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TECHNICAL COMMITTEE III.1
ULTIMATE STRENGTH

COMMITTEE MANDATE

Concern for the ductile behaviour of ships and offshore structures and their structural components under ultimate conditions, including accidental loads. Attention shall be given to the influence of fabrication imperfections and in-service damage and degradation of reserve strength. Uncertainties in strength models for design shall be highlighted. The work shall be coordinated with that of Committee VI.2.

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KEYWORDS

Ultimate strength, ships, offshore structures, plates, shells, beams, finite element method, geometrical non-linearity, physical non-linearity, buckling, plasticity, yielding, overloading, imperfections, residual stresses, reliability, accidental loads, composite structures, aluminium structures, damage, grounding, collision, tearing.

CONTENTS

1 INTRODUCTION

The report of this committee addresses the subject of ductile behaviour of ships and offshore structures and their structural components under ultimate conditions, including accidental loads. Consideration is given to the influence of fabrication imperfections and in-service damage and degradation of reserve strength. The main emphasis of the report is a review of the progress accomplished in the field since 1996.

In Chapter 2 fundamentals of non-linear behaviour are discussed. The next four chapters discuss analytical, numerical, experimental and reliability methods for analysis of ultimate strength. Chapters 7 to 10 consider the ductile behaviour of the structural components of ship and offshore structures, i.e. beams, joints, plates and shells. Chapter 11 addresses the overall collapse behaviour of ship and offshore structures, which is not covered by Committee VI.2. The next two chapters are dedicated to two areas where the most progress has been made. In Chapter 12 the structural response to accidental loads is discussed, and Chapter 13 considers the ultimate behaviour of non-ferrous structures. Finally, Chapter 14 gives conclusions and recommendations. Benchmark carried out by the committee may appear in Volume III of the proceedings.

2 FUNDAMENTALS

2.1 General

Because of the development of fast computers and robust methods for non-linear finite element analysis (FEA), there has been a tremendous increase in studies of structures under accidental actions, notably ship-ship collisions and ship grounding, and offshore structures exposed to fires and explosions. However, even with today's computers and software, such analysis is very complex. Considerable effort is therefore devoted to the development of simplified methods for rapid assessment and design purposes, like phenomenological models (e.g. idealised structural unit methods) and yield line analysis.

2.2 Types of Over-loading

Ships and offshore structures are exposed to many types of "loads". This may be, for example, forces/loads applied directly to the structure or imposed or constrained deformations, imposed acceleration, uneven settlement, or earthquakes. ISO (1999) applies the notation "action" to represents "load" in the general sense. Most often overloading is related to extreme environmental actions and accidental events. Extreme environmental actions are notably due to waves, wind and current. The contribution from each of them depends on the structural design and the climate of the location. Environmental actions are characterised by maximum value and time variation. The importance of the time aspect depends upon the characteristics of the structural response, as discussed in Section 2.3. Frequently the time aspect is neglected and the action is considered as static or quasi-static.

Other "normal" actions include permanent loads and variable functional loads. Normally these actions are not the predominant cause of overload-situations, but their contribution to total action needs to be considered. Accidental actions are notably due to collision, grounding, dropped objects, explosions, fires and unintentional flooding of buoyancy compartments. Collision, grounding and dropped objects are characterised by their kinetic energy, governed by mass and velocity. Their nature is dynamic, but quasi-static methods are often used for assessment based on simple energy considerations. Explosions are characterised by pressure-time variation and fires by heat flux or temperature histories. Except for explosions and fires, where sequence effects may be important (e.g. damage to passive fire protection by explosion prior to fire), accidental events are normally assumed not to be interrelated. Earthquakes impose displacements on those parts of fixed structures embedded in soil. The frequency content is important. Overload conditions are generally considered for the operation phase, but may also occur during pre-service and removal phases.

2.3 Forms of Collapse

Most often, the form of collapse is defined in relation to an action exceeding the ultimate strength or ultimate strength of a component in a structural system. However, in conjunction with the response to accidental actions, the ultimate strength is often of less importance compared to the energy dissipation capacity of the member, given by the area under the resistance – deformation curve for the member as illustrated in Figure 1. Though belonging to the same collapse process, the physical mechanisms behind the response in the pre-ultimate and the post-ultimate strength region are generally different.

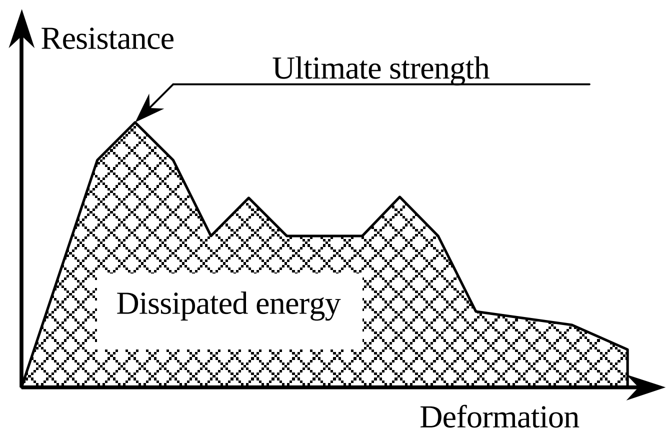


Figure 1: Definition of strength and energy dissipation.

The type of response can be classified with respect to temporal issues. It may here be convenient to adopt a categorisation used in conjunction with explosion response. Depending on whether the fundamental period of vibration is considerably longer, of the same order, or considerably smaller than the duration of the action, the response is denoted impulsive, dynamic or static, respectively. In the impulsive and static domains, various effects may be neglected. If the rate of action is large, inertia effects are important, even if the duration of action is long. The failure modes categorised according to the number of actions are described below. Sandwich panels may fail by yielding and buckling in the same manner. Local failure may occur as face wrinkling, face dimpling (intercellular buckling) and shear. The core, which carries the major part of the shear force, is prone to shear stress failure or shear crimping. Potential failure modes for composite structures are buckling, local delamination, and fatigue fracture. Anisotropy should be considered in conjunction with buckling.

Single excursion failure
This is the most frequently considered failure mode and is related to ultimate strength. It comprises numerous buckling modes of failure for components like columns, beam-columns, stiffened and unstiffened plates, and shells subjected to some degree of compression. Local buckling of cross-sections may significantly influence buckling failure modes for components. This is normally controlled by code compactness requirements for ultimate limit state (ULS) design. For accidental actions where energy dissipation is crucial, it may be necessary to include quantitatively the effect of local buckling. Generally, little information is available on the interaction between local and global buckling. Buckling is often associated with local yielding, but gross cross-sectional yielding takes

place in very stocky compressive members and members subjected to tension. Many steel materials and aluminium alloys possess significant post yield strength reserves (strain hardening). Strain hardening is, in fact, essential with respect to redistribution of action effects upon component failure and energy dissipation. Ultimately tension members may fail by fracture due to excessive straining. The critical strain depends upon many factors, notably material toughness, presence of defects, strain-rate and presence of strain concentrations. If any of these factors are "critical", fracture may occur even prior to gross cross-sectional yielding. Once fracture is initiated, further growth may be unstable or stable. A major challenge to the use of non-linear FEA methods in the analysis of overload situations (notably accidental actions) is reliable determination of fracture in sections undergoing severe plastic deformations. Component failure implies global collapse for determinate structures. For redundant structures, post collapse behaviour becomes important and needs to be considered.

Cyclic failure
Structures subjected to multiple excursions (e.g. a sequence of storm waves or earthquakes) may fail by incremental collapse where permanent deformations accumulate for each action cycle until the structure becomes globally unstable. This degradation of resistance may be accelerated if the material experiences strain softening causing localisation of plastic zones.

Extreme low cycle fatigue (< 100 cycles)
This is a potential failure mode for components subjected to variable actions causing tension/compression cycles. Components experiencing local buckling are especially prone to low cycle fatigue due to reverse straining in the local buckling region.

Continuous crushing
This failure mode is very important for structures subjected to impact actions like collisions and dropped objects. In addition to buckling, these failure modes often include many physical effects like yielding/plastic deformation, folding, fracture etc. The deformations may be of the same order as the member size. Initial buckling is important to the extent that this may determine geometry for the subsequent deformations. The ultimate strength (buckling) is of less importance than the energy dissipation, which is governed by the area under the resistance-deformation curve.

Tearing
Tearing occurs notably during collisions and grounding. It signifies a process where sharp objects force a crack to move in a plate with little plastic deformation except in close vicinity of the crack tip. Bending and folding of adjacent material often accompanies this process.

2.4 Material and Fabrication Factors

Considerable work has been devoted to development of high strength steel and aluminium materials. For marine structures, the use of high strength material is often limited by fatigue constraints. Another factor, which should be acknowledged in conjunction with ultimate strength, is strain hardening and ductility. Strain hardening is essential to avoid localisation of plastic strains in small zones when the strains exceed the yield/proof strain. High strength material tends to have less hardening capability and may therefore exhibit a more "brittle" behaviour in a global sense. New developments in steel making have enabled production of high strength steel with exceptional toughness and weldability. In cases where members deform inelastically, it is imperative that they possess adequate ductility. Rickles *et al.* (1998) discuss mechanical characteristics of new high strength steel in the light of compactness criteria for flexural members.

Specialist Panel V.8, ISSC 1997, discussed the effect of fabrication factors on ultimate strength at considerable length. Manufacturing and fabrication processes influence ultimate strength in several ways. Discontinuities and micro-structural changes affect the material behaviour locally at the weld. The temperature field induced by thermal processes leads to residual stresses and initial distortions, affecting strength on both component and system levels.

Imperfections normally have a detrimental effect on the ultimate strength of individual elements. Some codes (ECCS, Eurocode 3) use the concept of equivalent out-of-straightness to derive design equations for column buckling. The out-of-straightness is then assumed to capture the combined effect of initial distortions and residual stresses. On a system level, initial distortions may be favourable or unfavourable with respect to element buckling, depending on whether they are compatible or incompatible with the governing failure mode.

For high strength steel, with yield strengths above 460 MPa, it is often difficult to achieve overmatch in welded connections (weld metal has a yield strength 10% or more than the base material) as found by Lotsberg *et al.* (1998). Overmatch is essential to ensure that plastic straining takes place in the base material outside the weld area.

There is an increasing interest in the evolution of weld induced residual stresses and distortions. If they can be predicted at the design stage, the amount of strength degradation can be calculated more precisely and favourable procedures for their minimisation identified. Rigorous analysis of the effects of the welding process on ultimate strength is complex and requires insight into different scientific disciplines like physical metallurgy, thermodynamics, continuum mechanics and FEA, see: Myhr *et al.* (1999).

The required computational effort in rigorous analysis, however, often becomes so large that simplified approaches are needed for the simulation of practical structures. Several researchers Seung and Jang (1999) and Ueda (1998) circumvent the physical metallurgy aspect and consider only the thermal elasto-plastic process.

3 ANALYTICAL METHODS

The number of publications on analytical methods for calculation of load carrying capacity is quite limited. However, new analytical methods are still being developed and published at a high rate. For discussion of analytical methods regarding energy absorption see Chapter 12 and for non-ferrous structures see Chapter 13. Some of the papers reviewed in this chapter are indeed not purely analytical, since the involved mathematics requires a computer for efficient evaluation. Analytical should rather be understood here as mathematical, non-finite-element methods.

Höglund (1997) presents a comprehensive study of the shear buckling resistance of steel and aluminium plate girders. Based on the ideal tension field theory, Höglund describes a so-called rotated stress field theory, which is applicable to unstiffened, transversely and longitudinally stiffened and trapezoidally corrugated web girders. Höglund compares the rotated stress field theory, Euro Code 3 and drafts of Eurocode 9 to 93 tests with aluminium specimens and 273 tests with steel specimens. It is found that the rotated stress field theory with some modifications agrees best with the experiments. In a comparison with 363 tests, the ratio between the measured ultimate capacity and the prediction by the rotated stress field theory varies between 0.98 and 1.45, with a mean of 1.17 and a coefficient of variation of 0.10.

Mahendran (1997) presents an analytical study of two idealised collapse mechanisms in plate panels under compression; the so-called roof mechanism and the flip-disc mechanism. It is postulated that initial buckling and first yield determine the post buckling collapse pattern. Based on solutions of Marguerre's equations for varying imperfections it is shown that plates with large slenderness (b/t) ratios or large imperfections are more prone to collapse in the flip-disc mode whereas the roof mechanism governs collapse of thicker plates. The ultimate strength is determined as the intersection between the elastic solution of Marguerre's equations and rigid plastic solutions based on the two considered mechanisms. Experiments verified the predicted dependence of the mechanism on slenderness ratio and imperfections. By increasing the imperfections it was possible to change the collapse mode from the roof-type to flip-disc as predicted theoretically. However, the experiments showed that the difference in ultimate capacity was less than predicted.

Hughes and Ma (1996a, 1996c) and Ma and Hughes (1996) present an energy method for the lateral buckling behaviour ("tripping") of beams subjected to axial load, end moment, distributed lateral load and a lateral point load. The classical analysis based on a rigid web (i.e. angles between members in the cross-section are retained during buckling) is extended to take into account the distortion of the web. A strain distribution along the stiffener is assumed and the total potential energy functional is derived. The study explores the effect of plate rotational restraint and the previously unresolved question regarding plate mode shape is solved. The accuracy of the method is verified by use of ABAQUS. The analysis shows that for short beams the classical method may seriously overestimate the critical load. In Hughes and Ma (1996b) the elastic model is extended into the inelastic range, using deformation theory and an iterative and incremental formulation. Comparison with experiments shows good agreement.

Paik and Pedersen (1996) present a method for prediction of the ultimate strength of plate panels, which have welding induced residual stresses and initial deflections. The first part of the load-deflection curve is determined by elastic large-deflection theory and the post-ultimate part by idealised rigid-plastic mechanisms. A comparison with 33 elasto-plastic FEA solutions shows good agreement. Cui and Mansour (1998, 1999) adopt the same basic solution methodology to investigate the effect of various parameters on the ultimate strength. It is confirmed that in addition to the amplitude, the initial deflection shape has a significant effect on the ultimate strength. Based on the parameter study, empirical formulas are proposed for the strength reduction due to geometric imperfections and the welding induced residual stress.

Soares and Gordo (1996) emphasize the need for taking into account the bi-axial loading of plate panels. They present a comprehensive literature review for ultimate strength of bi-axially loaded plates. Based on a total of 385 data points they propose new interaction curves for the ultimate strength of plates subjected to a combination of longitudinal and transverse compression:

$$\left(\frac{\sigma_x}{\sigma_{x,u}}\right)^2 + \left(\frac{\sigma_y}{\sigma_{y,u}}\right)^2 = R_{r\delta}^2 \qquad (1)$$

where σ_x and σ_y are the longitudinal and transverse loads on the plate, $\sigma_{x,u}$ and $\sigma_{y,u}$ are the ultimate strengths under uniform loading and $R_{r\delta}^2$ is a correction term that depends on the initial distortions and residual stresses. The paper shows that the proposed formulas are unbiased with less model uncertainty than other known interaction formulas. Since bi-axial loading of plates has not received much attention despite its great importance, the paper may be a good source of information for future theoretical studies in this field.

Paik *et al.* (1999a) present an analytical method for calculating the ultimate strength of a stiffened panel subject to uni-axial compression. The behaviour of the stiffened panel is analysed by using a plate-stiffener combination model as representative of the stiffened panel. Three collapse modes, namely plate induced failure, stiffener induced failure and local buckling of stiffener web are considered. The influence of initial imperfections (initial deflection and welding induced residual stresses) for both plating and stiffener are taken into account. As verification, the theoretical solutions from the study are compared with some existing experimental results for stiffened panel strength under uni-axial compression. The effective width of plating between stiffeners is formulated analytically, accounting for applied compressive loads, initial deflections, and welding induced residual stresses.

Lehman and Zhang (1998) present a large number of valuable formulas and analytical theories for predicting the load carrying capacity of beams, plates and shells, taking into account material and geometrical non-linearities.

Most recently, Paik *et al.* (1999b) developed ultimate strength design formulations for ship plating subject to any combination of the following four load components: bi-axial compression / tension, edge shear and lateral pressure loads. The influence of post-weld initial imperfections in the form of initial deflections and residual stresses is taken into account. The validity of the proposed ultimate strength equations is studied by comparing with non-linear FEA and other numerically based solutions. They also developed a complete set of the ultimate strength design equations for stiffened steel panels having one-sided stiffeners in either one or both directions, see Paik *et al.* (1999c). Any combination of all potential load components in ship stiffened plating, namely bi-axial compression / tension, bi-axial in-plane bending, edge shear and lateral pressure loads, is accommodated. The post-weld initial imperfections are included in the design formulations as parameters of influence. The potential collapse modes for stiffened panels are classified into six groups and the ultimate strength design equations are developed for individual failure modes.

Jones (1997) performed an extensive survey of the studies related to dynamic plastic behaviour of marine structures that have been published over the last two decades. According to his review, the ship bottom plating can be subjected to impact pressure loads due to slamming and can collapse. For advanced strength design of ship structures, it is important to understand the collapse strength characteristics of ship plating under dynamic / impact in-plane and/or lateral pressure loads.

4 EXPERIMENTAL ANALYSIS

4.1 General

For the last two decades, several experimental research programmes have been conducted to investigate the ultimate strength of structural elements for ships and offshore structures such as steel stiffened panels and cylinders. Design guidelines against buckling and plastic collapse for conventional structures subjected to design loads have then been established by classification societies and scientific societies. Experimental research on the ultimate strength of ships and offshore structures has tended to focus on the following research subjects in recent years: damaged structural elements, new structural elements and accidental loads.

4.2 Damaged Structural Elements

The actual ultimate strength of aged structures in operation is of great concern and is the subject of much research. From this point of view, experimental work on dented side plates and cylindrical columns has been continued.

As for dented tubular and cylindrical columns of offshore structures, a number of test programmes were conducted over the last decade and were summarized in the report of Committee III.1 in the Proceedings of the 13th ISSC. Walker and McCall (1998) provided additional experimental data for damaged and repaired stiffened cylinders under combination of external pressure and axial compression using precise small scale welded models. Röhr *et al.* (1996, 1999) give experimental data for large scale dented and repaired stiffened cylindrical columns under axial compressive loads to validate the procedures of FEA.

The Canadian Forces and the US Interagency Ship Structure Committee (SSC) jointly sponsored a full-scale testing project to study the load-carrying characteristics of single stiffened panels under combined axial and lateral loads and with various types of damage. Hu *et al.* (1997) reported the above test results of 12 stiffened panels which included 'as-built', 'deformed' and 'damaged' specimens. The specimens failed by combined plate and flexural buckling, stiffener tripping or local collapse, depending on the magnitude of lateral loads and local damage. In this test series, it was found that a small lateral load could change the failure mode from flexural buckling to tripping and a dent in the specimen could significantly decrease the load carrying capacity, as shown in Figure 2. In principle, the tests can be criticised for a number of reasons, namely, single span, only one panel in width, and edge restraints that may inhibit plate buckling. Nevertheless, the test quality is such that the results could be exploited by complementary numerical modelling, Hu and Jiang (1998). The FEA models were established by a direct mapping of measured imperfections to nodal points. Residual stresses were introduced using a thermal stress analysis procedure. The good agreement between the experimental and numerical results indicates that non-linear FEA is capable of predicting plastic post-buckling behaviour of stiffened panel structures.

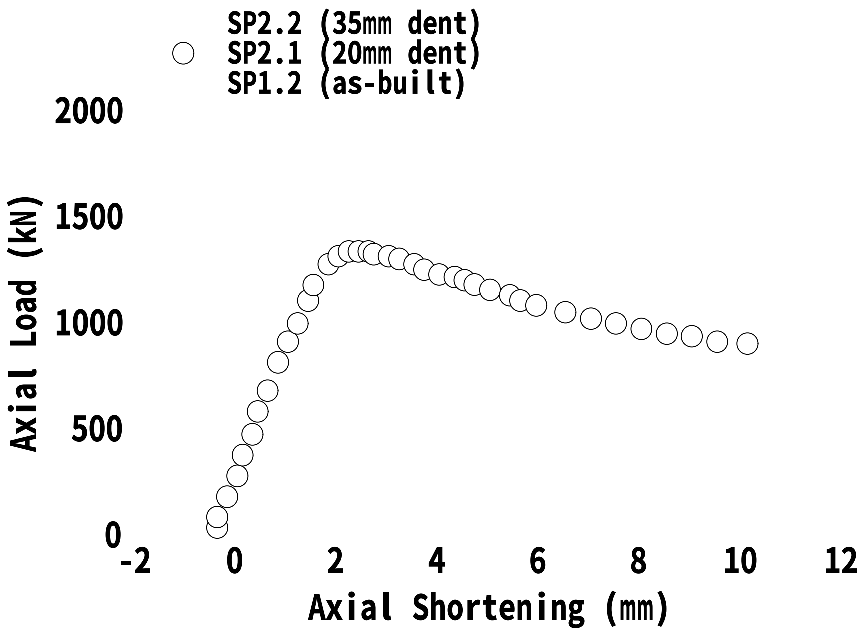
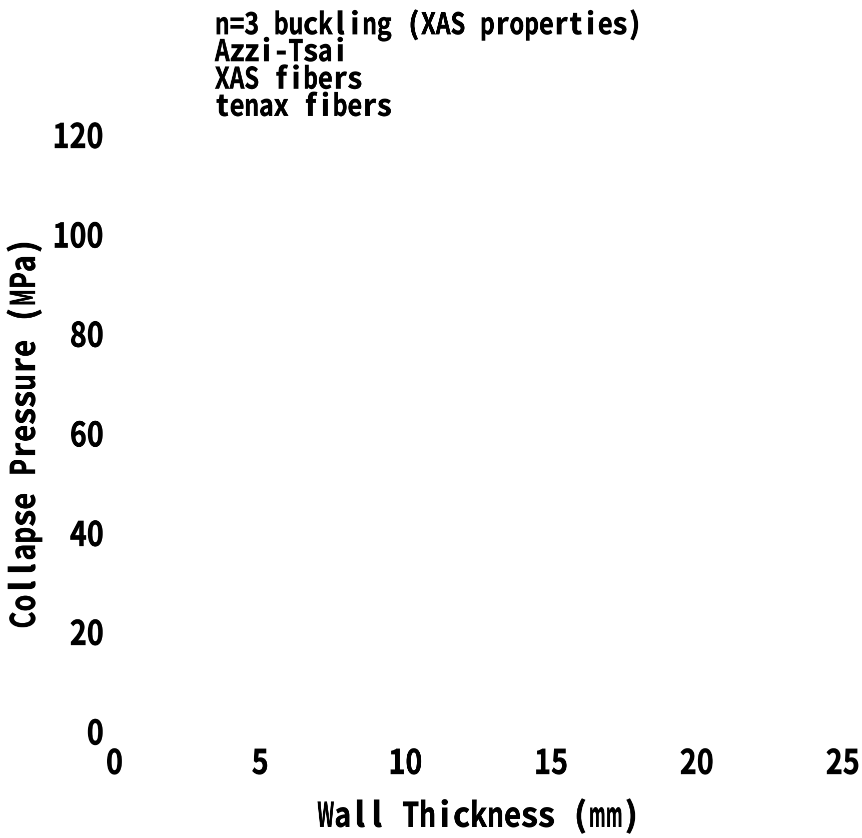


Figure 2: Load-shortening curves of stiffened panel, Hu *et al.* (1997).

Akhras *et al.* (1998) conducted an ultimate bending strength test of a box girder which simulated the behavior of a ship's hull. The scantlings of the section were approximately half those of a typical Canadian warship, but the overall cross-section was approximately 1/15 that of a full-size frigate. After failure, the tested box girder was flipped over and tested again to evaluate the residual strength of a damaged box girder. It was found that the ultimate moment of the damaged girder reached approximately 0.75 times that of the as-built box girder.

4.3 New Structural Elements

Cylinders and stiffened panels made of fibre reinforced plastics, sandwich steel panels and cellular hull sections have been developed for ships and offshore structures to meet the demands of reduced weight and additional functions such as protection against fire and impact. The design guidelines for these new structural elements have not yet been established and experimental work is desired.

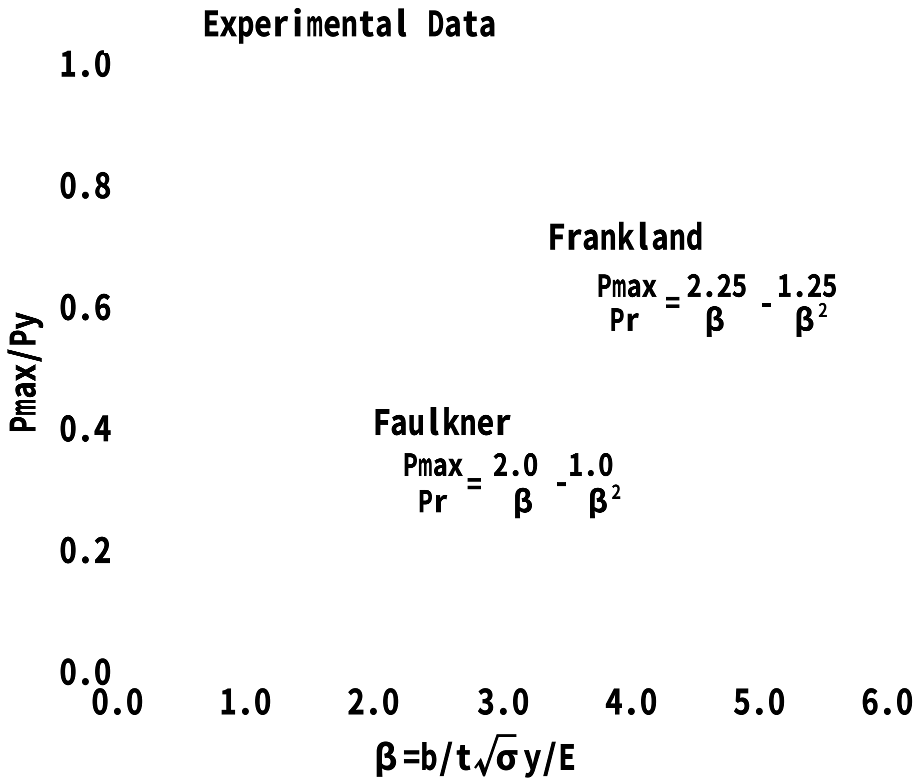


DERA Dunfermline, UK, has been continuously involved in the development of composite pressure hulls for deep diving submersibles. In this programme, Graham (1996) reported experimental data on 14 small scale cylindrical models with an internal diameter of 125 mm and a large scale one with an internal diameter of 450 mm under external pressure. The models were made of carbon fibre reinforced plastic. The collapse pressures for the small models are shown in Figure 3. The small model tests identified a transition region where collapse was very unpredictable possibly controlled by an interactive mode of failure. The relatively thin walled cylinders with nominal wall thicknesses of 6 and 8 mm buckled elastically with very little scatter. The 20 mm thick cylinders failed consistently due to material failure. The large scale pressure hull model was successfully tested to a pressure equivalent to depth of over 6000 m.

Figure 3: Summary of collapse pressures of hydrostatically tested small cylinders, Graham (1996).

Elghazouli *et al.* (1998) presented the results of buckling tests on 6 laminated woven GFRP cylinders with an internal diameter of 600 mm under axial compression. The results of this experimental study demonstrated the influence of laminate orientation. The 0/90 cylinders exhibited the largest axial buckling strength, while the 0/0 models indicated the highest axial stiffness. This study provided carefully measured thicknesses and initial imperfections of the models to validate a buckling analysis using FEA.

For stiffened panels made from glass fibre reinforced plastic, a new composite framing technology was developed involving the casting of dry glass fibre reinforced plastic fabric into shape in a closed mold with a foam core to reduce the fabrication cost of GFRP composites. Mouring (1999) presented experimental results of buckling and ultimate strength tests of 6 composite panels using the above technology under in-plane uniaxial compressive loads and discussed the effect of the fibre orientation for the preform frames.



The US Navy is considering a unidirectional stiffened double hull which is an unstiffened cellular structure not interrupted by transverse floors between transverse bulkheads. Dexter *et al.* (1996) conducted 9 large scale compression tests on high-strength single-cell and multiple-cell box sections with plate width-to-thickness ratios ranging from 48 to 96. It was found that the compressive ultimate strength of plates was dominant to that of the cellular hulls and the empirical equations of ultimate strength of plates by Frankland and Faulkner gave a very good prediction of the ultimate load carrying capacity of the cellular structures as shown in Figure 4.

Figure 4: Load carying capacity of cellular structures, Dexter *et al.* (1996).

Some major European shipyards are concentrating on building passenger cruiser ships which require light weight, less distortions and fire-resistance. Corresponding to the above requirements, laser welded sandwich panels have been developed. Metschkow and Roland (1999) conducted a couple of full scale bending tests to verify the corresponding load carrying capacity.

4.4 Real Life Examples

Flooding and sinking of the Derbyshire in 1980 was investigated by Faulkner and Williams (1997), Faulkner (1998) and Pullin(1998).

A Russian tanker, the MV Nakhodaka, broke in two in the Sea of Japan on January 2, 1997 and spilled heavy oil causing serious pollution to the coast of Japan. Yao *et al.* (1998d and 1998e) reported the investigation on structural strength of the vessel at the time of the accident through the governmental committee for the investigation of the causes of the casualty of the Nakhodka. The authors conducted an intensive inspection of the fore part of the vessel which drifted ashore. Then, they measured the actual thickness of the structural members and observed fracture surfaces at the broken cross-section. The mechanism of failure was predicted based on the evidence and measurements of thickness reduction of the actual structural members, measurements of mechanical properties of the actual material, progressive collapse analysis of the hull girder applying Smith's method, fracture mechanics analysis of the bottom longitudinals and dynamic elastoplastic large deflection analysis using an explicit FEA, LS-DYNA3D. The investigation indicated that corrosion damage reduced the elongation capacity of material and not just the thickness of the plate. As for the actual ultimate strength of aged structures in operation, experimental work is needed on corroded structures.

5 NUMERICAL ANALYSIS

5.1 General

Numerical methods, mainly FEA, remain the most advanced tool for ultimate strength analysis. Therefore, this chapter addresses aspects of non-linear FEA relevant for the simulation and assessment of typical responses of structures and their components in the highly non-linear range.

Current efforts for obtaining realistic information on the ultimate capacity of structures are focused on the development and application of effective procedures for modelling of elasto-plastic material behaviour, large displacements and rotations, structural bifurcations as well as considering cyclic loading effects. The consideration of imperfections due to fabrication and in-service damages requires complex theoretical and numerical methodologies as well as experimental verification and usually requires extremely time-consuming calculations.

In order to meet such complex demands, advanced technologies such as parallel computers accompanied by the development of qualified FEA software, offer novel and extended methods. These systems will enable new levels of sophistication in modelling of structural systems, which were not previously available.

In the meanwhile, extensive work has been done, which provides improved robustness and reliability of non-linear FEA formulations and solution procedures. A posteriori error estimators based on residual and average error criteria have progressed significantly in recent years. In order to objectively improve the discretizations of structural problems, various adaptive FEA- procedures, combined with mesh refinement techniques, have been created improving the predictive capability for linear and non-linear assessments.

New FE methods for limit analysis, incorporate specific cyclic loading effects such as hardening, softening and shake down. Consideration of the accumulated cyclic plastic strain rate may be essential for insight and basic understanding of ductile collapse mechanisms, simulation of structures altered in-service and the degradation of their ultimate capacity.

It is beyond the scope of this report to present an exhaustive discussion of the recent literature (approx. 5600 papers in 1996 alone). For this reason this chapter is limited to selected works that characterize the progress and current trends, and identify the crucial theoretical developments, including several practical applications in marine structural analysis.

5.2 Solution Procedures

The efficiency and predictive capability of solution procedures for ULS and post collapse bifurcation analysis depend on both the quality of the individual FEA formulation and on the stability of solvers of large linearized systems of equations. Currently available solvers include Newton-Raphson schemes, subspace iteration methods, arc length algorithms as well as implicit or explicit procedures. Fast iterative solvers under development are based mainly on methods of parallel processing. An overview of general outlines together with prognoses of further trends in this area are offered by Noor (1997). With the progress of parallel computational platforms, domain decomposition or substructured-based iterative algorithms have been designed increasingly for solving large systems of equations arising from structural mechanics problems. Farhat *et al.* (1998) discuss a unified framework for the transient Finite Element Tearing and Interconnecting (FETI) method, providing an improvement in the robustness and performance of iterative procedures and the design of new substructuring algorithms with Lagrange multipliers based on the FETI concept. The FETI algorithms are a family of substructuring methods with Lagrange multipliers that have been designed for iterative parallel solving of large–scale systems of equations arising from FEA. By these methods the computational domain is decomposed into substructures and a set of Lagrange multipliers is introduced at the substructure interfaces to enforce the compatibility of the substructure displacement solutions.

Klaas *et al.* (1996) propose a Lanczos solver combined with multilevel preconditioning for redetermination of limit and bifurcation points, which performs the iteration in cases of non-positive definite matrices in complex vector space. This concept is especially designed for parallel processors. Bertolini and Lam (1998) provide an improved criterion to accelerate subspace iteration using adaptive multiple inverse iteration.

In order to simulate the post-collapse bifurcation behaviour of axisymmetric shells with non-symmetric bifurcation buckling, Teng and Lou (1997) recommend a so-called accumulated arc-length method that enables the detection of the existence of a bifurcation point located anywhere on the load-deflection path. Further issues in convergence improvement for non-linear FEA are pointed out by Esche *et al.* (1997). In the highly non-linear range, available iterative solution procedures, like Newton-Raphson, may be slow or divergent. The contribution focuses on techniques to overcome these numerical difficulties by means of a combination of various line search algorithms with a continuation method. Bulenda (1997) discusses in this context an Arnoldi-Newton algorithm for pathfollowing in non-linear static problems with four general approaches and a wide range of application.

The development and utilisation of error-controlled and mesh-adaptive FEA represents substantial progress in the area of non-linear analysis. In the past this research has been mainly focused on linear problems. Recent work related to the elasto-plastic regime are presented by Gallimard *et al.* (1996) and Shi *et al.* (1996). The latter used a posteriori error estimation according to an error norm and its distribution with the objective to minimize the total error energy norm. An advanced methodology for error measurement and mesh optimization for non-linear geometry problems is proposed by Bussy and Mosbah (1997). The error is expressed as a norm of the elastic energy of the difference of an approximately and a statically admissible Piola-Kirchhoff stress field in the Lagrangian configuration. By means of several numerical applications it is illustrated that the methodology may also be coupled with material non-linearities. Nordlund *et al.* (1998) developed an adaptive mesh-updating method for non-linear shell analysis. Due to the grid moving during the incremental loading process, excessive mesh distortions can be avoided and refined parts are forced to follow high deformation gradients. This enables the accuracy and reliability of the numerical model to be maintained over a large range of loading and the frequency of complete remeshing to be reduced.

Recent FEA developments are increasingly suitable for considering actual physical and geometrical properties of designed structures. Thus, the collapse assessment of space frames has become a frequently used tool in the design of offshore-structures. For the large displacement analysis of frame structures Park and Lee (1996) present an effective stress update algorithm with successive control of residuals on yield surfaces. A material tangent stiffness matrix is derived considering kinematic and isotropic hardening and is combined with the geometric tangent stiffness matrix. The present formulation is shear flexible and satisfies the yield condition in a pointwise sense. By means of several numerical tests, robustness and accuracy are demonstrated. In additional to conventional beam kinematics, Shakourzadeh *et al.* (1996) take into account torsional warping effects involving the distinct position of centers of torsion and gravity of beam sections. Developments for spatial stability analysis of thin-walled space frames are proposed by Kim *et al.* (1996) based on a linearized virtual work principle and Vlasov's kinematic assumption for cross-sections. Second order terms of finite rotations and all bending-torsional coupling effects due to unsymmetric cross-sections are taken into account. Warping restraint connections and effects of torsional-lateral buckling are considered.

A fast algorithm for non-linear FEA of beam structures on parallel computers is outlined by Gummadi and Palazotto (1997). A twelve degree-of-freedom curved element has been developed using Green strains and the 2nd Piola Kirchhoff stress tensor. Concepts like loop splitting are introduced at the stiffness matrix generation level to suit parallel computing calculation procedures. Significant speed inprovement and efficiency are achieved by means of these techniques. In order to evaluate the performance of the various available non-linear FEA for framed structures, Petrolito and Legge (1997) propose an accurate benchmark solution. The paper presents a series of benchmark solutions for two-dimensional frames subjected to follower forces. Developers and users are encouraged to evaluate the accuracy of their own techniques.

In analysing general shell structures by means of FEA there is a consensus that it remains difficulte to identify the most effective and robust element-scheme currently available. With a view to convergence, one aims to achieve invariability of the geometric distorted mesh, node positions and axial rotations and to avoid locking phenomena and spurious energy modes in thin shell limit analysis. In principle, the approximations for a given FEA discretization should be independent of structure thickness and reflect sufficient convergence properties for any encountered membrane- or bending dominated state, especially in the non-linear range. In order to fulfill these crucial requirements, Capelle and Bathe (1998) derive a numerical test methodology that could be valuable in the search for improved finite shell models.

A state-of-the-art summary review providing insights into theoretical and numerical progress on shell problems is presented by Ibrahimbegovic (1997). Important aspects are cited and discussed, such as assumed strain interpolation, finite rotation parametrization and consistent linearization of the non-linear shell problem. The last is crucial for numerical robustness of Newton iteration procedures in non-linear shell buckling problems.

In the following a limited selection of recent shell element approaches is presented for non-linear applications. Bischhoff and Ramm (1997) describe the concept of shear deformable continuum based shell formulations. The objective is to derive an enhanced assumed strain approach for geometric non-linearities based on the conventional 5-parameter shell formulation. For consideration of thickness stretch, a so-called 7-parameter interpolation scheme that avoids “thickness locking” is discussed. A large displacement model including elasto-plastic materials is proposed by Brank *et al.* (1997). The quadrilateral shell formulation is continuum based and employs standard assumptions for the distribution of displacements and finite rotations of the director field. Particular attention is devoted to consistent linearization of the shell kinematics and non-linear material behaviour to ensure quadratic convergence of the Newton-Raphson procedure. The present model is applicable in failure analysis as well as in bending-dominated shell problems connected by formation of plastic hinges.

Boisse *et al.* (1996) propose a simple three-node shell element with fifteen degrees of freedom, utilizing linear interpolation for isoparametric Ahmed kinematics, combined with an assumed strain method to avoid shear locking. The adopted and updated Lagrangian formulation allows the simulation of shell problems with large rotations, and involves no spurious energy modes for any element patch. The simplicity of the element formulation provides considerable practical advantages for the incremental method associated with the Newton scheme. A so-called solid-shell concept incorporating only displacement degrees of freedom for geometrical non-linear analysis is presented by Hauptmann and Schweizerhof (1998). By means of this approach, certain disadvantages of the degenerated shell concept related to boundary conditions, the connection with continuum elements or the update of the rotation vector in non-linear problems can be avoided. This robust formulation is especially able to satisfy the essential demands of a practical tool.

The conventional approach to ultimate strength analysis is usually based upon quasi-static load assumptions and response. In order to assess the actual ultimate capacity, the complex in-service history of a structure has to be considered, including cycling loading and overloading. It has been proven by means of experimental tests that structural failure may occur at values below monotonic loading estimated ultimate capacities as a result of accumulated inelastic straining and accompanying local buckling.

In previous experimental investigations Amdahl *et al.* (1995) observed that the untimely failure of tubular members subjected to extreme cyclic tension and bending loading depends on their slenderness. From the results, it is shown that correlation exists between the energy dissipation per cycle and the number of cycles to through thickness cracking in the post buckling state.

In principle, the complete simulation of real dynamic phenomena requires the inclusion of any form of dissipation in material models, as presented by Damjanic *et al.* (1996) for the long-term dynamic behaviour of shells. Actual material properties are significant to estimate structural shake-down effects. A numerical approach for space frames is outlined by Pycko (1997). For the determination of quasi-static shake-down loading, a cycle-incremental analysis is proposed based on a classical optimization problem, which is reformulated in view of an incremental analysis with transient plastic phases. By means of numerical calculations, the considerable differences between elastic, shake-down and limit loads are demonstrated.

A general FEA technique for shake-down assessment of axisymmetrical shells is described by Franco and Ponter (1997). This method is based on a reformulated kinematic shake-down theorem with piecewise linear yield condition. The discretized problem is reduced to a minimization problem solved by means of linear programming. Theoretical compatibility equations of inelastic strains for shake-down problems as a basis of a numerical procedure are provided by Atkociunas (1997). The proposed approach arises from criteria similar to the Kuhn-Tucker conditions. Further examples of the implementation of progressed constitutive laws related to hardening and softening in FEA-routines are demonstrated by Lourenco *et al.* (1997) for orthotropic materials and by Hashagen and Borst (1997) for composites. A summarized discussion of suitable constitutive equations related to cyclic material and structural phenomena is presented by Weiß and Postberg (1998).

5.3 Recommended Practice for Non-linear FEA

Despite the remarkable progress achieved in numerical analysis, as ever, the prediction of complex non-linear structural behaviour requires experience and last, but not least, experimental verification for the most important structural problems. For this reason, reviews of systematical non-linear FEA-applications related to marine structures are rather unusual and only a few references have been found.

Results of extensive investigations to assess the ultimate load behaviour of both stiffened plates and shells of ship structures are presented and discussed by Lehmann and Zhang (1998). To validate experimental data based on large-scale tests as well as analytical formulae, non-linear FEA calculations have been performed using NASTRAN and MARC. It is pointed out that ultimate load behaviour is especially characterized by the onset of membrane stresses after the beginning of yielding and is accompanied by reduced bending stiffness. In detail, the results for deck plating subjected to concentrated loads (e.g. wheel loads), and for collision damaged tanks and tubular offshore members prove the necessity of considering both material (v. Mises criterion) and geometrical non-linearities (updated Lagrange method).

A complex study related to the effects of impact damage on the capacity of tubular members has been carried out by Zeinoddini *et al.* (1998). Various FEA models have been used to simulate the impact-contact problem. The results presented have been validated by means of experiments. In detail, the effects of end conditions, the deformation modes due to impact and the effects of axial pre-existing load are discussed. It has been found that pre-existing axial loading remarkably influences the lateral collapse load of the member and especially the level of energy that can be absorbed.

A complete non-linear FEA to assess the ultimate axial capacity and the postbuckling behaviour of damaged and repaired cylindrical stiffened structures is outlined by Röhr and Zhang (1996). By means of a non-linear step by step procedure, a sequence of the relevant events during lifetime of the structure “Fabrication-Damage-Repair” is simulated. The coupling of non-stationary thermic and elasto-plastic analyses results in a complex initial state of structure involving residual stresses due to welding from fabrication and patch-repair superimposed with lateral denting damage. Röhr *et al.* (1999) have verified this numerical procedure by means of large scale tests and have obtained sufficient agreement on essential points. It has been proven that the assessment of the ultimate capacity of a structure in-service has to include all of the above aspects. Furthermore it can be stated, that patch-welding repair is suitable to compensate for the degradation of ultimate load capacity caused by denting.

The investigations by Schlüter and Meinken (1998) are devoted to the FEA of structure stability of large open inland vessels. Caused by collisions, grounding, corrosion and fatigue the ship structure undergoes a degradation of strength and structure stability. The safety against overall collapse decreases in the course of time. A non-linear FEA model has been developed for assessment of the ultimate hull strength, which includes the alteration of the structure due to in-services imperfections and damage. By means of numerical studies it is demonstrated that results obtained may be strongly dependent on the assumptions adopted for boundary conditions and the modelling of non-linearities. Other recent references on the subject are Paik *et al.* (1998b), Shanmugam *et al.* (1999), Vafai and Estekanchi (1999) and Ha *et al.* (1998).

6 RELIABILITY

6.1 General

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 requires the ultimate strength discussion to include the likely use of strength prediction tools and information in a structural reliability-based process. Reliability methodologies have historically been within the domain of ISSC Committee IV.1 on Design Principles and Criteria, with a brief mention in the 1997 report of ISSC Committee III.1. Expansion of this coverage is in line with the wealth of ongoing research in this area.

Reliability analysis and design traditionally consider ULS to define a failure event. For an ULS, the resistance or capability is represented by some measure of a structure's strength, representing a maximum value of the structural resistance. Failure is said to occur when the predicted load or demand exceeds the predicted strength. The dominant strength failure modes are usually some form of collapse or ductile overload. Proper inclusion of a strength prediction in a structural reliability context requires the characterization and consideration of all possible strength uncertainties. Such characterization is predominantly conducted in a probabilistic format. Strength uncertainties exist in both the basic strength variables (i.e. plate thickness, yield strength, distortion) and strength prediction technique or model.

Strength uncertainty and its propagation in reliability-based design and analysis methodologies will be discussed in this chapter. Reliability analysis techniques incorporating ULS's are discussed, but exploration of research and publications regarding reliability analysis and design remain the domain of Committee IV.1.

6.2 Ultimate Strength Modelling Bias and Uncertainty

A reliability analysis requires formal and quantitative measurements of basic variables and modelling uncertainties. Modelling bias and uncertainty will be considered in this section. The modelling bias is typically considered in the form of a ratio between experimental or numerical data to a strength prediction, and is presented as a mean and coefficient of variation (COV) for an assumed (usually) normal distribution. A bias greater than unity is conservative, representing an underprediction.

An approximate analytical prediction model for orthogonal grillages under axial and in-plane loading is described in Mikami and Niwa (1996). The model allows inclusion of coupled local and global buckling events, eccentric loading, and non-uniform stiffeners. For the case of collapse without local buckling, the modelling uncertainty was found to have a mean of 1.24 and COV of 0.135 for longitudinal stiffening and a mean of 0.983 and a COV of 0.047 for orthogonal stiffening. For collapse involving local buckling, the modelling bias was found to have a mean of 1.24 and COV of 0.074 for longitudinal stiffening, and a mean of 1.34 and COV of 0.249 for orthogonal stiffening.

Pu *et al.* (1997) present an extension to Faulkner's original stiffened panel strength model to include an effective width formulation by Soares, which explicitly considers imperfections. Comparisons with experimental data reveal a bias of 1.039 and COV of 0.143 for the original model and a bias of 0.992 and COV of 0.099 for the new model. Soares and Gordo (1997) compare three strength prediction models to experimental and numerical analysis results reported in the literature, for longitudinally stiffened panels under uniaxial comression and lateral pressure. Methods attributed to Faulkner, Carlsen and the American Bureau of Shipping (ABS) are compared to experimental results as shown in Table 1. A modification to the current ABS effective width formulation is reported by the authors (ABS-mod) to give slightly conservative results. The effect of lateral pressure on axial compressive strength was also considered and found to reduce the scatter while weakening the strength.

Atua (1998) and Assakkaf (1998) conducted research in support of a US Navy effort to develop reliability-based, load and resistance factor design (LRFD) criteria for surface ship structures. Atua

(1998) focuses on hull girder ultimate strength and stiffened panel strength. Eight strength predictive models for longitudinally stiffened panels under axial compression and lateral pressure are compared to experimental data from the literature. The developed modelling uncertainties are shown in Table 2 for axial compression and for axial compression with lateral pressure. Assakkaf (1998) considers unstiffened panels and develops comparative biases between prediction techniques to facilitate identification of simplified approaches for use in a design environment.

TABLE 1
STRENGTH MODELLING BIAS FOR LONGITUDINALLY STIFFENED PANELS, SOARES AND GORDO (1997).

Method	Faulkner	Carlsen	ABS	ABS	ABS-mod	ABS-mod
Tripping included?	No	No	No	Yes	No	Yes
Mean	0.980	1.188	0.805	0.889	1.079	1.189
COV	0.103	0.151	0.204	0.222	0.138	0.213

TABLE 2
STRENGTH MODELLING BIAS FOR LONGITUDINALLY STIFFENED PANELS, ATUA (1998).

Load		Hughes	Paik, Lee	Herzog m=1.2	Herzog m=1.0	Herzog m=0.8	Adam-chak	API	AISC	AAS-HTO	US Navy
Axial only	Mean	1.085	1.030	0.837	1.004	1.255	0.844	0.794	0.819	0.818	0.784
	COV	0.173	0.182	0.184	0.184	0.184	0.291	0.255	0.205	0.205	0.204
Axial & pressure	Mean	1.316	1.061	0.828	0.994	1.242	1.08	0.758	0.777	0.709	-
	COV	0.230	0.151	0.183	0.183	0.183	0.232	0.617	0.556	0.683	-

Paik and Kim (1997) compare eleven strength prediction models to experimental and numerical analysis results reported in the literature, for uniaxially compressed, longitudinally stiffened panels. Significant differences in the listed strength predictions are considered as a result of differences in collapse modes, effective width of plating, initial imperfections and rotational restraints. A summary of the modelling uncertainty is shown in Table 3.

TABLE 3
STRENGTH MODELLING BIAS FOR LONGITUDINALLY STIFFENED PANELS, PAIK AND KIM (1997).

Method	Imperial Colege	Faulkner	Carlsen	Modified Carlsen	Paik	LR	ECCS	API	IACS	BV	DnV
Mean	0.845	1.012	0.939	0.995	1.020	0.962	0.820	0.864	0.782	0.769	0.778
COV	0.270	0.170	0.223	0.193	0.144	0.192	0.377	0.324	0.224	0.213	0.212

Hess *et al.* (1998) contains the results of a US Navy survey and probabilistic characterization of material and geometric strength uncertainties, and a demonstration of the resulting uncertainty in a strength prediction for a longitudinally stiffened panel under axial loading and lateral pressure. The uncertainty in the strength prediction was shown to range as high as 10% due to basic strength variable uncertainty found using Monte Carlo simulation.

Östergaard *et al.* (1996) present a comparison of structural modelling techniques for containership hull structure to determine modelling uncertainties in linear-elastic stress calculations. Stresses resulting from a whole ship FEA model, two FEA models of a midships region and two thin-walled, beam formulation analyses are compared to obtain a measure of the uncertainty resulting from modelling approaches. For primary stress, the coefficients of variation representing modelling choice uncertainty are reported as 9% for principal stresses and 45% for shear stresses.

Al-Sharif and Preston (1996) use first and second order reliability analyses for the setting of Oman India Pipeline pipe wall thickness requirements to guard against pipe collapse. Collapse failure is considered as a result of external pressure and bending forces. Measurement and experimental data was analysed to probabilistically characterise the modelling uncertainty in the collapse prediction and basic strength variable uncertainty. Basic variable uncertainty measures are reported for ovality, thickness deviation, hoop compressive and axial tensile yield stresses, and hoop and axial strain hardening exponents. Bea *et al.* (1998) summarises the development of risk-based criteria for the design and requalification of pipelines and risers for the platforms in the Bay of Campeche. Analytical strength prediction models and uncertainties are described and utilised in reliability analyses, considering pipelines under internal and external pressure loads, time-dependent corrosion rate, hydrodynamic stability and sea floor soil movement.

Lacasse and Nadim (1996) report and compare the modelling uncertainties of pile axial capacity predictions in clay and sand for multiple prediction models. The authors recommend the prediction method presented in the API RP2A 20th Edition as it is judged to have the best combination of conservatism and uncertainty. The results are shown in Table 4, with an assumed normal distribution except in the case of dense and very dense sand where the lognormal distribution is more appropriate.

TABLE 4

MODELLING UNCERTAINTY RESULTS FOR PILE AXIAL CAPACITY, LACASSE AND NADIM (1996).

Material	Relative Density	Bias	COV
Clay	Normally consolidated	1.00-1.20	0.10-0.15
	Overly consolidated	1.00	0.20
Sand (pile in tension)	Dense/very dense	1.10-1.25	0.4
	Medium dense	1.10	0.35
	Loose	1.00	0.30
Sand (pile in compression)	Dense/very dense	1.30	0.50
	Medium dense	1.10-1.20	0.40
	Loose	1.00	0.30

Strength prediction models of dent-damaged tubular, steel bracing members under axial compression are discussed and compared to existing experimental data in Ricles and Bruin (1998). Three levels of model complexity are considered: 1) simplified strength equations, beam-column formulations and unity checks (Ellinas, DENTA and Loh); 2) moment-thrust-curvature relationships (M-P-F); and 3) non-linear FEA. The modelling uncertainties are shown in Table 5. As DENTA is proprietary software, the authors recommend the use of Loh’s formulation for general use.

TABLE 5

STRENGTH MODELLING UNCERTAINTY FOR DAMAGED TUBULAR MEMBERS, RICLES AND BRUIN (1998).

Method	Ellinas	DENTA	Loh	M-P-F	FEA
Mean	1.14	1.15	1.14	1.10	0.99
COV	0.19	0.08	0.13	0.18	0.07

6.3 Ultimate Strength Reliability Analysis

Reliability analyses of ship and offshore structures requires load information, which is beyond the scope of this committee. For reliability analysis and design, strength uncertainty is most often considered in a probabilistic manner and propagated through the strength model and reliability process. Research and applications in the combination of strength and load uncertainties to predict a reliability will be discussed in this section.

Mansour *et al.* (1997a) utilise primary, secondary, tertiary and fatigue limit states to demonstrate reliability analysis for surface ship structures. This paper is a summary of the work found in Mansour *et al.* (1997b). Mansour *et al.* (1997c) discuss a methodology for reliability-based design code development with a demonstration of its use for two hull girder limit states: an initial yield limit state and an ULS based on a reduced, initial yield bending resistance. Material yield strength randomness constitutes the strength uncertainty for the chosen strength predictions. Videiro (1998) utilises ULS, interaction equations in the development of a reliability analysis methodology for structural components of a Floating Production System, semi-submersible platform.

The impact of corrosion on the ultimate hull girder reliability is considered in Soares and Garbatov (1997) complementary to Wirsching *et al.* (1997). Assuming a random, time-invariant corrosion rate, and a simplified yield-based, strength treatment, the authors present and demonstrate a methodology for deriving the time-varying hull girder reliability with inspections and repairs. The corrosion rates between panels are allowed to have varying amounts of correlation, as a function of their physical separation distance in the cross-section. This approach is extended in Soares and Garbatov (1999) to include the section property reductions due to crack growth. The approach of the authors is an application of renewal theory with inspection and repair. While the reliability is held as the performance quality of interest, the availability of the ship as a function of corrosion and cracking effects, and inspection and repair strategies might better serve the ship design and operation decision process. This approach would necessarily consider the time needed for inspections and to make repairs. Paik *et al.* (1998a) consider reliability with regard to hull girder collapse of an ageing double hull tanker, with member corrosion and renewal. The time-invariant corrosion rate is considered to be random with initiation at 5 and 10 years from construction. The reliability is calculated using a second order reliability method. Changes time in the section modulus and ultimate strength are compared against the nominal values and attendant reliabilities.

Chryssanthopoulos (1998) presents a review of methodologies for probabilistic buckling and collapse analysis of thin-walled plates and shells and their use in reliability analyses. Attention is given to the manufacturing, material and geometric, basic strength variable uncertainties and their inclusion in a First Order Reliability Method (FORM) prediction. As the number of stiffeners in an axially stiffened cylinder increases, the axial collapse load reliability transitions from being most sensitive to imperfection uncertainty, to being most sensitive to yield stress uncertainty. Unstiffened plate buckling reliability is noted as relatively insensitive to imperfections, while the reverse is true for stiffened plates.

Gurvich and Pipes (1998) proposes a simplified methodology for prediction of an anisotropic material in a random 2-D or 3-D stress state. Experimental approaches and analysis techniques are presented to obtain the needed uncertainty characterisations along with correlation factors. Based on assumed strength and stress distributions and a linearized failure envelope, an exact reliability prediction is produced. Ibnabdeljalil and Curtin (1997) consider composite strength and its size dependence with local load sharing (LLS) using a Monte Carlo simulation model based on the 3-D lattice Green's function technique. An analytical formulation was derived and demonstrated, mapping the reliability of a small composite structure under LLS to a larger structure whose strength is governed by it's weakest bundle of fibres. Koksharov (1996) uses a characteristic volume with probabilistically characterised levels of damage in developing a critical distortion energy for the fracture strength of a unidirectional composite. The approach allows inclusion of composite structural reserve strength in reliability predictions for both static strength and fatigue. Lin *et al.* (1998) use stochastic FEA and second order perturbation techniques to derive the strengths of a laminate under inplane loads based on 1st ply failure (using the Tsai-Wu criterion) and buckling. The material properties, fibre angles and lamina thicknesses are treated as random variables. SFEA and Monte Carlo simulation are used to develop failure probabilities using three different strength distributions (normal, lognormal and Weibull). Randomness in lamina thickness is shown to have the greatest effect on the failure probability of angle ply laminates. Yushanov and Bogdanovich (1998) give an overview of the state of the art in reliability prediction methods for composite structures. The authors present an analytic reliability prediction methodology and example applications for laminates under inplane loads, using analysis of rare passages of a state vector (stress, strain or displacement) stochastic process beyond the stochastic limiting surface. The laminate reliability is developed as a serial treatment of lamina reliabilities.

6.4 Ultimate Strength Reliability-based Optimisation

Leheta and Mansour (1997) use reliability as a behavior constraint in a least-weight optimization of a stiffened panel. The method is contained in a computer program OPTIREL, developed to work with CALREL and CALSYS. The software is applied to the design of an amidships tanker deck panel, and provides a 20% weight savings without reducing the level of safety.

Groen and Kaminski (1996) consider cost optimisation of ring-stiffened cylinders under hydrostatic pressure, in the presence of deterministic and reliability constraints. The reliability constraints are included because new materials and construction techniques may have different uncertainties than those assumed in existing design codes. Stochastic models are presented for local and spatial out-of-circularity variability. The reliability constraints are included to allow for uncertainty reduction resulting from improved materials and production techniques.

António *et al.* (1996) present ULS, reliability formulations for a composite material system in the context of multi-objective optimisation. The advanced second moment, reliability prediction is based on failures of the first and last layers, the latter a function of a mechanical property degradation model and global load sharing due to matrix cracking. Degenerated shell finite elements were used for the structural analysis. The design variables considered are number of plies and ply angle and thickness.

7 MEMBERS

7.1 Beam-Columns

There are few papers published related to the ductile collapse of frames and girders. A major research programme involving the behaviour of slender cross-section square hollow sections and I-sections was performed at the University of Sydney. The results of the tests were compared against design rules in a special issue of Thin-Walled Structures, Rhodes (1998), dedicated to recent developments in thin-walled structures. More detailed analysis of these series of tests may be found in Rasmussen (1997), Young and Rasmussen (1997), Rasmussen and Hasham (1998), Sully and Hancock (1998), Hasham and Rasmussen (1998), and Young and Rasmussen (1998a). Unfortunately these tests are more related to civil engineering structures than to ship structures. Nevertheless some of the conclusions may be applied in both fields, e.g. the interaction curve between axial force and end-moment applied in a constant ratio gives a conservative result and the shape of these interactions curves is close to linear if bent about the major principal axis.

One of the few studies related to ship structures is due to Röhr and Fehlhaber (1999) who have analysed the non-linear range of girders with web openings and concluded that the main cause of failure of these type of girders is due to local yielding and inelastic buckling associated with the presence of the openings. Substructures are analysed under complex loading by FEA. It is concluded that interaction curves of shear, bending moment and lateral pressure may be constructed using this powerful tool to define the ULS of the substructure.

Experimental studies were performed on continuous plate girders with different spans, while varying the width to thickness ratio of the web and the flange (Pasternak and Branka, 1997, in German). Comparison of the tests against design codes has shown that the degree of underestimation can rise up to 30% in case of the shear collapse mechanism. It is recommended that the effective section of the web should be taken into consideration when evaluating of the ultimate bending moment.

Rahman (1998b) describes a computerised methodology for tracing the development of ‘hinges’ in the ultimate strength analysis of ships’ transverse frames. The hinges can be either normal fully plastic hinges or moment capacities limited by flexural-torsional buckling. The effects of axial force and shear on the moment capacities are addressed. The accuracy of the procedure is reasonably well established through simulations of portal frame tests. It is then used in a limited parametric study of two-sided frame configurations. The method is based on the incremental elastic-plastic FEA oriented to the analysis of plane frame structures. The method is specially oriented to reduce the computational time in an optimisation software (Rahman, 1998a), assuming that the frames are strong enough to avoid longitudinal members experiencing interframe collapse before any grillage collapse occurs. The effects of shear, axial force and instability are also considered in the evaluation of the ultimate strength of frames by a simplified procedure, but with acceptable accuracy. According to Rahman the plasticity condition for the formation of a hinge in ship transverse frames is given by:

$$\left|M_L\right| = \left(1 - \left|\frac{T}{T_p}\right| - \left|\frac{V}{2 \cdot V_p}\right|\right) \cdot \left|M_{cr}\right| \qquad (2)$$

where M_L and M_{cr} are the actual limit moment of the frame and the critical moment, respectively, $T_p = \sigma_y A$ and $V_p = \tau_y A_{web}$, and T and V are the actual axial and shear load effects, respctively.

The elastic instability and post-buckling equilibrium of a uniform thin walled open cross-section are well established in Ioannidis and Kounadis (1999). A detailed example for a pinned ‘L’ bar is given and a comparison is made between linear and the non-linear elastic analyses. Aspects related to the instability of the tension flange of I-beams may be found in Axhag and Johansson (1999). The inelastic lateral buckling of asymmetric beams are analysed by Pi *et al.* (1999) using the FEA.

An energy method is used by Bradford (1998b) to analyse the effects of the twist restraint on the buckling of I-beams under uniform loads. He concludes that an increase in the number of restraining elements increases the number of harmonics for the lowest buckling load and promotes local failure instead of lateral-torsional buckling. Studies related to the buckling of T-section cantilevers under several load conditions are also available based on a FEA procedure in Bradford (1998a) and Bradford (1999) where it is shown that the distortions during buckling under restrained end conditions are much higher than on simply supported conditions.

According to Earls (1999), the increased use of high tensile steel brings about problems that are not predicted by the material initial assumptions. A series of beams in HSLA80 modelled in ABACUS and supporting moment gradient loads present two distinct inelastic buckling patterns of failure, which are influenced in a different manner by the cross-section proportions and initial imperfections.

An analytical solution for the pre-collapse of beam-columns of any cross-sections is proposed by Drazetic *et al.* (1999). The post-collapse mechanism is fully discussed in Drazetic *et al.* (1999). Young and Rasmussen (1998b) and Young and Rasmussen (1999) present an experimental study of the behaviour of symmetric columns. Comparison of the nature of the buckling is made for pinned and fixed end conditions. Sivakumaran and Rahman (1998) implemented a test program on cold-formed stub-columns in order to validate a FEA model for post-local buckling behaviour.

7.2 Tubular Members

The Committee V7 of ISSC94 has initiated a study on the structural behaviour of a non-bonded flexible riser cross-section. Witz (1996) has published a paper where the results of 10 different institutions that have participated in the study are compared with experimental data. A full description of the case study is available. Despite the discrepancies between the results of the flexural structural response of flexible riser presented by the participants, it was concluded that there are suitable methods for predicting the structural response of a flexible riser subjected to axisymmetric loading. These methods have in common the ability to account for the interaction between the component layers.

The collapse of thick-walled tubes under combined complex loading system has been analysed by Bai *et al.* (1997). Thin walled tubes with and without drilled cut-outs are tested and reported by Gupta (1998) and it is concluded that the presence of these holes may alter the mode of collapse and the buckling load.

8 JOINTS

8.1 Basic Issues for Tubular Joints

The discussion herein is limited to joints involving tubular members, with most emphasis on circular hollow sections (CHS). In addition to some fundamental issues requiring further clarification there are many connection types and operating environments which still require a research effort to provide the necessary guidelines for good design and ultimate strength assessment. The core issues for conventional tubular joints, which have been the subject of much research, include:

- definition of ultimate strength,
- ultimate strength under the individual and combined actions of punching shear - N, in-plane bending moment - M_{ip}, and out-of-plane bending moment - M_{op},
- effect of chord prestress (axial force and bending moment in the chord).

Other important issues less well resolved for design and assessment purposes include: incremental collapse under repeated load, effect of interaction between braces at a joint for multi-planar joints, effect of stiffeners, and strength of grouted sleeve and concrete filled joints. These issues are more difficult to resolve due to the immense variety of joint configurations and loading that are used in practice.

8.2 Definition of Ultimate Limit State under Static Load

The one ULS must accommodate the many failure modes that occur. The majority of the failure modes are associated with failure in the wall of the through or chord member. With braces in compression this can involve the inelastic buckling of the chord wall, or the formation of a collapse mechanism in stocky members (low D/T). With braces in tension the possibility exists of ductile fracture in or near welds. Especially for braces in tension, unacceptably large deformation can occur before peak load is reached. In these cases a deformation limit is imposed, defining the ultimate strength for design and assessment purposes.

It is usual to refer to local deflection, δ, of the chord wall in defining load-deflection curves of joints. Typical load-deflection curves are shown in Figure 5, Makino *et al.* (1996). The curves are characterised by a yield strength point, a crack initiation point, a deformation limit and an ultimate strength. Yield strength, variously defined, is used for serviceability checks. Crack initiation occurs occasionally, and is difficult to predict. Ultimate strength is defined as the least of peak load (where the curve has a maximum, curves b and c), of load at which stiffness is minimum before increasing again (curve d), and of load at which the deformation limit is reached (curve a).

Curve a is typical for braces loaded in tension, where deformation can be very large. Curve b is typical for braces loaded in compression, where local inelastic buckling occurs in the wall of the chord member. Curves c and d are characteristic of some cases of applied moment or combined loadings of N and M.

Lu *et al.* (1994) proposed a modification to Yura's deformation limit for circular hollow sections (CHS), setting δ at 3.0% of D, the diameter of the CHS chord. This has been validated by Zhao (1999) for δ versus B of rectangular hollow section (RHS) chord members.

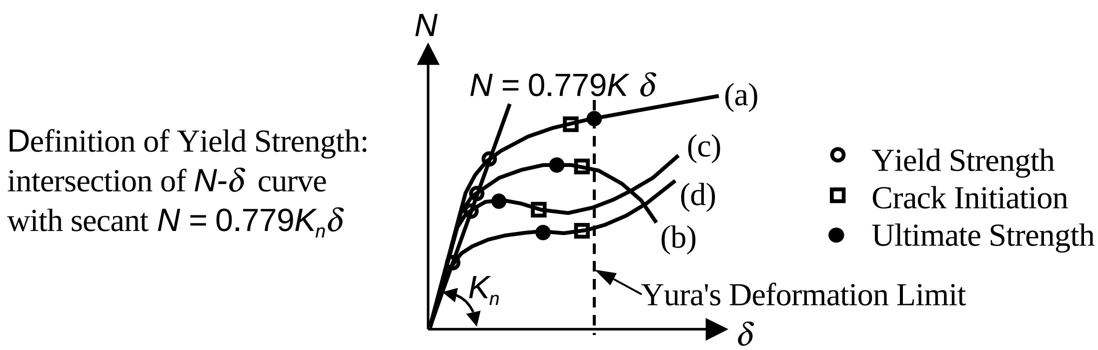


Figure 5. Schematic load-deformation curves, Kurobane *et al.*, (1984).

8.3 Unstiffened Tube-to-Tube Joints

This discussion is restricted to the ultimate strength of joints where all members are tubular, mostly circular hollow sections (CHS), and the material is low alloy steel. Most applications in offshore engineering involve hot rolled steel plate formed into "cans" with a longitudinal full penetration seam weld. The cans are often large enough to permit the insertion of internal ring stiffeners as required at joints, before being assembled into members by circumferential butt welds. Many laboratory tests have been conducted on small scale members made of continuously formed hot rolled or cold rolled CHS members. These are admitted to the database for determining ultimate strength provided that the chord diameter exceeds 140 mm. The ultimate strength is deemed to have low sensitivity to scale or to the method of fabrication within these limits.

A significant advance has been the publication by Makino *et al.* (1996) of a data base, maintained at Kumamoto University, of all laboratory studies and FEA of unstiffened CHS tubular joints. Only those FEA results calibrated against laboratory tests are included. Approximately 1670 planar (T-, X- and K-) joints and 630 three-dimensional (TT-, XX-, TX-, and KK-) joints are included. These data are useful for verification of strength formulas. Nevertheless, care is required in using the database. Healy and Zettlemoyer (1994) have previously noted significant differences in ultimate moment capacity of Y-joints depending on whether the moment is opening or closing the acute angle, and they further noted the need to eliminate premature brace failures from the data.

There is an immense variety of joints, with only the simpler joints supported by the database mentioned. However, these data can be judiciously extended to more complex joints. It appears that sensitivity of ultimate strength to interaction between adjacent braces is high in three-dimensional joints, compared with planar joints, where interaction is often ignored.

Further tests and numerical studies have been carried out on planar joints, on K-joints by Dexter and Lee (1998b), on KT-joints by Wilmshurst *et al.* (1998), on KK-joints by Yonemura *et al.* (1996), on RHS X-joints by Yu and Wardenier (1996), on tubular frameworks by Hyde *et al.* (1999), on DT-joints, looking at the effect of weld size by Kang *et al.* (1998), and on L-joints by Puthli *et al.* (1999). The effect of overlap has received further study for K-joints by Dexter and Lee (1996) and (1998a), by Gazzola *et al.* (1999), for RHS K- and X-joints by Davies *et al.* (1996). The ultimate strength of cracked joints has been explored by Cheaitani and Burdekin (1994). Bolt (1995) observed cracking in K-joints in full scale tests of a frame structure which was not replicated in isolated joint tests. She also noted the superior performance with regard to ductility and redistribution of X-joints compared with K-joints.

Some progress has been made on the wide variety of multiplanar joints. Tests on multiplanar XX-joints have been reported by van de Vegte and Wardenier (1996), and Yu *et al.* (1998). KK-joints have been studied by Lee and Wilmshurst (1996). Multiplanar DX- and XT-joints have been studied by Chiew *et al.* (1997), and by Chan *et al.* (1998). In these studies it is noted that there is high interaction between structural actions in orthogonal planes, with joints where all braces are in tension or compression performing better than joints with alternating tension and compression in adjacent planes.

FEA modelling and boundary conditions have a significant impact on accuracy of numerical analysis, and in the latter case, on ultimate strength obtained numerically or by test. Often a connection can exhibit higher strength within a complete structure compared with the strength obtained from testing an isolated joint, but not necessarily for K-braced frames. This is due to the non-linear redistribution of structural actions that takes place in the full structure as the load is increased. Reporting large-scale tests of tubular frame structures Bolt *et al.* (1994) noted different ultimate strength behaviour in connections from tests on isolated connections. Useful inputs to this question have been provided by Liu *et al.* (1998a, 1998b and 1998c) and Hyde *et al.* (1998).

8.4 Design Guidance for Tube-to-tube Joints

Some extensions of ultimate strength formulations for unstiffened joints have been provided, based upon the research reported in the previous section. Traditionally, there are two formulae for punching shear of brace in a chord - one based upon transfer of axial forces to adjacent braces and the chord, without significant chord bending, and the other based upon resistance to punching by bending of the chord, so-called prestress of the chord. The punching shear strength is made up of a combination of these two components. In fact, adjacent braces influence the punching shear strength. Morita *et al.* (1996) and Yamada *et al.* (1998) have developed continuous formulae for the ultimate strength of T-, TT-, X-, K- and KK-joints. Updates to formulae for static strength arising from Joint Industry Projects (JIPs) have been reported by Dier and Lalani (1998).

JIPs have also led to the provision of design guides, Smedley and Bolt (1994). An ISO standard for offshore structures is currently under development (ISO-13819, Part 2). Zettlemoyer (1996) has highlighted aspects of harmonisation of guidance on strength of tubular joints.

8.5 Other Welded and Bolted Connections

For stiffened tube-to-tube joints the variety of stiffening options makes it difficult to establish standard formulae for strength. Ring stiffeners continue to be studied, with useful additions to the literature by Lee and Llewelyn (1998) and Willibald *et al.* (1999). Doubler or collar plates have been considered by Choo *et al.* (1998). Elastoplastic FEA remains the main tool for assessing stiffened complex joints.

I-beam-to-CHS-column connections are important in decks and topside structures. They constitute an active area of research. Ariyoshi *et al.* (1998) report a database of gusset-plate to CHS tube joints, which pulls together much of the information. This research on individual plates precesedes that on full I-beams. Individual gusset plates are considered for CHS by Ariyoshi and Makino (1999), and for RHS by Hörenbaum *et al.* (1998) and by Koteski *et al.* (1999). Full I-beam connections are considered by Winkel and Wardenier (1996), by Kamba and Taclendo (1998) and by Morita *et al.* (1998).

8.6 Grouted Joints

The principal application of grouted joints for new construction is in transferring loads from offshore structures to the sea bed. This is achieved through grouted pile-sleeve connections at the base of the structure, and primary pile-insert pile connections for deep piles. Ultimate strength has not been the focus of recent studies, which have concentrated on fatigue and installation issues. However, the question of enhancing performance by generating isostatic prestress in the grout generated chemically through expansion after setting is being studied, with some promising results allowing short splice lengths and the elimination of costly shear keys, Grundy and Foo (1991). Grundy (1995) has presented the analytical basis of the performance of these connections.

Currently most applications of grouted sleeve joints involve strengthening, repair or retrofit of damaged structures, using split sleeves bolted together and grouted. Prestress is generated by tightening the bolts clamping the sleeve after the grout has hardened. The possibility of using grouted joints for initial fabrication, using a chemical expanding agent to generate prestress, is being investigated, with some data reported by Ure *et al.* (1996). Connection strength is also enhanced by completely filling the through member in the vicinity of the connection. Lalani *et al.* (1996) report increased stiffness and strength compared with unfilled joints, particularly for compressive forces on the joint, but less so for tensile forces. An interesting related problem is the transfer of tensile loads from pile caps to tubular piles using reinforced concrete plugs. Al-Mahaidi *et al.* (1999) have reported dramatically higher capacity than has been up till now considered, with the potential for significant cost reduction.

8.7 Effect of High Amplitude Repeated Loads

The phenomenon of incremental collapse of frames under variable amplitude loading has been identified, although it has not been found to be critical compared with collapse under an individual extreme load such as a maximum wave in a storm. Such analyses have included member behaviour but not joint behaviour under repeated load. Incremental collapse of tubular joints under cyclic load has been observed in laboratory tests at Monash University, Goh and Grundy (1994), Milani and Grundy (1996 & 1997). Reductions up to 20% of static strength were observed. Failure by cracking through exhaustion of ductility in local areas can occur. This makes it difficult to distinguish failure from incremental collapse from fatigue failure. The analytical model using classical shake-down theory, see Grundy (1994), is being used for numerical modelling of the basic T-joint, Dale *et al.* (1999).

9 PLATES

9.1 General

Ultimate strength analysis of plates including stiffened plates, corrugated panels and sandwich panels are reviewed in this chapter. In Chapters 3 to 5, the analytical, experimental and numerical analysis are discussed in general, whereas here the emphasis is on presenting the applications developed for plates used in marine structures. First the unstiffened plates are touched upon and thereafter the stiffened and corrugated panels are considered. Finally the research and applications related to steel sandwich panels are discussed.

9.2 Unstiffened Plates

The ultimate compressive strength of unstiffened plates is very important from the design and safety viewpoint. The ultimate compressive strength of these panels depends quite significantly on the initial welding distorsions and residual stresses. Currently, most of the research concerning the effect of welding distortions concentrates only on the maximum initial distortion amplitude. However, the evidence indicate that the welding distortion shape affects the ultimate compressive strength significantly.

Mateus and Witz (1997, 1998) present the results of an investigation into the buckling and post-buckling behaviour of typical marine structures plating under uniaxial loading using non-linear FEA. The effects of general corrosion are introduced into the plate FEA models using the traditional uniform thickness reduction and a recently proposed quasi-random thickness surface model. The results show that there are significant discrepancies in the prediction of plate post-buckling behaviour between the two general corrosion approaches, indicating that the uniform thickness reduction approach produces optimistic results and is inadequate for design purposes.

The effect of welding on the local buckling of aluminium thin-walled sections is addressed by Mazzolani *et al.* (1998). By considering different hardening parameters as well as plate slenderness, the effect of welding in terms of geometrical imperfections, residual stresses and heat affected zones are analysed by means of a FEA. The obtained numerical results emphasise the influence of welding on the strength of slender plates, which has been only partially shown by experimental analyses.

Characteristics of initial imperfections in panels and stiffeners due to welding are discussed in Yao *et al.* (1998a). The buckling/ultimate strength of ship bottom, stiffened plating subjected to combined bi-axial thrust and lateral pressure is extensively investigated, and is based on the results of new and recent analyses considering the influences of initial deflection and welding residual stresses, Yao *et al.* (1997a, 1997b, 1997c, 1998b). The studies indicate that the buckling strength of a local panel between stiffeners can increase owing to the influences of lateral pressure, welding residual stresses reduce both buckling strength and ultimate strength and the mode of initial deflection has a minor effect on the ultimate strength. The classification society formulations for ultimate strength under bi-axial thrust are found to be on the safe side. The same topic is also studied by Fujikubo *et al.* (1997) for thick (15-25 mm) rectangular plates indicating that the classification society rules can also give somewhat unsafe results with high transverse compression and high intitial deflections ($w_{max} = 0.1 \beta t^2$).

The behavior of ship plating normally depends on a variety of influential factors, namely geometric / material properties, loading characteristics, initial imperfections, boundary conditions and local deterioration arising from corrosion, fatigue cracking and accidental dents. To achieve a more advanced buckling and ultimate strength design of ship plating, we are still confronted with a number of problem areas that require more sophisticated solution methods than most existing simplified approaches. Most recently, Paik *et al.* (2000) present a paper focusing on the following five subjects which have been studied by the authors theoretically, numerically and experimentally: modelling of post-weld initial imperfections (i.e., initial deflections and residual stresses) in ship plating, effects of rotational restraints and torsional rigidity of support members on the plate buckling strength, ultimate strength design equations under combined loads including biaxial compression / tension, edge shear and lateral pressure, and dynamic collapse strength characteristics under axial compressive dynamic loads or slamming induced impact pressure loading. Useful results, important insights and conclusions developed in the study are summarized and recommendations are made with respect to both technologically improved design procedures, and also needed future research.

9.3 Stiffened Panels

Paik *et al.* (1998b) investigated numerically the characteristics of tripping failure of flat-bar stiffened panels subjected to uniaxial compressive loads and studied the accuracy of two available design formulations.

Paik *et al.* (1998c) study analytically the characteristics of local buckling of the stiffener web in the stiffened panels under uniaxial compressive loads. A plate-stiffener combination model is used as representative of the stiffened panel. The elastic buckling condition for the stiffener web is analytically derived by solving the characteristic value problem involving the governing differential equation under the corresponding loading and boundary conditions. Closed-form approximate expressions for predicting the buckling strength of the stiffener web are derived taking into account the influence of rotational restraints at the plate-stiffener web connection and stiffener web-flange intersections. Finally, design considerations for preventing buckling of the stiffener web are discussed, especially for the flat bar stiffener case.

Wang and Moan (1997) performed a study on the ultimate strength of stiffened panels subjected to biaxial and lateral loading. The objective was to assess the beam-column approach used in design rules for ships and offshore structures. Non-linear FEAs of two representative midship bottom and deck panels from an offshore oil production ship were made, for which the corresponding ultimate longitudinal compressive strengths were calculated accounting for the effects of initial imperfections. The calculated results are compared with the predictions using a beam-column formulation. For the interaction of axial compression and significant lateral pressure, it is found that the considered beam-column model is nonconservative in plate-induced failure mode, while it generally very conservative in stiffener induced failure mode. The bias associated with the model is found to be a function of the transverse stress and lateral pressure.

Hurst and Campbell (1997) present a comparison of FEA modelling practices for stiffened plate structures applying the SESAM package. The main focus of this study was to determine how to model stiffened plate behaviour in global models of floating structures. Results from 10 different FEA models representing the same geometry are compared, and based on these comparisons, recommendations for proper FEA modelling are given. Also, Yao *et al.* (1998c) have studied the FEA modelling principles for stiffened plates concluding that a triple span model is somewhat better than a 2 span model for studying collapse behaviour under combined thrust and lateral loads.

Grillages are one of the major structural components of various onshore and offshore structures. Generally, plates of ship structures are stiffened longitudinally by stiffeners of a relatively small size and transversely by girders of a larger size. There are many kinds of strength formulations proposed for predicting the ultimate strength of stiffened panels, but few are applicable to grillages. Cho *et al.* (1998a, 1998b) have developed a robust ultimate strength formulation for grillages subjected to combined axial compression, end bending moment and lateral pressure loadings. The so-called generalised Merchant-Rankine formula is adopted as its basis. The predictions using the proposed formulation provide improved accuracy compared with other existing approaches, and optimisation can be performed on all the design variables for grillage structures. Test results of stiffened panels which undergo loading far beyond their ultimate state show the interaction of the column buckling of the stiffener together with associated plate buckling and the torsional buckling (tripping) of the stiffener. A simple equation is also derived to represent the average strain and stress relation of stiffened plates for post ultimate state.

An experimental and numerical investigation is carried out to study the buckling behaviour of aluminium plates with longitudinal stiffeners subjected to axial compression by Aalberg *et al.* (1998). The test specimens, 2000mm long, are built up with extruded aluminium profiles connected with welding. Two types of stiffened plates are investigated; one with open section (L shape) stiffeners and the other with closed stiffeners, both in aluminium alloy AA6082 temper T6. Numerical simulations of the tests are carried out using the FEA code ABAQUS. It is found that the FEA simulations predict quite accurately the behaviour and the resistance of the stiffened aluminium plates, both for the observed global buckling and the stiffener tripping (for the L shaped stiffeners only). The experimental results are also compared with the resistance calculated from the design rules in ENV 1999-1-1 (EC 9) for aluminium structures. In all experiments the measured maximum load exceeds the EC 9 design resistance. The ultimate strength of aluminium extruded panels has also been studied by Tanaka *et al.* (1996) applying FEA and laboratory experiments.

Fujikubo *et al.* (1999) summarize the results of extensive studies in Japan to evaluate ultimate strength of stiffened plates under thrust. A continuous stiffened plate is idealised as a double-span beam column model with an effective width of a panel as a flange, and a simplified method to evaluate ultimate compressive strength is developed by modifying the Carlsen method. The panel/stiffener interactions are taken into account considering the influence of torsional rigidity of a stiffener on the local buckling strength of a panel. Also the influence of the initial deflections of the stiffener are included. A series of ultimate strength calculations have been performed by applying the proposed method to continous stiffened plates with flat-bar, angle-bar and tee-bar stiffeners. Comparison with non-linear FEA calculations shows good agreement.

9.4 Corrugated Panels

The ultimate strength of corrugated bulkheads has been studied by Paik *et al.* (1997a) to obtain experimental data on collapse strength of steel corrugated bulkhead models and also to develop a simple analytical formulation for ultimate strength useful in the design of corrugated bulkheads. Extensive laboratory testing with models having five bays of corrugations are carried out, varying the corrugation angle, the plate thickness and the type of loading (axial compression and /or lateral pressure). The existing design research results and design formulations are thoroughly studied and for purposes of rapid first cut estimates of strength, a new and simple analytical formulation for predicting the ultimate strength of corrugated bulkheads under hydrostatic pressure is derived. The new formulation is based on a calculation of the moment carrying capacity of the corrugation cross-section applying ultimate strength based design guidelines.

Grundy and Geiro (1998) discuss the design and analysis of corrugated bulkheads. The relevant IACS rules are demonstrated to not necessarily provide an adequate safety margin against accidental flooding particularly if the corrosion allowance is fully (and uniformly) used. Both loading and resistance issues are addressed, and both appear wanting. Load transfer at the lower stool is also noted to be a cause of concern particularly if construction quality is below standard. A similar problem is addressed by Rainey *et al.* (1998). However, here the emphasis is on possible sloshing of water in flooded holds, precipitating fatigue fracture of welds following buckling, but not complete collapse of the bulkhead. An appendix considers corrosion rates in bulk carriers.

9.5 Sandwich Panels

The need to reduce weight at an affordable cost has always been a major issue e.g. within the fast ship industry. The development and testing of an alternative ship structural concept, to replace the conventional steel plate and tee-beam construction in the form of laser- welded corrugated core panels has been reviewed by Furio and Bird (1997). Since 1998, a continuously welded form of corrugated core panel, LASCOR (LASer corrugated CORe), has been investigated for lightweight structural use and this concept has shown additional promise for ship applications. LASCOR, a development of laser welding technology, consists of two face sheets laser welded to an inner corrugated core to form a lightweight / high stiffness metallic sandwich structure. The potential of this concept is evaluated for the fast ferry industry, where lightweight, high stiffness steel structure could be an option for conventional aluminium structure where a strength limitation exists.

Adhesively bonded, steel corrugated core, sandwich construction suitable for marine applications is studied by Knox *et al.* (1998). These sandwich structures are also shown to be an efficient form of panelling. Using both experimental techniques and numerical analyses, the structural performance of adhesively bonded steel corrugated core sandwich beam elements was investigated in bending transverse to the corrugations, under both static and fatigue loading.

Kujala (1998) has reviewed the research related to ultimate strength of all steel sandwich panels conducted in Finland. The studies include laboratory strength testing, FEA and development of design formulations for these panels. The ultimate strength is analysed under hydrostatic loading and under local point loading. Three cases can be classified for the collapse modes. For large loading areas and for small core plate thicknesses, elastic buckling of the core plate is the dominating collapse mode. For thicker plates, core yielding and buckling are causing the failure. The third type of collapse mode occurs when the face plate is thin, then the applied ultimate load causes high compressive bending stresses on the face plate causing face plate buckling before the collapse of the core plate.

Roland and Metschkow (1997) summarise the potential applications of all steel sandwich panels for both shipbuilding and various areas of structural steel engineering such as bridges, railway vehicles and buildings. To provide a base for successfull application, a considerable amount of structural testing along with the development of efficient manufacturing and assembly methods and the approval of the structure by classification societies has been necessary, see Figure 6.

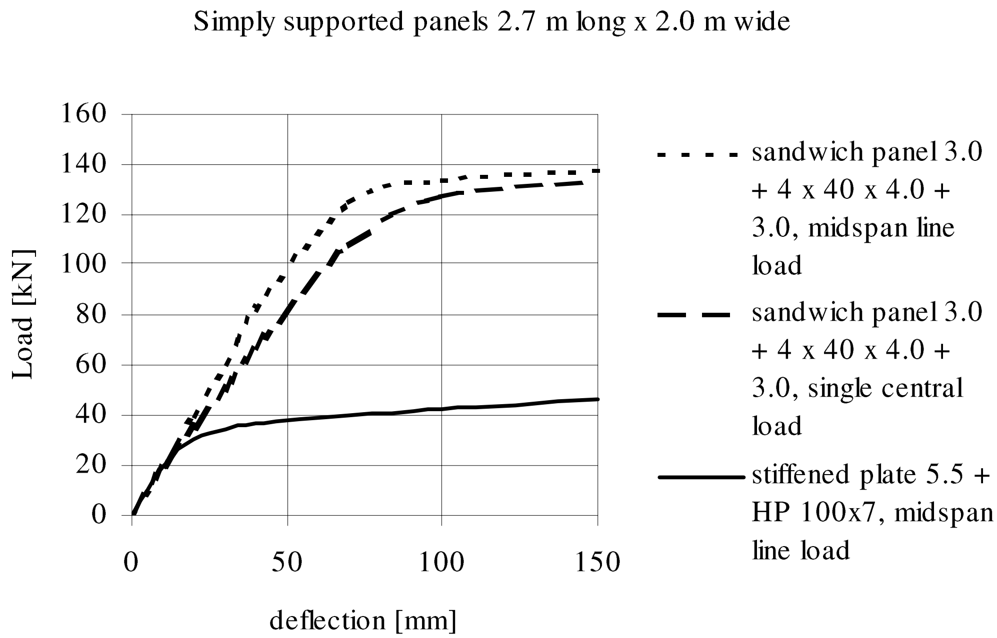


Figure 6: Static strength of laser welded panel compared to conventional panel of equal weight, Roland and Metschkow (1997).

10 SHELLS

10.1 General

Unstiffened and stiffened shell members are used in a variety of marine structures, ranging from platform primary members, to dome ends and hulls of advanced marine vehicles. Unconventional geometry, dimensions and capacity to carry complex loading require a deeper analysis of the buckling in the elasto-plastic regime that is affected by geometric imperfections, material non linearity and residual stresses caused by fabrication process or in-service damage. These topics have been studied in the past by adopting numerical methods and experimental tests. The same approach has been also used in recent works. In addition, the development of the software and the availability of sophisticated numerical codes have allowed the analysis of more realistic structures. Nevertheless, the support of the experimental investigations is required to validate the assumptions connected with the mathematical models.

10.2 Unstiffened Shells

Although the unstiffened shells are the most appropriate structural shapes applied to dome ends, literature shows several works based on cylindrical shells. In fact, present research on the buckling of unstiffened shells generally considers the following topics: behaviour of thin shells and shell intersections, internal and external loads for dome ends, effects of initial geometric imperfections and material non-linearity and alternative numerical techniques. FEA has been used by Eberlein and Wriggers (1998) in order to examine finite plastic strains in shell intersections. They have presented a distinctive parameterisation concept useful for creating FEA models of both smooth parts and shell intersections. The proposed model can be considered as a starting point for the implementation of the parameter model accounting for thickness strains.

Blachut (1998) has numerically and experimentally investigated the buckling performance of externally pressurised shallow torispheres. He obtained a good agreement between numerical and experimental results including shape of domes after collapse.

The relationship between the collapse mechanism and the various types of geometrical imperfections has been numerically and experimentally investigated by Boote *et al.* (1996). The good agreement of the results allows investigation of the influence of imperfections on a statistical basis.

A parametric analysis of the dynamic strength of initially curved columns and cylindrical shells with initial local deflections has been carried out by Tsubogo *et al.* (1996). The obtained results emphasise the influence of shape factor, degree of impact velocity and initial deflections on the buckling strength. The researchers also analysed the local buckling failure of a damaged steel column.

Fukuchi *et al.* (1996) present the results of an investigation having as it's main objective the numerical large deflection analysis of thin shells. The authors used a modified version of a hybrid method proposed by Atluri *et al.*, which allows a considerable reduction of computer time.

An analytical approach describing post-buckling behaviour of thin shells has been developed by Tovstick (1997). He proposes approximate, two-dimensional, elasticity relations for the axisymmetric deformation of a thin shell of revolution based on non-linear three-dimensional equations of the theory of elasticity. Tovstick and Bauer (1998) have extended the method to spherical shells under concentrated loads. The domes subjected to internal pressure, as those in LNG ships, are experimentally investigated by Blachut (1997).

10.3 Stiffened Shells

Stiffened shells, mainly the cylindrical ones, are structural components used in various applications of marine structures. The development of new marine vehicles (fast ships, unconventional vessels, submergible research vehicles) has also required various types of stiffening (circumferential – longitudinal – orthogonal) in order to satisfy the structural strength. This is the source of a wide range of failure modes involving shell and shell-stiffening elements either locally (shell buckle alone) or totally (general instability of shell, frames and stringer). Therefore, the research has been focused on the better utilisation and distribution of the material with respect to the applied loads and their combinations, on residual stresses and on spatial variation of geometrical imperfections.

The fast buckling behaviour of stiffened laminated cylindrical shells subject to combined loading of external liquid pressure and axial compression was investigated by Hui and Shen (1998). Morandi *et al.* (1996) present a new equation for inelastic tripping of ring frames in cylinders under external pressure.

Large parts of especially smaller ships are built of single or double curvature shells. When exposed to distributed loads such shells may carry a significantly larger load than plane panels. Bozhevolnaya and Frostig (1997) studied the mechanics of sandwich shells subjected to distributed lateral loading in order to investigate the strength of the ship bilge and other curved panels in a ship bottom or side.

11 SYSTEMS

11.1 Offshore Structures

Shetty *et al.* (1997) use a system reliability approach in relation to fixed offshore steel jacket structures to consider:

(a) a sequence of member / joint / pile strength failures under extreme storm loading that leads to overall collapse,
(b) a sequence of joint fatigue failures over time that leads to collapse under either operational loading or moderate storm conditions,
(c) the initial fatigue failure of joint(s) followed by collapse in a moderately severe storm.

Only a limited number of failure paths or sequences contribute significantly to system failure. Thus, it is usually satisfactory to identify ‘probabilistically dominant failure sequences’ and evaluate their probabilities in the determination of system failure probabilities. Environmental loading is input via a response surface in wave height, period, current velocity, marine growth, etc. Fatigue loading follows a conventional spectral approach. The authors use the ‘virtual distortion method’ to deal with structural non-linearities.

For (a), when failure is dominated by tubular member failure, all failure paths are highly correlated, a result of strength variability being much less than the variability in loading. Thus, frequently, only one sequence needs consideration. In this case, the result is similar to that found by treating a jacket as a single component for which overall collapse is determined deterministically via a pushover analysis, and then treating this overall collapse strength as a random variable.

For (b), joint fatigue failure is registered as complete fracture or major loss of stiffness. A simplification is used to eliminate the need to re-run the (expensive) spectral analysis. Instead, the original spectral solution is exploited on the basis of stresses determined statically for the damaged versus the intact structure. Joint failures are highly uncorrelated so a large number of sequences contribute significantly to system failure.

For (c) conditional probabilities are used based on the result of (a) and (b) to determine overall failure probabilities in near extreme storm conditions, given fatigue failure occurs first.

Total system reliability is the union of all failure sequences. The above are exploited to assist in inspection planning for which the main components are: ranking of joints, target reliabilities, inspection schedule, and reliability updating.

It is applied to a relatively shallow water North Sea jacket. Overall collapse dominates the assessment during the early platform years, combined failures contributing in later life. Both MPI and FMD (Flooded Member Detection) are exploited as inspection techniques. It is found that in some cases MPI can be eliminated from the inspection schedule.

Nichols *et al.* (1997) considers how system assessments of jacket structures can assist the engineer to achieve designs that comply with the goal setting safety regime now established by regulation in the UK. It describes the (blind) benchmarking of software against 2D frame test data. The lessons learnt from this were salutary involving weaknesses of both software and users. This led to the oil industry preparing a guide on the execution of ultimate strength analyses.

In exploiting ultimate strength through pushover analysis, the need to check for excessive deflections that might impinge on the safety of operations is noted. Notwithstanding, the benefits gained from rationalising inspection strategies in the light of such analyses are to be noted.

The basic goal setting requirements in the UK regulatory regime are summarised as: a demonstration of safety against identified hazards, a demonstration of control of natural hazards, an assessment of accidental hazards, identification and independent verification of safety critical elements, and setting of performance standards. The last of these is noted to present the biggest challenge to the industry that is used to exploiting prescriptive requirements which have implicit default performance standards.

Health & Safety Executive (1998) reports on a (limited) quantification of changes in design philosophy for North Sea jackets over a 20 year period (1975 and 1996). Overall loading as determined by base shear is found to be similar, the larger wave heights and smaller drag coefficients of early designs being replaced by smaller wave heights, higher drag coefficients and consideration of marine growth. Current structural configurations are heavily influenced by lifting as a means of installation. Somewhat surprisingly, the joints of the older platform are stronger than those of the present generation although it appears to be a reflection of the 'now passed' practice of ensuring joints were stronger than intersecting members. The pushover strength of the newer platform was less than that of the older structure. However, overall reliabilities were reversed because the later platform had a larger air gap, the older platform suffering deck inundation under 5000 year return period storms.

Some comments in relation to the modelling for ultimate strength analysis suggest that there are advantages in using analysis programs that already contain the effects of construction effects such as initial out-of-straightness and welding residual stresses. Leaving the designer-analyst to determine the relevant input values clearly causes problems in the interpretation of results.

A reliability-based design approach is proposed by Manual *et al.* (1998). It begins with a target failure probability and then determines an ultimate load event (here wave height) at which collapse is initially estimated. Allowing for reserves of strength beyond the usual design checks, for example, to API (1993), a design-level wave height can be derived. Based on this, the structure is sized in the conventional way. The pushover strength is determined next and used to establish the structure's reliability. The latter is compared with the target and the cycle revisited as necessary.

The procedure is illustrated with a North Sea jacket. A target annual failure probability is proposed of 0.0005 based on the apparent typical reliability of new designs to API (1993) guidelines. Using a simple relationship between platform capacity and wave height and allowing for the asociated uncertainties (in wave height, loading modelling, overall strength modelling) leads to the selection of an ultimate wave return period of 72890 years. This is acknowledged to be large but the structure apparently still escapes deck inundation. A reserve strength ratio (RSR) of 2.25 is very simply derived from which the design wave height is extracted (here 22.7 m for an ultimate wave height of 34.1 m). Although some of the modelling adopted in the paper is simplistic, it can be extended to deal with a variety of load sources (earthquakes, ice, etc.) provided the relevant relationships between strength and loading can be established. If these prove to be complex, then the general applicability of the approach may be limited to research environments.

The theoretical background for the (efficient) collapse analysis of a tubular framed structure is presented by Krenk *et al.* (1999). It is based on a FEA formulation for describing exact beam-column response between nodes at which plastic hinges might develop. A co-rotating element approach is used so that finite rotations can be considered. An allowance for prescribed initial beam-column lack of straightness is made and shear flexibility explicitly accounted for. The plastic hinge formulation accounts for the finite length of a hinge. A simple kinematic hardening rule is used allowing for representation of the Bauschinger effect during cyclic loading. A detailed discussion is presented on the procedure adopted for correcting plastic hinge stress states to the yield surface. This seems to be achieved in a few iterations. Two example solutions are presented. The first relates to the simulation of a 2D frame test. Reasonably good correlation is apparently achieved after the inability of the program to account for constructional residual stresses is recognised. The second relates to a small jacket subjected to ship impact. Sixteen hinges had formed when the analysis was stopped at a maximum displacement of 1.0 m, 129 increments of 1 to 2 iterations being required in the process.

Frieze and Morandi (1997) reported some of the findings of a comparative jacket versus jack-up reliability study. This particular study is concerned with tubular member component strength formulations (as proposed for the new ISO fixed steel structures standard) and their statistical descriptions determined from screened test data bases. The reference describes the basis of the pushover analyses adopted (Marshall Strut and beam-columns with hinges) and its relative performance in one of the benchmarking studies described by Nichols *et al.* (1997). The presented results indicate just how large the differences can be between different pushover analysis software packages even in the elastic range.

In a companion paper, Morandi *et al.* (1997), the emphasis is on loading and its Type I (aleatory) and Type II (epistemic) uncertainties. These are discussed in the context of environmental wave load recipes as reflected in the latest guidance for jackets API (1993) and for jack-ups SNAME (1994). Comparative utilisation and reliability results are presented for the jacket and jack-up at both component and system levels. An order of magnitude difference is found between component and system reliability levels. Sensitivity factors are discussed: they are dominated by wave plus current loads and resistances. Modelling of the jack-up leg-hull interaction had an important impact on component behaviour but little on overall response. The presented results are incomplete because the study had not, as yet, considered foundation failure and the corresponding reliability.

In a further related paper, Morandi *et al.* (1999), the emphasis is on jack-up modelling and the basis of the comparison. The basic ‘design’ requirements differ in that the jacket is sized for a 100-year extreme wave and associated wind, current and water level based on joint probabilities derived from response-based considerations whilst the jack-up sizes are determined on the basis of 50-year extreme wave, current and wind values. Jack-up dynamics are treated using the quasi-static inertial load approach. The unusual shape of the jack-up leg chord required the special determination of a corresponding P-Mx-My plastic failure surface.

11.2 Ship Structures

Damonte and Figari (1996) report on a hull ultimate bending moment formulation and comparisons with numerical and experimental results. It exploits an ultimate strength module of a commercially available ship design and optimisation program. The ultimate strength module is based on simplified beam-column formulae and widely-used assumptions concerning failure modes of typical ship structures, e.g., frames support panels so transverse collapse is excluded, longitudinal collapse occurs between adjacent frames, etc.

The modelled structure relates to a 1/3 scale version of the mid-body of a UK Leander Class frigate, as built and tested at DERA Dunfermline. Although the experimental model initially demonstrated orthotropic response, it eventually failed by interframe buckling. The ultimate strength only replicates the latter. Notwithstanding, response in the linear was well predicted but not as panel failures commenced. The beam-column unloading model was apparently unnecessarily steep inhibiting redistribution capabilities. Further, neither initial imperfections nor welding residual stresses are accounted for. A sensitivity analysis of the factors affecting ultimate moment capacity found plate thickness to dominate, followed by yield stress, and elastic modulus. The lack of importance of E was noted because the buckling is elastic-plastic in nature and not purely elastic as one may think.

Damonte *et al.* (1997) present an integrated approach to the design of naval vessels. It exploits, to a large extent, existing software packages, including that discussed in connection with Damonte and Figari (1996). The transfer of the hydrodynamic loading represents the biggest challenge in this overall process: this is discussed. Also, the interpretation of the hydrodynamic loading results in terms of an "equivalent design wave" is discussed in the light of the long calibrated use of the design wave approach in ship design.

Dow (1997) presents summaries of the intact and damaged strengths of typical stiffened steel hull components, i.e., plates and stiffened panels. Compressive strength is considered as well as that under combined load conditions, including lateral pressure. Hull ultimate bending strength, particularly when analysed from the viewpoint of being composed of plate and stiffened plate components of known longitudinal behaviour, is briefly discussed. How this is exploited under biaxial bending, under torsion and in the presence of pressure, is also described.

The results of a series of calculations of hull ultimate bending strength accounting for hard corners, mixed framing and damage are summarised. From these, recommendations are made for ship design regarding plating and stiffened panel slendernesses in order to realise cross-sections with suitable levels of redundancy. The weaknesses of transversely framed vessels are highlighted but they are noted to benefit from hard corners as, of course, do longitudinally framed ships.

McVee and Cross (1997) report on an approach for assessing weapon damaged hull strength. It exploits some of the early work described in Dow (1997) and uses a random approach for identifying damage locations and extents. Both above and underwater damage are considered and approximately linear relationships between hull vertical bending strength and area of damaged plate are determined. Similar relationships exist between residual strength safety factors and area of damage.

Wirsching *et al.* (1997) examine the effect of corrosion on ship hull reliability using a simplified hull strength model. A time dependent approach is used.

An example is presented to demonstrate the application of the theory. In addition to the examination of differing corrosion rates, the effects on reliability of using a range of design allowable stresses, different inspection intervals, and varying degrees of correlation between corrosion rates of neighbouring elements are also usefully considered.

Lambiase *et al.* (1997) describe in considerable detail the derivation of a methodology for estimating hull ductile collapse strength. They exploit analytical solutions for plate and stiffened panel compressive and tensile strength accounting explicitly for the proportional limit in material response, shear lag, plate buckling, welding residual stresses, initial distortions, and differing yield stresses in plating and stiffeners. Plastic hinge formulations are developed that account for the effects of axial loading for both simply supported and clamped beams. Load shortening equations are derived covering elastic, plateau and unloading regimes. Cross checks are conducted with a number of available results with mixed success. The methodology for determining hull longitudinal strength is then described. Comparisons are presented with the results of other methodologies and very limited number of full-scale and model test failure data. A significant proportion of the analyses find that vessels fail in sagging at load levels below their first yield moment. Typically both stiffness and strength are over-predicted compared with other findings. The emphasis on comparing with other prediction methodologies rather than with experimental results is disappointing.

Paik and Thayamballi (1998) discuss the strength of corrugated bulkheads and the longitudinal strength reliability of corroded bulk carriers including a survey of eight bulk carriers. The survey covered primary longitudinal and transverse members and corrugated bulkheads. Plate and bulkhead characteristics are tabulated and rigidities discussed in respect of restraining adjacent elements from buckling.

The corrugated bulkhead topics covered are tests under lateral pressure, axial compression, and combined compression and pressure, and analytical/numerical strength determinations. The models contained five corrugations, were made of three thicknesses and had two corrugation angles. The two thinner models demonstrated surprisingly low yield stresses and elastic moduli. Not surprisingly, corrugation angle has a major impact on pressure capacity (starting with the same overall material width). The interaction between compressive and pressure capacity is demonstrated (by one set of tests) to be approximately linear. The tests apparently confirmed earlier experimental observations that one corrugation typically behaves as its neighbours and thus can form the basis of design and/or analysis of such bulkheads.

For design of corrugated bulkheads, the rotational stiffnesses of typical adjoining upper and lower components are defined. The moment capacity of a corrugation is given defined by buckling strengths of the compression flange and compressed web and yielding of the tension flange and tensed web. Reasonable correlation with the test results is demonstrated although the buckling strengths are not given in detail. Numerical results are presented based on the use of a special-purpose FEA package which includes a check on possible ductile failure of the material. The importance of simulating the stiffnesses of supporting structure correctly was demonstrated. Of note was that the light adjacent structure can apparently contribute to premature failure.

Corrosion models are developed for transverse bulkheads and longitudinal strength members based in part on existing information and in part on full-scale surveys by the authors. The information is used to determine the longitudinal bending strengths of typical tanker and bulk carrier vessels taking account of possible coating breakdown. This is fed into a reliability model and the findings discussed although not presented in detail.

Boote *et al.* (1999) present the results of ultimate strength evaluations of the longitudinal and transverse strength of twin hull vessels. One set of results is obtained from a conventional non-linear FEA whilst the other is determined using a computerised design software package. The latter gives reasonable estimates of FEA strength for longitudinal loading but not for transverse loading. The differences are attributed to the inability to deal with non-linear strain distributions and the method by which loading is applied.

Ohtsubo (1999) describes the results of a casualty investigation into the loss of a tanker in the Sea of Japan. The vessel broke in two during a storm, the aft section sinking after 5 hours whilst the fore section drifted ashore. Considerable oil was spilt. The sunken section was remotely photographed and the fore section subject to forensic tests. The vessel was seriously corroded at the time including the separation of deck longitudinals. Detailed analysis found: large sagging moments from excess oil cargo, large wave-induced moments, reduced longitudinal strength due to the corrosion, incomplete welding to bottom longitudinals resulting in their fracture, then separation from bottom plating precipitating fracture of the plating close to a transverse bulkhead.

12 STRUCTURAL RESPONSE TO ACCIDENTAL LOADS

Recent years have revealed an ever increasing focus on analysis methods and design procedures for accidental loads, in particular ship-to-ship collision and ship grounding events. The nature of these accidents poses two fundamental challenges to the community. The first challenge is to understand the relevant scenarios with the large inherent degree of uncertainty that characterizes these accidents.

The second challenge is to calculate the structural damages and the consequences following this damage.

To illustrate the complexity of the structural response, Figure 7 shows a model of a double-side or a double-bottom penetrated by a rigid indentor. The mechanics includes large deflections and rotations, fracture, friction, and large plastic deformations.

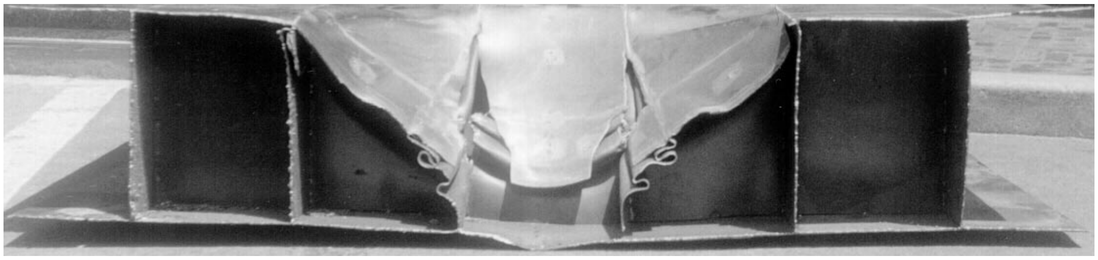


Figure 7: Crushing and fracture damage of plated structures, Paik *et al.* (1999e).

This chapter is divided into two parts. The first part reviews work with development and validation of analysis methods. The second part is mainly concerned with works that apply the analysis methods to design ship structures for collision and grounding loads.

12.1 Development of Analysis Methods

The complexity of the structural mechanics requires experiments, both for development and validation of theories. Several institutions are performing collision and grounding tests both at small and large scale.

Rodd (1996a, b) describes a large-scale grounding test machine and test results. The test set-up is capable of measuring the ground reaction force during ship grounding on a pinnacle (conical) rock. Horizontal and vertical reaction forces are presented for four tests with various double bottom structures (double bottom height is 0.4 m and plate thickness is 3 mm). A possible weakness of this arrangement is that the rock encounters the outer bottom at a position at which no longitudinal continuity exists. This may inhibit the development of membrane stresses that would exist in a real grounding condition.

Lemmen *et al.* (1996) describe the set-up of a series of another six large-scale grounding tests. However, the paper does not describe the details of the specimens or the results. The Technical University of Hamburg Harburg, Germany and TNO, Netherlands performed grounding tests with a model of the structure of the European E-3 tanker-project in scale 1:3 (double bottom height is 1m, shell plate thickness is 5 mm). The tests are described by Peschman and Kulzep (1996), Kulzep and Peschmann (1998) and Lehmann, Peschmann and Kulzep (1997). Peschmann and Kulzep (1999) and Kulzep and Peschmann (1999) also describe a collision experiment conducted by German, Dutch and Japanese partners. The experiment was carried out with two converted inland waterway tankers. The struck ship side structure was a 1:3 model of 40.000 tdw tanker (double side depth is 0.7m and shell plate thickness is 5mm).

The mechanics of bottom raking damage due to ship grounding has been subject to extensive theoretical studies in the period. Wang *et al.* (1997) present a simplified method for assessment of grounding bottom damage. This method is based on a set of simple formulas for the resistance of shell plating and transverse members. Comparison with two large-scale tests showed good agreement.
The research team at MIT led by Professor T. Wierzbicki has been working with collision and

grounding damage since 1990. In addition to more than 70 reports the research has resulted in the computer program DAMAGE, which may be used to calculate the damage of a ship-to-ship collision or a grounding event. Bracco and Wierzbicki (1997) study the cutting of an advanced double hull. Experimental results are presented and closed-form solutions derived, taking into account plasticity, fracture and friction. Simonsen and Wierzbicki (1996) present a model that takes into account the coupling between the global ship motions and the internal damage process at a detailed level. The procedure is further developed by Simonsen (1997a, b, c). The model takes into account the effect of all structural members in a conventional ship bottom, i.e., shell plating, longitudinals, transverse web frames, solid floors, girders, bulkheads etc. and was validated by use of seven large-scale tests.

A number of Ph.D. studies on ship collisions and grounding have been undertaken worldwide. Wang (1995) presents a simplified theoretical approach for predicting the damage of vessels in a head-on collision or in a bottom raking scenario. Yu (1996) makes several contributions to the understanding of ductile instabilities and fracture involved in collision and grounding events. Lee (1997) develops a theoretical formulation for estimating the damage of tanker structures in grounding with a forward speed or in stranding at standstill. The method is formulated in closed form, and takes into account the vertical crushing caused by ship rigid body motions as well as horizontal raking (i.e., cutting) caused by the forward movement of vessel. Simonsen (1997a) develops mathematical models for predicting the loads and hull girder response of vessels in grounding on a soft seabed or on a rock pinnacle. The models take into account the global ship motion as well as deformations of the sea bed and the ship bottom. Chung (1996) develops a theoretical procedure for analysing the damage and crushing strength of ship's bow in a head-on collision. A series of crushing tests under quasi-static and dynamic loading were carried out on thin-walled square tubes with axial and/or circumferential stiffeners, and also on an un-stiffened specimen. Zhang (1999) presents a comprehensive set of simplified formulations for the analysis of structural damage in ship collisions and grounding.

Based on a large number of experiments, Pedersen and Zhang (1999a) develop three simple expressions that relate the energy absorption capability of a structure in collision and grounding to the volume of the deformed material, a few material parameters and a few parameters related to the overall geometry of the structure. Comparison with several experiments shows good agreement. By use of simplified crushing models, Pedersen and Zhang (1999b) investigate how the collision and grounding damage is dependent on ship structure and vessel size. One of the conclusions is that ship collision side damage is quite insensitive to the ship size, whereas bottom raking damage increases with vessel size, given similar impact conditions for small and large vessels.

Simonsen and Ocakli (1999) investigate the mechanics of deep plastic collapse of a girder or a deck subjected to a localised load, for example in a collision event. Based on experiments they developed an idealised mode of deformation and derived an analytical expression for the energy absorption during collapse. Comparison with small-scale experiments shows very good agreement.

The dynamics of a collision or grounding event may be important under special circumstances. Three aspects of dynamic loading are relevant, namely material strain rate sensitivity, inertia effects and dynamic frictional effects, Paik and Chung (1999). To estimate the dynamic yield strength of the material as a function of the strain rate, the Cowper-Symonds equation has been widely used. It has been observed that the Cowper-Symonds coefficients for mild steel under dynamic loading are different from those for high-tensile steel materials (Paik *et al.* 1999e), as shown in Figure 8. The crushing effects and yield strength increase as the loading speed gets faster, while any fracture or tearing of steel occurs earlier. To estimate the critical fracture strain as a function of the strain rate, the approximate formula is widely used, which is the inverse of the Cowper-Symonds equation. However, it is seen that the coefficients used in the equation of the dynamic fracture strain differ from those of the dynamic yield stress (Paik *et al.* 1999e), as shown in Figure 9.

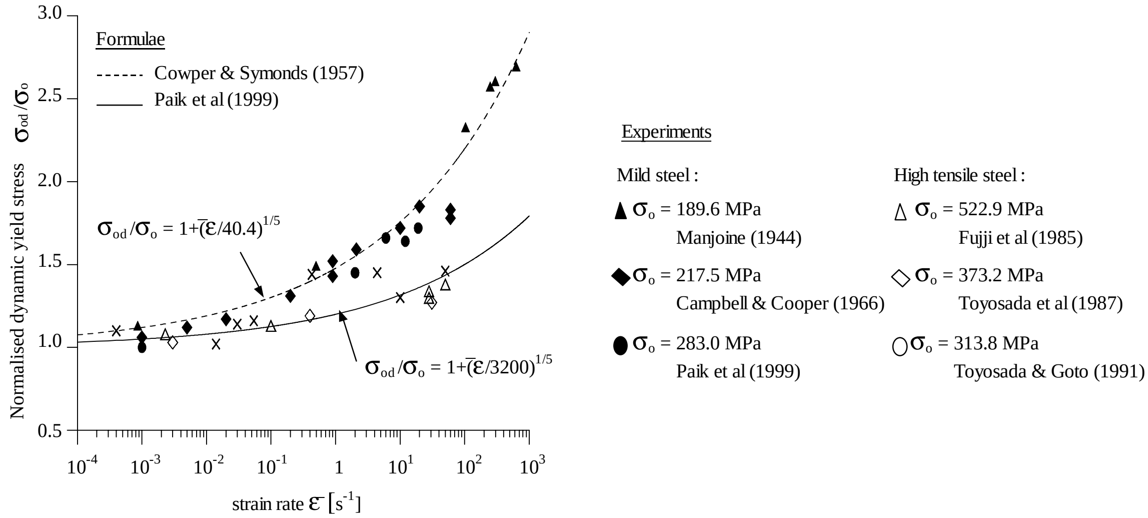


Figure 8: Strain-rate sensitivity of mild and high tensile steels, Paik *et al.* (1999e).

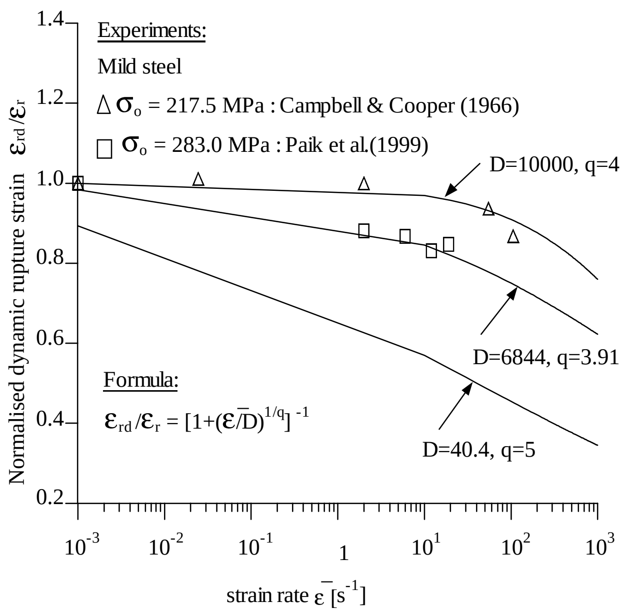


Figure 9: Fracture strain sensitivity to strain-rate for mild steels, Paik *et al.* (1999e).

Lützen *et al.* (2000) investigate the mechanics of ship-to-ship collision with particular focus on the interaction between bow deformation and ship side deformation. In many studies it has been assumed for convenience that the bow is rigid. It is shown however, that the rigid-bow assumption is only valid under certain restrictions of ship size and stiffening configuration. Lehman and Yu (1996) investigate the detailed mechanics of plastic hinges and derived closed form expressions for the amplification of energy absorption due to strain rate effects. Ohtsubo and Wang (1996) present a set of simple analytical formulas for the crushing and tearing resistance of various structural members. By comparisons with various experiments they show that the simplified formulations can be used to obtain the crushing response of assembled, complex structures. Wang *et al.* (1998) considered the mechanics of indentation of a sphere into a circular plate. Simple formulas for the plastic resistance are derived and it is shown that the plastic resistance is a strong function of the radius of the sphere.

Paik *et al.* (1996) considered the residual strength of ship hull girders damaged in either a collision or grounding scenario. It is argued that the methodology is useful to assist decision support following a collision or grounding accident. The paper presents theories for the external dynamics as well as for the internal mechanics, and parametric and sensitivity studies on collision resistance of a double hull VLCC side structure using ALPS/SCOL program, which is based on the idealized structural unit method. Parts of the theory are validated against experiments and a modified Minorsky formula is derived based on a large parametric study.

Paik *et al.* (1999e) reported the summary of six double skinned structural model tests to investigate structural crashworthiness for the case where a rigid indenter like a bow structure penetrated the models. The tests were conducted varying plate thickness and initial contact point. They tried to estimate the absorbed energy from penertared volumes of the indenter not crushed volumes of damaged structures.

Zhu and Faulkner (1996) study the mechanics of repeated impact by a rigid wedge on a clamped plate. The phenomenon could for instance model repeated impact of a supply vessel on an offshore platform. The paper extends existing analytical solutions for lateral impact on plates to cover repeated impacts. Experiments are performed and there is shown to be good correlation between the predicted and measured deformations as a function of the number of impacts. The simple models presented in the paper illustrate well the mechanics of the worst-case scenario, where the colliding objects strikes at exactly the same position at each impact. The authors noted that for a more realistic analysis, the study should be extended to cover different impact positions.

Ammerman and Daidola (1996) compare collision damage predictions of a FEA, the Minorsky method and other simplified methods. Rather large discrepancies are found between the predictions and various difficulties and sources of error in theoretical modelling of ship-to-ship collision events are discussed.

Little *et al.* (1996) present some of the underlying ideas of the computer program DAMAGE, which was developed at MIT under the Joint MIT-Industry Program on Tanker Safety. DAMAGE can be used for rapid assessment of structural damage due to grounding and collision. The program is based on summing up contributions from super-crush-elements. Since the super-element solutions are in closed form, the calculation time is very small compared to FEA. The theory and validation for the collision calculation module is described by Simonsen (1999b).

Schleyer and Campbell (1996) discuss the structural response to blast and fire loading. A series of blast and fire experiments was performed and analytical theories were developed. Comparison between experiments and theories showed good agreement.

Cho *et al.* (1997) conducted small scale impact tests on 96 plates and 12 stiffened panels varying the collision velocities and striking masses and gave a simple analytical expression for predicting the depth of dent of the plate due to collision.

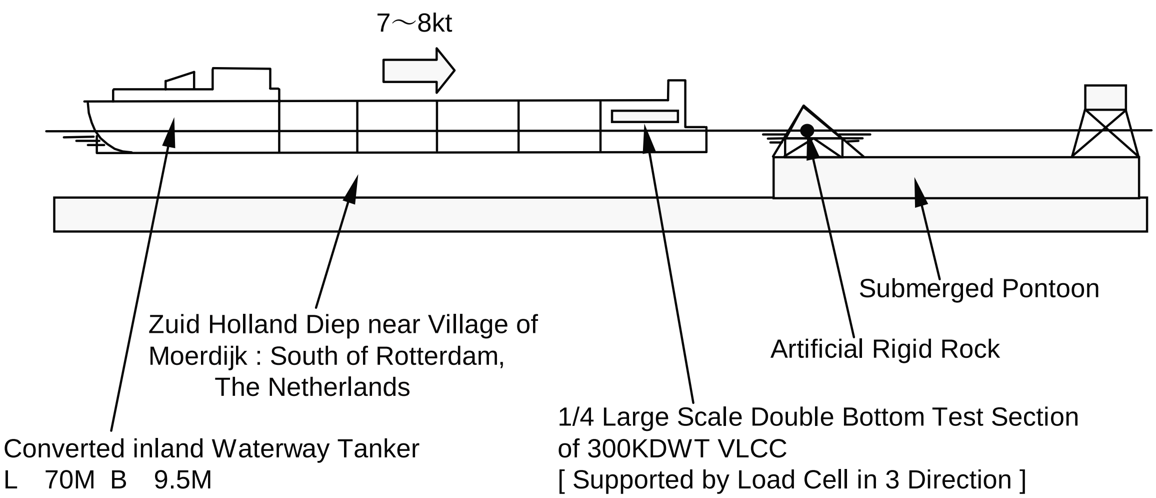
Simonsen and Ocakli (1999) performed a series of small scale static crush tests relating to the decks, stringer decks and deep longitudinals in the side structures of a double-hull tanker in the event of a side collision. They discussed the effects of eccentricity of a striking load, local and boundary conditions at transverse frames. Finally, practical expressions were derived to predict the load-penetration relationship in plastic collapse.

Wang and Ohtsubo (1997) and Simonsen and Wierzbicki (1997) proposed, based on existing experimental data and plastic theory, equations for predicting the resistance capacities of side plates subjected to lateral load, deck plates subjected to in-plane load, and bottom plates against raking. Paik and Wierzbicki (1997) conducted a benchmark study on several formula for predicting the crushing strength and cutting resistance of plate structures during collisions or grounding.

12.2 *Application of Analysis Methods for Design*

Several research programmes for determining the resistance capability against marine accidents have been conducted in different countries for the last decade reflecting the increased focus on risk due to serious accidents like: flooding and sinking of Derbyshire in 1980, grounding and oil spilling of Exxon Valdez in 1989, collision and fire of Maersk Navigator in 1993, flooding and sinking of Estonia in 1995, corrosion and breaking of Nakhodka in 1997 and corrosion and breaking of Erika in 1999.

In late 1994 to early 1995, a series of large scale grounding tests of 1/4 scale double hull bottom structures of a VLCC were carried out as a joint research program between Japan and the Netherlands. These experiments were conducted fitting a model in the bow structure of an inland waterway tanker to obtain simultaneously the experimental data on reaction forces, structural failure and ship motions, see Figure 10. Kitamura and Kuroiwa (1996) reported the results of the large scale grounding tests comparing with numerical simulations using LS-DYNA3D and MCOL. The paper illustrates the tremendous calculation effort required in this type of analysis: the simulation of 15 seconds of the ship grounding event required 450 hours of CPU time on a fast workstation computer.



Neogi and Tessier (1997) conducted a grounding test with syntactic foam using the same model as a conventional structure model in the previous tests and demonstrated improvement of the energy absorption capacity by a novel composite material.

Figure 10: Overview of large-scale grounding experiments, Kitamura and Kuroiwa (1996).

A series of large scale collision tests of improved double-skinned side structures was conducted as a joint research programme between Japan, the Netherlands and Germany during the years 1997 and 1998. The side structure models were fitted to the recessed side of a target waterway ship. Then, a colliding ship with a rigid bulbous bow of 1 m in depth rammed into the models with a velocity of approximately 9 knots.

Kitamura (1996) presents a comprehensive comparative study of the collision resistance of seven different side structures for a VLCC. The seven different side structures are considered to be penetrated by the same rigid bow. LS-DYNA3D is used for the analysis, however in a customized version that may take into account the rigid body motions of the ships, the failure of fillet and butt welds, and ductile failure of the steel plating. The seven analysed structures differ in material as well as in structural layout. Table 6 shows the calculated crashworthiness index based on strain energy in the side structure to the point of fracture initiation of the inner shell, i.e. up to the point where the last cargo tank barrier is opened.

TABLE 6

CRASHWORTHINESS INDEX FOR VARIOUS SIDE STRUCTURES, KITAMURA (1996).

Type of side structure	Crashworthiness Index
1. Standard VLCC with double side	100
2. Increased material strength, same material ductility	124
3. Additional three stringers arranged in the double side	108
4. Additional top tank as in an OBO carrier	123
5. Strut in side cargo tank	99
6. Unidirectional girder stiffening system	125
7. Sandwich panels for both shell and inner side plating	176

It is seen that the energy absorption can be increased by up to 76 % by using a different structure. However, the steel weight of this particular design was increased by 22 % compared to the standard design so – as also for the other alternatives - the benefit compared to the cost is quite limited. A general conclusion of the study is that the effect of design alterations on the energy absorption capability is quite limited.

Kitamura *et al.* (1998) presented the results of an improved Japanese model using a frame panel made of a newly developed steel as compared to a conventional double hull model. In *Schiff und Hafen* (1998) the test on an improved Dutch model having a double hull filled with plastic foam is reported. Japanese and Dutch models were produced at full scale to investigate the local strength behavior of improved double skinned side structures. The tests showed that the modifications improved the energy absorption capacity. In the German tests, reduced scale models of conventional structures were used to study the entire structural strength behavior of existing double hull structures, Lehmann (1999).

Rodd (1997) describes the interpretation of large-scale (1/5) model grounding tests performed by NSWCCD on a range of vessels. These included variants of the Advanced (Unidirectional) Double Hull (ADH) design, and conventionally framed designs of the US Navy T-5 Tanker and the MARAD PD328. The focus of the experiments was the determination of structural failure mechanisms and comparisons of energy dissipation.

Differences in layout between the considered ADH variants and conventional hull are described. Their general performance during grounding is discussed. For double bottoms of, say, 2 m, penetration of at least 2 m is necessary before tank rupture and therefore oil spillage occurs. Beyond this penetration, membrane stresses develop in the inner bottom. These can grow significantly without rupture (1 m is discussed in the paper) but, on the encounter with a full depth continuous transverse member, inner bottom rupture occurs.

The weld connecting this transverse member and the inner bottom is described as the “Achilles Heel” during oil tanker groundings. This is a consequence of the fracture induced in the frame from tearing/splitting of the outer bottom. The fracture in the frame spreads rapidly to the inner bottom because of the large membrane stresses present. In doing so, three rupture initiation modes are noted: these are described in detail.

Actual collision and grounding accidents of crude oil tankers were simulated using a customized explicit FEA by Kuroiwa and Kusuba (1997) and Kuroiwa (1996). One was an collision accident between a 100 kDWT oil tanker and a 1446 TEU container ship at Malacca Straight in 1992. Another was a grounding accident of a 240 kDWT oil tanker. They investigated the effects of friction to rocks and strength of fillet welds on structural failure and energy absorption capacity. According to these investigations, the strength of fillet welds between bottom plates and longitudinal stiffeners was important to estimate the crashworthiness of actual ships. Especially, scaling of fillet welds is essential in case of scale model tests.

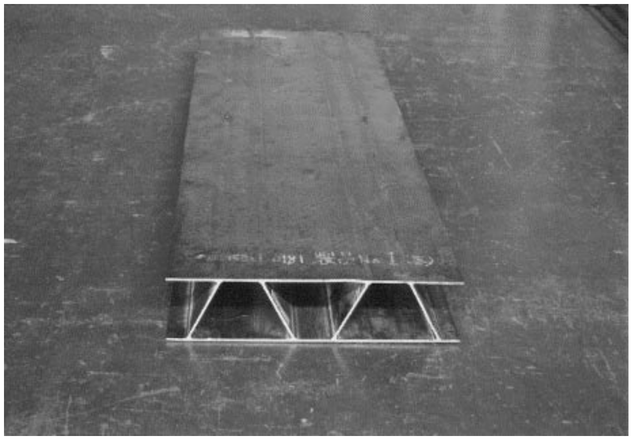


Figure 11: View of panel model, Kitamura (1997)

As for improvement in crashworthiness of double hull oil tankers against collision, a comparative study was performed involving conventional and improved double hull side structures in Kitamura (1997) and Kitamura *et al.* (1998). They proposed a new design concept in which the frame panels shown in Figure 11 were adopted instead of conventional stiffened panels in side structure and a ballast tank was installed at top of a side double hull space. The new side structure increased the allowable collision speed by approximately 50 % compared with standard double hull structures as shown in Table 7.

Samuelides (1996) presents an analysis of oil outflow following collision damage to tankers. Based on 176 collision accidents that occurred in the first semester of 1995, he derives a probability density function for the impact kinetic energy. Then, using a simple model for prediction of the collision damage and oil outflow following damage, he derives probability density functions for the oil outflow of a ‘basis’ tanker and of a tanker with an extra stringer deck. Although some of the intermediate assumptions are rather simplistic, the methodology illustrates the necessary steps in rational, probabilistic design against collision accidents.

Professor Brown and co-workers, Crake and Brown (1998) and Rawson and Brown (1998), used the DAMAGE program and Monte Carlo simulation of the most uncertain input parameter to derive statistical distributions of collision and grounding damage. The basic idea is to determine the set of probability distributions for the input parameters that produced observed damage distributions. This ‘inverse’ method for determining impact scenarios is appealing and a step forward towards performance based design criteria. In study by Simonsen and Hansen (1999) it was also attempted to determine relevant grounding scenarios from statistical data. Furthermore, a theoretical damage model is presented and it is shown that certain statistical trends for the damage can be predicted theoretically.

Sano *et al.* (1996) use LS-DYNA3D to investigate how the structural resistance to collision loading can be improved by a ‘soft’ connection between longitudinals and web frames. By using a so-called apple-slot instead of the conventional connection with a rigid stiffener between the frame and the longitudinal, the energy absorption up to fracture of the inner shell is found to increase by 16 %. At the same time the fatigue strength of the structure is increased and the number of hull components is reduced. Although the study indicates an increase of energy of only 16 % the basic idea of improving the design of critical areas is promising and further development could lead to significant improvements.

TABLE 7

ALLOWABLE MAXIMUM COLLISION SPEED (KNOTS), KITAMURA *ET AL.* (1998).

Double Hull VLCC	Handy		SuezMax		VLCC	
	Ballast	Laden	Ballast	Laden	Ballast	Laden
Δ+A.W.M.	31130	55330	75000	173000	155100	379500
Colliding ship with standard bow						
Standard	6.2-7.1	6.7-7.7	4.8-5.7	4.9-5.8	4.3-4.7	4.5-4.9
New Type	9.2-10.5 ↑	12 ↑	7.1-8.4 ↑	12 ↑	6.3-6.9 ↑	12 ↑
Colliding ship with crushable bow						
Standard	9.5	10.5	7.7	7.9	6.3	6.8

Note: Struck Ship in Laden Condition (Δ +A.W.M. = 345000+91000 = 436000 ton)

Pinkster *et al.* (2000) study the possibility of increasing the crashworthiness of ships of 80 – 100 m length by strengthening the ship sides. This is of particular interest for this class of vessels because the existing fleet cannot comply with new IMO regulations. Vredeveldt *et al.* (2000) study the effect of foam filled spaces on the energy absorption and survivability of RoRo ships exposed to collision loads.

High Speed Craft (HSC) are rapidly gaining popularity. Compared to conventional ships, the HSC travel faster, they are lighter and they are typically built of welded high strength aluminium, which exhibits a rather brittle behaviour. Therefore, the collision and grounding damage to HSC must be expected to be quite different from that to conventional ships. Daidola and Pet (1996) compare three relatively simple methods for calculating the bow crushing loads on High Speed Craft. This is of relevance because the High Speed Code of IMO allows alternative methods of bow crushing analysis. The methods considered in the paper are: the method prescribed in the High Speed Code, a modified Minorsky method and a method based on quasi-static crushing longitudinal plate intersections. The conclusion is that there may be up to 100 % difference between the accelerations and crush zone lengths predicted by the three methods. Simonsen (1999a) investigates the mechanics of grounding of HSC. Based on the idea that conventional ships and HSC meet the same types of ground and on a theoretical grounding damage model, the damage of the conventional ships has been scaled to apply to HSC. The paper shows that there is a significant risk of full-length bottom damage to HSC in the case of a grounding accident. Furthermore it is shown that large vessels are more likely to experience full-length damage than small vessels.

Reardon and Sprung (1996) analysed sixteen collision accidents and found that the formula for the internal energy absorption proposed by the Minorsky method correlated well with the new data points. Maestro and Marino (1996) investigate an actual collision accident and derived a modified Minorsky method based on the observed damage.

Brown and Amrozowicz (1996) presented a risk model for tanker oil spills. The paper demonstrates how the prediction of structural damage due to grounding and collision is an important but limited part of a total risk assessment procedure for ship transportation. Pippenger *et al.* (1996) discuss possible development towards more performance based regulations, i.e. regulations taking into account the crashworthiness of the structure.

13 NON-FERROUS STRUCTURES

13.1 General

For design and construction of weight critical vehicles such as fast ferries, structural weight saving is one of the major considerations. The use of aluminum alloys and composites would be effective in meeting this requirement. Extensive considerations for practical marine application of such non-ferrous materials have been made in the reports of the previous ISSC committees V.8 on "Composite Structures" (Chalmers *et al.* 1988, Gullberg *et al.* 1991) and on "Weight Critical Structures" (Lu *et al.* 1994). The report of the ISSC'97 committee III.1 on "Ultimate Strength", Jensen *et al.* (1997), describes some potential failure modes for composite structures. The fundamentals and practices for design of non-ferrous structures are also described in the handbooks or textbooks (Plantema 1966, Allen 1969, Zenkert 1995, Zenkert 1997, Vinson 1999).

In the shipbuilding industry, aluminum alloys and composite materials have primarily been used either for small size vessel hull structures or for non-strength part of structures, even if they have many advantages, including high ratio of strength to weight. One of the reasons why these materials have been restrictively applied to the marine industry is that their specific stiffness is low. To overcome this disadvantage, sandwich construction is frequently adopted instead of increasing material thickness. This type of construction consists of thin two facing layers separated by a core material. Potential materials for sandwich facings can be aluminum alloys and composites. Several types of core shapes (e.g. honeycomb) and core material have been applied to the construction of sandwich structures. A sandwich construction may provide excellent structural efficiency, i.e., with high ratio of strength to weight. Other advantages offered by sandwich construction are elimination of welding, high insulating qualities and design versatility.

The characteristics of several hull materials for larger high speed vessels have been surveyed by many investigators, e.g., Paik and Lee (1995). Their results showed that aluminum alloys, high tensile steels and composites would be the promising candidate materials for such applications. Table 8 represents comparative physical and mechanical properties of the three materials. For composite materials, there can be significant differences in physical properties on the type, direction, and orientation of the fibres and matrices. For convenience, therefore, polyester bi-axial fibre glass which is a commonly used material in GRP sandwich construction is chosen as those shown in Table 8. The table indicates that the composite material is excellent from the viewpoint of strength to weight ratio, but the elastic modulus to weight ratio is only 17% of that of the aluminum alloy in the sandwich construction. Hence composite single skin structures can have relatively large deformations when they are applied to the design of larger vessel structures compared with steel and aluminum alloy structures.

To enhance the attractiveness of such non-ferrous materials to the design and fabrication of larger weight critical transportation systems, it is essential to better understand the failure mechanism of individual strength members and global system structures. Figure 12 shows potential failure modes of sandwich panels, Zenkert (1997). This chapter surveys recent research and development on the areas related to the buckling and ultimate strength design technology for composite and aluminum structures including both single skin and sandwich construction.

13.2 Composite Structures

Primary failure modes for composite structures are buckling, local delamination, and fatigue / fracture. Buckling is one of the most important failure modes for composite structures, which have low modulus of elasticity. In the structural design, buckling can in principle be handled by using the FEA, but the three dimensional nature of the composite construction makes the buckling design complicated. Also, there is still a lack of knowledge for the buckling of anisotropic materials. For all kinds of loading on skins and joints between composite materials, local delamination will be one of the severe failure modes since it can result in catastrophic failure for the global system structure. Interlaminar shear strength and through-thickness normal strength must then be carefully designed to prevent composite structures from local delamination. For steel structures, there exists a long history with extensive experience and a vast data base for the fatigue and fracture. For composite materials, however, a similar database is not available and the fatigue strength of composite structures depends on temperature as well as loading cycle due to the visco-elastic characteristics of the material. Since the majority of composite construction is made by hand lay-up, the quality may be variable. Therefore, it would be more difficult to establish the appropriate fatigue strength design procedure for composite structures than steel structures.

TABLE 8
MECHANICAL PROPERTIES OF SELECTED SHIPBUILDING MATERIALS, PAIK AND LEE (1995).

Materials Item	Aluminum5083-O	CompositeWR/bi-ax.	SteelH36
Density (ρ, g/cm^3)	2.70	1.6	7.8
Tensile strength (σ_T, N/mm^2)	275	123	490
Elastic modulus (E, N/mm^2)	70,000	7,000	206,000
Specific tensile strength (σ_T /ρ)	102/102*	77/77*	63
Specific rigidity (EI /ρ)	26/960*	4/162*	26

Notes:

- The values marked by * are for a sandwich beam.
- Sandwich skin thickness is 1/2 that of typical single skin thickness.
- Sandwich core depth is 3 times the typical single skin thickness.
- Sandwich beam width is 12 times the typical single skin thickness.
- Relative weight of sandwich is roughly 1.06 times single skin weight.
- Specific flexural strength data and specific rigidity data are for local panel bending strength and stiffness.

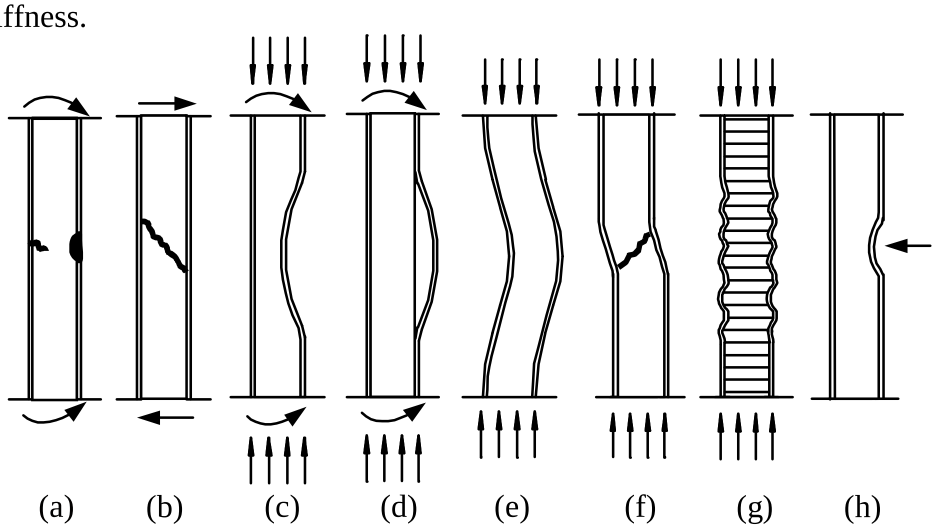


Figure 12: Potential failure modes of sandwich panels, Zenkert (1997).
Face yielding / fracture, (b) core shear failure, (c) (d) face wrinkling, (e) general buckling, (f) shear crimping, (g) face dimpling and (h) local indentation.

Based on relevant buckling strength criteria, Hughes (1997) demonstrated the MAESTRO program to design a large (100m, 1,000 ton) monohull fast ferry structure using all aluminum and then adapting the design to be all composite. He points out that one of the most striking features of composite design is the large number of options and variables, namely single or sandwich, type and sequence of lay-up, materials for the fibres, resins and cores, and types of moulding and other fabrication techniques. All of these involve quite different costs and they produce a variety of structural properties. Clearly, experience is needed in order to make the correct decisions in all of these areas. Another feature of composite structures is that there are three levels of fabrication, and thus fabrication is an integral part of composite design. Moreover, fabrication has such a strong influence on the properties of the finished product that composite design always requires physical testing of sample products.

Weissman-Berman *et al.* (1996) predicted the flexural response of FRP (fibre-reinforced plastic) sandwich plates with a core acting as an elastic foundation using a modified set of Levy's solution applicable to the bending of rectangular plates. The method used was verified by a comparison with skin stresses and center deflections for FRP sandwich plates as obtained by the experiments.

Xuanling *et al.* (1996) applied the Rayleigh-Ritz method to determine the critical temperature at which delamination buckling occurs for a symmetrical composite laminate subjected to a uniform temperature field and containing a single elliptical delamination damage. Temperature-dependent elastic and thermal properties for composite material are considered. The critical temperature values for delamination thermal buckling are investigated for the delamination with different influential parameters including angles between the local axis of elliptical delamination and the global axis of the laminate.

Walker *et al.* (1996) studied the optimal bucking designs of symmetrically laminated rectangular plates under uniaxial compressive loads that have a non-uniform distribution along the plate edges. It is observed that differences in the optimal fibre orientations and buckling loads for the cases with and without Poisson's effect are significant. Also, if the compressive axial loads are non-uniform, a uniform approximation will lead to non-conservative estimates of the buckling load.

Tsouvalis and Papazoglou (1996) developed an effective analytical method for the analysis of non-linear large deflection response of simply supported laminated plates under the action of various types of time dependent lateral loads, based on the classical lamination theory applying the Galerkin approach.

Wang (1997) presents the B-spline Rayleigh-Ritz method for buckling analysis of thin skew fibre-reinforced composite laminates under either biaxial compression or edge shear. Regardless of the types of material anisotropy, the method provides accurate solutions of the buckling load.

Bailey and Wood (1998) studied the influence of cutout shape, size and orientation on the buckling and post-buckling responses of graphite-epoxy panels with cutouts loaded in uniaxial compression numerically and experimentally. It was found that either circular or square cutouts have similar buckling loads and post-buckling responses. Also, the cutouts eccentrically placed along the horizontal axis tend to reduce the buckling strength of the plate slightly, while a cutout eccentrically placed along the vertical axis tends to increase the buckling capacity of the plate.

Wang and Dawe (1999) studied the post-buckling response of rectangular composite laminated plates under in-plane loading. The analysis method used is in the context of classical theory based on the spline finite strip approach by taking into account the through-thickness shear effects. The computational results for relatively thick composite laminated plates showed that the effect of through-thickness shear deformation is significant. As for the ultimate strength during fire, Dao and Asaro (1999) presented a collapse test on a GFRP plate with thermal insulation under combinations of thermal loads and compressive loads to investigate fire degradation.

13.3 *Aluminum Structures*

The SSC report made by Altenburg and Scott (1971) some three decades ago will still be useful for understanding the design technology of aluminum ship hull structures. Table 9 summarizes minimum mechanical properties for typical marine grade aluminum alloys and steels, Violette *et al.* (1998). It is seen that the ultimate tensile strength is much lower for most aluminum alloys than for steels. The modulus of elasticity and rigidity for aluminum alloys are one-third of steel. The yield stress for aluminum alloys may decrease significantly after welding.

TABLE 9

PROPERTIES OF MARINE ALUMINUM ALLOYS AND STEELS [MPa], VIOLETTE *ET AL.* (1998)

	0.2% proof stress Yield stress		Ultimate tensile strength		Plain material fatigue strength at $5*10^7$ cycles
	Unwelded	Welded	Unwelded	Welded	
5083-O	125	125	270	270	
5083-H321	215	140	300	270	
5083-H11	215	125	330		170
5086-O	95	95	240	240	
5086-H112	110	110	240	240	
5086-H321	195	130	270	240	
6061-T6	170	135	230	160	85-90
Mild steel	235		400-490		210-220
AH32	315		440-590		
AH36	355		490-620		
AH40	390		510-650		290 (bending)

Regarding fire accidents to offshore structures, column models made of AA 6082 aluminum alloy were tested under elevated temperature by Langhelle *et al.* (1998). Some of the tests were carried out with constant load and increasing temperature, while other tests involved increased load under constant elevated temperature.

Tanaka and Matsuoka (1996) studied the buckling strength of aluminum (single skin) stiffened panels both experimentally and numerically varying the shapes of section. In addition to the extrusions made of A5083S-H112 alloy and pi-shaped section which have frequently been used for design of aluminum vessel hull structures, buckling and ultimate strength characteristics for extruded hollow sections made of A6N01S-T5 alloy and pre-ribbed panels made of A5083P-321/A5083S-H112 were studied. They showed that the conventional non-linear FEA could be successfully applied to the analysis of buckling and ultimate strength of aluminum stiffened structures. Paik *et al.* (1997b) developed buckling and ultimate strength criteria for aluminum honeycomb sandwich panels and used them to design a larger hypothetical high-speed car ferry hulls.

The load-deformation behaviour and global stability of curved sandwich panels have been studied by Skvortsov and Bozhevolnaya (1997) applying the Reissner plate theory. The obtained results, in the form of compact formulae governing singly curved sandwich panels under lateral loading, allow the prediction of buckling behaviour. Bozhevolnaya and Frostig (1997) have extended the investigation to the non-linear analysis of sandwich curved panels with transversally flexible core, assuming a geometrical non-linearity of the sandwich faces. The influence of local damage such as debonding or delamination is also taken into account. The results of the experimental and theoretical investigations on the non-linear analysis of the curved plate theory are presented by Skvortsov *et al.* (1998). The level of accuracy and the range of applicability of the used models can be considered useful tools for many practical applications.

Hopperstad *et al.* (1997) studied the ultimate strength of aluminum plate elements under uniaxial compression by a comparison with numerical and experimental results, showing that the non-linear FEA would provide accurate solutions of the ultimate strength for thin-walled aluminum structural elements under compressive loading. Langseth and Hopperstad (1997) studied the local buckling behavior of square thin-walled aluminum tubes in axial compression. Paik and Chung (1999) studied the static and dynamic crushing behavior of single skin stiffened square tubes of aluminum alloy as well as steels.

Paik *et al.* (1999d) investigated the structural failure characteristics of aluminum sandwich panels with aluminum honeycomb core, theoretically and experimentally. A series of strength tests were carried out on aluminum honeycomb-cored sandwich panel specimen in three point bending, axial compression and lateral crushing loads. Simplified theories were applied to analyze bending deformation, buckling / ultimate strength and crushing strength of honeycomb sandwich panels subject to the corresponding load component. Figure 13 shows a selected test result representing the effect of the core height on the ultimate strength of the aluminum honeycomb sandwich panel.

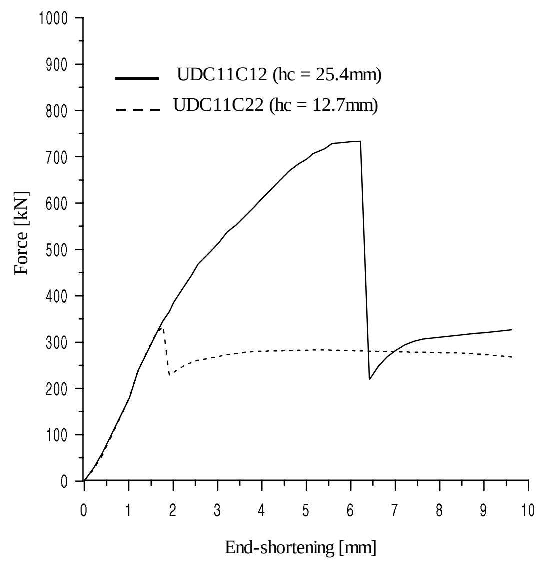


Figure 13. Effect of core height on the collapse of aluminum sandwich panels, Paik *et al.* (1999d).

From the axial compression collapse tests on the aluminum honeycomb sandwich panel specimen varying various potential influential parameters, namely the core height, core cell thickness and panel aspect ratio, it was observed that the core height would be a crucial parameter affecting the sandwich panel ultimate compressive strength. Also, the delamination between core and facing layers could occur when the height of core became large. A dramatic decrease of internal force after collapse was observed to occur by such delamination. On the other hand, it was seen that the influence of core cell thickness on ultimate strength under axial compression would be small. The influence of aspect ratio on the collapse behavior of aluminum sandwich panels subject to axial compression may also be an influential factor affecting the collapse strengths of aluminum sandwich panels even if it is not the most crucial.

14 CONCLUSIONS AND RECOMMENDATIONS

There is a strong trend towards the use of detailed FEA. The availability and powerfulness of commercial non-linear FEA codes has, however, not eliminated the need for experiments and easyto-use analytical theories.

From the points of efficient transportation and environmental safeguards, the assessment of the structural integrity of aged ships and offshore structures remains an important research subject. Experimental work on the ultimate strength of deformed and corroded structures should be continued to increase the certainty of the above assessments.

In general the following topics represent recent worldwide developments in numerical procedures for non-linear analysis including their advanced theoretical background: solution strategies for non-linear problems related to parallel computing, improvement of FEA formulations in non-linear range, error estimators and adaptive FEA.

In order to derive and to ensure simplified structural models as well as design formulae, there is a need for systematic non-linear studies regarding the ultimate and post ultimate behaviour of structural members and complex structures. In this context, experimental programmes are indispensable for validating complex non-linear models.

Structural reliability considerations continue to be investigated in strength uncertainty studies and methodology development for metal and composite components. Reliability as an optimization constraint has been explored, with the theory implemented in at least one computer code.

Comparative assessments of stiffened panel strength formulations are being couched in a probabilistic manner supporting future use in reliability analyses. Variations in new and existing strength prediction techniques have been documented, with a wide range in both mean and coefficient of variation of the modeling bias. Consistent uncertainty treatment of the full breadth of strength prediction techniques is recommended to assist the structural reliability analyst in choosing the optimal prediction formula for their needs. Stiffened panel formulations are generally conservative, but there is a nonconservative trend in some design formulations that is cause for concern. It is recommended that developers and design agents reconsider formulae giving consistent underpredictions with high variability.

Time-dependant reliability methodologies have been developed for ship structures subject to corrosion, fatigue cracking and repair. Renewal theory has been introduced to account for down-time during inspection and repair. While the reliability is held as the performance quality of interest, the availability of the ship as a function of corrosion, cracking effects, and inspection and repair strategies might better serve the ship design and maintenance processes.

The reliability measure is of increasing interest to the ship and offshore structures, owners community for extreme, rare events resulting in overloads and high consequence failures. The degree to which the ships service is interrupted for structural repair and inspection due to more probable failure modes, may be reduced through greater emphasis on modeling the availability of the ship, using extensions of renewal theory, accounting for in-service decay of the structure, and inspection and repair strategies.

Some aspects of the collapse of beam-columns are well described in the literature available. Most of the work covers local and overall buckling based on tests results and FEA calculations. Special attention is given to particular boundary conditions that may influence the type of collapse. However, few works are available to cover some aspects of real importance to ship structures, like the ductile collapse of frames and girders, influence of holes, degradation of strength due to corrosion, interaction between primary structural members, redundancy, etc. In conclusion, more research is needed in some of these issues as applied to typical thin walled ship structures.

The database of strength of unstiffened tubular joints continues to grow, with more useful data on multi-planar joints emerging. The disparity between ultimate strength of joints tested in isolation (where the data lies) and joints within frames continues to receive attention, but a general procedure to take advantage of the higher capacity found in frames has yet to be found. Similarly, where fracture is the mode of failure, criteria for identifying when this is critical require further development. Useful extensions to the knowledge of stiffened joints and I-beam-to-tubular column connections have been made. Grouted joints using expanding grout have been explored, but further work is required to develop design standards. The phenomenon of incremental collapse under high amplitude cyclic loading has been identified. The significance of this phenomenon in determining the ultimate strength of offshore structures has yet to be established.

The ultimate strength of plates with stiffeners have been widely studied during the reported period and new formulations have been developed. The most advanced formulations also include the effect of stiffener tripping on ultimate strength. New welding procedures such as laser welding can significantly reduce initial deflection and residual stress effects and should be studied further. These studies are most important for marine structures with thin platings as used, e.g., in fast ships. Another new area is the application of all metal sandwich panels on ships. The design formulations for these structures are missing at present and extensive research is needed to evaluate sound design basis for these panels.

The ultimate behaviour of individual structural members can be considered as the first useful step to understand the overall structural performance and to predict potential failure mechanisms of more complex structures. This concept has been used in the past and can be also adopted as a starting point for forthcoming studies.

Unstiffened and stiffened shell members are in fact extensively used in well-known marine structures, and interesting results in terms of structural response are now available. However, in the recent past the development of new vehicles has enlarged the frontiers regarding both composite materials and complex load combination due to singular working conditions. In these cases, many problems still require research effort and the contribution of in-service experience.

Numerical methods still represent the most essential tool for the ultimate analysis of shells, but experimental verifications (both model and full scale) and theoretical support have to be extensively adopted in the future in order to validate the results and to suggest effective contributions to the practical design of ship and marine structures.

Considerable effort has been put into the examination of bulk carriers although it might, in simple terms, be too late. For example, studies on bulkheads of bulk carriers appear to confirm inadequacies in their design, and in the connections to supporting structure. Attempts to exploit design-based or phenomenological based ultimate strength software have highlighted the weakness that it may not account properly for all possible failure modes if used outside its original terms of reference. Nor, in some cases, has such software necessarily been properly calibrated against existing quality test data. Some reported sensitivity study findings suggest that a lack of full appreciation of the problem under investigation exists.

The inherent ruggedness with respect to grounding of double bottom vessels has been clearly confirmed. Also, simply by varying a double bottom structural arrangement, the energy absorption capability can be doubled. However, the ‘Achilles Heel’ in such groundings is the welded connection between a major transverse member and the inner bottom plating.

The development of analytical models to replicate energy absorption mechanisms during groundings and collisions continues seemingly with some success. The IMO recommendations for vessel crashworthiness design are supported only in part by the findings from one major grounding study.

Ever increasingly complex corrosion models including replacement are being included in ship reliability analysis. However, a realistic model to accurately reflect the onset and development of in-service corrosion still seems a long way off.

The emphasis in offshore structure work continues to be dominated by considerations of ultimate strength (pushover analysis) and reliability analysis. New procedures for the former are still being developed whilst the latter has been extended to include the occurrence of fatigue fractures before ultimate strength is realised. Pushover analysis software benefits from the existence of 2D and 3D frame tests against which it can be calibrated. A cautionary note regarding excessive deflections with respect to some operational issues during the realisation of ultimate platform strength is appropriately made.

An examination of the change in design practice for North Sea steel jackets over 20 years is reported. Overall base shear is similar, larger waves and small drag coefficients giving way to smaller waves, larger drag coefficients and consideration of marine growth. Pushover strength has reduced because joints are no longer required to be as strong as their adjacent members, while reliability increased because of adequate air gap requirements.

Part of a comparative study on jacket versus jack-up reliability is reported. Some significant differences are determined but the omission, at the stage reported, of some spudcan fixity contributes importantly to this. Special care is required in the modelling of jack-ups with respect to the leg-hull connection and in the determination of some chord ultimate strengths.

Numerous methods have been proposed for prediction of grounding and collision damage. However, before the models can be used for design and structural optimisation they need to be validated at the component level, i.e., it must be validated that each structural member in the methods absorbs the correct amount of energy. It is not sufficient to compare the total energy absorption in a test with the total predicted energy absorption.

Prediction of fracture initiation and propagation is still associated with large uncertainty. For both ship-to-ship collision and ship grounding analyses this poses problems because fracture initiation is often considered to be the critical point and a large part of the structural response may be under influence of fracture propagation. Therefore, the area needs further theoretical development.

Most focus is on the development of theoretical models for crushing mechanics. However, there is an equivalent need to determine the accidental loading conditions, i.e., probability distributions for impact speeds, impact location, shapes of collision objects, etc. As new advanced materials are being more commonly used there is a need for prediction tools for crushing of structures of such materials. The last few years have revealed interesting studies of actual design of ship structures for crashworthiness. As prediction tools become more reliable and as the loading conditions become less uncertain, it will hopefully soon be possible to design ship structures for cost-effective crashworthiness.

While existing methods for buckling and ultimate strength analysis of steel structures can be successfully applied to single skin non-ferrous construction, we are confronted with a number of problem areas for sandwich structures. Primary among the concerns are some known obstacles to using sandwich construction for strength members in dynamically loaded structures. Sandwich laminates are not isotropic. The facing skin on the laterally loaded side of the sandwich panel may buckle due to bending. The buckling and collapse strength characteristics of sandwich panels are not yet fully understood. Debonding or delamination between the center core and outer facing plates is also a likely concern. Sandwich panels can also be suspect in resisting impact loads. Some of the impact energy dissipation characteristics of cores remain unclear. Fatigue is a crucial problem to be solved in order to more effectively incorporate sandwich panels into the design and construction of large weight critical structures.

REFERENCES

Aalberg, A., Langseth, M., Hopperstad, O.S. and Malo K.A. (1998). Ultimate strength of stiffened aluminium plates. *Thin- Walled Structures*, 2nd Intl Conf. on Thin-Walled Structures, 93-100.

Akhras, G., Gibson,S., Yang, S. and Morchat, R. (1998). Ultimate strength of a box girder simulating the hull of a ship. *Canadian Journal of Civil Engineering* **25:5**, 829-843.

Allen, H.G. (1969). Analysis and design of structural sandwich panels, *Pergamon Press*, Oxford.

Al-Mahaidi R., Grundy, P. and Bean, W. (1999). Pullout strength of concrete plugs in piles. *9th ISOPE*, Brest, **4**, 24-29.

Al-Sharif, A.M. and Preston, R.(1996). Structural Reliability Assessment of the Oman India Pipeline. *OTC*, May 6-9.

Altenburg, C.J. and Scott, R.J. (1971). Design considerations for aluminum hull structures (Study of aluminum bulk carrier), Ship Structure Committee, Report No. SSC-218.

Amdahl, J., Skallerud, B.H., Eide, O.I. and Johansen, A. (1995). Recent developments in reassessment of jacket structures under extreme storm cyclic loading. *OMAE95.*

Ammerman, D. and Daidola, J. (1996). A comparison of methods for evaluating structure during ship collisions, *DMCGPS*, San Francisco, paper 6-1.

António, C.A.C., Marques, A.T. and Gonçalves, J.F. (1996). Reliability Based Design with a Degradation Model of Laminated Composite Structures, *Structural Optimization* **12**, 16-28.

API (1993). Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design, 2A-LRFD (RP 2A-LRFD), First Edition.

Ariyoshi, M. and Makino, Y. (1999). Load-Deformation Relationships for Gusset-Plate to CHS Tube Joints Under Compression Loads. *9th ISOPE*, **4**, 54.

Ariyoshi, M., Wilmshurst, S.R., Makino, Y., Vegte van der, G.J. and Choo, Y.S. (1998). Introduction to the database of gusset-plate to CHS tube joints. *ISTS VIII*, Singapore, 203-210. Balkema.

Assakkaf, I.A. (1998). Reliability-Based Design of Panels of Fatigue Details of Ship Structures, *PhD Dissertation*, University of Maryland, College Park.

Atkociünas, J. (1997). Compatibility equations of strains for degenerate shake-down problems. *Computers & Structures* **63:2**, 277-282.

Atua, K.I. (1998). Reliability-Based Structural Design of Ships Hull Girders and Stiffened Panels, *PhD Dissertation*, University of Maryland, College Park.

Axhag, F. and Johansson, B. (1999). Tension flange instability of I-beams, *Journal of Constructional Steel Research* **49**, 69-81.

Bai, Y., Igland, R.T. and Moan, T. (1997). Tube collapse under combined external pressure, tension and bending. *MS* **10**, 389-410.

Bailey, R. and Wood, J. (1997). Post-buckling behavior of square compression loaded graphite epoxy panels with square and elliptical cutouts, *Thin-Walled Structures* **28: 3/4**, 373-397.

Bea, R.G., Ramos, R., Valle, O., Valdes, V. and Maya, R. (1998). Risk Assessment and Management Based Criteria for Design and Requalification of Pipelines and Risers in the Bay of Campeche, *OTC*, May 4-7.

Bertolini, A.F. and Lam, Y.C. (1998). Accelerated subspace interation using adaptive multiple

inverse iteration. *Computers & Structures* **66:1**, 45-57.
Bischoff, M. and Ramm, E. (1997). Shear deformable shell elements for large strains and rotations. *Int. J. Num. Meth. Eng*. **40**, 4427-4449.
Blachut, J. (1997). Minimum Weight of Internally Pressurised Domes Subject to Plastic Load Failure. *Thin Walled Structures* **27**, 127-146.
Blachut, J. (1998). Buckling of Sharp Knuckle Torisphers under External Pressure. *Thin Walled Structures* **30**, 55-77.
Boisse, P., Gelin, J.C. and Daniel, J.L. (1996). Computation of thin structures at large strains and large rotations using a simple C^o isoparametric three-node shell element. *Computers & Structures* **58:2**, 249-261.
Bolt, H.M., Billington, C.J. and Ward, J.K. (1994). Results from large-scale ultimate load tests on tubular jacket frame structures. *26th OTC*, Houston, Paper No. OTC 7451.
Bolt, H.M. (1995). Results from large-scale ultimate strength tests of K-braced frame structures. *27th OTC*, Houston, Paper No. OTC 7783.
Boote D., Mascia D., Monti M., Rizzuto E. and Tedeschi R. (1996). Elastic Instability of Thin Cylindrical Shells: Numerical and Experimental Investigation. *Ocean Eng.* **24**, 133-160.
Boote, D., Figari, M. and Iaccarino, R. (1999). Ultimate Strength Assessment of a Twin Hull Vessel. *Symposium on High Speed Mobile Vehicles*, Italy.
Bozhevolnaya, E. and Frostig, Y. (1997). Non-linear closed-form high-order analysis of curved sandwich panels, *Composite Structures* **38:1-4**, 383-394.
Bracco, M.D. and Wierzbicki, T. (1997). Tearing resistance of advanced double hulls. *J. of Ship Research* **41:1**, 69-80.
Bradford, M.A. (1998a). Distortional buckling of elastically restrained cantilevers. *Journal of Constructional Steel Research* **47**, 3-18.
Bradford, M.A. (1998b). Inelastic buckling of I-beams with continuous elastic tension flange restraint. *Journal of Constructional Steel Research* **48**, 63-77.
Bradford, M.A. (1999). Elastic distortional buckling of tee-section cantilevels. *Thin-Walled Structures* **33:1**, 3-17.
Brank, B., Peric, D. and Damjanic, F.B. (1997). On large deformations of thin elasto-plastic shells: Implementation of a finite rotation model for quadrilateral shell element. *Int. J. Num. Meth. Eng*. **40**, 689-726.
Brown, A. and Amrozowicz, M. (1996).Tanker environmental risk – Putting the pieces together, *DMCGPS*, San Francisco, paper 15-1.
Bulenda, Th. (1997). Arnoldi (IOM)-Newton algorithm for pathfollowing in non-linear statics. *Computers & Structures* **63:4**, 813-826.
Bussy, P. and Mosbah, Y. (1997). An error calculation method for finite element analysis in large displacements. *Int. J. Num. Meth. Eng*. **40**, 3703-3728.
Chalmers, D., Critchfield, M.O., Gullberg, O., Keizer, E.W.H., Kimpara, I. and Kozolwski, J.P. (1988). *Report of the ISSC Committee V.8 Composite Structures*, 10th ISSC Congress.
Chan, T.K., Soh, C.K. and Fung, T.C. (1998). Experimental study of a full-scale multiplanar tubular XT-joint. *ISTS VIII*, Singapore, 131-138. Balkema.
Chapelle, D. and Bathe, K.J. (1998). Fundamental considerations for the finite element analysis of shell structures. *Computers & Structures* **66:1**, 19-36.
Cheaitani, M.J. and Burdekin, F.M. (1994). Ultimate strength of cracked tubular joints. *ISTS VI*, Melbourne, 109-114. Balkema.
Chiew, S.P., Soh, C.K. and Fung, T.C. (1997). Large scale testing of a multiplanar tubular DX-joint. *7th ISOPE*, Honolulu, 112-118.
Cho, S.R., Choi, B.W. and Song, I.C. (1998a). Post-ultimate behaviour of stiffened panels subjected to axial compression. *Thin- Walled Structures*, Research and development, 2nd Intl Conference on Thin-Walled Structures, 433-440.
Cho, S.R., Choi, B.W. and Frieze, P.A.(1998b). Ultimate strength formulation for ship’s grillages

under combined loadings. PRADS 98, Elsevier Science.

Cho, S.R., Lee, S.B. and Kim, I.W. (1997). Side collision resistance of ship's stiffened panels. ISOPE **4**, 431-438.

Choo, Y.S., Li, B.H., Vegte van der, G.J., Zettlemoyer, N. and Liew, J.Y.R. (1998). Static strength of T-joints reinforced with doubler or collar plates. *ISTS VIII,* Singapore, 139-144. Balkema.

Chryssanthopoulos, M.K. (1998). Probabilistic Buckling Analysis of Plates and Shells, *Thin-Walled Structures* **30**, 135-157.

Chung, J.Y. (1996). On bow collision strength of ships, Ph.D. Thesis, Department of Naval Architecture and Ocean Engineering, Pusan National University, Pusan, (in Korean).

Crake, K. and Brown, A. (1998). A Probabilistic Assessment of Ship Damage in Collision Events. Joint MIT-Industry Program on Tanker Safety, Report No. 62.

Cui, W. and Mansour, A.E. (1998). Effects of welding distortions and residual stresses on the ultimate strength of long rectangular plates under uniaxial compression, *MS* **11**, 251-269.

Cui, W. and Mansour, A.E. (1999). Generalization of a simplified method for predicting ultimate compressive strength of the panels. *Int. Shipbuilding Progress* **46:447**, 291-303.

Daidola, J. and Pet, E. (1996). Application of structural collision analysis procedures to high-speed craft. *DMCGPS*, San Francisco, 1996, paper 4-1.

Dale, K., Zhao, X.L. and Grundy, P. (1999). Application of finite element method in shake-down analysis of CHS joints. *9th ISOPE,* Brest, **4**, 104-107.

Damjanic, F.B., Tonello, N., Briseghella, L. and Brank, B. (1996). Non-linear finite element formulation for long-term elasto-dynamic computation of shells. *Third Asian-Pacific Conference on Computational Mechanics*, September 16-18, Seoul, Korea.

Damonte, R. and Figari, M. (1996). Ultimate Bending Moment of the Ship Hull Girder. *1st International Conference on Marine Industry*, MARIND' 96, Varna, Bulgaria.

Damonte, R., Porcari, R., Sebastiani, L. and Spanghero, B. (1997). Global Strength Assessment of Naval Surface Vessels in Rough Sea. *In.l Conf. on Ships and Marine Research*. NAV'97, Italy.

Dao, M. and Asaro, R.J. (1999). A study on failure prediction and design criteria for fibre composites under fire degradation. *Applied Science and Manufacturing* **30:2**, 123-131.

Davies, G., Kelly, R. and Crockett, P. (1996). Effect of angle on the strength of overlapped RHS K - and X-joints. *ISTS VII*, Miskolc, 123-130. Balkema.

Dexter, E.M. and Lee, M.M.K. (1996). Effects of chord can length and overlap on the strength of K-joints in CHS tubular members. *ISTS VII*, 131-138. Balkema.

Dexter, E.M. and Lee, M.M.K. (1998a). Effect of overlap on the behaviour of axially loaded CHS K-joints. *ISTS VIII,* Singapore, 249-258. Balkema.

Dexter, E.M. and Lee, M.M.K. (1998b). Ultimate capacity of axially loaded K-joints in CHS. *ISTS VIII,* Singapore, 259-268. Balkema.

Dexter, R.J., Ricles, J.M. Lu, L., Pang, A.A. and Beach, J.E. (1996). Full-scale experiments and analyses of cellular hull sections in compression. *Journal of OMAE* **118:3**, 232-237.

Dier, A.F. and Lalani, M. (1998). New code formulations for tubular joint static strength. *ISTS VIII,* Singapore, 107-114. Balkema.

Dow, R. (1997). Structural Redundancy and Damage Tolerance in Relation to Ultimate Ship Hull Strength. *Int. Conference Advances in Marine Structures III*, DERA Rosyth, UK, Paper No. 30.

Drazetic, P., Payen, F., Ducrocq, P. and Markiewicz, E. (1999). Calculation of the deep bending collapse response for complex thin-walled columns. I. Pre-collapse and collapse phases. *Thin-Walled structures* **33:3**, 155-176.

Earls, C.J. (1999). On the elastic failure of high strength steel I-shaped beams. *Journal of Constructional Steel Research* **49**, 1-24.

Eberlein R., Wriggers P. (1998). On the calculation of Finite Strains in Shell Intersections with Finite Elements. *Technische Mechanik* **18**, 181-188.

Elghazouli, A.Y., Chryssanthopoulos, M.K. and Spagnoli, A. (1998). Experimental response of glass-reinforced plastic cylinders under axial compression. *MS* **11**, 47-37.

Esche, S.K., Kinzel, G.L. and Altan, T. (1997). Issues in convergence improvement for non-linear finite element programs. *Int. J. Num. Meth. Eng*. **40**, 4577-4594.

Farhat, C., Chen, P., Risler, F. and Roux, F. (1998). A unified framework for accelerating the convergence of iterative substructuring methods with Lagrange multipliers. *Int. J. Num. Meth. Eng*. **42**, 257-288.

Faulkner, D. (1998). Hatch covers – the Achilles heel of bulkers?. *The Naval Architects*, 32-33.

Faulkner, D. and Willams, A. (1997). Formal hazard analysis applied to the OBO carrier Derbyshire : a technical note. *The Naval Architects*, 9-10.

Franco, J.R.Q. and Ponter, A.R.S. (1997). A general approximate technique for the finite element shake-down and limit analysis of axisymmetrical shells. Part 1: Theory and fundamental relations. *Int. J. Num. Meth. Eng*. **40**, 3495-3513.

Frieze, P.A. and Morandi A.C. (1997). The Collapse of Offshore Structures: Recent Advances and Remaining Uncertainties in Its Prediction. *International Conference Advances in Marine Structures III*, DERA Rosyth, UK, Paper 21.

Fujikubo, M., Yao, T. and Varghese, B. (1997). Buckling/Ultimate Strength of Rectangular Plates Subjected to Combined Inplane Loads. *Transactions of the West-Japan Society of Naval Architects* **93**, 81-89, (in Japanese).

Fujikubo, M., Yanagihara, D. and Yao, T. (1999). Estimation of Ultimate Strength of Continuous Stiffened Plates under Thrust. *Journal of the SNAJ* **185**, 203-212.

Fukuchi, N., Sugita, N. and Okada K. (1996). An Elasto-plastic Analysis and Resisting Mechanism during Large Deflection of Thin Shell Structures. *Journal of the SNAJ* **180**, 427-433.

Furio, A.J. and Bird, J. (1997). Lightweight metalic corrugated core structures, an option for the future. *13th Fast Ferry Intl Conference*, Singapore. Fast Ferry Intl Ltd, Tenterden, UK.

Gallimard, I., Ladevèze, P. and Pelle, J.P. (1996). Error estimation and adaptivity in elastoplasticity. *Int. J. Num. Meth. Eng*. **39**, 189-217.

Gazzola, F., Lee, M.M.K. and Dexter, E.M. (1999). Strength Prediction of Axially Loaded Overlap Tubular K-Joints. *9th ISOPE*, Brest, **4**, 1-8.

Goh, T.K. and Grundy, P. (1994). Shake-down Analysis of Tubular Structures. *ISTS VI*, Melbourne, 511-517. Balkema.

Graham, D. (1996). Buckling of thick-section composite pressure hulls. *Comp. Struct.* **35:1**, 5-20.

Groen, H.T.F. and Kaminski, M.L. (1996). Optimisation of Pressure Vessels Under Reliability Constraints, *Proceedings of OMAE*, Safety and Reliability **2**, 177-185.

Grundy, P. (1994). Incremental Collapse of Hollow Sections. *ISTS VI*, Melbourne, 497-503. Balkema.

Grundy, P. (1995). Grouted Sleeve Tubular Splices. *5th ISOPE*, The Hague, **4**, 116-120.

Grundy, P. and Foo, J.E.K. (1991). Prestress Enhancement of Grouted Pile/Sleeve Connections. *ISOPE*, Edinburgh, 130-136.

Grundy, P. and Geiro, A. (1998) Ultimate Strength Limit State Assessment of Transverse Bulkheads. *International Conference on Design and Operation of Bulk Carriers*, Paper No. 10.

Gullberg, O., Critchfield, M.O., Dodkins, A., Kozolwski, J.O., Kimpara, I., Porcari, R. and Ragout, I. (1991). *Report of the ISSC Committee V.8 Composite Structures*, 11th ISSC, China.

Gummadi, L.N.B. and Palazotto, A.N. (1997). Non-linear finite element analysis of beams and arches using parallel processors. *Computers & Structures* **63:3**, 413-428.

Gupta, N.K. (1998). Some aspects of axial collapse of cylindrical thin-walled tubes. *Thin-Walled Structures* **32**, 111-126.

Gurvich, M.R. and R.B. Pipes (1998). Reliability of Composites in a Random Stress State, *Composites Science and Technology* **58:6**, 871-81.

Ha, C.C., Pecknold, D.A., Mohr, W.C. (1998). FE modelling of dt tubular joints with chord stress. *OMAE 98-0560*.

Hashagen, F. and de Borst, R. (1997). A plasticity model including anisotropic hardening and softening for composite materials. *Finite Elements in Engineering and Science*, 261-272.

Hasham, A.S. and Rasmussen, K.J.R. (1998). Section capacity of thin-walled I-sections beam-

columns. *Journal of Structural Engineering* **124:4**, 351-359.
Hauptmann, P. and Schweizerhof, K. (1998). A systematic development of „solid-shell“ element formulations for linear and non-linear analyses employing only displacement degrees of freedom. *Int. J. Num. Meth. Eng.* **42**, 49-69.
Healy, B.E. and Zettlemoyer, N. (1994). Significant issues relating to the in-plane bending strength of circular tubular joints. *ISTS VI*, Melbourne, 191-198. Balkema.
Hess, P.E., Bruchman, D. and Ayyub, B.M. (1998). *Uncertainties in Material and Geometric Strength Variables in Marine Structures, Uncertainty Modelling and Analysis in Civil Engineering*, Ed. Bilal M. Ayyub, CRC Press, Ch 14.
Höglund, T. (1997). Shear buckling resistance of steel and aluminium plate girders, *Thin-Walled Structures* **29:1-4**, 13-30.
Hopperstad, O.S., Langseth, M. and Hanssen, L. (1997). Ultimate compressive strength of plate elements in aluminum, *Thin-Walled Structures* **29:1-4**, 31-46.
Hörenbaum, C., Cao, J.J., Packer, J.A. and Puthli, R.S. (1998). Failure Modes and Limit States of Longitudinal Plate to RHS Connections. *8th ISOPE*, Montreal, **4**, 16-23.
HSE (1998). Health & Safety Executive. Comparison of Reserve Strength Ratios of Old and New Platforms. *Offshore Technology Report*, OTO 97 046.
Hu, S.Z., Chen, Q., Pegg, N. and Zimmerman, T.J.E. (1997). Ultimate Collapse Tests of Stiffened-Plate Ship Structural Units. *Marine Strctures* **10:8-10**, 587-610.
Hu, S.Z. and Jiang, L. (1998). A finite element simulation of the test procedure of stiffened panels. *Marine Strctures* **11:3**, 75-99.
Hughes, O. (1997). Two first principles structural designs of a fast ferry – all-aluminum and all-composite, *Proc. of the 4th Int. Conf. On Fast Sea Transportation* (FAST’97) 1, 91-98.
Hughes, O. and Ma, M. (1996a), Elastic tripping of asymmetrical stiffeners, *Computers and Structures* **60:3**, 369-389.
Hughes, O. and Ma, M. (1996b), Inelastic analysis of panel collapse by stiffener buckling, *Computers and Structures* **61:1**, 107-117.
Hughes, O. and Ma, M. (1996c). Lateral distortional buckling of monosymmetric beams under point load, *J. of Engineering Mechanics* **122:10**, 1022-1029.
Hui – Shen Shen (1998). Post-buckling Analysis of Stiffened Laminated External Liquid Pressure and Axial Compression. *Engineering Structures* **20**, 738-751.
Hurst, G.L. and Campbell, R.B. (1997). Evaluation of finite element modelling practices for stiffened structures. *BOSS* **3**, 19-33.
Hyde, T.H., Ou, H. and Leen, S.B. (1999). Experimental and Finite Element Investigations on the Static Collapse of a Plane Tubular Framework Structure. *9th ISOPE*, Brest, **4**, 63-68.
Hyde, T.H., Saad, S.B., Khalid, Y., Leen, S.B. and Warrior, N.A. (1998). A critical assessment of the finite element method for predicting the static strength of tubular T- and YT-joints. *ISTS VIII*, Singapore, 293-302. Balkema.
Ibnabdeljalil, M. and W.A. Curtin (1997). Strength and Reliability of Fibre-Reinforced Composites: Localized Load-Sharing and Associated Size Effects, *Int. J. of Sol. and Struc.* **34:21**, 2649-68.
Ibrahimbegovic, A. (1997). Stress resultant geometrically exact shell theory for finite rotations and ist finite element implementation. *Appl. Mech. Rev.* **50:4**.
International Standard Organisation, ISO/TC &//SC / N222, Petroleum and Natural Gas Industries – Offshore Structures – Part 2: Fixed Structures, Draft, 1999-05-14.
Ioannidis, G.I. and Kounadis, A.N. (1999). Flexural-torsional postbuckling analysis of centrally compressed bars with open thin-walled cross-section. *Engineering Structures* **21**, 55-61.
Jensen, J.J., Caridis, P., Cho, S.R., Damonte, R., Dow, R.S., Gordo, J.M., Kaminski, M.L., Kozliakov, V.V., Pegg, N.G., Röhr, U., Rutherford, S.E., Yao, T. and Zhang, S. (1997). *Report of the ISSC Committee III.1 Ultimate Strength*, 13th ISSC Congress, Norway.
Jones, N. (1997). Dynamic plastic behaviour of ship and ocean structures, *Trans. RINA* **139**, 65-97.
Kamba, T. and Taclendo, C. (1998). CHS column connections without stiffener. *ISTS VIII*,

Singapore, 567-576. Balkema.

Kang, C.T., Moffat, D.G., Mistry, J. and Ong, K.T. (1998). The effects of weld size on the ultimate strength of a double-tee tubular joint under brace compression or bending. *ISTS VIII*, Singapore, 277-283. Balkema.

Kim, M.Y., Chang, S.P. and Kim, S.B. (1996). Spatial stability analysis of thin-walled space frames. *Int. J. Num. Meth. Eng*. **39,** 499-525.

Kitamura, O. (1996). Comparative study on collision resistance of side structure. *DMCGPS*, San Francisco, paper 9-1. Also *Marine Technology* **34:4**, 293-308, Oct. 1997.

Kitamura, O. and Kuriowa, T. (1996). Large-scale grounding experiments and numerical simulations. *Ship Technology Research* **43:2**, 62-69.

Kitamura, O., Kawamoto, Y. and Kaneko, E. (1998). A study on the improved tanker structure against collision and grounding damage. *PRADS98*.

Klaas, O., Niekamp R. and Stein, E. (1996). Algorithms for the calculation of limit and bifurcation points of stability problems in structural mechanics using krylov based methods on a MIMD parallel computer. *Numerical Methods in Engineering*, 204-210.

Knox, E.M., Cowling, M.J. and Winkle, I.E. (1998). Adhesively bonded steel corrugated core sandwich construction for marine applications. *MS* **11:4-5**, 185-204.

Koksharov, I.I. (1996). An Estimation of Reliability of Unidirectional Composites by Catastrophe Theory, *Mechanics of Composite Materials* **32:4**, 374-80.

Kosteski, N., Packer, J.A. and Cao, J.J. (1999). Experimental Study of Through Plate, Transverse Plate and Stiffened Plate-to-RHS Member Connections. *9th ISOPE*, Brest, **4**, 38-43.

Krenk, S., Vissing-Jorgensesn and Thesbjerg, L. (1999). Efficient Collapse Analysis of Framed Structures. *Computers and Structures* **72**, 481-496.

Kujala, P. (1998). Ultimate strength analysis of all steel sandwich panels. *Journal of Structural Mechanics* **31**, 32-45.

Kulzep, A. (1999). LS-DYNA simulation of foam-filled shipstructures during collision (in German), Proc. 17. CAD-FEM Users' Meeting, Sonthofen, Germany.

Kulzep, A. and Peschmann, J. (1998). Final Report of the BMBF research project " Life cycle Design - D2" – Grounding of double hull tankers (in German), Technical University of Hamburg-Harburg, Germany, 1998.

Kulzep, A. and Peschmann, J. (1999). Final Report of the BMBF research project "Life cycle design - D2A" - Side collisions of double hull ships (in German), Technical University of Hamburg-Harburg, Germany, 1999.

Kuroiwa, T (1996). Numerical Simulation of Actual Collision and Grounding Accidents. *DMCGPS*, 7-1 – 7-12.

Kuroiwa, T. and Kusuba, S. (1997). Study on structural toughness against bottom raking due to grounding. OMAE, **2**, 165-172.

Lacasse, S. and Nadim, F. (1996). Model Uncertainty in Pile Axial Capacity Calculations. *OTC*, May 6-9.

Lalani, M., Moraham, D.J., Foeken van, R.J. and Wardenier, J. (1996). Fatigue behaviour and ultimate capacity of grouted tubular joints. *ISTS VII*, Miskolc, 349-354. Balkema.

Lambiase, F., Casella, G., Dogliani, M. and Navone, E. (1997). Ultimate Strength of Ship Hulls. *Registro Italiano Navale*, *RR 270*.

Langhelle, N.K., Eberg, E. and Amdahl, J. (1998). Comparative study between numerical models and buckling tests of aluminium columns at elevated temperatures. OMAE*98.*

Langseth, M. and Hopperstad, O.S. (1997). Local buckling of square thin-walled aluminum extrusions, *Thin-Walled Structures* **27:1**, 117-126.

Lee, M.M.K. and Llewelyn-Parry, A. (1998). Ultimate strength of ring stiffened T-joints - A theoretical model. *ISTS VIII*, 147-154. Balkema.

Lee, M.M.K. and Wilmshurst, S.R. (1996). Strength of multiplanar tubular KK - joints under anti symmetrical axial loading. *ISTS VII*, Miskolc, 146-156. Balkema.

Lee, T.K. (1997). A study on grounding strength of ships, Ph.D. Thesis, Department of Naval Architecture and Ocean Engineering, Pusan National University, Pusan (in Korean).

Lehata, H.W. and Mansour, A.E. (1997). Reliability-based Method for Optimal Structural Design of Stiffened Panels, *MS* **10**, 323-352.

Lehmann, E. (1999). Experimental Ship Structural Analysis. *VDI BERICHTE* 1463, 1-40.

Lehmann, E. and Yu, X. (1996). Energy dissipation of plastic hinges under dynamic loads, *Proc. of Int. Conference on Designs and Methodologies for Collision and Grounding*, paper 3-1.

Lehmann, E. and Zhang L. (1998). Non-linear behaviour of stiffened structures, Springer Verlag Berlin Heidelberg New York (in German).

Lehmann, E., Peschmann, J. and Kulzep, A. (1997); Grounding of Ships (in German), *Jahrbuch der STG*, Society of Naval Architects in Germany 91, Springer-Verlag Berlin, 1997.

Lemmen, P.P.M. and Vredeveldt, A.W. (1996). Design analysis for grounding experiments. *DMCGPS*, San Francisco, paper 14-1.

Lin, S.C., Kam, T.Y. and Chu, K.H. (1998). Evaluation of Buckling and First-Ply Failure Probabilities of Composite Laminates, *Int. J. of Solids and Structures* **35:13**, 1395-1410.

Little, P., Pippenger, D. and Simonsen, B.C. (1996). Development of a computational model for predicting damage to tankers. *DMCGPS*, San Francisco, paper 11-1.

Liu, D.K., Noordhoek, C. and Wardenier, J. (1998a). Effect of Support Conditions and Geometrical Imperfections on the Strength of CHS Uniplanar X-Joints. *ISTS VIII*, Singapore, 50-57.

Liu, D.K., Yu, Y. and Wardenier, J. (1998b). Effect of boundary conditions and chord preload or the strength of RHS uniplanar gap K-joints, Idem, 223-230.

Liu, D.K., Yu, Y. and Wardenier, J. (1998c). Effect of boundary conditions and chord preload on the strength of RHS multiplanar gap KK-joints. *dem*, 230-238.

Lotsberg, I., Musch, K., Måseide, M., Solland, G. and Storesund, W. (1998). Tested Capacity of Welded Connections Made of High Strength Steel, OMAE98-2864.

Lourenco, P.B., Borst de, R. and Rots, J.G. (1997). A plane stress softening plasticity model for orthotropic materials. *Int. J. Num. Meth. Eng*. **40**, 4033-4057.

Lu, L.H., Winkel de, G.D. and Wardenier, J. (1994). Deformation limit for the ultimate strength of hollow section joints. *ISTS VI*, Melbourne, 341-348. Balkema.

Lu, X.S., Costa, P.J., Franitza, S., Nallikari, M., Rowinski, L., Shenoi, R.A. and Tomita, Y. (1994). *Report of the ISSC Committee V.8 Weight Critical Structures*, 12th ISSC, Canada.

Lützen, M., Simonsen, B.C. and Pedersen, P.T. (2000). Rapid Prediction of Damage to Struck and Striking Vessels in a Collision Event, The Conference of the SSC, Washington, June 12-14.

Ma, M. and Hughes, O. (1996). Lateral distortional buckling of monosymmetric I-beams under distributed vertical load, *Thin-Walled Structures* **26:2**, 123-145.

Maestro, M. and Marino, A. (1996). Search for a predictive model of structural damage in ship collisions: from a case study to some proposals for a new approach. *DMCGPS*, paper 12-1.

Mahendran, M. (1997). Local plastic mechanisms in thin steel plates under in-plane compression, *Thin-Walled Structures* **27:3**, 245-261.

Makino, Y., Kurobane, Y., Ochi, K., Vegte van der, G.J. and Wilmshurst, S.R. (1996). Introduction to unstiffened CHS tubular joint database. *ISTS VII*, 157-164.

Mansour, A.E., Wirsching, P.H., Lucket, M.D., Plumpton, A.M. and Lin, Y.H. (1997a). Structural Safety of Ships, *SNAME Transactions* **105**, 61-98.

Mansour, A.E., Wirsching, P.H., Lucket, M.D., Plumpton, A.M. and Lin, Y.H. (1997b). Assessment of Reliability of Existing Ship Structures, SSC-398, U.S. Coast Guard, Washington, D.C.

Mansour, A.E., Wirsching, P.H., Ayyub, B. and White, G. (1997c). Code Development for Ship Structures - A Demonstration, *J. of Offshore Mechanics and Arctic Engineering* **119**, 114-119.

Manual, L., Schmucker, D.G., Cornell, C.A. and Carballo J.E. (1998). A Reliability-Based Design Format for Jacket Platforms under Wave Loads. *MS* **11:10**, 413-428.

Mateus, A.F. and Witz, J.A. (1997). Post-buckling of corroded steel plates: an assessment of the design codes. *BOSS* **3**, 3-17.

Mateus, A.F. and Witz, J.A. (1998). Post-buckling of corroded steel plates: a comparative analysis. OMAE 1998, *17th International Conference on Offshore Mechanics and Arctic Engineering*.

Mazzolani, F.M., Landolfo, R. and De Matteis, G. (1998). Influence of welding on the stability of alminium thin plates. *Stability and ductility of steel structures*. Elsevier, 225-232.

McVee, J.D. and Cross, R. (1997). Surface Warship Residual Strength Following Weapon Damage. *International Conference Advances in Marine Structures III*, DERA Rosyth, UK, Paper No. 33.

Metschkow, B. and Roland, F. (1999). Strain Measurement at Laser Welded Sandwich Panels. *VDI BERICHTE* 1463, 67-72.

Mikami, I. and Niwa, K. (1996). Ultimate Compressive Strength of Orthogonally Stiffened Steel Plates, *Journal of Structural Engineering* **6**, 674-682.

Milani, N.K. and Grundy, P. (1996). *Incremental Collapse of KT Joints under Variable Repeated Loading. ISTS VII*, Miskolc, 293-300. Balkema.

Milani, N.K. and Grundy, P. (1997). Behaviour of Innovative Tubular KT-Joints under variable Repeated Loading. 7*th ISOPE*, Honolulu, **4**, 21-28.

Morandi, A.C., Faulkner, D. and Das, P.K. (1996). Frame Tripping in Ring Stiffened Externally Pressurised Cylinders. *MS* **9**, 585-608.

Morandi, A.C., Frieze, P.A., Birkinshaw, M., Smith, D. and Dixon, A.T. (1997). Reliability of Fixed and Jack-Up Structures: A Comparative Study. *BOSS* **3**, Pergamon.

Morandi, A.C., Frieze, P.A., Birkinshaw, M., Smith, D. and Dixon A.T. (1999). Jack-Up and Jacket Platforms: A Comparison of System Strength and Reliability. *MS* , **12:4-5**, 311-325.

Morita, K., Ebato, K., Furusawa, K., Fujita, K. and Hamano, K. (1998). Experimental study of structural behaviour of beam-to-column connections reinforced by increasing plate thickness of column without diaphragms. *ISTS VIII*, Singapore, 585-594.

Morita, M., Makino, Y., Kurobane, Y. and Vegte van der, G.J. (1996). A new ultimate capacity formula for unstiffened CHS joints under compression - Continuous formula between T, TT and X-joints. *ISTS VII*, Miskolc, 165-172. Balkema.

Mouring, S.E. (1999). Buckling and postbuckling of composite ship panels stiffened with preform frames. *Ocean Engineering* **26:8**, 793-803.

Myhr, O.R., Fjær, H.G., Klokkehaug, S., Holm, E.J., Grong, Ø. and Kluken, A. (1999). Weldsim - An Advanced Simulation Model for Aluminium Welding. *Proc. 9th I.C. on Computer Technology in Welding, 28-30, Detroit, Michigan*.

Neogi, D., Tessier, N. and Daves, T. (1997). Energy absorbing characteristics of novel composite materials. *Structures Under Extreme Loading Conditions American Society of Mechanical Engineers, Pressure Vessels and Piping Division, PVP* **351**, 325-340.

Nichols, N.W., Birkinshaw, M. and. Bolt, H.M. (1997). Systems Strength Measures of Offshore Structures. *BOSS* **3**.

Nordlund, P., Giannakopoulus, A.E. and Häggblad, B. (1998). Adaptive mesh-updating methods for non-linear finite element analysis of shells. *Int. J. Num. Meth. Eng.* **43**, 1523-1544.

Norr, A.K. (1997). New computing systems and future high-performance computing environment and their impact on structural analysis and design. *Computers & Structures* **64:1-4**, 1-30.

Östergaard, C., Dogliani, M., Soares, G.C., Parmetier, G. and Pedersen, P.T. (1996). Measures of Model Uncertainty in the Assessment of Primary Stresses in Ship Structures, *MS* **9**, 427-447.

Ohtsubo, H. and Wang, G. (1996). Strength of ships during collision and grounding. *DMCGPS*, San Francisco, paper 10-1.

Ohtsubo, H., Yao, T., Sumi, Y. *et al.* (1999). Analysis of Casualty of MS NAKHODKA. Proceedings of OMAE’99, St. Johns, Newfoundland, Canada.

Paik, J.K. and Chung, J.Y. (1999). A basic study on static and dynamic crushing behavior of a stiffened tube, *Trans. The Korea Society of Automotive Engineers*, SAE No. 99370024, **7:1**, 219-238 (in Korean).

Paik, J.K. and Kim, D.H. (1997). A Benchmark Study of the Compressive Strength Formulations for Stiffened Panels, *J. Research Inst. Ind. Technol., Pusan Nat'l Univ.* **53:12**, 373-405.

Paik, J.K. and Lee, Y.W. (1995). A survey of hull materials and construction for larger high speed vessels, *J. of the Society of Naval Architects of Korea* **32:6**, 26-33 (in Korean).

Paik, J.K. and Pedersen, P.T. (1996). A simplified method for predicting ultimate compressive strength of ship panels, *Int. Shipbuilding Progress* **43:434**, 139-157.

Paik, J.K. and Thayamballi, A.K. (1998). The Strength and Reliability of Transverse Bulkheads and Hull Structure of Bulk Carriers. *International Conference on Design and Operation of Bulk Carriers*, Paper No. 9.

Paik, J.K. and Wierzbicki, T. (1997). Benchmark study on crushing and cutting of plated structures. *Journal of Ship Research*, **41:2**, 147-160.

Paik, J.K., Yang, S.H. and Thayamballi, A.K. (1996). Residual strength assessment of ships after collision and grounding. *DMCGPS*, San Francisco, paper 2-1.

Paik, J.K., Thayamballi, A.K. and Chun, M.S. (1997a). Theoretical and experimental study on the ultimate strength of corrugated bulkheads. *Journal of Ship Research* **41:4**, 301-317.

Paik, J.K., Lee, Y.W., Thayamballi, A.K. and Curry, R. (1997b). A novel concept for structural design and construction of vessels using aluminum honeycomb sandwich panels, *Trans. SNAME* **105**, 191-219.

Paik, J.K., S.K. Kim, S.H. Yang, and A.K. Thayambali (1998a). Ultimate Strength Reliability of Corroded Ship Hulls, *RINA Transactions* **140**.

Paik, J.K., Thayamballi, A. K., Lee, W. H. (1998b). A numerical investigation of tripping. *MS* **11,** 159-183.

Paik, J.K., Thayamballi, A.K. and Park, Y.E. (1998c). Local buckling of stiffeners in ship plating. *J Ship Res* **42:1**, 56-67.

Paik, J.K., Thayamballi, A.K. and Kim, D.H. (1999a). An analytical method for the ultimate compressive strength and effective plating of stiffened panels, *J. of Constructional Steel Research* **49**, 43-68.

Paik, J.K., Thayamballi, A.K. and Kim, D.H. (1999b). Advanced ultimate strength design equations of ship plating under combined biaxial compression / tension, edge shear and lateral pressure loads, Final Report to ABS.

Paik, J.K., Thayamballi, A.K. and Kim, D.H. (1999c). Advanced ultimate strength design equations of ship stiffened panels under combined biaxial compression / tension, bi-axial in-plane bending, edge shear and lateral pressure loads, Final Report to ABS.

Paik, J.K., Thayamballi, A.K. and Kim, G.S. (1999d). The strength characteristics of aluminum honeycomb sandwich panels, *Thin-Walled Structures* **35:3**, 205-231.

Paik, J.K., Chung, J.Y., Choe, I.H., Thayamballi, A.K., Pedersen, P.T. and Wang, G. (1999e). On Rational Design of Double Hull Tanker Structures against Collision. The *1999 annual meeting of the Society of Naval Architects and Marine Engineers*. Trans. SNAME **107.**

Paik, J.K., Thayamballi, A.K. and Wang, G. (2000). On advanced buckling and ultimate strength design of ship plating, *SNAME Annual Meeting*, Vancouver.

Park, M.S. and Lee, B.C. (1996). Geometrically non-linear and elastoplastic 3-dim shear flexible beam element of von-Mises-type hardening material. *Int. J. Num. Meth. Eng*. **39**, 383-408.

Pasternak, H. and Branka, P. (1997). *Behaviour of multispan girders with slender stiffened webs*. Fraunhofer-IRB, Stuttgart, 1-20, ISBN: 3-8167-4923-2.

Pedersen, P.T. and Zhang, S. (1999a). Absorbed energy in ship collisions and grounding - Revising Minorsky's empirical method, to be published in *J. of Ship Research*.

Pedersen, P.T. and Zhang, S. (1999b). Effect of ship structure and size on grounding and collision damage distributions, To be published *in Ocean Engineering*.

Peschmann, J. and Kulzep, A. (1996). Grounding of double hull tankers, Proc. BMBF-Statusseminar Entwicklungen in der Schiffstechnik, TUEV-Verlag Koeln. (in German).

Peschmann, J. and Kulzep, A. (1999). Side collision of double hull ships Proc. BMBF Statusseminar Entwicklungen in der Schiffstechnik, TUEV – Verlag, Koeln. (in German).

Petrolito, J. and Legge, K.A. (1997). Benchmarks for frames subject to follower loads. *Computers &*

Structures **63:3**, 379-384.

Pi, Y.L., Put, B. and Trahair, N. (1999). Lateral buckling strengths of cold-formed Z-sections beams. *Thin-Walled structures* **34:1**, 65-94.

Pinkster, J., Vredeveldt, A.W., Koelman, H. and Lansbergen, P. (2000). Crashworthy side structures and damage stability of coasters. Proceedings of 7th International Confrerence on Stability of Ships and Ocean Vehickles. Edited by Renilson, M., Australia, 256-269.

Pippenger, D., Sirkar, J., Little, P. and Cojeen, P. (1996). A design performance standard for oil tankers. *DMCGPS*, San Francisco, 1996, paper 16-1.

Plantema, F.J. (1966). Sandwich construction, *John Wiley and Sons*, New York.

Pu, Y., Das, P.K. and Faulkner, D. (1997). Ultimate Compression Strength and Probabilistic Analysis of Stiffened Plates, *Journal of Offshore Mechanics and Arctic Eng.* **119**, 270-275.

Pullin, J. (1998). Final verdict on the Derbyshire. *Professional Engineering* **11:6**, 24-26.

Puthli, R., Mang, F. and Karcher, D. Investigations on stiffened and unstiffened L-joints made of circular hollow sections. *ISTS VIII*, Singapore, 197-202. Balkema.

Pycko, S. (1997). A cycle-oriented incremental analysis of shake-down problems. *Int. J. Num. Meth. Eng*. **40**, 3163-3179.

Rainey, R.C.T., Mellor, B.G. and Hunt, G.W. (1998). Failure of Bulk Carrier Bulkheads after Flooding. International Conference on Design and Operation of Bulk Carriers, Paper No. 11.

Rahman, M.K. (1998a). Automated optimisation of transverse frame layouts for ships by elastic-plastic finite element analysis. *Struct Optim* **15:3-4**, 187-200.

Rahman, M.K. (1998b). Ultimate Strength Estimation of Ships' Transverse Frames by Incremental Elasto-Plastic Finite Element Analysis. *MS* , **11:7-8**, 291-317.

Rasmussen, K.J.R. (1997). Bifurcation of locally buckled members. *Thin-Walled Structures* **28:2**, 117-154.

Rasmussen, K.J.R. and Hasham, A.S. (1998). Flexural and flexural-torsional bifurcation of locally buckled beam-columns. *Thin-Walled Structures* **29:1-4**, 202-233.

Rawson, C. and Brown, A. (1998). A Probabilistic Assessment of Ship Damage in Grounding Events. Joint MIT-Industry Program on Tanker Safety, Report No. 61.

Reardon, P.C. and Sprung, J.L. (1996). Validation of Minorsky's ship collision model and use of the model to estimate the probability of damaging a radioactive material transportation cask during a ship collision. *DMCGPS*, San Francisco, paper 5-1.

Report of Committee V7 Slender Marine Structures (1994), *Proc. of 12th ISSC*, **2**, 297-338.

Rhodes, J. editor (1998). *Thin-Walled Structures* **32**.

Ricles, J.M. and Bruin, W.M. (1998). Evaluation of Analysis Methods for Response Prediction of Dent-Damaged Tubular Steel Bracing Members, *Proceedings of OTC*, May 4-7.

Rickles *et al.* (1998). See Volume III of this Proceedings.

Rodd, J.L. (1996a). Large scale tanker grounding experiments. *ISOPE* **4**, 483-494.

Rodd, J.L. (1996b). Observations on conventional and advanced double hull grounding experiments. *DMCGPS*, San Francisco, paper 13-1.

Rodd, J.L. (1997). Frame Design Effects in the Rupture of Oil Tanks During Grounding Accidents. *International Conference Advances in Marine Structures III*, DERA Rosyth, UK, Paper No. 22.

Röhr, U. and Fehlhaber, T. (1999). Dimensioning of girders with wide web openings. *Jahrbuch der Shiffbautechnischen Gesellschaft*, 509-515.

Röhr, U. and Zhang, L. (1996). Reassessment of ultimate strength of damaged and repaired structures. *Jahrbuch der Schiffbautechnischen Gesellschaft*, Springer Verlag Berlin Heidelberg New York, **90**, 178-188.

Röhr, U., Fethke, K. and Jackstell, B. (1999). Ultimate load in experiment - basis for numerical assessments of ultimate strength of repaired structures. *VDI-Berichte 1463*, VDI-Verlag Düsseldorf, 47-55.

Röhr U., Zhang L. and Fethke K. (1996). Simulation of Residual Stresses Caused by Welding for Estimation of the Ultimate Strength of Repaired Structures. *Schiffbauforschung* **1**, 24-38.

Roland, F. and Metschkow, B. (1997). Laser welded sandwich panels for shipbuilding and structual steel engineering. ODRA 97, *2nd Intl Conf on Marine Technology*, Szczecin, Poland. Computational Mechanics Publications, Southampton, UK.

Samuelides, M. (1996). Prediction of oil outflow based on energy considerations. *DMCGPS*, San Francisco, paper 1-1.

Sano, A., Muragishi, O., Yoshikawa, T., Murakami, A. and Motoi, T. (1996). Strength analysis of a new double hull structure for VLCC in collision. *DMCGPS*, San Francisco, paper 8-1.

Schiff und Hafen (1998). Vorerst letzter Tanker-Crashtest auf dem Hollandsdiep. **50:10**, 116.

Schleyer, G.K. and Campbell, D. (1996). Development of simplified analytical methods for predicting the response of offshore structures to blast and fire loading, *MS* **9**, 949-970.

Schlüter, H.J. and Meinken, A. (1998). FEM-calculations for the structure stability of inland vessels. *Jahrbuch der Schiffbautechnischen Gesellschaft,* Springer Verlag Berlin Heidelberg New York, **92,** to be published.

Seung, I.S. and Jang, C.D. (1999). A Study on the Prediction of deformations of Welded Ship Structures, *Journal of Ship Production* **15:2**, 73-81.

Shakourzadeh, H., Guo, Y.Q. and Batoz, J.L. (1996). On the large displacements and instabilities of 3D elasto-plastic thin-walled beam structures. *Numerical Methods in Engineering*, 197-203.

Shanmugam, N.E., Thevendran, V., Tan, Y.H. (1999). Design formula for axially compressed perforated plates. *Thin-Walled Structures* **34**, 1-20.

Shetty, N.K., Gierlinkski, J.T., Smith, J.K. and Stahl, B. (1997). Structural System Reliability Considerations in Fatigue Inspection Planning. *BOSS*, **3**, Pergamon.

Shi, J., Nobukawa, H., Kitamura, M., Ohtsubo, H. (1996). A posteriori error estimation and adaptive mesh generation in two-dimensional elasto-plastic finite element analyses for an integrated system. *Journal of the Society of Naval Architects of Japan* **180**, 463-470.

Simonsen, B.C. (1997a). Mechanics of ship grounding, Ph.D. Thesis, Department of Naval Architecture and Offshore Engineering, Technical University of Denmark.

Simonsen, B.C. (1997b). Ship Grounding on Rock – I. Theory. *MS* **10:7**, 519-562.

Simonsen, B.C. (1997c). Ship Grounding on Rock – II. Validation and Application. *MS* **10:7**, 563-584.

Simonsen, B.C. (1999a). Bottom raking damage to high speed craft, Accepted for publication in *RINA Transactions*.

Simonsen, B.C. (1999b). Theory and Validation for the Collision Module, Joint MIT-Industry Program on Tanker Safety, Report No. 66.

Simonsen, B.C. and Hansen, P.F. (1999). Statistical and theoretical analysis of ship grounding accidents, accepted for publication in *J. of Offshore Mechanics and Arctic Engineering*.

Simonsen, B.C. and Ocakli, H. (1999). Experiments and theory on deck and girder crushing. *Thin-Walled Structures* **34**, 195-216.

Simonsen, B.C. and Wierzbicki, T. (1996). Grounding Bottom Damage and Ship Motion over a Rock. *ISOPE* **6:3**, 195-202.

Simonsen, B.C. and Wierzbicki, T. (1997). Plasticity, fracture and friction in steady-state plate cutting. *International Journal of Impact Engineering* **19:8**, 667-691.

Sivakumaran, K.S. and Rahman, N.A. (1998). A finite element analysis model for the behaviour of cold-formed steel members. *Thin-Walled structures* **31:4**, 305-324.

Skvortsov, V. and Bozhevolnaya, E. (1997). Overall behaviour of shallow singly-curved sandwich panels. *Composite Structures* **37:1**, 65-79.

Skvortsov, V., Bozhevolnaya, E. and Kildegaard A. (1998). Assessment of models for analysis of singly-curved sandwich panels. *Composite Structures* **41**, 289-301.

Smedley, P. and Bolt, H. (1994). Comprehensive guidance for the design and reassessment of tubular joints. *ISTS VI,* Melbourne, 183-190. Balkema.

SNAME (1994). Recommended Practice for Site Specific Assessment of Mobile Jack-Up Units. *SNAME T&R Bulletin*, 5-5A, First Edition.

Soares, C. and Garbatov, Y. (1997). Reliability Assessment of Maintained Ship Hulls with Correlated Corroded Elements. *MS* **10:8-10**, 629-653.

Soares, C. and Garbatov, Y. (1999). Reliability of Corrosion Protected and Maintained Ship Hulls Subjected to Corrosion and Fatigue, *Journal of Ship Research* **6**, 65 - 78.

Soares, C. and Gordo, J.M. (1996). Compressive strength of rectangular plates under biaxial load and lateral pressure, *Thin-Walled Structures* **24**, 231-259.

Soares, C. and Gordo, J.M. (1997). Design Methods for Stiffened Plates Under Predominantly Uniaxial Compression, *MS* **10**, 465-497.

Sully, R. and Hancock G.J. (1998). The behaviour of slender square hollow section beam-columns. *ISTS VIII*, Singapore. Balkema.

Tanaka, Y. and Matsuoka, K. (1996). Buckling strength of aluminum stiffened panels, Proc. of Japanese Symposium on the State-of-the-art for aluminum ships, *The Japanese Society of Light Metal Welded Structures*, November, 166-174 (in Japanese).

Tanaka, Y., Matsuoka, K., Kitamura, S. and Sakuma, M. (1996). Strength of Aluminium Alloy Members for Hull Structures - Buckling Strength. J. *SNAJ* **180**, 455-462, (in Japanese).

Teng, J. G. and Lou, Y. F. (1997). Post-collapse bifurcation analysis of shells of revolution by the accumulated arc-length method. *Int. J. Num. Meth. Eng*. **40**, 2369-2383.

Tovstick P.E. (1997). Post-buckling Axisymmetric Deflections of Thin Shells of Revolution under Axial Loading. *Technische Mechanik* **16**, 117-130.

Tovstick P.E. and Bauer S.M. (1998). Buckling of Spherical Shells under Concentrated Load and Internal Pressure. *Technische Mechanik* **18**, 135-139.

Tsouvalis, N.G. and Papazoglou, V.J. (1996). Large deflection dynamic response of composite laminated plates under lateral loads, *MS* **9**, 825-848.

Tsubogo T., George T. and Okada H. (1996). Dynamic Buckling Strength of Columns and Cylindrical Shells with Initial Deflections. *J. of the Kansai Society of Nav. Arch.* **226**, 169-176.

Ure, A., Grundy, P. and Eadie, I. (1996). Strain Concentration Factors and Load Capacity of Innovative Tubular Joints. *6th ISOPE* Los Angeles, **4**, 74-77.

Ueda (1998). See Volume III of this Proceedings.

Vafai, A., Estekanchi, H.E. (1999). A parametric finite element study of cracked plates and shells. *Thin-Walled Structures* **33**, 211-229.

Videiro, P.M. (1998). Reliability Based Design of Marine Structures, *PhD Dissertation*, Norwegian University of Science and Technology. Trondheim. Doktoringeniøravhandling, 118.

Vinson, J.R. (1999). The behavior of sandwich structures of isotropic and composite materials, Technomic *Publishing Co. Inc*. U.S.A.

Violette, F.L.M., Polezhayeva, H.A., Chung, H.W. and Cheng, F.Y. (1998). Basic parameters governing the fatigue of aluminum ships, *Proc. of the 3rd Int. Forum on Aluminum Ships*, Haugesund, Norway, May.

Vegte van de, G.J. and Wardenier, J. (1996). The static behaviour of multi-planar tubular XX-joints loaded by in-plane bending moments on the in-plane and out-of-plane braces. *ISTS VII*, Miskolc, 181-188. Balkema.

Vredeveldt, A.W., Journee, J.M.J. and Vermeer, H. (2000). The effect of crashworthiness and solid buoyancy on survivability of damaged and flooded Ro-Ro ships. Proc. of 7th Int. Confrerence on Stability of Ships and Ocean Vehicles. Edited by Renilson, M., Australia, 396-407.

Walker, A.C. and McCall, S. (1998). Experimental Investigation of Damaged Stiffened Cylindrical Shells. *Thin-Walled Structures* **30**, 79-94.

Walker, M., Adali, S. and Verijenko, V.E. (1996). Optimal design of symmetric angle-ply laminates subject to non-uniform buckling loads and in-plane restraints, *Thin-Walled Struct.* **26:1**, 45-60.

Wang, G. (1995). Structural analysis of ships' collision and grounding, Dr. Eng. Dissertation, Department of Naval Architecture and Ocean Engineering, University of Tokyo, Tokyo.

Wang, G. and Ohtsubo, H. (1997). Deformation of ship plate subjected to very large load. *OMAE* **2**, 173-180.

Wang, G., Ohtsubo, H. and Liu, D. (1997). A simple method for predicting the grounding strength of ships. *J. of Applied Mechanics* **41:3**, 241-247.
Wang, G., Ohtsubo, H. and Arita, K. (1998). Large deflection of a rigid-plastic circular plate pressed by a sphere. *J. of Ship Research* **6**, 533-535.
Wang, S. (1997). Buckling of thin skew fibre-reinforced composite laminates, *Thin-Walled Structures* **28:1**, 21-41.
Wang, S. and Dawe, D.J. (1999). Spline FSM post-buckling analysis of shear-deformable rectangular laminates, *Thin-Walled Structures* **34**, 163-178.
Wang, X. and Moan, T. (1997). Ultimate strength analysis of stiffened panels in ships subjected to biaxial and lateral loading, *Int. Journal of Offshore and Polar Engineering* **7:1**, 22-29.
Weissman-Berman, D., Lahiri, S. and Marrey, R. (1996). Flexural response of sandwich plates with core as elastic foundation, *Trans. SNAME* **104**, 491-518.
Weiß, E. und Postberg, B. (1998). Material-ratcheting, improved assessment of structural behaviour modern material models. *Materialprüfung* **40:11-12**, 475-479.
Witz, J.A. (1996). A case study in the cross-section analysis of flexible risers. *MS* **9**, 885-904.
Willibald, S., Herion, S. and Puthli, R.S. (1999). The Static Strength of Ring-Stiffened Tubular Joints. *9th ISOPE*, Brest, **4**, 18-24.
Wilmshurst, S.R., Morita, M., Sakae, S., Makino, Y. and Kurobane, Y. (1998). Static strength tests of CHS KT-joints under axial loading. *ISTS VIII*, Singapore, 269-276. Balkema.
Winkel de, G.D. and Wardenier, J. (1996). Parametric study on static behaviour of uniplanar I - beam-to-tubular connections loaded with in-plane bending moments combined with pre-stressed columns. *ISTS VII*, Miskolc, 229-236. Balkema.
Wirsching, P.H., Ferensic, J. and Thayamballi, A. (1997). Reliability with Respect to Ultimate Strength of a Corroding Ship Hull. *MS* **10:7**, 501-518.
Xuanling, W., Yifen, Z. and Haoran, C. (1996). Non-linear thermal buckling for composite laminate with elliptical delamination, *J. of Dalian University of Technology* **36**, (in Chinese).
Yamada, Y., Morita, M., Makino, Y. and Wilmshurst, S.R. (1999). A new ultimate capacity formula for unstiffened CHS T-, TT-, X-, K- and KK-joints under axial brace loads. *ISTS VIII*, Singapore, 213-220. Balkema.
Yao, T., Fujikubo, M., Varghese, B., Yamamura, K. and Niho, O. (1997a). Buckling/Plastic Collapse Strength of Wide Rectangular Plate under Combined Pressure and Thrust. *Journal of the Society of Naval Architects of Japan* **182**, 561-570.
Yao, T., Niho, O., Fujikubo, M., Vergese, B. and Mizutani, K. (1997b). Buckling/Plastic Collapse Strength of Ship Bottom Plating. *Journal of the Society of Naval Architects of Japan* **181**, 309-321, (in Japanese).
Yao, T., Fujikubo, M. and Nie, C. (1997c). Development of a Simple Dynamical Model to Simulate Collapse Behavior of Plates with Welding Residual Stresses under Inplane Load. *Transactions of the West-Japan Society of Naval Architects* **94**, 171-182.
Yao, T., Fujimoto, M., Yanagihara, D., Varghese, B. and Niho, O. (1998a). Influences of welding imperfections on buckling/ultimate strength of ship bottom plating subjected to combined bi-axial thrust and lateral pressure. *Thin- Walled Structures*, Research and development, 2nd Intl Conference on Thin-Walled Structures, 425-432.
Yao, T., Fujikubo, M., Yanagihara, D., Zha, Y. and Murase, M. (1998b). Post-Ultimate Strength Behavior of Rectangular Panel under Thrust. *Journal of SNAJ* **183**, 351-359, (in Japanese).
Yao, T., Fujikubo, M., Yanagihara, D. and Irisawa, M. (1998c). Considerations on FEM Modelling for Buckling/Plastic Collapse Analysis of Stiffened Plates. *Transactions of the West-Japan Society of Naval Architects* **95**, 121-128, (in Japanese).
Yao, T., Sumi, Y., Takemoto, H., Kumano, A., Sueoka, H. and Ohtsubo, H. (1998d). Evaluation of Strength of MS Nakhodka at the Casualty. *SNAJ* **183**, 443-453.
Yao, T, Sumi, Y., Takemoto, H., Kumano, A., Sueoka, H. and Ohtsubo, H. (1998e) Analysis of the accident of the MV Nakhodka. Part. 2. Estimation of structural strength, *Journal of Marine*

Science and Technology **3**, 181-191.
Yonemura, H., Makino, Y., Kurobane, Y. and Vegte van der, G.J. (1996). Tests on CHS planar KK - joints under anti-symmetrical loads. *ISTS VII*, Miskolc, 189-196. Balkema.
Young, B. and Rasmussen, K.J.R. (1997). Bifurcation of singly symmetric columns. *Thin-Walled Structures* **28:2**, 155-177.
Young, B. and Rasmussen, K.J.R. (1998a). Inelastic bifurcation analysis of locally buckled channel structures. *2nd International Conference on Thin-Walled Structures*, Singapore.
Young, B. and Rasmussen, K.J.R. (1998b). Tests of fixed-ended plain channel columns. *Journal of Structural Engineering* **124:2**, 131-139.
Young, B. and Rasmussen, K.J.R. (1999). Behaviour of cold-formed singly symmetric columns. *Thin-Walled Structures* **33:2**, 83-102.
Yu, X. (1996). Strukturverhalten mit grosser Verformung bis zum Brucheintritt und mit dynamischer Zusammenfaltung, Dr.-Ing. Dissertation, University of Hamburg, Hamburg, (in German).
Yu, Y. and Wardenier, J. (1996). Analytical and numerical investigation on the static strength of full width RHS X - joints under differential load cases. *ISTS VII*, Miskolc, 197-204. Balkema.
Yu, Y., Liu, D.K. and Wardenier, J. (1998). The static behaviour of multiplanar XX-joints loaded with in-plane bending moments and axial forces. *ISTS VIII*, Singapore, 157-164. Balkema.
Yushanov, S.P. and Bogdanovich, S.E. (1998). Analytical Probabilistic Modelling of Initial Failure and Reliability of Laminated Composite Structures, *Int. J. of Solids and Struc.* **35:7-8**, 665-85.
Zeinoddini, M., Harding, J.E. and Parke, G.A.R. (1998). Effect of impact damage on the capacity of tubular steel members of offshore structures. *MS* **11**, 141-157.
Zettlemoyer, N. (1996). ISO Harmonization of Offshore Guidance on Strength of Tubular Joints. *6th ISOPE*, Los Angeles, **4**, 9-14.
Zenkert, D. (1995). An introduction to sandwich construction, *Engineering Materials Advisory Services*, Ltd., London.
Zenkert, D. (1997). The handbook of sandwich construction, *Engineering Materials Advisory Services* Ltd., London.
Zhang, S. (1999). The mechanics of ship collisions, Ph.D. Thesis, Department of Naval Architecture and Offshore Engineering, Technical University of Denmark.
Zhao, X.L. (1996). Verification of the deformation limit for T-joints in cold formed RHS sections. *ISTS VII*, Miskolc, 183-190. Balkema.
Zhu, L. and Faulkner, D. (1996). Damage estimate for plating of ships and platforms under repeated impacts. *MS* **9:7**, 697-720.

BOSS	International Conference on Behaviour of Offshore Structures,
DMCGPS	Designs and Methodologies for Collision and Grounding Protection of Ships,
ISOPE	International Offshore and Polar Engineering Conference,
ISTS	International Symposium on Tubular Structures,
MS	Journal of Marine Structures,
OTC	Offshore Technology Conference,
PRADS	Practical Design of Ships and Mobile Units.