylindrical shells constructed from many welded panels. The imperfections in an example specimen were examined to show that they had a realistic pattern. Even though this work was performed for onshore structures, this technique may be of some interest for marine structural engineers.

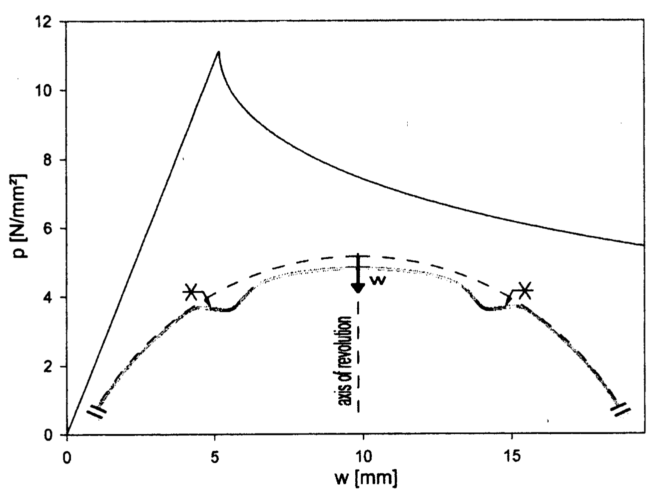


Figure 9.3: Load-deflection curve of welded HY-80 spherical shell

Grunitz and Franitza (2004) investigated buckling strength of welded HY-80 spherical shells subjected to hydrostatic load considering the influence of welding residual stress which is produced by multi-pass welding. Firstly, direct numerical calculation is performed to produce welding residual stress and deformation during welding process including metallurgical phase change, which are taken as initial condition for a nonlinear buckling analysis, see Figure 9.3. They found that the influences of welding residual stress and deformation are rather small for the R/t ratio they considered (R/t = 100).

9.4 Novel Shell Structures

Some novel shell structures to withstand hydrostatic pressure were introduced in the open literatures. Blashut (2003) performed experimental investigations on toroids subjected to hydrostatic pressure. He provided details about the manufacturing, pre-experiment measurements and testing of three, nominally different, steel toroids. Two of them were manufactured from mild steel by spinning two halves and welding them. The third one was assembled by welding four 90-degree stainless elbows.

Haixu (2003a, 2003b) investigated the possibility of double cylindrical shell structures to withstand hydrostatic pressure. The outer and inner cylinders were connected by ring-stiffeners and cylinders, and were stiffened by stringers. He developed a calculation method for deflections, stresses and a solution scheme to obtain critical pressures. The predictions were substantiated with model test results.

Liang *et al*.(2004) performed the optimum design of a multiple intersecting deep-submerged pressure hull subjected to hydrostatic pressure, which can be constructed by connecting several spheres. In their study, the thickness of the shell, the width of the rib-ring, the inner radius of the rib-ring and the angle of intersection of the spherical shell were selected as design variables. A sensitivity analysis was also performed to study the influence of the design variables on the strength of the optimal structure.

10. SHIP STRUCTURES

10.1 Strength Analysis of Ship Structures

Since the previous ISSC, the situation for the strength analysis has not changed significantly. According to the Class Rules, the strength assessment of ship structures is carried out in three steps. Longitudinal strength assessment of the hull girder is carried out by beam theory. The loads applied to the hull girder are vertical and horizontal bending moments, vertical shear forces and torsional moments. The magnitude of the hull girder loads depends significantly on geometrical parameters of the ship's hull. The distribution of the loads over the ship length is taken from long term statistic calculations and is unified by the rules of the classification societies (IACS, 1997). The combination of the different load components is considered by load combination factors. Local structural members as plates and stiffeners are also dimensioned by applying the beam theory whereas they are loaded by loads resulting from sea pressure and inertial loads of the cargo. The strength of primary supporting members (e.g. longitudinal girders, floors, web frames) is assessed by using the FEM. In all cases, the safety of the structure is assessed by a defined permissible stress. ULS (Ultimate Limit State) assessments are not yet mandatory for all ship types.

10.2 Common Structural Rules for Bulk Carriers and Tankers

In the past, classification societies had to face reproaches that they were competing for minimised scantling dimensions and steel weight to the detriment of ships' safety. As a consequence, classification societies started to develop rules for the structural design of bulk carriers and double hull tankers several years ago which after adoption by all member societies of the IACS will be mandatory for all classification societies. The development was carried out by two projects where three societies were joined to develop the tanker rules and seven societies to develop the bulk carrier rules. As a novelty during the development of the rules, industry was given the opportunity to comment on the meanwhile published draft rules. Extensive discussions with shipbuilding and shipping industries about the consequences and the background of the rules took place and had influenced on the final draft of the rules. One essential part of the new rules which falls under the subject of this committee is the ULS assessment of the hull girder as well as plates and stiffened plates.

In case of bulk carriers specified by JBP-Rules (Bureau Veritas *et al.*, 2005), the ULS assessment is carried out for intact, flooded and harbour condition taking the sum of vertical still water bending moment and the wave bending moments for the respective condition into account multiplying the wave bending moments with a partial safety factor of $\gamma_w = 1.2$. The ultimate bending moment capacity of the hull girder transverse section, in hogging and sagging conditions, is defined as the maximum value of the bending moment capacity, M_U, on the bending moment M versus the curvature χ curve of the transverse section considered. The capacity of the cross-section divided by a safety factor of $\gamma_R = 1.1$ has to be greater than or equal to the loading moment. The procedure to determine the capacity is a simplified incremental-iterative approach. For individual structural members, distinctive stress-strain relationships are provided for the respective failure modes.

In case of tankers specified by JTP-Rules (American Bureau of Shipping *et al.*, 2005), the ULS assessment is carried out for a sagging intact at sea condition taking the sum of the vertical still water bending moment and the vertical wave bending moment which will be multiplied by a partial safety factor of $\gamma_w = 1.3$. The bending moment capacity of the cross-section is determined by a single step procedure where a reduced section modulus of the deck is multiplied with the minimum yield stress of the deck structure material, and further it has to be shown that the bending moment capacity does not exceed the minimum yield strength of the bottom plating. The basic assumption for the calculation of reduced section modulus of the hull girder cross-section is that all stiffened plate panel have buckled and effective longitudinal members remain. The partial safety factor for the capacity is $\gamma_R = 1.1$. The rules for tankers allow alternative methods for the ULS assessment as there is the incremental-iterative procedure or nonlinear finite element analysis.

A comparison of the two rules with the computer code HULLST has been carried out by Yao (2005b) for a sample of twenty-four different designs of bulk carriers, tankers and a container ship coming to the conclusion that the ULS assessment by JTP-Rules seems to give good estimations, see Figure 10.1. The JBP rules give good estimations as well, see

Figure 10.2. In many cases, however, both rules lead to results on the un-safe side compared to the results by HULLST. Further, he concluded that the initial yielding strength calculated by multiplying the yield strength of the deck plating (at corner) with the elastic section modulus could be a good measure of the ULS under sagging condition, see Figure 10.3 (a). On the other hand, initial yielding strength of the bottom plating without considering the yielding of deck plating results in the overestimation of the ultimate hull girder capacity in hogging, see Figure 10.3 (b).

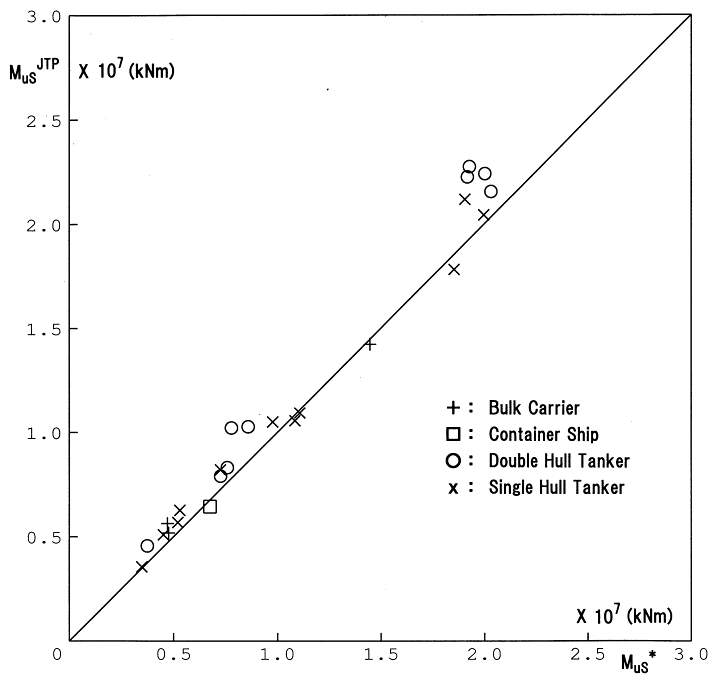
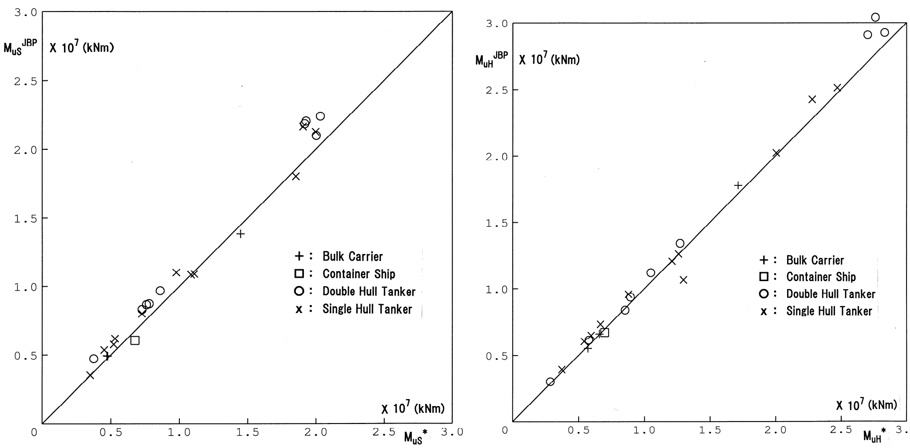


Figure 10.1: Comparison of ultimate hull girder strength by JTP method and HULLST (Sagging)

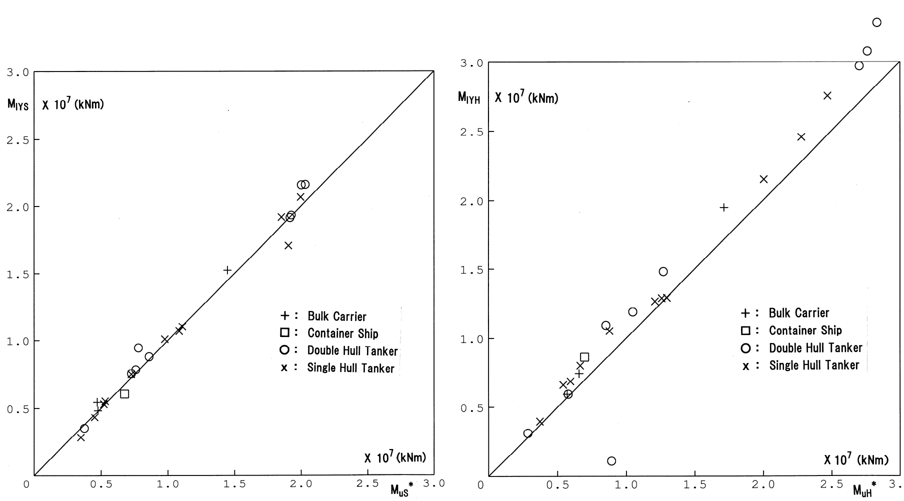
10.3 Ultimate Hull Girder Strength

A summarising paper on ultimate hull girder strength have been presented by Paik (2004). Besides a general introduction into the subject, a comparison of design formulae with the software ALPS is shown. In a comprehensive summary, Paik *et al.* (2005b) present several ULS test results for stiffened aluminium panels, and compare them with different analysis procedures considering fabrication related geometric imperfection and the influence of the HAZ. It is shown that the results of non-linear FEM calculations vary with the modelling technique and the way the imperfections are given to the model. They concluded that more reliable results can be achieved by using the computer code ALPS/HULL. The results had been verified by comparison with two full scale experiments. Finally the ultimate bending capacity and vertical bending moment had been derived for a high speed catamaran.



(a) Sagging (b) Hogging

Figure 10.2: Comparison of ultimate hull girder strength by JBP method and HULLST



(a) Sagging (b) Hogging

Figure 10.3: Comparison of ultimate hull girder strength by HULLST with initial yielding strength

Apart from vertical bending, the ultimate capacity under torsional loads has been investigated by Sun and Guedes Soares (2003). The collapse loads of two models have been tested under pure torsional loads and have been compared with a non-linear FEM analysis with a half length model. The numerical analysis clearly shows that the degree of warping restraint has significant effect on the ultimate capacity. The full restrained FE-model had a capacity twice as high as the unrestrained FE-model, whereas the test results were near to the analysis results of the unrestrained model. The ratio of the ultimate torque of the unrestrained model to the initial yielding torque was 1.1. In view of the effect of the degree of warping restraint in real ship structures and the uncertainties of its application to an analysis model, it seems sufficient to use the yielding torque as a limiting capacity for practical application in the design process. As a supplement to the above investigation, Zhang and Wang (2004) have proposed a coefficient based method to be used for the prediction of ultimate torque capacity based on coarse mesh FEM-analyses.

In case of a bulk carrier in alternate loading condition, high shear force is produced near transverse bulkheads as well as high bending moment. To clarify the influence of shear force on the ultimate hull girder strength, Yao *et al.*(2004) tried to modify the Smith's method. The first step is to calculate elastically the distributions of shear stress and warping of the cross-section subjected to combined bending moment and shear force applying analytical method. Then, warping strain is added to the bening strain so that the influence of warping can be considered. On the other hand, influence of shear stress is considered in the buckling and yielding strength estimation. They concluded that the ultimate hull girder strength could be increased owing to the warping of the cross-section in many cases, see Fig. 10.4.

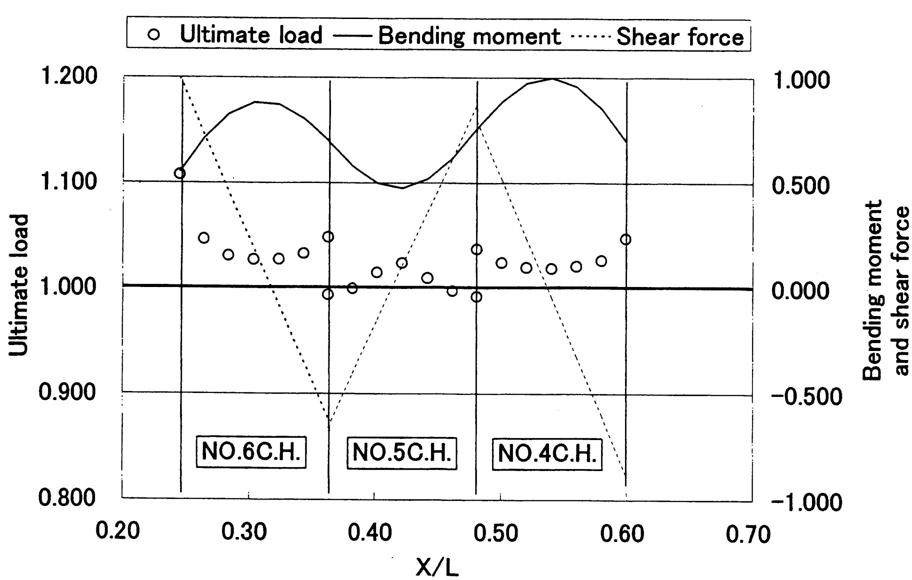


Figure 10.4: Influence of vertical shear force on ultimate hull girder strength

Further to investigations on intact ships, papers deal with the ultimate capacity of damaged ships. Hu and Cui (2004) have focussed on the shear capacity of a bulk carrier with collision damage. Herbert Engineering (2005) had performed an investigation of the ultimate strength capacity by applying the software ULSTR to a modern passenger ship taking three different loading scenarios under three flooding scenarios into account. The calculations take changes in the buoyancy distribution due to flooding and the heeling angle into account. As a result, it can be stated that modern passenger ships have sufficient reserve.

As a basis for a quick estimation of the hull girder bending capacity, Ziha and Pedesic (2002) offer a graphical presentation of curves of equal residual hull girder bending capacity in percent of the maximum capacity depending on the extent of the damage to the hull's deck, side plating or bottom. The curves have to be calculated in advance by using the iterative procedure as presented. The procedure considers the vertical bending moment only. The basic assumption was that, at the very beginning of a damage scenario, the ship is in upright position.

Corrosion can be seen as a kind of damage of the hull structure. Paik *et al.*(2003d) present an investigation of the corrosion propagation for bulk carriers. Based on the statistical evaluation of long term corrosion measurements, a corrosion models for average corrosion and for pitting corrosion for different members of the structures are proposed and was used for the determination of the ultimate hull girder bending capacity. Uncertainties of the corrosion propagation due to the different coating life are noted, and further studies of this effect are found to be necessary.

The above mentioned uncertainties can be considered by reliability based approaches. Moan *et al.* (2005) have done an investigation on the influence of the uncertainties on the ultimate hull girder capacity under bending and shear. By recalculating previously published experiments under consideration of the effects of different load shedding patterns, residual stresses, initial imperfections and modelling techniques, a comparison was done with the JTP approach. Some of the influential parameters lead to an uncertainty $X \leq 1$, while others lead to $X \geq 1$. Further investigations in this field are deemed necessary.

In context with probabilistic methods, Texeira and Guedes Soares (2005) have worked on partial safety factors. For four different tanker structures, partial safety factors for the wave bending moments defined in classification rules and for the still water bending moment have been elaborated under full load condition (sagging) and ballast load condition (hogging). The factors are dependant on the ship's length, whereas the partial safety factors for the ultimate bending capacity can be assumed as constant for different ship length. For full load condition, the wave bending moment is the dominating load, while for ballast load condition, the still water bending moment dominates. As a result of this study, it can be mentioned that the hogging condition has to be investigated as well for tanker structures. Finally, the results of the study were used to optimise a tanker structure to meet a preset reliability level. Compared with the initial design in the example, the deck thickness had to be increased whereas the bottom thickness could be decreased.

11. OFFSHORE STRUCTURES

11.1 Jack-up Platforms

Jack-up drilling platforms are used for the exploration and operation of offshore oil and gas fields as well as for servicing of fixed structures. A special issue of ***Marine Structure*** (Volume 17 – Numbers 3-4, 2004), organised edited by C.D'Mello, B. McKinley and L.F. Boswell, contains some papers presented at the Ninth International Conference on Jack-Up Platforms held on 23-24 September 2003 in London. Papers of interest for the Ultimate Strength of jack-up units are outlined below.

Cassidy *et al*.(2004) reviewed the development of numerical models for the analysis of spudcans on both clay and sand for application in the response analysis of jack-up platforms. A formulation is presented for a six degrees-of-freedom model that describes the load-displacement behaviour. Strain-hardening plasticity theory has been incorporated in the formulation. Using this model, any load or deformation path can be applied to the footing and the corresponding deformations, and loads then calculated. The formulation allows the model to be implemented into three-dimensional structural analysis programs.

Meyer *et al*.(2004) reviewed the effectiveness of the phased foundation assessment procedure presented in SNAME T&R Bulletin 5-5A (2002) to safeguard against gross foundation failure during abnormal environmental events. Analyses were performed for four jack-up units at two North Sea locations. Foundation assessment checks for normal and abnormal environmental events are compared and the effectiveness of the assessment procedure to safeguard against gross foundation failure is considered. Amendments to SNAME T&R Bulletin 5-5A are proposed. The target reserve strength ratio (RSR) for fixed platforms (1.85-1.90 minimum for North Sea studies) is in line with the RSR that would be achieved for jack-up foundations in compliance with SNAME requirements. However, it is emphasised that reliance on factored design event as a proxy for meeting the 10,000-year abnormal environmental loading is only valid, for fixed structures, when ultimate system failure is dominated by member or similar component failures without the intervention of foundation failure. In general, compliance with the SNAME foundation criteria will provide satisfactory foundation performance in the event that 10,000-year load levels are experienced provided the jack-up unit has sufficient air gap to prevent wave-in-deck loads.

Nataraja *et al*.(2004) reported full-scale measurements and analyses of environmental conditions and dynamic response of the GSF Magellan jack-up during five winter seasons for calibration of seabed fixity. During this time, the unit was operating at the Elgin and Franklin platform sites in the North Sea in 90 *m* of water depth and storms with up to 8 *m* significant wave were recorded. The paper discusses the analysis methodology and results related to jack-up foundation behaviour. Comments and conclusions are case-specific and should not be directly extrapolated to other jack-ups and other sites. The results for both the Elgin and Franklin sites suggest that there has been no degradation in soil properties due to the passage of storms. For both locations, it was found that the present SNAME T&R 5-

5A (2002) predicted soil stiffness values which are overly conservative. These conservative values may severely limit the operational envelope of jack-up units. The dynamic fixity values of about 60% observed in the measurement campaign suggests that soil fixity contributes significantly to enhance the operational envelope.

Hunt and Marsh (2004) proposed some methods for ensuring that necessary control measures are in place so that risks associated with structural and/or foundation failure are managed effectively. Recent industry accidents during jack-up drilling operations have resulted in substantial structural damage to the units themselves and to adjacent platforms, risers and pipelines. The number of these incidents indicates that some of the basic control measures, necessary for the successful deployment are absent. Despite the lack of detailed information on many of the incidents, some general observations can be made:

- the incidents are not confined to a particular part of the world;
- the prevailing weather conditions played little or no part in many of the incidents;
- the incidents are not confined to one particular jack-up design;
- when leg damage is noted, this will almost certainly have required a shipyard repair with attendant impact on costs and schedule;
- two of the rigs destroyed adjacent platform over which they were drilling when they collapsed;

SNAME 5-5A (2002) site specific assessment in isolation will not provide a sufficient understanding of the challenges that the rig will face at a new location. The risks associated with in-transit and jacking stages of deployment are typically covered by the owners' rig move procedures with the operating company providing marine advisors. Several specific opportunities for improvement have been identified. These range from the data provided in the Rig Owner's Operations Manual and/or Jacking Procedure to the actions defined in the Rig's Emergency Response Procedure.

Howarth *et al.*(2004) presented the methodology and some results of a study considering the wave loads generated on a typical jack-up structure, if the air gap provision is eroded, and the consequent dynamic response to storm loading when inundation occurs. The effects of structural response to waves, foundation modelling and hull inundation levels on maximum structural response to wave-in-deck loading were assessed by performing time-domain analyses. The results indicated that large horizontal and vertical wave-in-deck loads are generated during inundations and that the jack-up reacts statically to the vertical loading. The foundation modelling affected the predicted response, with coupled, non-linear foundation springs increasing horizontal response by 50% over the linear foundation case. The work summarised in the paper demonstrates that the consideration of any possible wave-in-deck loading on a jack-up unit is important to determine extreme structural response. Wave-in-deck loads, in particular overturning moment, can represent a large proportion of the total load on the structure when inundation occurs. The most important implication of wave-in-deck loading is its potential to cause windward leg lift-off. This is due to the large overturning moment generated by the horizontal wave-in-deck loads in combination with very large buoyancy loads.

Stonor *et al*.(2004) described the methods that were used to recover the GSF Monarch jack-up after it suffered damaged leg bracings while jacked up adjacent to the Shell UK Exploration and Production Leman D platform. The analyses undertaken in this study confirmed that the damaged leg could withstand the 50-year extreme storm as long as the rack chocks were in place. Under such conditions, there was virtually no additional load carried by the brace members, and the strength of the leg was largely determined by the chords, which had considerable reserve capacity. A variety of additional analyses were used to confirm that the non-buckled members of the leg were not excessively stressed as a result of the large applied rack phase difference (RPD). These calculations used a number of approximations for the damaged leg members, including both complete removal and replacement with forces to represent a lower bound of the buckled brace residual capacity. Careful study of the mechanics of the RPD effect have clarified the particular importance of eccentric spudcan loads which can easily arise for this class of jack-up when operating on hard soils and some conditions of sloping seabed.

11.2 Nonlinear Frame Analysis

The accuracy in the prediction of an offshore platform response subjected to static extreme environmental loads depends primarily on many important factors. The representation of local component behaviour, including the joint-frame interaction determines directly the load redistribution once member or joint failure occurs. The accurate modelling of the boundary conditions including soil-structure interaction affects both the static as well as the dynamic frame response.

BOMEL (1992) and Bolt and Billington (2000) organised an international joint industry project s with large-scale 2D and 3D frame experiments. The initial phase of the program tested ten large-scale 2D frames, which consisted of six double-bay X-braced frames and four single-bay K-braced frames, as illustrated in Figure 11.1. The second phase of the project tested a 3D frame under three different loading conditions, as shown in Figure 11.2. The X-joint in 2D and 3D frames experienced large deformation, and consequently caused redevelopment of the joint strength due to the direct contact of two compressive braces, as described in Figure 11.2. The regain in the joint strength generated a higher global frame capacity compared to the frame designed with a strong joint. The BOMEL JIP concluded that the local joint flexibility introduces a significant effect on the global frame response.

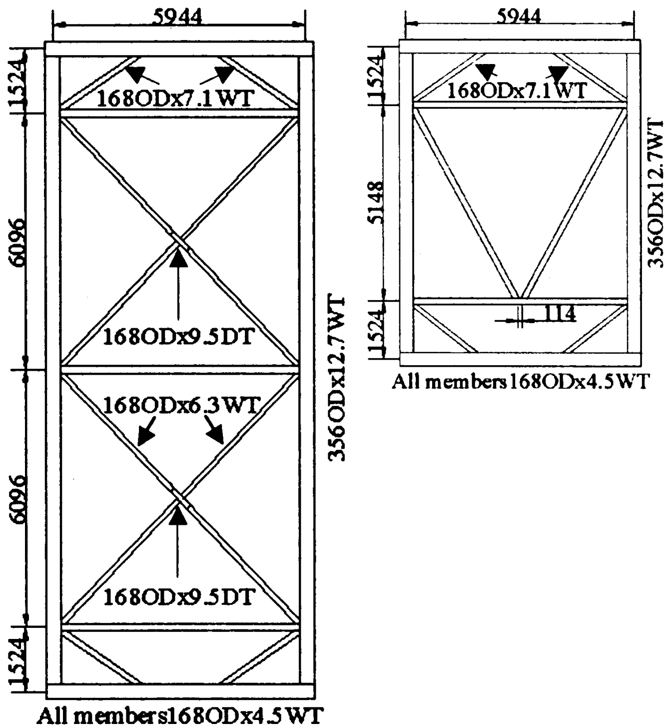


Figure 11.1: Configuration of 2D BOMEL test frames

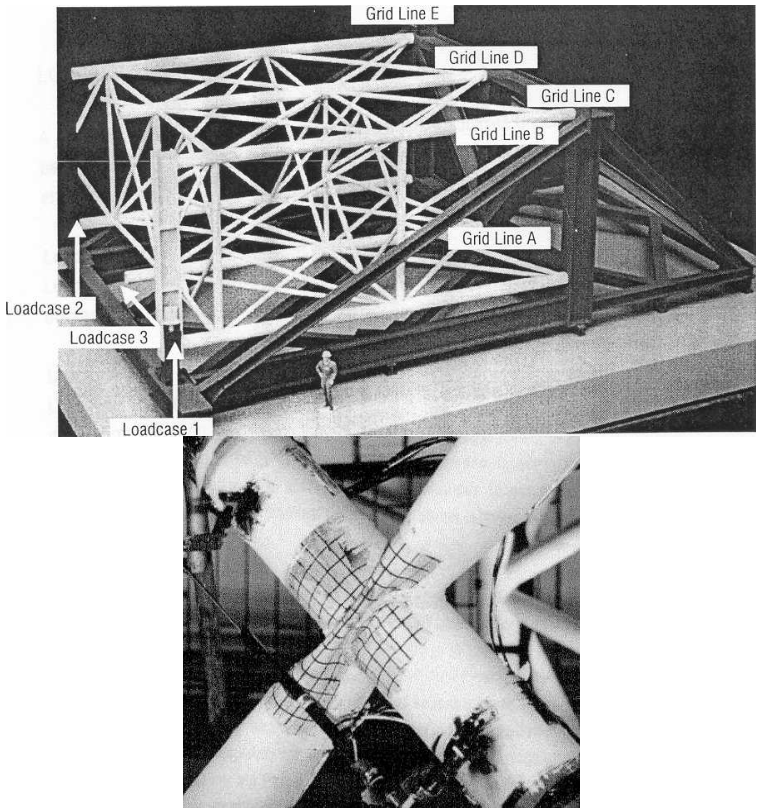


Figure 11.2: Configuration of 3D BOMEL test frame and the corresponding joint failure

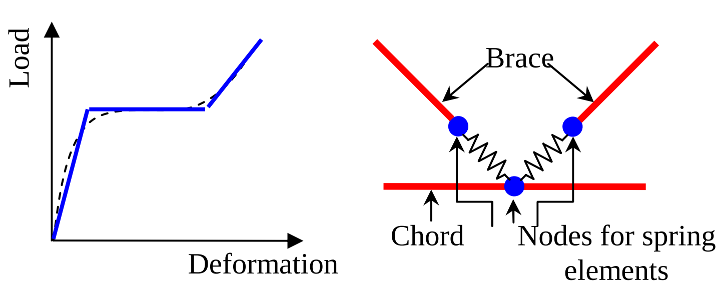


Figure 11.3: Phenomenological representation of the local joint stiffness and strength

The current design approach, based on linear-elastic analysis of the global frame with an ultimate check on the local component, ignores the reserve strength available in the structure and provides a very conservative solution. Choo *et al*.(2005) present an approach to include the local stiffness and strength in the nonlinear analysis of the global structure, using a phenomenological representation illustrated in Figure 11.3. The formulation for the stiffness and strength of CHS X- and K-joints derives from a very detailed finite element study of the corresponding joints (Qian, 2005). The comparison of the proposed joint formulation with the BOMEL test data shows close agreement, as illustrated in Figure 11.4.

Nelson *et al*.(2004) investigated the effect of primary member damage on the redistribution of stresses in offshore platforms. The damage tolerance of a structure depends highly on the structure redundancy. Consequently, the X-braced frames prove to be more tolerant to member damages than the K-, inverted K-, and diagonally braced frames. The reliability study on different bracing systems demonstrates that frames with high redundancy are more reliable in resisting extreme storms and fatigue damages. A subsequent study by Nelson and Sanderson (2005) focussed on the effect of multiple member damage on the reliability of X- and K-braced jacket frames. They found that the dual member failure does not cause significant strength reductions compared to single member failure. However, in cases of low redundancy, dual member failure weakens considerably the structural capacity.

Mostafa *et al*.(2004) studied the dynamic response of the fixed jacket structure, with the soil-pile interaction included, using a set of load-deformation curves determined and modified from the API guidelines. The study concluded that the resistance of the top soil layer remains most critical to the dynamic response of the jacket and the pile.

The global response of a jack-up platform depends on the accurate modelling of the hull-leg connection and the spudcan foundation. Tan *et al*.(2003) presented a numerical method to predict the jack-up response under jacking operation. The finite element approach adopted a spring and dashpot system to model the interactions between the pinion and the chord, and between the guide and the chord. The study considered the boundary conditions on the jack-up by assuming pinned or fixed on different vertical legs.

12. COMPOSITE STRUCTURES

Composite structures are increasingly being considered and used for lightweight, advanced applications, in areas with high corrosion, and in areas requiring the integration of the structure with other ship systems. Uses include composites for naval vessels, i.e. patrol boats, minecountermeasure vessels, and corvettes; composite substructures; composite masts; composite propulsion systems, i.e. propellers, propulsors and shafts; composite secondary structures and machinery-fittings; and composite submarine structures, i.e. pressure hulls, control surfaces, and masts.

A multi-year program headed by the University of Maine has been considering composite material variability prediction and control from the coupon level to the component or structural level. As part of this study, probabilistic finite element analyses were conducted of a tabbed material coupon under axial tension according to ASTM D3039 by Fayad *et al*.(2005), to develop an understanding of the linkage between material property variability spatially distributed through the coupon and the coupon breaking strength. Strategies are proposed for determining model inputs and spatial correlations. In support of the same project, Lua *et al*.(2004) propose a method by which a more complex relationship between composite constituent properties are combined to simulate the component progressive failure through ultimate, using the Thermal-Mechanical Analysis Tool (TMAT) and Multi-Continuum Theory (MCT). Once the linkage is made using deterministic methods, the goal is to evolve the process into supporting probabilistic analyses. Key *et al*.(2004) use the same suite of tools to develop a failure model for a solid laminate plate being loaded to failure under lateral pressure in the Hydromat test fixture (ASTM D6416). The Hydromat test fixture is found to be inappropriate for this use without modification to the fixture to account for higher compressive loads and increased displacements.

Blake, *et al*.(2002) use modelling and test to investigate the static structural response of a composite E-glass/vinyl ester hat stiffener containing a viscoelastic insert between the core and the plate or flange material. The progressive failure of the hat stiffener in 3-point bending is developed using ABAQUS with the Tsai-Hill failure criteria. The results of the prediction are examined in detail relative to a single representative test. The predicted displacement at failure was similar to the test but the predicted reaction load was 20% less than the test value.

The effects of geometry and debonds in a glass fibre T-joint were explored numerically and experimentally by Dharmawan, *et al*.(2004). Such a joint is meant to represent the intersection of a deck or bulkhead with the hull, being designed to withstand a pull-off load. Changes in the critical strain were evaluated for different overlaminate angles, hull thicknesses and disbands between the overlaminate and the filler. The FEA was validated by mechanical tests with surface strain gauges and displacement transducers on T-joints with a range of geometries and defects. Two sets of boundary conditions were used to bound the problem, fixed but free to slide and fixed. The optimum overlaminate angle was found to be 45°. The hull thickness and resulting stiffness was found to affect the strains in the joint. Four cases of damaged and non-damaged specimens were tested to validate the FEA results. It was found that the test strains were within the range defined by the two sets of FE boundary conditions.

Kelly and Hallström (2005) explore bolt pull-through strength of vinyl ester and epoxy resin system composite plates of varying size. Vinyl ester plates were more likely to fail through global collapse while epoxy plates fail due to pull-through. The authors conclude that damage accumulation dictates the failure strength and that first-ply failure can occur at 20-25% of the ultimate failure load, which can have a significant bearing on the joint fatigue strength.

The durability strength of composite materials is of continuing concern for marine applications due to moisture, temperature and cyclic loading effects on the residual strength. Kootsookos and Mouritz (2004) compare glass/polyester and glass/vinyl ester to carbon/polyester and carbon/vinyl ester with respect to seawater durability, moisture absorption behaviour, degradation mechanisms and mechanical properties when immersed for two years in 30ºC seawater. Four-point bending testing (ASTM D790) was used to measure the flexural modulus and flexural strength. The Mode I inter-laminar fracture toughness was measured using Double Cantilever Beam tests (ASTM D5528). After 30 days of immersion, the flexural strength of the polyester specimens degraded 20-40% for both glass and carbon. The vinyl ester sample strengths degraded 40-50%. The polyester resin system was not expected to fare better than the vinyl ester system due to greater chemical stability of the vinyl ester resin system in seawater, and the authors recommend further investigation. The authors found that Mode I fracture toughness was not significantly affected by immersion in sea water.

Chu, *et al.*(2004) investigated the deterioration of pultruded E-glass/vinylester composites due to immersion in deionised water and alkaline solution for up to 75 weeks, with degradation acceleration through use of a range of elevated temperatures. Coupon tension tests (ASTM D3039) and short-beam-shear tests (ASTM D2344) were used to evaluate material strength. It was shown that alkali exposure is more severe than deionised water, and that the higher temperatures accelerate material strength degradation. Table.1 presents the amount of strength degradation resulting from the conditioning.

Table 1
Residual strength after 75 WEEKS immersion.

Fluid	Tensile (23C)	Tensile (80C)	Shear (23C)	Shear (80C)
Alkaline Solution	58.2%	37.5%	75.1	46.6
Deionised water	65.2%	28.2%	77.4	49.8

13. ALUMINIUM STRUCTURES

13.1 Research Subjects

An extensive major work has been done by the Committee III.1 of the 15th International Ship and Offshore Structures Congress, ISSC'03 (Simonsen *et al.*, 2003), related to the ultimate strength of aluminium stiffened panels. A sensitivity analysis covering the weld types, initial imperfections including residual stresses and material properties allowed to conclude that the reduction in the ultimate strength may be up to 30% (Rigo *et al.*, 2003).

Since then, the major points of interest are concentrated on:

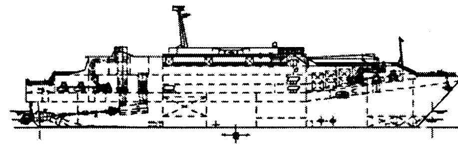
- welding effects,
- boundary conditions,
- ultimate strength formulations,
- Finite Elements Analysis applied to aluminium,
- developments of Eurocode 9,
- structural details,
- Methodologies,
- Aluminium alloys and their comparison.

From the viewpoint of the geometry and load systems, the research activity on aluminium structures on the last three years has covered plates under compression, stiffened panels, multi-hull structures and I-beams and deck profiles, subjected to simple or complex load combinations.

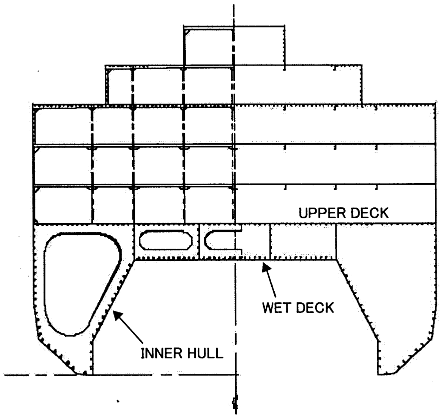
13.2 Welding Effects

Rigo *et al.*(2004) dedicated attention to the effects of welding on the ultimate strength, concentrating on the location of welding, HAZ width and the corresponding degradation on the material properties due to heating. It was concluded that the parameters to have larger influence on the ultimate strength are the yield stress and the width of the HAZ. The level of residual stresses and initial imperfections are considered to have influence of the second order. The inclusion of the transverse welding fillets on the FE model conducted to the worst case of strength degradation, up to 27.5%. The location of the transverse fillet seems to be irrelevant since the strength degradation is of the same level.

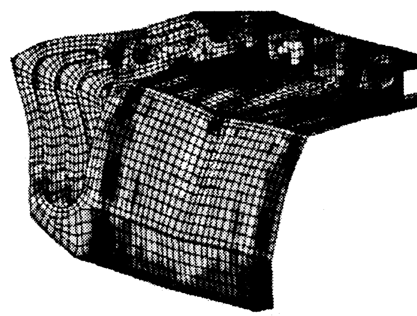
However, a more detailed and recent work related to the reduction in the ultimate strength of panels due to the degradation of the yield stress in HAZ indicates that the reduction is of a lower level than that initially expected (Richir, 2004). It was found that the ultimate strength of the ISSC panel has low sensitivity to the variation in the HAZ yield stress. In that respect, more research is needed.



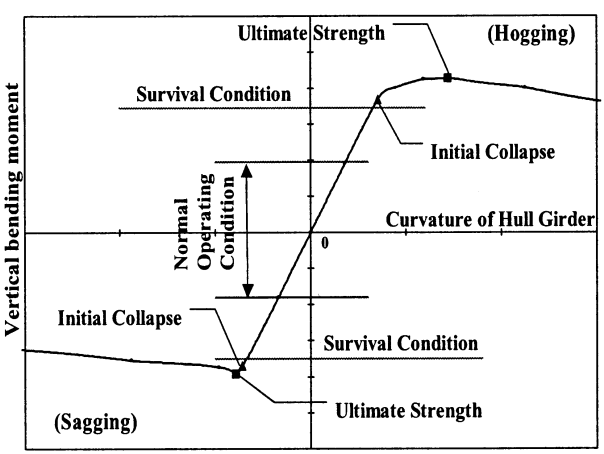
(a) General arrangement



(b) Mid-ship section



(c) Buckling collapse mode by FEM



(d) Moment-curvature relationship

Figure 13.1: Design of high-speed aluminium passenger ship of catamaran type

13.3 Structural Design of Aluminium Ship

Adhesively bonded aluminium superstructures were analysed by Jarry *et al.*(2004). The structural strength under shear and tension of the adhesive connection between aluminium units and aluminium to steel joints was evaluated by tests and numerically. The increase in the adhesive bond thickness reduces the strength of the connections both in terms of the ultimate carrying capacity and stiffness. Special care should be paid to the surface of the steel to be bonded.

A 140 *m* aluminium ship was designed by the so-called 'design by analysis' procedure (Koshio *et al.*, 2005). Two limit states were considered for the structural analysis: the normal operational condition and the survival condition. The latter was used for the establishment of the ultimate strength requirements. In order to minimise the problems associated with the traditional aluminium shipbuilding, extruded profiles and stir friction welding were extensively used. The ultimate strength of the ship was accessed by the progressive collapse analysis with the computer code 'HULLST'(Yao and Nikolov, 1991; 1992) and by 3D-FEM analysis of the whole ship model. The FE model uses a coarse mesh for global ship analysis and a medium size mesh for the ultimate transverse strength analysis. Figure 13.1 shows the general arrangement, mid-ship section, collapse mode by FEM and moment-curvature relationship of the hull girder.

13.4 Ultimate Strength Design Methods

Paik *et al.*(2005c) extend the classification of the collapse modes for steel structures to aluminium based ships. A comparison is made between aerospace and land based structures with two computer codes used for marine structures, DNV's PULS (Steen and Ostvoid, 2000) and ALPS/ULSAP (2005). The latter uses the formulas derived for evaluation of the ultimate strength of aluminium plates and panels for marine applications (Paik and Duran, 2004).

The formulas consider that the plates are simply supported along four edges and subjected to axial compression. It takes into account three different regions according to the plate slenderness, which are stocky, intermediate and slender plates, and evaluates the ultimate stress, σ_{xu}, as follows:

$$\frac{\sigma_{xu}}{\sigma'_{Yp}} = \begin{cases} 1.0 & \text{for } \beta' \le 0.46 \\ -0.215\beta' + 1.1 & \text{for } 0.46 < \beta' < 2.2 \\ -0.083\beta' + 0.81 & \text{for } \beta' \ge 2.2 \end{cases} \tag{13.1}$$

The main feature is to consider explicitly the effect of the softening in the heat affected zone on the definition of a corrected yield stress, σ'_{Yp} that is used on the definition of the plate slenderness, β'. This is simply done by:

$$\sigma'_{Yp} = \frac{(a - 2b'_p)(b - 2b'_p)\sigma_{Yp} + 2[ab'_p + (b - 2b'_p)b'_p]\sigma'_Y}{ab}$$

Where *a* and *b* are the main dimensions of the plate with a yield stress of σ_{Yp}, b' is the breadth of softening in HAZ with a yield stress of σ'_Y. For aluminium panels under uniaxial compression, Paik *et al*.(2004) proposed a formula where the softening of HAZ in the stiffener is also considered.

A modified Faulkner's formula for the ultimate strength of plates was proposed by Wang *et al*.(2005) in order to account for the effects of the welding in the HAZ. They consider a reduction factor due to softening in HAZ, ψ, that corrects the plate slenderness as □'=□/ψ. The reduction factor is defined by:

$$\Psi = 1.142 - \frac{1.42}{\beta^{0.5}}(1-\eta) \quad \text{for} \quad \eta < 1 - 0.1\beta^{0.5}$$

and is equal to unity for different η. The method was validated against FE models, where the stress-strain relationship is the Ramberg-Osgood proposal. The method gives 10% conservative ultimate strength but coefficient of variation is only 4.6% for 56 FEA stiffened plates results. Similar work was done by Bezkorovainy *et al*. (2003) without considering residual stresses. The stress-strain curves of unstiffened plates are defined as a generalised Winter curves calibrated by a series of FEM analyses.

An analytical method to simulate the behaviour of stiffened plates under combined loads was proposed by Paik and Lee (2005). The elastic large deflection response of stiffened plates are joined by the plasticity effects considering that plasticity should be taken into account on the membrane components of stiffness matrix but not on the bending components.

13.5 Stiffeners

The ultimate compressive strength of stiffeners modelled by plate elements supported along one edge was investigated by Xiao and Menzemer (2003). A comparison between the analytical results and available experimental data showed that current design for compressive strength of outstanding elements is conservative. It is suggested that the differences are related to the establishment of the boundary conditions. The behaviour of the same type of elements has been analysed numerically and experimentally by Zha and Moan (2003).

The development of Eurocode 9 for aluminium structures leads Tryland *et al*.(2003) to study numerically the behaviour of I beams and deck profiles under concentrated loading in the beam's transverse direction. The results were validated against data obtained from an experimental program. Comparisons have shown that design formulas developed for steel beams (Eurocode 3) should be adjusted to account for the difference in material properties when applied to aluminium beams.

14. BENCHIMARK

14.1 Outline of Benchmark

During the last decade, the superstructure size of large passenger ships has expanded significantly due to the growing need for open spaces in restaurants, theatres and atriums. A modern passenger ship has a high and long superstructure, which is supported by pillars and longitudinal bulkheads and is accompanied by large recess area for lifeboats, see Figure 14.1.

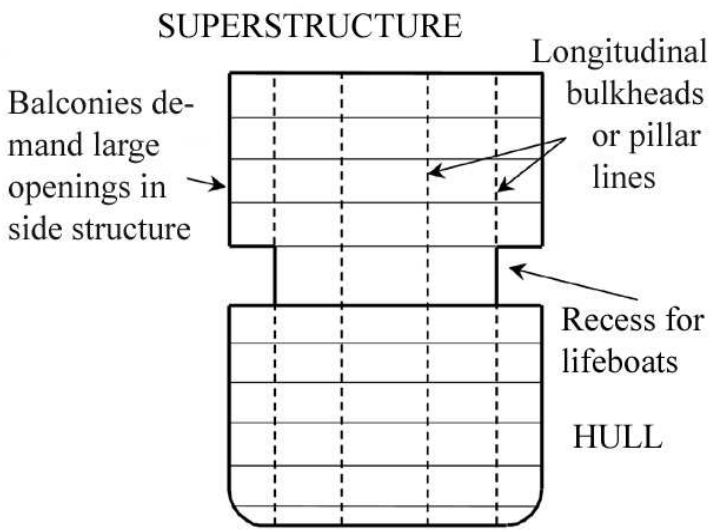


Figure 14.1: Typical cross-section of a modern passenger ship

The longitudinal bulkheads in the superstructure are normally of around 5 - 8 *mm* thickness, and the side shell structure is discontinuous due to the balcony openings. As a result, the superstructure has low shear stiffness, and the structural members like longitudinal bulkheads and side shell plating can suffer from high shear stress as well as high normal stress due to bending. Therefore, complex structural behaviour may take place because of large openings in the longitudinal structures together with transfer mechanism of shear stresses through not only vertical plating but also decks in the area of lifeboat recess, which is called shear lag effect.

Such structural characteristics and behaviours are quite different from those of tankers and bulk carriers. At the same time, a large passenger ship carries plenty of ordinary people and the safety assessment is much more important compared to the ordinary merchant ships. Because of these, concern for the evaluation of the global strength of large passenger ships has been increasing, and this is the reason why this benchmark is carried out.

14.2 Typical Post-Panamax Passenger Ship in Bending

Naar *et al.*(2005) performed a FEM-based strength calculation for idealised post-Panamax type passenger ship. The length of the ship is approximately 270 *m* and the ship has totally thirteen decks. In order to simplify the FEM calculations, the model with prismatic shape is considered. The structure is loaded with distributed load of which shape is a single cosine mode having maximum values at a mid-ship and both ends, see Figure 14.2. The moment distribution calculated from this distributed load has maximum value at mid-ship and will vanish at both ends. This type of loading will be similar to the design moment distribution given by Classification Societies although their design loads are linearly distributed. The maximum moment at a mid-ship is taken as $8.94 \cdot 10^6\ kNm$ which corresponds to the sum of the wave and still water bending moments.

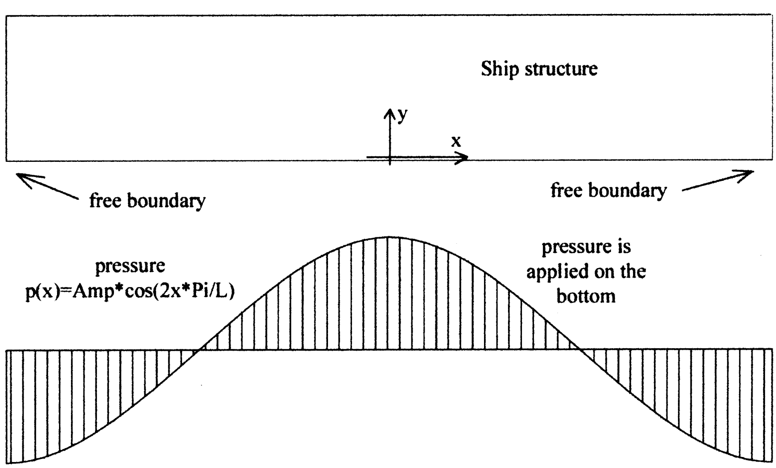


Figure 14.2: Applied pressure loads on bottom structure

Figure 14.3 shows the mid-ship section of a typical post-Panamax passenger ship and the normal stress distribution under the action of the above mentioned distributed load on the ship bottom structure. The normal stress is discontinuous between side shell plating and recess wall plating as well as between recess wall plating and longitudinal bulkhead. It is not indicated in the figure, but the above mentioned discontinuous normal stresses are continuous at the 4th deck (D4) between points B and C as well as at the 6th deck (D6) between points D and E. This is a so-called 'shear lag' phenomenon.

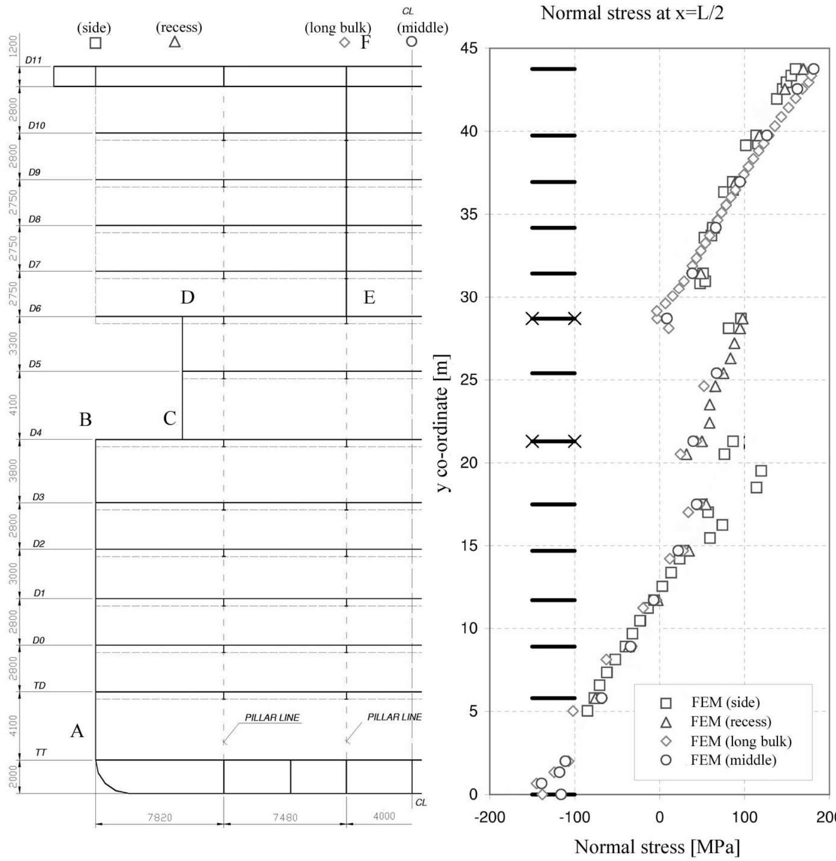


Figure 14.3: Main frame of a post-Panamax type passenger ship and its normalstress distribution

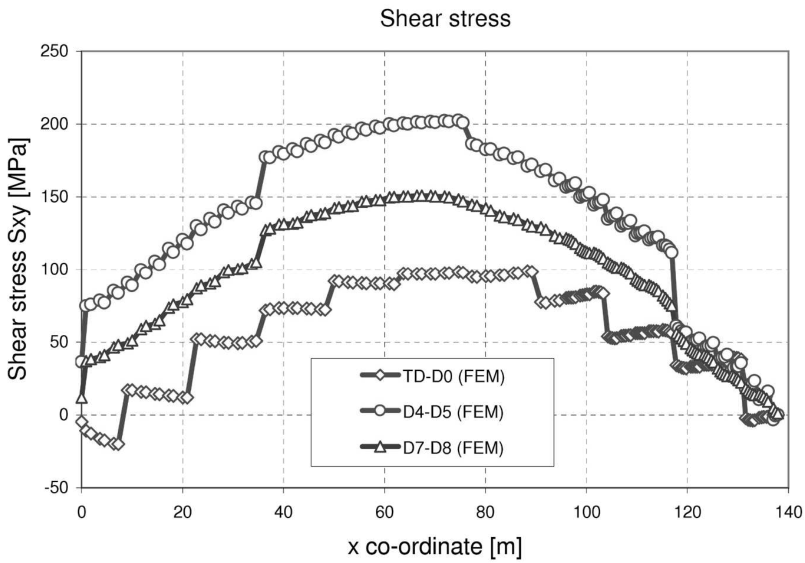


Figure 14.4: Shear stress distribution in side shell plating

On the other hand, Figure 14.4 presents the longitudinal shear stress distributions calculated in the side shell plating between the tween deck (TD) and the 0th deck (D0), in the recess wall plating between the 4th deck (D4) and the 5th deck (D5) and at the longitudinal bulkhead between the 7th deck (D7) and the 8th deck (D8). The shear stress is the highest at the longitudinal bulkhead between the 4th and the 5th decks. This may be because the thickness of the longitudinal bulkhead here is thinner compared to the main hull and the side shell plating does not exist to provide lifeboats recess area. The transverse watertight bulkheads and fire bulkheads cause the jumps in the shear stress distributions. It should be noticed that the magnitude of shear stress is almost the same as that of normal stress by bending.

14.3 Problem Definition

(1) Hypothesis

The fact that the bending stress/strain over the cross-section is not linearly distributed can cause some complexities in the collapse behaviour. At the same time, the fact that the shear stress in the longitudinal plating can reach a level comparative to the normal stress can also cause some complexities in the collapse behaviour. As a result, the ultimate hull girder strength of a modern passenger ship can not be as high as that expected by conventional simplified analysis such as the widely used Smith's method. The idea of this benchmark is to compare different approaches and their applicability for this type of ultimate hull girder strength analysis.

(2) Restrictions

In order to simplify analysis, the initial deflections and residual stresses are not considered in the FEM analysis. For the same reason, a prismatic hull girder structure is considered. In addition to these, the effects of the water pressure on local panels in the bottom and side shell plating are not considered.

(3) Benchmark structure

The benchmark ship structure is shown in Figure 14.5. It has seven decks and the length of the ship is 165 *m*. The structure is prismatic all over the length. The superstructure starts from the 2nd deck with recess area and has large side openings with dimensions of 1800x1800 mm at every deck above the 3rd deck. The web frame spacing of the ship is 3,000 *mm*.

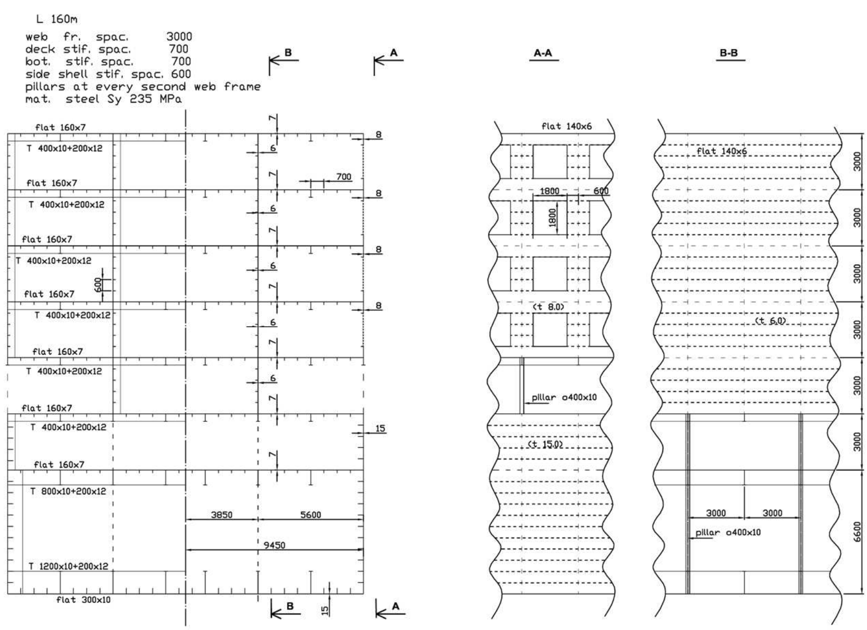


Figure 14.5: Mid-ship section of the benchmark hip

The superstructure is reinforced with longitudinal bulkheads at position 3,850 *mm* apart from the centre line. In order to support the longitudinal bulkhead vertically, pillars are installed every two web frames below the longitudinal bulkhead. The thickness of the bottom and the side shell plating of the main hull is 15 *mm*.

Bottom girders and floors have dimensions of 1,200x10 *mm* for the web and $200\times12\ mm$ for the flange. Bottom plating is additionally stiffened with flat-bar longitudinals having dimensions of $300\times10\ mm$ with spacing of $700\ mm$. Web frames of the main hull consist of $800\times10\ mm$ web and $200\times12\ mm$ flange. The side shell plating of the main hull and the bottom plating have the same type of stiffeners. All the decks have a plate thickness of $7\ mm$. They are reinforced with longitudinals and deck beams with $400\times10\ mm$ web and $200\times12\ mm$ flange. The exception is the 1st deck where the deck beams are identical to the deck girders attached to the 1st deck. Decks have also flat-bar longitudinals of $160\times7\ mm$ with spacing of $700\ mm$. The side shell of the superstructure has a thickness of $8\ mm$ and the longitudinal bulkheads $6\ mm$. Both are reinforced with $140\times6\ mm$ flat-bar longitudinals.

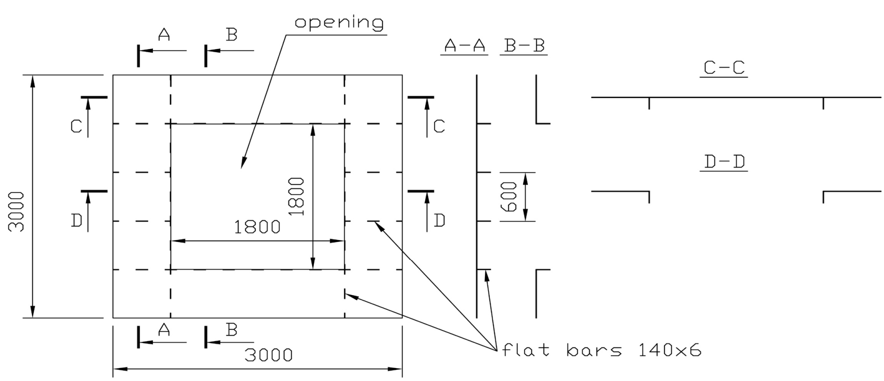


Figure 14.6: Local design of balcony openings

TABLE 14.1
DIMENSIONS FOR STRUCTURAL ELEMENTS

Structural element	Location	Dimensions [mm]
Bottom plating	Bottom	15
Deck plating	all decks	7
Side plating	hull	15 (below recess) 8 (above recess)
Longitudinal bulkhead plating	superstructure	6
Web frame & girders	bottom	T-profile web 1200x10 flange 200x12
Web frame & deck girders	1st deck	T-profile web 800x10 flange 200x12
Web frame & deck girders	superstructure & 2nd deck	web 400x10 flange 200x12
Pillar	Between 2nd & 3rd deck and between bottom and 3rd deck	diameter 400 wall thickness 10

The transverse bulkheads have a plate thickness of $10\,mm$ in the lower part between the bottom and the 2nd deck, whereas that of $6\,mm$ in the superstructure between the 2nd and the 7th deck. The lower part of the bulkhead is stiffened with T beams with the $800\times10\,mm$ web and $200\times12\,mm$ flange. The upper part of the transverse bulkheads is stiffened with T beams with the $400\times10\,mm$ web and $200\times12\,mm$ flange. In the transverse bulkheads, flat-bar stiffeners of $160\times7\,mm$ are additionally provided. The side openings of the superstructure are reinforced with flat-bar stiffeners as shown in Figure 14.6. The dimensions of all structural members are indicated in Table 14.1.

(4) Material

The material is a normal strength steel (MS = mild steel) with a yield stress of $235\,MPa$. It is assumed that the material shows an elastic-perfectly plastic behaviour with a Young's modulus of 210 *GPa* and a Poisson's ratio of 0.3, see Figure 14.7.

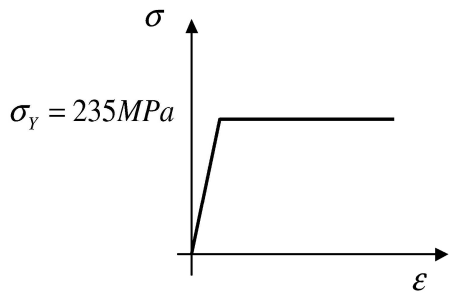


Figure 14.7: Assumed stress-strain curve for steel material

14.4 Methods of Analysis

The analysis is performed in three stages. In the first and the second stage analyses, the Smith's method and the IUSM are applied for one frame space model, whereas in the third stage analysis, the 3D nonlinear Finite Element Method is applied for the whole ship structure. Table 14.2 summarises the methods of analysis applied in the benchmark calculations.

TABLE 14.2

Method/performer	Smith	ISUM	FEM	References
FEM / Naar			x	Hallquist, 1998.
ISUM / Fujikubo		x		Fujikubo and Kaeding, 2002. Fujikubo *et al.*, 2005.
Gordo	x			Gordo and Guedes Soares, 1996.
Procol-Hughes/ Rigo-Toderan	x			Rahman and Choudhury, 1996. Rigo *et al.*, 2001.
Procol-Imperial College / Rigo-Toderan	x			Bonello *et al*, 1993. Dowling, 1991. Rigo *et al.*, 2001.
Procol-Paik / Rigo-Toderan	x			Paik and Lee, 1996. Paik and Mansour, 1995. Rigo *et al.*, 2001.
Paik / Paik & Seo		x		ALPS/ULSAP, 2005.
RULTIM / Principia Marine				Quesnel *et al.*, 2002.
HULLST / Yao	x			Yao and Nikolov, 1991; 1992

METHOD USED IN BENCHMARK CALCULATION

The difference between the first and the second stage analyses concerns the assumption made for bending strain distribution. In the first stage analysis, it is assumed that the strain distribution is linear in the cross-section. On the other hand, in the second stage analysis, nonlinear strain distribution obtained from linear FEM analysis is utilised as the strain distribution. Figure 14.8 shows the nonlinear stress distribution at the mid-ship section obtained by the linear FEM analysis when the maximum bending moment of $1.043 \cdot 10^6\ kNm$ is produced at the mid-ship section. This distribution can be represented with the help of deck efficiency parameters indicated in Table 14.3. The deck efficiency parameter at the bottom plating is taken as 1.0.

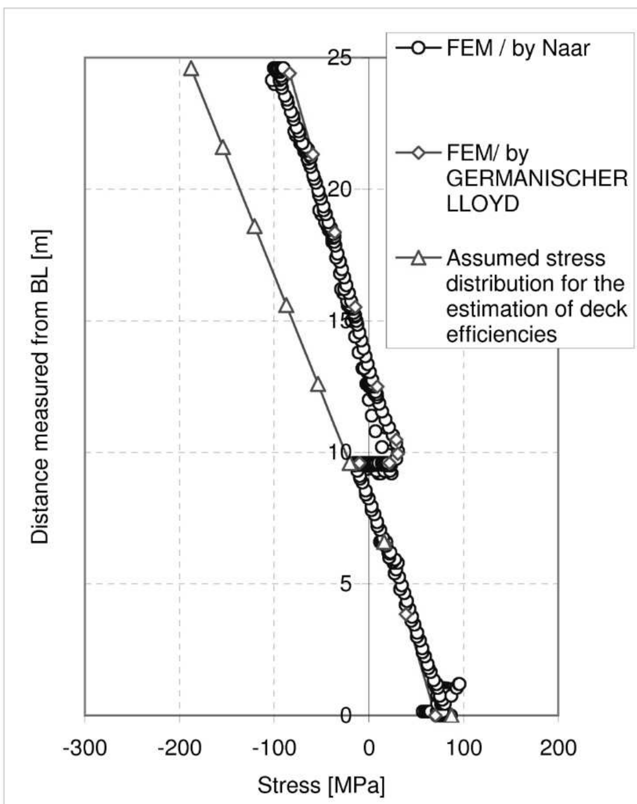


Figure 14.8: Normal stress distribution at mid-ship section calculated by linear FE-analysis

TABLE 14.3

Pos.	Bott.	D 1	D 2	D 3	D 4	D 5	D 6	D 7
deck eff.	1.000	1.000	1.000	-0.088	0.244	0.345	0.433	0.492

DECK EFFICIENCIES FOR SHIP'S HULL (D means Deck)

14.5 FEM-Analysis

In the third stage analysis, the progressive collapse analysis is performed to evaluate the ultimate strength of the hull girder applying the 3D FEM code, LS-DYNA (Hallquist, 1998). For the FEM analysis, 1/2 model is used imposing symmetry boundary conditions on the symmetry plane, see Figure 14.9. Transverse bulkheads are provided at both ends of the hull girder and the superstructure to stiffen the whole structure against shear deformation. In order to fix vertical movements, one end of the structure is vertically supported. The total number of nodal points used in the model is 1.92 millions and the total number of elements is 1.90 millions.

The load is applied according to the prescribed sinusoidal pressure distribution on the bottom structure, see Figure 14.2. Because the original structure had local failure at the bottom structure under the hogging loading, the scantlings of the web frames in the bottom structure were increased. That is, instead of dimensions given in Table 14.1, frames with web of $1200 \times 12\,mm$ and flange of $200 \times 15\,mm$ were used. The FEM model is shown in Figures 14.9 and 14.10.

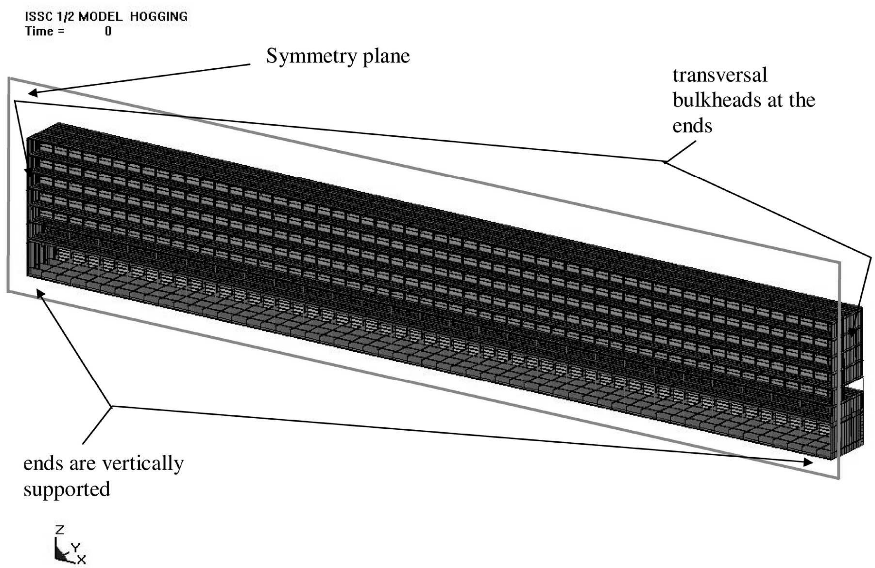


Figure 14.9: FE-model of benchmark ship

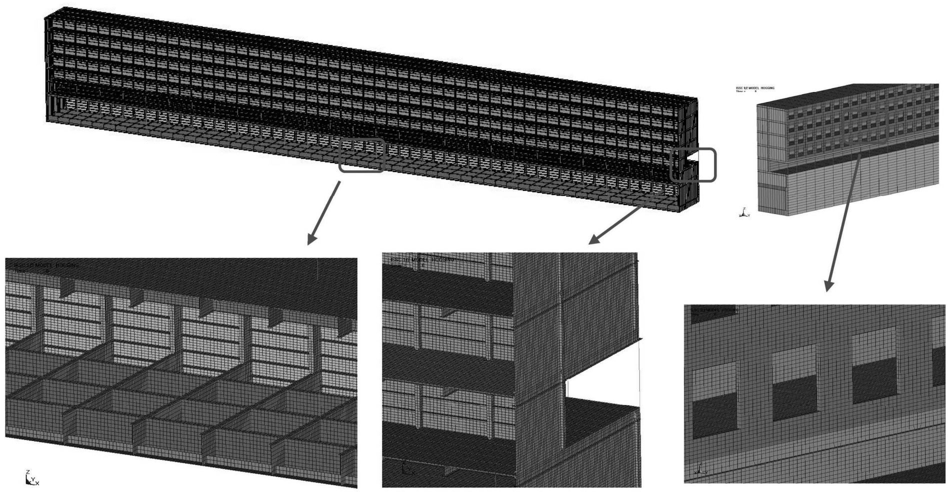
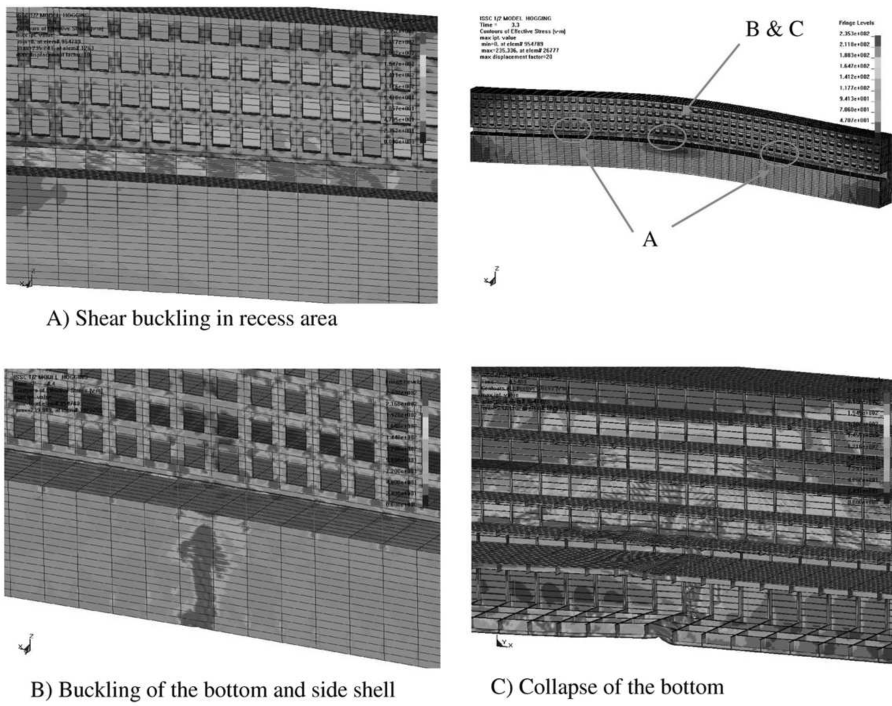


Figure 14.10: FE-mesh of passenger ship model

In the FEM modelling, the four noded shell elements are used for plated structures, and two noded beam elements for pillars. The plate field between stiffeners is formed by 6x20 element mesh, which is able to represent deformation modes in case of plate bucking. The longitudinal stiffeners have two elements in the direction of its height and web frames and deck girders have four elements. The FE-mesh can be seen in Figure 14.10.

The analysis reveals that, in both cases of sagging and hogging loadings, the failure starts by shear buckling at recess area located at a quarter length from both ends, see Figure 14.11. With the further increase in the applied loads, the final collapse of the ship hull is caused by compressive buckling collapse of decks in case of sagging loading and by compressive buckling collapse of bottom structure in case of hogging loading, see Figure 14.11.



A) Shear buckling in recess area

B) Buckling of the bottom and side shell

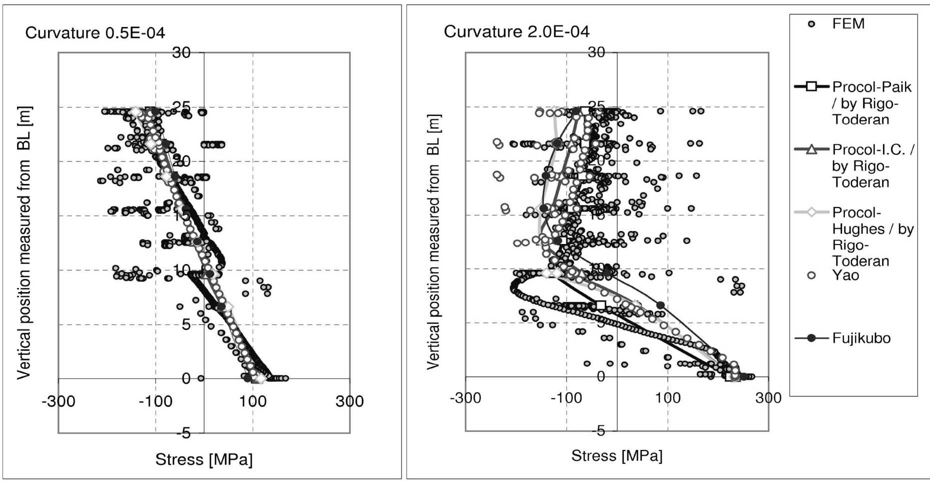
C) Collapse of the bottom

Figure 14.11: Failure modes in hogging condition

14.6 Comparison of Calculated Results

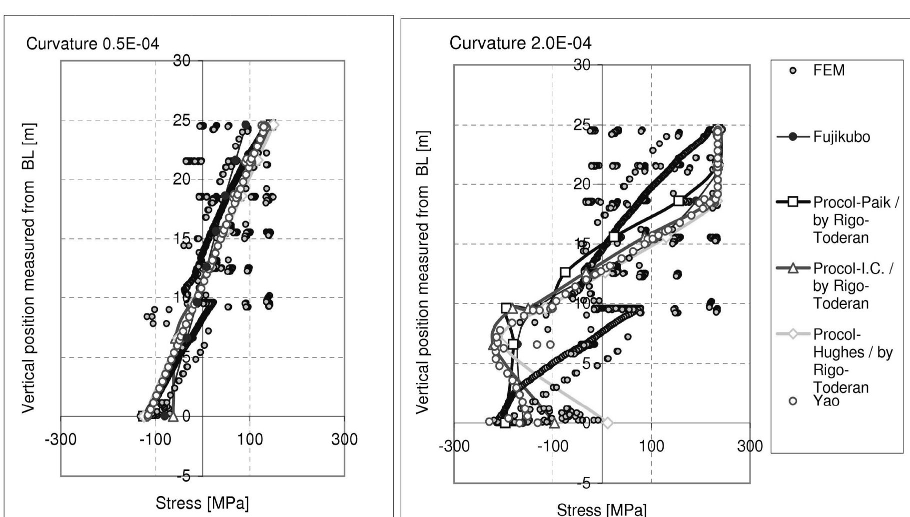
The bending stresses at a mid-ship section obtained by the first stage analysis are plotted in Figures 14.12 and 14.13 together with those obtained by the FEM analysis in the third stage analysis. It can be seen that there is no big difference in the calculated results of the first stage analysis. The curvature can be defined using the curvature of the main hull or the averaged curvature, which is defined using the averaged panel deformations in the 7th deck and the bottom. Curvatures indicated in the figures are the averaged ones.

The comparison of the first stage results with the FEM results indicates that the stress jump in the lifeboats recess area is the main difference in case of small deformations (0.5×10^{-4} curvature). On the other hand, in the post-collapse range, the stress distribution in the main hull obtained by the first stage analysis is different from that by the FEM analysis especially under the hogging loading. This may be partly attributed to the influence of shear buckling at lifeboats recess area, which is not taken into account in the first stage analysis. Another reason may be that the shear lag effect accompanied by yielding disturb the bending stress distribution in a compression side of bending.



(a) Elastic range (b) Post-collapse range

Figure 14.12: Bending stress distribution at mid-ship section under sagging condition (stage 1: with linear strain distribution)



(a) Elastic range (b) Post-collapse range

Figure 14.13: Bending stress distribution at mid-ship section under hogging condition (stage 1: with linear strain distribution)

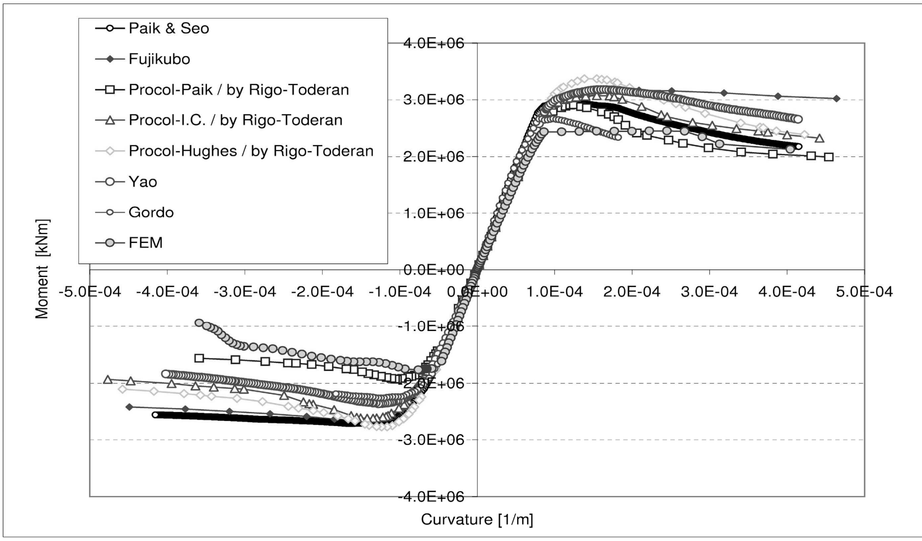
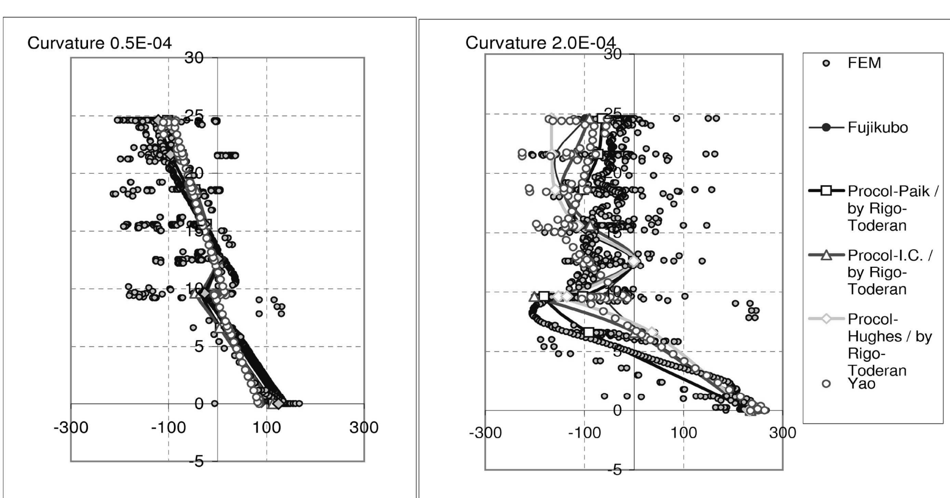


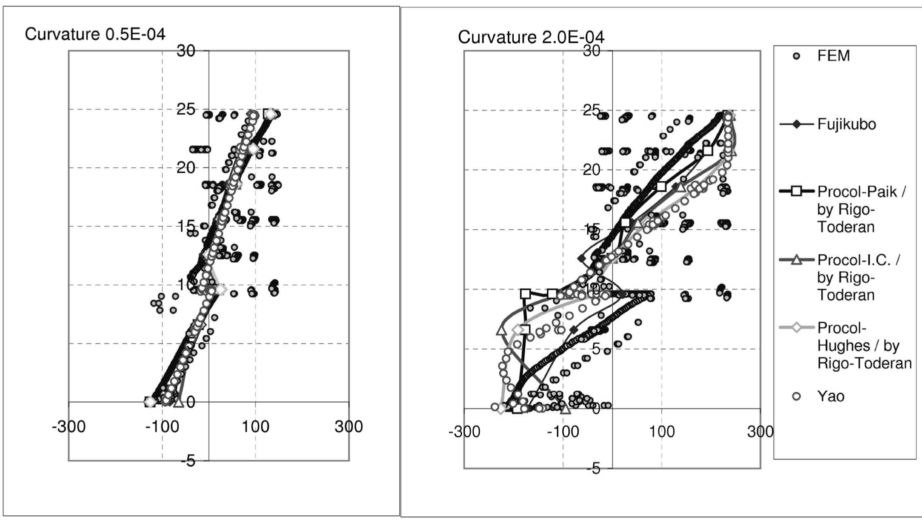
Figure 14.14: Moment-curvature relationships in first stage analysis
(plus: hogging; minus: sagging)

These differences in normal stress distributions have strong influence on the moment-curvature relationships as indicated in Figure 14.14. All first stage approaches, with few exceptions (Gordo and “Procol-Paik” by Rigo), overestimate the ultimate hull girder strength by the FEM analysis. In case of Paik’s approach, the reason is probably the fact that this method includes initial imperfections as much as half of the plate thickness, which significantly reduces the ultimate strength of the structural components in compression, and so the ultimate hull girder strength.



(a) Elastic range (b) Post-collapse range

Figure 14.15: Bending stress distribution at mid-ship section under sagging condition (stage 2: with nonlinear strain distribution)



(a) Elastic range (b) Post-collapse range

Figure 14.16: Bending stress distribution at mid-ship section under hogging loading (stage 2: with nonlinear strain distribution)

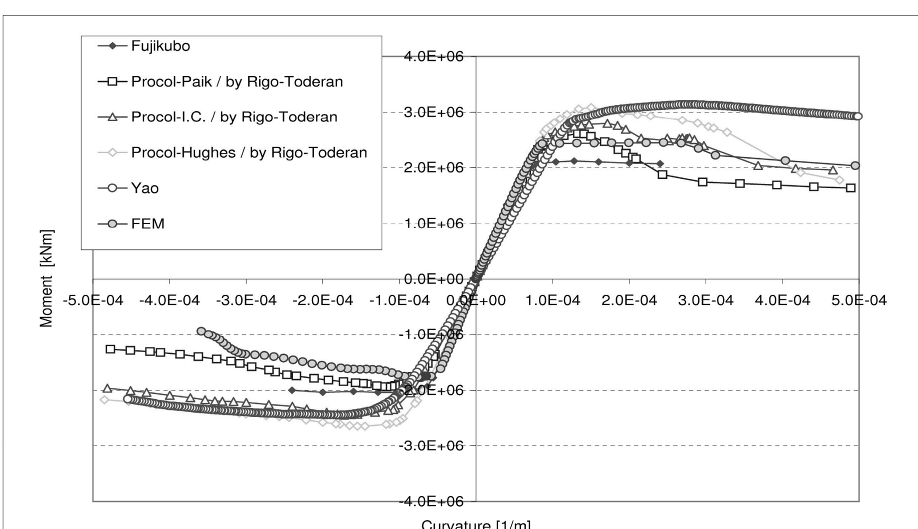
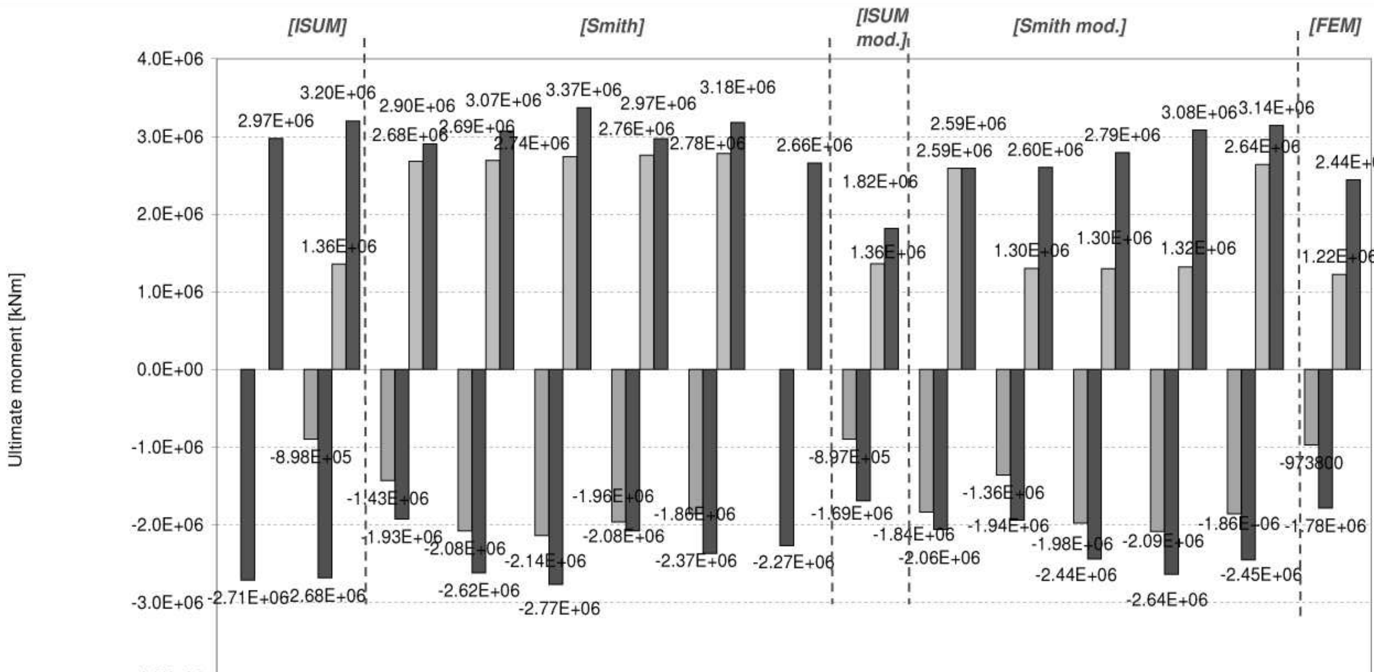


Figure 14.17: Moment-curvature relationships in second stage analysis (plus: hogging; minus: sagging)

The bending stresses at mid-ship section obtained from the second stage analysis are compared in Figures 14.15 and 14.16 together with the FEM results. They correspond quite well to the stress distribution obtained by FEM analysis in the elastic range. In the post-ultimate strength range, however, the scatters are observed among the results calculated by different approaches.



	Paik & Seo	Fujikubo	Procol-Paik / by Rigo-Toderan	Procol-I.C. / by Rigo-Toderan	Procol-Hughes / by Rigo-Toderan	Principia Marine	Yao	Gordo	Fujikubo	Principia Marine	Procol-Paik / by Rigo-Toderan	Procol-I.C. / by Rigo-Toderan	Procol-Hughes / by Rigo-Toderan	Yao	Naar
First failure in sagging		-8.98E+05	-1.43E+06	-2.08E+06	-2.14E+06	-1.96E+06	-1.86E+06		-8.97E+05	-1.84E+06	-1.36E+06	-1.98E+06	-2.09E+06	-1.86E+06	-973800
Ultimate strength in sagging	-2.71E+06	-2.68E+06	-1.93E+06	-2.62E+06	-2.77E+06	-2.08E+06	-2.37E+06	-2.27E+06	-1.69E+06	-2.06E+06	-1.94E+06	-2.44E+06	-2.64E+06	-2.45E+06	-1.78E+06
First failure in hogging		1.36E+06	2.68E+06	2.69E+06	2.74E+06	2.76E+06	2.78E+06		1.36E+06	2.59E+06	1.30E+06	1.30E+06	1.32E+06	2.64E+06	1.22E+06
Ultimate strength in hogging	2.97E+06	3.20E+06	2.90E+06	3.07E+06	3.37E+06	2.97E+06	3.18E+06	2.66E+06	1.82E+06	2.59E+06	2.60E+06	2.79E+06	3.08E+06	3.14E+06	2.44E+06

Figure 14.18: Ultimate hull girder strength of benchmark ship estimated by ISUM, Smith's method and FEM (plus: hogging; minus: sagging)

Especially, in the main hull cross-section, distributions by different analyses show different features even among the results by simple second stage analyses. These differences are partly because of the occurrence of shear failure of the wall of lifeboats recess area at the location a quarter length apart from both ends appeared in the FEM analysis, see figure 14.11. Influence of such shear collapse is not considered in the second stage analysis. Due to this shear buckling, the superstructure can be considered as if it is partly separated from the main hull at the buckled part, which may affect the stress/strain distribution at a mid-ship section. Another reason could be the influence of yielding on the shear lag phenomenon. The shear lag strain distribution may be different in the elastoplastic range from that in the elastic range, whereas the elastic distribution is used in the second stage analysis regardless of the magnitude of the applied curvature throughout the whole loading process up to the post-collapse range. Thus, the strain distribution obtained from linear FEM analysis can not fully be applied throughout the whole loading process. High shear stress appeared in the FEM analysis may also be the reason of discrepancy. That is, in the simplified methods, the influences of shear stress both on buckling and yielding strength are not taken into account.

Figure 14.17 shows the moment-curvature relationships obtained by the second stage analysis and the FEM (the third stage analysis). Relatively large scatter is observed in the flexural rigidity of the cross-section as well as in its ultimate strength. The scatter in the flexural rigidity may be attributed to the different treatments how to represent the nonlinearity in the applied strain distribution over the cross-section. This leads to different stress distributions in the elastoplastic range as can be seen in Figures 14.15 and 14.16, and consequently the different moment-curvature relationships in Figure 14.17.

The ultimate hull girder strength obtained by different methods is summarised in Figure 14.18 together with the first failure load. Even in the second stage analyses, the ultimate strength lies between 5 and 40 % of that obtained by the FEM analysis (the third stage analysis). This is not very ‘comfortable’ when a simplified method like the Smith’s method is applied. Indeed the accuracy of the FEM simulation has also to be verified in more detail as well.

14.7 Concluding Remarks

This benchmark indicates that, in case of a modern large passenger ship with a high and long superstructure having large lifeboats recess area and large balcony openings, the failures do not always starts at the mid-ship section but also in other areas, like in the present case, at a quarter length from both ends where the shear failure occurs. Therefore, it could lead to wrong and overestimated evaluation of the ultimate hull girder strength if attention is focussed only on the mid-ship section where the bending moment shall be the maximum.

The use of nonlinear strain distribution in the second stage approaches indicates that it could give some strength reduction. However, the collapse is dominated not only by the nonlinear strain distribution but probably also by other factors, for example influence of yielding on nonlinear strain distribution at a mid-ship section, influence of high shear stress on buckling yielding strength of structural components and earlier shear buckling at recess wall plating. In this sense, the possible collapse phenomena have to be studied more carefully and in more detail in order to understand how the simplified methods could be applied.

The use of ISUM will probably be more efficient when the whole ship structure is modelled for analysis. However, to perform such analysis properly, ISUM elements which can accurately simulate the shear collapse behaviour and redistribution of nonlinear strain over the cross-section has to be developed.

The present benchmark ship structure was designed so that the typical behaviour of the hull with a high and long superstructure could be as similar to the real ship structures as possible. However, due to the need to simplify the analysis, the whole structure was also simplified as much as possible. Therefore, it should be noticed that there is no warranty that the failure modes pointed out in this benchmark can be directly extrapolated to real ship hulls with a high and long superstructure.

15. CONCLUSIONS

This report describes the results of literature survey and benchmark calculations related to buckling and ultimate strength of components and systems of marine structures, which have been conducted during the last three years. The report consists of fifteen chapters.

In Chapter 1, after briefly describing a historical review on assessment of buckling and ultimate strength of marine structures, three big movements in the marine society since last ISSC are introduced, which are GBS (Goal-Based New Ship Construction Standards) in IMO, CSR (Common Structural Rules) by IACS and ULS (Ultimate Limit State) assessment by ISO. These three are closely related to the subject of this committee, and may have to be carefully watched from now by this committee or totally by ISSC.

Chapter 2 describes what are fundamentals in the buckling/plastic collapse behaviour of members and systems of marine structures. In connection to the fundamentals of buckling/plastic collapse, contents of individual chapters of this report are briefly introduced.

In Chapter 3, empirical and analytical methods are introduced to evaluate buckling and ultimate strength of structural members and systems. In order to perform the limit state design for marine structures, the nonlinear structural analysis is now becoming the task not only of researchers but also of designers. It is, therefore, necessary to develop handy tools for structural designers, which do not require huge amount of time and cost. Developemnt of simple but accurate empirical and/or analytical methods may be one of the solutions to reduce the complex procedure. Since the last ISSC, many simplified methods have been proposed to predict the ultimate strength and the behaviour beyond the ultimate limit state for unstiffened and stiffened plates. However, the effects of the interaction between failure modes have not been fully accounted in the proposed methods, especially those for overall buckling of multi-bay stiffened plates, where the scantling of transverse stiffeners can play some roles. This is still remaining as a future task.

Chapter 4 describes the recent developments in numerical methods for collapse analysis. The FEM have been increasingly applied to predict ultimate strength of structural components, such as plates and stiffened plates. However, there has been little development in improving the computational efficiency of FEM analysis to evaluate ultimate strength in the last three years. As an alternative method to FEM, Mesh-Free Method is proposed, but no application can be seen to collapse analysis on structural members and systems. This may be a future task. On the other hand, new ISUM rectangular plate element, which can accurately simulate the collapse behaviour, has been developed during the last three years. This element is still under development to extend its applicability.

Chapter 5 deals with experimental methods. Although new measuring technique has not been found since the last ISSC, a system is presented to create three-dimensional imperfection maps of a cylinder.

In Chapter 6, reliability-based structural analysis is introduced, which continues to be focussed mainly on the hull girder collapse failure mode as a measure of the structural system performance, whether intact or damaged, with varying levels of detail in the calculation. Further development of actual system reliability models for ship and offshore structures is recommended to go beyond mid-ship collapse probability and consider probabilities of failure along the length of a ship or a platform from onset of damage, or first failure, up to overload of the cross-section, and over the expected life of the structure.

Chapter 7 is related to tubular members and joints. It summarises the major research works on the ultimate strength of tubular connections. Many developments and innovations can be seen in tubular connections of offshore structures in the last decade, and the recent research efforts are focussed on the assessment of failure strength of tubular connections with initial defects such as fatigue cracks. At the moment, there is no theoretical background to assess failure strength of tubular connections in the industry. This is the reason for the requirement of detailed understanding of the ultimate strength of tubular connections with due emphasis on the large wall thickness, presence of initial defects, presence of reinforcement and the effect of chord stresses for a safe and economical design. The related research works are still on going.

Chapter 8 is concerned to plates and stiffened plates. Plates and stiffened plates are the fundamental structural members, and their buckling and ultimate strength have been investigated for many years including the last three years. The research involves development of empirical and/or analytical formulas to evaluate buckling/ultimate strength, development of analytical/semi-analytical methods to simulate buckling/plastic collapse behaviour, assessment of influences of initial imperfections such as initial deflection and welding residual stresses or fatigue cracks and so on. As for the evaluation of the buckling/ultimate strength and/or simulation of collapse behaviour, numerous formulas or methods may be available in case of rectangular plates subjected to combined uni/bi-axial thrust and lateral pressure. However, for other configuration and/or other loading conditions, further research is necessary. In connection with the CSR, ultimate strength of stiffened plates subjected to bi-axial thrust is calculated applying JTP and JBP methods. Through the comparison of the calculated results with those by the nonlinear FEM analysis, it was concluded that CSR methods give relatively valid results although some more clarifications are necessary regarding some issues.

In Chapter 9, shells are dealt with. Until now, many tests results on ring and/or stringer stiffened cylinders have been reported in the open literatures. However, those for stiffened conical shell, hemi-sphere and tori-sphere are difficult to find, even though they are the major structural members of underwater vehicles, especially of submarines. Shell structures are well known to be shape imperfection sensitive. In numerical analyses reported in the open literatures, the lowest elastic buckling mode is commonly adopted to represent the imperfect shape of the structure. But the actual shape is quite different from the assumed. Further works are necessary to find more adequate equivalent modes having physical meanings. Curved plates are commonly used in ship structures as bilge strake. Container ships have wide curved part which are stiffened with longitudinal stiffeners. In design offices, the strengths of stiffened curved plates are predicted with the design formulations for stiffened flat plates neglecting the effects of curvature. Therefore, it is necessary to investigate into the real collapse behaviour and to develop design formulas for stiffened curved plates.

Chapter 10 deals with the hull girder strength. In this chapter, how the assessment of the ultimate hull girder strength is performed in the new Common Structural Rules (CSR) for bulk carriers and tankers is briefly introduced as well as longitudinal strength assessment applying the conventional Class rules. Then, the ultimate hull girder strength evaluated by two CSRs are compared with that calculated by HULLST applying the Smith’s method. It has been indicated that relatively good agreements are obtained between two results. Recent research works on ultimate hull girder strength are also reviewed and introduced. The remaining work may be the assessment of ultimate hull girder strength of a container ship subjected to combined bending moment, shearing force and torsional moment although some research works on this subject has been already performed.

Chapter 11 concerns to offshore structures as a system. Regarding the jack-up platforms, some papers in a special issue of ***Marine Structures*** (Vol.17, No.3-4 in 2003) are briefly introduced. These are the selected papers from those presented at the ninth International Conference on Jack-up Platforms held on 23-24 September 2003 in London. These papers deal with development of numerical models for analysis of spudcans, effectiveness of phased foundation assessment procedure, full-scale measurements and analysis of environmental conditions and dynamic response, wave loads generated on typical jack-up structure and so on. Regarding the nonlinear frame failure analysis, the accuracy in the prediction of offshore platforms depends on many factors such as modelling of joint-frame interaction, boundary conditions including structure-soil interaction, hull-leg interaction and so on. Research works on these issues during the last three years are also described. In these research field, still research works are remaining.

In Chapter 12, composite structures are concerned. Composite materials are increasingly used for ship structures to reduce its weight, to avoid corrosion and for other reasons,. Uses of composite material for naval vessel are also increasing in many aspects. In this chapter, at first, research works in the multi-year program headed by the ***University of Maine*** are introduced. They include probabilistic FEM, composite constituent properties, failure model of a solid laminated plate and so on. The research works other than of this project are also introduced. They are effects of geometry and debonds in a glass fibre T-joint on pull-off strength at the intersection of a deck or bulkhead with the hull, pull-through strength of vinyl ester and epoxy resin system composite plates of varying zone, durability strength of composite materials by moisture, deterioration of pultruded E-glass/vynylester due to immersion in deionised water and alkaline solution, and so on. It may be said that these subjects are still remaining as research subjects in future.

Chapter 13 deals with aluminium structures. At the beginning, major issues in considering the strength of aluminium structures are described, which are weld effects, ultimate strength formulations, FEM analysis, structural details and design, ultimate strength design methods, and so on. From these points of view, the research works in the last three years have been reviewed and introduced. Regarding the structural design, that of a high-speed aluminium passenger ship is introduced. As for the ultimate strength design methods, some empirical formulas are shown to evaluate the ultimate strength of aluminium stiffened plates subjected to uni-axial thrust load. A recommendation is that Eurocode 3 for steel beams has to be adjusted to account for the difference in material properties when applied to aluminium beams.

In Chapter 14, benchmark is described. The subject of benchmark is to perform progressive collapse analysis and calculate the ultimate hull girder strength of a modern large passenger ship with a high and long superstructure having a large lifeboats recess area and large openings for balconies. According to the results of linear FEM analysis, shear lag phenomenon is observed at the lifeboats recess part which connects a main hull and a high and long superstructure. Because of this, strain and stress do not distribute over the ship depth linearly. This causes some problems when Smith's method is applied, which assumes linear strain distribution over the cross-section. In the benchmark calculation, however, Smith's method is applied by six members, ISUM by two members and FEM by one. The analyses are performed in three stages. In the first stage, linear strain distribution is assumed, whereas in the second stage, nonlinear strain distribution is used on the basis of the elastic FEM analysis. The third stage is a nonlinear FEM analysis. According to the results of a FEM analysis, the longitudinal bulkhead firstly buckles by shear at the location of a quarter ship length from both ends. Then, buckling collapse of the uppermost deck or bottom plating at a mid-ship dominates the hull girder collapse. Regarding the application of simplified methods, it has been found that even the second stage analysis applying Smith's method gives higher ultimate hull girder strength compared with that by a nonlinear FEM analysis. It was concluded that special attention has to be paid when Smith's method is applied to evaluate the ultimate hull girder strength of a passenger ship with a high and long superstructure having large openings and lifeboats recess area.

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