15th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS 2003
AUGUST 11-15, 2003
SAN DIEGO, USA

VOLUME 1

COMMITTEE III.1
ULTIMATE STRENGTH

COMMITTEE MANDATE

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

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KEYWORDS

Ultimate strength, plated structures, stiffened panels, offshore structures, ship structures, buckling, yielding, ductile, fracture, structural collapse, steel structures, aluminium structures, heat affected zone, composite structures, imperfections, in-service degradation, uncertainties, reliability

CONTENTS

1. INTRODUCTION

This is the report of the ISSC Technical Committee III.1 on Ultimate Strength covering the period from 2000 to 2003.

Despite its relatively long life, the area of ultimate strength is still being actively investigated and developed by practitioners and researchers worldwide. Indeed, many of the large maritime disasters that have occurred throughout the world over the past decade (Erika, Nakhodka, Prestige, P-36) are related to ultimate loads and strength. This type of public disaster will most likely continue to remind us about the importance of the field.

Accurate assessment of the ultimate strength of a structure is important not only for the initial design but also for the operation, maintenance, repair, and modification of the structure. The range of structures and materials for the initial design is obviously quite wide. When the types of in-service degradation are to be considered, the range of structures and loads becomes enormous. With approximately 250 papers and books referenced, the present report covers a good part of those configurations. But as it will appear, the growing demand for optimum structures throughout a structures lifetime makes plenty of room for improvements and expansions.

Chapter 2 outlines the fundamental ingredients of the area of Ultimate Strength. Chapter 3 discusses empirical and analytical methods. Chapter 4 covers numerical methods, i.e. mainly the finite element method but also advances in the alternative mesh-free methods and general solution techniques. Chapter 5 describes some new, interesting experimental methods of relevance to ultimate strength. Chapter 6 covers reliability methods. Chapter 7 discusses tubular members and joints, mainly of interest for offshore structures. Chapter 8 covers work on stiffened and unstiffened plates which are the fundamental building blocks for ships. Chapter 9 covers shells, i.e. curved plate structures, which might be used in pipelines. Chapter 10 and 11 cover ship and offshore structures, respectively, i.e. the strength of a system composed of the components considered in the previous chapters. Chapter 12 and 13 cover ultimate strength issues for non-ferrous structures, i.e. composite and aluminium, respectively. Finally, Chapter 14 shows the results of a comprehensive study carried out by the Committee members with the objective to investigate the strength of welded aluminium panels subject to axial compression.

2. FUNDAMENTALS

2.1 General

The maximum load carrying capacity, here called the ultimate strength, is of relevance for

- parts of a structure such as a stiffened plate, a tubular member or a joint,
- substructures such as a bulkhead, hatch cover or deck, or
- entire assembled structures such as a hull girder in bending or a steel jacket subjected to overturning forces.

Ideally, global ultimate strength should be achieved in a ductile and predictable manner. In practice this is difficult to achieve because elements of a structure might fracture in regions of high plastic strain in tension, or they might shed load rapidly as buckling occurs with some local yielding. Even if overall failure is less than fully ductile, it is important that components exhibit significant post-elastic deformation capacity.

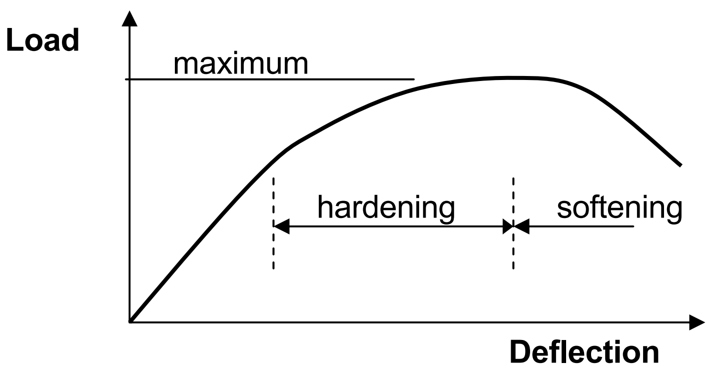


Figure 1 Load-deflection characteristics of a structural element

Figure 1 describes typical load-deformation behaviour of a structural element. The hardening domain of behaviour which follows the initial elastic behaviour is important for redistribution of actions within a structure after yielding commences so that the structural elements share carrying the load more equally. If the weakest element fails too quickly then overall collapse can be triggered by a local failure. This is the tripping phenomenon of stiffened plate, which has the potential to cause overall collapse. For these reasons it is not sufficient to have a formula for ultimate strength of an element. The ductility characteristics must also be known. This is only possible with a combination of laboratory testing and historical analysis in the time domain.

Another reason for historical analysis is concerned with impact loading such as grounding and collision. In this case the load-deformation relationship is needed to determine the energy absorbed.

Of course the value of the ultimate load capacity and confidence are vital questions for assessing the lifetime safety of a structure subjected to operational and environmental loads. Practical design requires knowledge of the ultimate load capacity and the degree of certainty with which that is known – typically represented by a probability distribution function, or at least data on standard deviation. Therefore one needs to know the *sensitivity* of the estimate of structural ultimate strength to variable factors affecting strength.

2.2 Types of Loading

It is appropriate to recall the types of load as stated in the 14th ISSC related to ultimate strength.

"Slowly" applied loads
The majority of loads to be considered fall into this category. These are environmental and operational loads due to wind, wave, current, cargo, drilling, etc., including inertial forces due to motion of the structure. The loading rates are slow enough for there to be no elevation of yield stress through high strain rates, or shock waves through the structure. There are generally statistical parameters regarding the distribution of these loads through the design life of the structure.

Cyclic loads
This is the case of repeated loads of high amplitude, relatively few in number, resulting in alternating or incremental plasticity. Such loads can arise from waves in a single storm, or an earthquake.

Dynamic (impulsive) loads
These are loads of duration less than or in the order of the period of vibration of the global or local structure at the point of impact. Wave slam and supply vessel docking forces are typical examples. Inertial forces are significant in mitigating maximum load effects, and elevation of yield stress due to high strain rates can be significant. An extreme case is impulsive loading due to explosion.

Crash loads
Major collisions and grounding accidents are examples of crash loads, which are covered by another ISSC Committee. In this case energy absorption is the most significant issue. Material strain rate effects, tearing, buckling, large plastic deformations, friction and ductile fracture are typically involved.

2.3 Forms of Collapse

Single excursion failure
This is the case of collapse under monotonic loading established by time series analysis. It is the basic case for assessment of safety under operational and environmental loads. It includes the effects of nonlinear material and geometric behaviour, and the parameters affecting ultimate strength as listed below.

Cyclic failure
Load capacity under cyclic loading can be significantly less than the "static" strength under a single load excursion. Alternating plasticity can occur under fully reversed loading. Without accumulating visible permanent deflection the material subjected to alternating plasticity will rupture. It can be described as low cycle fatigue. Typical locations of such failures will be at discontinuities, such as misaligned butt welds in members and geometric discontinuities at joints. More often the loading is not fully reversible and incremental collapse occurs. Permanent deflections are seen to grow with each cycle of load until the structure becomes unserviceable or local ductility is exhausted at geometric discontinuities, resulting in fracture.

<u>*Crushing and tearing*</u>
This form of failure is typically associated with collision or grounding, where the load is, in fact, an accident. Here, the issue is energy absorption, and in the case of tankers, for example, integrity of containment.

2.4 Assessment of Ultimate Strength

Practical design is traditionally achieved by using simplified models of load and load effect, assuming elastic behaviour of the material, to be compared with simplified models of strength of both elements and the whole structure. These simplified models of strength are derived from extensive experimental, analytical and numerical studies where conservative combinations of imperfections, residual stress, thickness loss, etc., are assumed. Formulas for hull girder strength, stiffened panels, tubular joints, etc., are being refined as more and more studies are carried out, and as new materials and forms are considered.

However, as computational power increases, it is becoming feasible to contemplate direct analysis of ship and offshore structures combining computational fluid dynamics (CFD) with structural finite element modelling. For this reason, this report includes chapters on empirical, analytical, numerical and experimental methods. There have been significant advances in numerical modelling (for example finite element modelling, FEM) that have made it possible for a structural engineer to predict the ultimate strength of highly complex structures by non-linear modelling.

2.5 Sensitivity Assessment

Still, due to the complexity and uncertainties involved in ultimate strength predictions, any analysis – as well as this report – should include considerations regarding the sensitivity of the strength to
- material behaviour, such as material yield stress, ultimate strength, and strain hardening,
- initial geometric imperfections and residual stresses due to welding and assembly,
- plate thickness including thickness loss (from corrosion),
- mechanical damage resulting from service, for example fatigue cracks or impact dents,
- loading rate, load introduction, alignment of actions, and boundary conditions.

Chapter 15 of this report by Committee III.1 contains an example of a sensitivity analysis of a stiffened aluminium panel continuous over three spans, subjected to axial compression.

Many more such studies are needed to establish the basis for a fully rational risk-based design.

3. EMPIRICAL AND ANALYTICAL METHODS

3.1 Needs for empirical and analytical methods

For an accurate estimation of the ultimate strength of structural members and systems, it is necessary to simulate the collapse behaviour considering the influences of yielding and buckling. In theory, the most versatile and accurate method to perform such an analysis is the FEM. However, incremental analysis is in general required, and this causes troubles related to computation time and memory in some cases. To avoid this, non-finite element methods are also used for strength analysis of ship structures. They can be grouped into two, which are empirical methods and analytical methods.

3.2 Empirical methods

Paik *et al* (2000a) derived empirical design formulas to evaluate buckling strength and ultimate strength of a rectangular plate subjected to general combined load on the basis of analytical and numerical results. In deriving the formulas, influences of initial imperfections, perforations *etc.* were considered. Paik and Thayamballi (2000) derived empirical design formulations to evaluate the local buckling strength of a stiffened plate by curve fitting on the basis of the analytical solutions considering the influence of constraint by stiffeners. Regarding the ultimate strength of stiffened plates, Paik and Kim (2002) derived advanced, yet design-oriented ultimate strength expressions for stiffened panels subjected to combined axial load, in-plane bending and lateral pressure assuming six patterns in collapse mode. These formulas were used by Paik *et al* (2002) to estimate the ultimate longitudinal strength of ship hulls.

For the perforated plate subjected to uni-axial thrust both in longitudinal and transverse directions, Yao *et al* (2001a, 2002c) derived simple formulas to evaluate the elastic buckling strength and the ultimate strength on the basis of the results of FEM analyses. Harada and Fujikubo (2001) also derived the empirical formulas for the same problem.

The average stress-average strain relationship for rectangular plates under uni-axial thrust was generated on the basis of the existing design formulas for both long and wide rectangular plates by Hu and Sun (1999). Hu *et al* (2001) used this relationship to evaluate ultimate hull girder strength of bulk carriers.

3.3 Analytical methods

Fujikubo and Yao (1999) derived an analytical formulation for accurate estimation of the elastic local buckling strength of a continuous stiffened plate subjected to bi-axial thrust considering the influences of plate/stiffener interaction and welding residual stress. The stiffener web was modelled by a plate, and very accurate buckling strength was obtained as indicated in Figure 2.

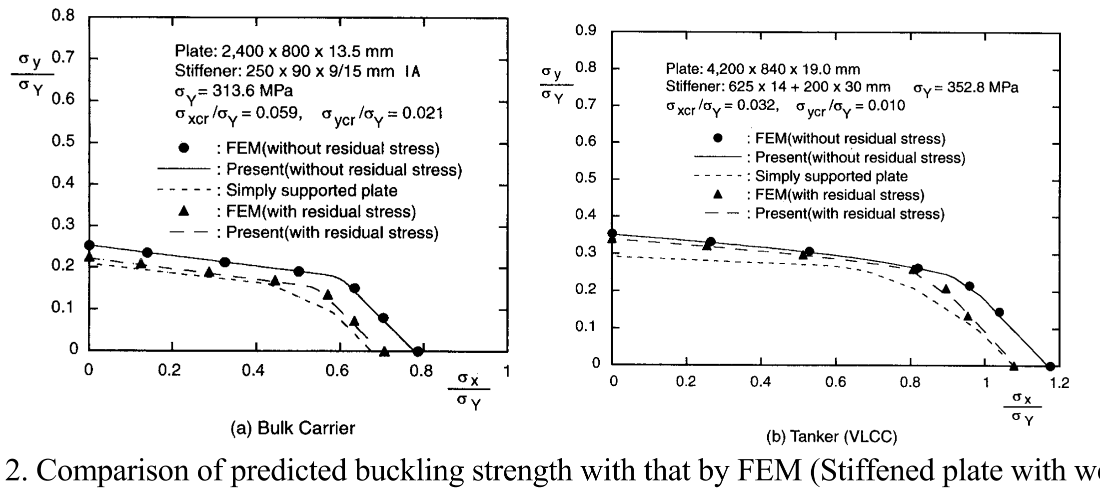


Figure 2. Comparison of predicted buckling strength with that by FEM (Stiffened plate with welding residual stress: σ_x, σ_y are buckling stresses and σ_Y is yield stress). Fujikubo and Yao (1999).

Murakami *et al* (2002) show an analytical formulation to simulate dynamical elastic secondary buckling accompanied by dynamical snap through. The analytical results showed good correlation with the FEM results. Cui *et al* (2002) generalised simplified analytical method to deal with ultimate strength of rectangular plates accompanied by initial deflection and welding residual stress under the combined bi-axial thrust, shear and lateral pressure loads.

Analytical and numerical methods are combined to simulate the elastoplastic large deflection behaviour of plates by Paik *et al* (2001b). That is, geometrical nonlinearity was treated by analytically solving the nonlinear governing equations of the elastic large deflection plate theory, while material nonlinearity is dealt with implicitly by using a numerical procedure.

To simulate the elastic/plastic buckling behavior of a simply supported rectangular composite plate subjected to edge compression, a theoretical approach based on the plastic theory has been developed by Soh *et al* (2000). For the analysis on composite laminated plates exposed to a combined loads, Yang and Zhang (2000) tried semi-analytical approach. In this approach, the formulations were based on the classical laminated plate theory (CLPT), and include the plate-foundation interaction effects via a two-parameter model (Pasternak-type) from which Winkler elastic foundation can be recovered as a limiting case.

Xue and Hoo Fatt (2001) used a five-plastic-hinge model to describe the non-axisymmetric post-buckling collapse of non-uniform circular ring subjected to external pressure loads. In the formulation, the principle of virtual work and upper bound theorem are applied to find the collapse pressure and collapse mode. The plastic hinge method was also applied in combination with geometrical nonlinearity by Kim *et al* (2002) to analyse the collapse behaviour of a space frame considering the influence of lateral torsional buckling. Tian *et al* (1999) performed a rigid plastic mechanism analysis to find the post-buckling response, and the Ritz method was applied to evaluate elastic buckling strength of shells with ring-stiffeners under general pressure load.

Hu *et al* (2000) simulated a tripping of stiffeners in stiffened panels subjected to combined loads on the basis of the Vlasov's differential equation for torsional buckling by applying the Galerkin's Method. In their formulation, a beam-column approach is employed taking into account the influence of panel local buckling on the constraint.

Paik *et al* (2001d) modelled a stiffened panel as an equivalent orthotropic plate, for which various elastic constants characterising structural orthotropies are determined in a systematic manner using classical theory of elasticity. The ultimate strength is determined from the condition that the highest edge stress reaches the yielding stress. The ultimate strength interaction relationships are also derived.

Byklum and Amdahl (2002) derived analytical formulations to simulate elastic buckling and post-buckling behaviour of local panels in stiffened plating subjected to combined loadings. In their formulations, deflection of a panel is expressed as a sum of simply supported mode and clamped mode, both consisting of trigonometric series. The stiffener web is also treated as a plate but overall deflection of the stiffened plating is not considered. The calculated results showed good correlation with FEM results. The ultimate strength is defined as the initial yielding strength on the basis of the Von Mises' yield condition.

Hopperstad *et al* (1999) applied the classical Stowell's theory for plastic buckling to evaluate the ultimate compressive strength of aluminum stiffened plate in combination with the effective width concept, and with ultimate strength formulas recommended in the literature.

4. NUMERICAL METHODS

4.1 General

Numerical methods, such as the finite element method (FEM) and the mesh-less or particle method, have been an area of extremely active worldwide research for the last few decades. Therefore, it would be formidable task to review all published papers on the subjects (probably several thousand papers a year). The focus of this chapter is only on some recent developments in FEM and mesh-less or particle methods for the ultimate strength assessment and non-linear analysis of the thin-walled structures.

4.2 Finite Element Method

Finite element simulations generally involve the solution of large sparse linear systems of equations for modeling in ever increasing detail geometrical and physical features. In order to meet such time and memory consuming demands for solving these equations, considerable research has been carried out for the application of parallel mathematical operations in a finite element analysis due to the widespread availability of parallel machines with large memory. Scott (2001) presented the development of the parallel frontal solver for finite element equations based on dividing the finite element domain into subdomains and applying the frontal method to each subdomain in parallel. Farhat *et al.* (2000) present the newly developed transient finite element tearing and interconnecting (FETI) methods and their application to the parallel analysis of large-scale linear and geometrical nonlinear structures. The numerical examples show that the present FETI method operates more efficiently on large numbers of subdomains and offers greater robustness, better performance, and more flexibility for implementation on a wider variety of computational platforms.

It is generally recognized that the return mapping algorithms, such as the radial return method, the closest point projection method and the spectral return-mapping method are robust and efficient for large inelastic computations. Lof *et al.* (2001) propose an adaptive return mapping algorithm for the integration of elasto-viscoplastic constitutive equations based on a combination of the beginning and end of the increment. Lee and Fenves (2001) present the stress updating formulation and consistent tangent modulus for rate-independent plastic-damage models on the basis of the spectral return-mapping algorithm. The equations were expressed in terms of the principal stresses and plastic multiplier in the spectral return-mapping scheme and the update stresses and plastic strains as well as the scalar parameter for damage are obtained by solving a nonlinear scalar equation.

Error control and adaptive algorithms play an important role in improving the approximation behavior of FEM. The error estimation and adaptive mesh generation were initially proposed in the 1970s for estimating the discretization error resulting from finite element analysis of linear problems based on residual and average error criteria. Subsequent studies on adaptive FEM based on error estimation were extended to include consideration of geometrical and material nonlinearities. Ladeveze (2001) developed a posteriori error estimators based on constitutive relation residuals, in which the classical error sources such as the space discretization, the time discretization and the iterative technique are included. Lopez (2001) presents an asymptotic predictor-corrector algorithm based on residual error minimization for tracing the equilibrium path of geometrically nonlinear plates and shells. Mang *et al.* (2001) present the practical application of adaptive FEM in ultimate load prediction of reinforced concrete shells. Askes and Rodriguze-Ferran (2001) propose a so-called rh-adaptive approach in order to combine the advantageous properties of both r-adaptive and h-adaptive strategies. It is performed by means of splitting the domain under consideration into two subdomains and the h-adaptive scheme is employed in one subdomain whereas the r-adaptive approach is used in the other subdomain. Duster *et al.* (2001) present an implementation of a three-dimensional p-adaptive FEM for curved thin as well as thick walled structures based on a hexahedral element formulation and the blending function method. Hand and Wriggers (2000) derived an error indicator for h-adaptive analysis of elastoplastic shells based on the super-convergent patch recovery procedure.

Another great important issue in FEM is the element model. Iintensive research efforts have been devoted and different techniques have been used to develop "simple, robust, generalized, extended, refined, efficient, modified, …" element models. Kolahi and Crisfield (2001) present a large strain elastoplastic shell formulation based on the co-rotational description of the faceted Morley triangle. The obtained formulation is invariant to the node numbering by re-visiting the origins of the Morley triangle and re-casting the formulation as a special form of discrete Kirchhoff approach. Levy and Gal (2001) introduce a new approach to the geometrical nonlinear analysis of shells by perturbing the equilibrium equations. All contributions to the response of the same order of magnitude are included. Zielinski and Frey (2001) discuss the transformation and linearization of the finite element equations and present the expressions for the tangent matrix in the framework of the Total Lagrangian, Updated Lagrangian and co-rotational formulations.

Wang and Theirauf (2001) propose the two modifications for the finite rotation formulation and for the rotation update scheme in order to avoid the singularity of the rotation update procedure and improve the numerical stability of the iterative solution algorithm. Ibrahimbegovic *et al.* (2001) developed alternative parameterizations for constrained finite rotations in terms of the chosen rotation vector. The modification of finite rotation expression leads to a symmetrical tangent stiffness matrix and the simple implementation of the proposed additive iterative updates. The other typical research activities were the works of Hauptmann et al. (2000) on the application of the solid-shell concept for nonlinear analysis of large elastoplastic deformations and the works of Maccarini et al. (2001) on the nonlinear finite element formulation for shells of arbitrary geometry.

In recent years, the rotation-free shell element models have attracted considerable attention, in which the curvatures over an element are approximated in terms of the deflection of the nodes in a surrounding patch of elements. It leads to several advantages of the rotation-free shell elements, such as it becoming unnecessary to process finite rotational increments in nonlinear analysis, compared to the conventional shell elements with both translational and rotational degrees of freedom. Onate and Zarate (2000) present a general methodology for deriving rotation-free thin plate and shell triangular elements based on the combination of the standard finite element interpolation with finite volume concepts. Flores and Onate (2001) made an extension to nonlinear analysis of plates and shells by using an updated Langrangian formulation and elastic plastic model. The element performance is better than that of conventional triangular elements for linear problems in terms of the degrees of freedom. Very good results have been obtained in several examples including large displacement and large strain problems.

Motivated by the significant progress in computer-aided geometrical design, Cirak and Ortiz (2000) developed a so-called subdivision element model for thin shell analysis based on the subdivision surface concept. The element energy is given by a direct evaluation of the Kirchhoff-Love energy function. However, it is different to conventional element interpolation, as the displacement field of the subdivision element is interpolated from nodal displacement only and does not need nodal rotations. The displacement field within the subdivision element is dependent not only on the displacements of the nodes attached to the element but also on the displacements of all the immediately adjacent nodes in the triangulation. Recently, Cirak *et al.* (2001) extended the subdivision element to nonlinear shell analysis accounting for finite membrane and bending strains as well as thickness stretching and large deflections.

4.3 Mesh Free Method

Research efforts have recently been directed to eliminating or at least easing the requirement for meshing the domain to be analyzed. Most mesh-free methods do in fact need a mesh for the integration required in the principle of virtual work, so 'mesh-free' only refers to the fact that the spatial interpolation is carried out without a mesh. The interpolation functions are related to a node (a particle), which extend in all special directions and are therefore not confined to an element.

Comprehensive overviews of the theory and application of mesh free methods can be found in Belytschko et al (1996) and Li and Liu (2002).

The methods usually suffer from an important computational cost. Therefore, a combined approach based on coupling of FEM and mess-less or particle method is expected to achieve cost-effective procedure for practical application as discussed by Huerta and Mendez (2000).

The element free Galerkin method (EFG) was developed by Krysl and Belytschko (1996) for numerical analysis of the thin plate/shell based on Kirchhoff theory. It was extended by Donning and Liu (1998) to the analysis of moderately thick/thin beams and plates by using Mindlin-Reissner theory. Good convergence was achieved by using moving least-square interpolation functions and cardinal spline interpolation functions respectively. Recently Noguchi *et al.* (2000) enhanced EFG to deal with three-dimensional general shell and spatial structures by mapping the geometry of arbitrary curved surfaces in the two-dimensional space. The total Lagrangian formulation is employed to process the geometrical nonlinear behavior and the bi-cubic and bi-quadratic basis functions are adopted in the moving least square interpolation. Leitao (2001) proposes a mesh-less method for the approximate solution of the Kirchhoff plate problem based on the radial basis functions. The governing equations and the boundary conditions of the plate are satisfied at selected points by using the Hermite collection method. The formulation of this EFG method is straightforward and is similar to the degenerated approach in the FEM.It is also very simple to implement, computationally efficient and expected to be useful for more practical applications in engineering problems.

Yagawa and Furukawa (2000) presented a free mesh method (FMM), which is performed on a node-by-node basis without the global meshing. The FMM represents the domain to be analyzed in the discrete form of the appropriate allocation of nodes for creating local elements with a prescribed radius. The local elements are performed at each node in an autonomous manner according to the nodal information. The modifications of FMM have been proposed by Furukawa *et al.* (2000) with quadrilateral elements instead of the triangular elements to improve the accuracy of simulation. The FMM has good compatibility with parallel computers because its nodal information can be individually distributed to processors and the local elemental equations for each node are all constructed and analyzed in the processors independently. The significant advantage of FMM in comparison to other mesh-less methods is the reliability of its solution as the construction of the global equations is based on FEM, which has a documented level of accuracy.

4.4 Idealized Structural Unit Method (ISUM)

The ISUM can be regarded as a kind of FEM, but the elements (structural units) used in ISUM are usually more sophisticated and a larger part of the structure is considered as an element when it is compared the ordinary FEM. The theoretical background and the development of the ISUM were well explained by Ueda (2000). According to this, ISUM can be divided into two categories, which are ISUMs of the first generation and the second generation. ISUMs of the first generation were based on the empirical formulations derived from the observations of the experimental and numerical/theoretical results, while the second generation is on the basis of mathematical approximations.

The ISUM of the second generation could be said to be a very sophisticated method, but at present it still fails to simulate the actual collapse behavior accompanied by the localization of plastic deformation at a certain region and the resulting elastic unloading at remaining regions in the post-ultimate strength range. This is because a periodical deflection mode such as a buckling mode is assumed for the shape function of the element even beyond the ultimate strength. To overcome this problem, Fujikubo *et al*. (2000a) developed a new shape function for the lateral deflection of ISUM rectangular plate element. They proposed a new lateral shape function, which consists of two deflection terms on the basis of the characteristic deflection modes, observed in the collapse simulation by FEM. The ratio of the two deflection terms changes depending on the average strain. The applicability and the favorable accuracy of the newly proposed ISUM element have been demonstrated through comparison of the calculated results by ISUM and FEM analyses. Figure 3 shows the comparison of the element representation by FEM, ISUMs of the first and the second generations and new ISUM for the case of a rectangular plate subjected to longitudinal thrust.

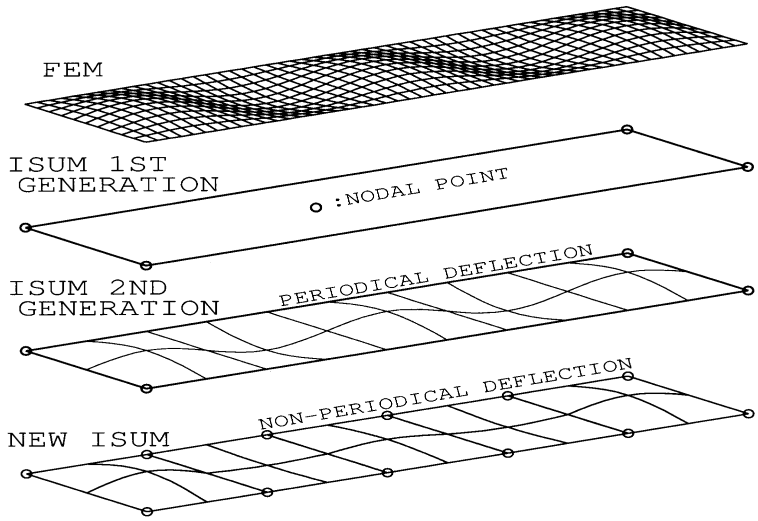


Figure 3. Comparison of element representations by different methods of analyses (Rectangular plate subjected to longitudinal thrust). Fujikubo *et al*. (2000a).

Fujikubo et al. (2000b) extended this ISUM element with a new modeling technique to evaluate overall buckling of stiffeners with attached plating as well as local buckling of plates. The collapse behavior of stiffened plate under bi-axial thrust as well as uni-axial thrust is simulated by this ISUM plate element in combination with a beam-column element. Kaeding and Fujikubo (2001) used this new ISUM element to simulate collapse behavior of a VLFS. Recently, Fujikubo *et al*. (2002) developed new ISUM elements to analyze the collapse behavior of double bottom structures. Large plate elements and beam-column elements are used for inner and outer bottom plating and stiffeners, respectively, and Timoshenko beam elements for webs of girders and floors. All the elements can simulate buckling/plastic collapse behavior. With these elements, fundamental collapse modes with localized failures in double bottom structure were obtained under pressure loads, see Fig. 6 in Chapter 11.

5. EXPERIMENTAL METHODS

Due to the complexity of the phenomena involved in the prediction of ultimate strength, experiments will continue to be important for development and validation. Experiments should here be understood as conventional laboratory experiments as well as in-service and inspection monitoring. In addition to the specific methods listed in this chapter, examples of experiments will be presented in Figures 4, 5, 6 and 8.

5.1- Resonance Thickness Measurement (RTM)

Resonance Thickness Measurement (RTM) has been developed by Det Norske Veritas and Kongsberg Defence & Aerospace. The RTM method is based on the time an ultrasonic wave takes to travel through the thickness of a steel plate and return to the receiver. The technique effectively performs an integration over the area insonified by an acoustic pulse and over the frequency band of interest, yielding a measure of re-radiated energy in a given frequency band. The result can be directly translated into an estimate of the thickness within the insonified area. The acoustic technology may also be employed with other purposes, like determining whether corrosion is on the inside or on the outside of a pipe. This is enabled by the exact determination of the distance from the transducer's face to the reflecting surface.

There is also a very good signal-to-noise ratio for the RTM, that insures a good repeatability of the measurements. The reflected pulse is a result of the environmental influence upon the emitted pulse and it holds all the information about that environment. The receiving transducers and the processing software extract the desired values from the received pulse. A notable point is that the lower frequency range from RTM enable the signal to pass through graphitic and rust corrosion, in contrast to standard ultrasonic methods.

So far, the method was tested by DNV with good results, also on cast and ductile cast iron pipes. It was shown that the presence of rust does not affect the estimate of the steel thickness. Unfortunately no literature on the subject is made public at present.

5.2- Ultrasonic Stress Measurements

Research efforts have been invested in ultrasonic stress measurements during the last decade. Ultrasonic measurements are not only used to determine the thickness, but also for stress measurements. The ultrasonic methods are based on the stress sensitivity to ultrasound wave speed through the solid, Schneider (1997). Dependency is established using the Poisson ratio and Lame's material constants.

Noise factors can influence the measurement results because the stress-induced changes in the wave velocity are quite low. Material grain orientation, also known as texture, and the temperature are of great importance. Material acoustic constants are determined prior to the measurements. The calibration phase normally takes place using a free stress specimen.

Ultrasonic methods provide a measure of the macro stresses over a material volume. They are quick to implement, and are generally considered to be an attractive engineering tool. These methods are suitable for stress measurements in shipbuilding steel plates, thus providing important information about the plate buckling reserve.

5.3 - Strain Measurements with Thermovision

Thermovision is a new method used for the strain analysis of loaded steel members even into the plastic range, Pasternak and Müller (2002). It enables the visualization of the strain under variable loads. In this method, a high resolution infrared camera is employed to scan the heat radiation at the surface of the loaded structural member. A change of load will affect the heat radiation almost simultaneously.

The main principle behind the method is the transformation of the internal energy into heat that takes place especially by the plastic straining of the material. It enables the strain examination beyond limitations imposed by strain gauges. Moreover, the thermo-vision allows the strain visualization over an area, not only at a point, thus providing valuable information about the strain gradient. It should be noted that the thermal properties of surface coating are important, as they could prevent a proper scanning.

Infrared cameras are becoming less expensive, as well as being available nonmilitary applications. Dimensions of the domain to be studied are indeed limited by the possibilities of the camera, so the critical regions are to be localized and observed from the beginning.

6. RELIABILITY

This chapter addresses published research on the ultimate strength reliability of structural components and systems of ships and offshore structures.

In reliability analysis, limit state functions are normally expressed by the difference in capacity (resistance) and load effect. Therefore determining the uncertainties of capacity and load effect is very important. Uncertainties relating to load effect will be considered in other committees. Only the uncertainties of capacity will be discussed in this section.

In the structural analysis of ships, the analysis is conventionally divided into three different levels, namely primary strength, secondary strength and tertiary strength. This was initially proposed for deterministic analysis. The same idea is also used in reliability analysis. Tertiary strength is concerned with the strength of local components, such as openings, and mainly about fatigue performance. So it is out of the scope of this committee. The reliability of ultimate strength of only stiffened panels (secondary strength) and hull girder (primary strength) will be discussed here.

6.1 Ultimate Strength Modelling Bias and Uncertainties

Prediction of uncertainties involved in structural design is an important part of structural reliability analysis. Quite a few of publications were reviewed in the last ISSC report, but there are not many papers on this subject in this period. Soriano et al (1999) have presented the biases and uncertainties of foundation capacity along with metocean parameters, wave forces and tubular joints of offshore platforms.

Cui et al (2001) have proposed a method for calculating the mean and standard deviation of a function of random variables. In this method the mean and standard deviation of a function are calculated by a set of formulae, in which the mean and standard deviation of each random variable are used. The method has an accuracy of at least the second order Taylor series solution. New definitions of sensitivity factors were introduced. The uncertainties of ultimate strength of a stiffened panel were then estimated by this method.

In addition to their work reported in last ISSC'2000, Rigo et al (2001) presented more results on the uncertainties in prediction of ultimate hull bending moment using progressive collapse analysis. Several methods were used to generate average stress-strain curves of stiffened panels. The effects of these curves on the ultimate strength of hull girder were systematically investigated. In recognition of the importance of average stress-strain curves in ultimate hull girder strength prediction, Pradillon et al (2001) have carried out a comparative study for the prediction of ultimate strength of stiffened panels. Eighteen methods for predicting ultimate strength of stiffened plates were studied. Multi-criteria were used to assess these methods. Those methods that can quickly produce average stress-strain curves were further compared. The effects of these stress-strain curves generated by different methods on the ultimate strength of a box girder were demonstrated.

6.2 Ultimate Strength Reliability Analysis

In reliability analysis of plates, analytical formulae for ultimate strength prediction, which are validated by experimental data, can be conveniently used. All the reliability methods, especially first order and second moment (FORM), can be applied for this type of analysis because the limit state functions are explicitly expressed. But if more sophisticated methods are adopted for predicting the capacity of plates, such as non-linear finite element methods, the limit state function has implicit form. In this case, FORM is arguably not suitable, so other methods have to be used. The response surface method is considered as a good candidate.

Kmiecik and Guedes Soares (2002) applied a response surface method to determine the probability distribution of ultimate strength of plates. A linear response surface of the ultimate strength of unstiffened plates under compression was constructed based on the results of non-linear finite element prediction. The mean values of ultimate strength from the response surface method agree well with those from Monte Carlo simulation, but the standard deviations differ quite a lot. This methodology can be used when there is not an explicit limit state function in reliability analysis.

Zheng and Das (2000) carried out a reliability analysis of a stiffened plate using a new response surface method. In the analysis, the critical bucking of the plate was considered and predicted by the commercial finite element analysis package ABAQUS. These results were used to establish a failure surface function. In the proposed response surface method, a linear response function was first developed. The second order terms were then added to improve the accuracy.

A series of reliability analyses were carried out to determine the allowable imperfection tolerance of unstiffened plates under uniaxial compression, Mansour and Elsayed (1999). The ultimate strength of unstiffened plates was predicted by a simplified formula, in which initial deflection and residual stresses can be considered. Reliability analysis was performed under the assumptions that both resistance and applied stresses are normally distributed with a coefficient of variation of 10%. The allowable imperfection tolerance was presented as a function of plate slenderness.

In the reliability analysis of hull girder the way to predict hull girder failure could be classified into two categories:

(1) using an analytical formulation to predict the strength. Hence FORM can be applied to these cases.
(2) using progressive collapse analysis to predict the ultimate strength of hull girders. Even in this category, there are variations in how to carry out reliability analysis. One way is to calculate the mean value of the ultimate strength by a progressive collapse analysis method, and assume the c.o.v. of the ultimate strength is about 10-15%. In this way, FORM can be used for reliability analysis. The other way is to integrate a progressive collapse analysis method into a reliability analysis method. The limit state function then has implicit form.

The failure probability of bulk carriers was predicted for two different structural arrangements, namely single hull and double hull forms, Guedes Soares and Teixeira (2000). In the calculation of reliability index, a first order and second moment method was used. The extreme values of stillwater bending moment and wave-induced bending moment were adopted. An empirical formulation was used to consider the difference between sagging and hogging bending moment. The ultimate strength of the hull girder is used as measure of the failure of the ships. The uncertainty of ultimate moment was counted by using a model uncertainty factor with a mean of unity and a c.o.v. of 15%. The results show that the reliability of the double hull ship is higher than that of the single hull ship. In addition, the effect of corrosion on the reliability of the hull girder was also assessed. The paper also shows the dependency of predicted reliability on the definition of applied loadings.

A reliability analysis was carried out to predict the failure probability of floating production storage and off-loading systems (FPSO) by Maerli et al (1999). The ultimate strength of the hull girder was estimated by Lloyd's program LRPASS. The Ferry Borges-Castenheta load combination method was used to evaluate load combination factors for combining stillwater bending moment and wave-induced bending moment. Three different FPSOs were assessed. Their reliability indices were compared with those recommended by DNV rules. A similar methodology was applied to predict the reliability of a naval vessel by Das and Dow (2000). Instead of using Lloyd's program LRPASS, a non-linear analysis program, FABSTRAN, developed by Dow and Smith (1986) was used to generate average stress-strain curves of stiffened plates.

A procedure for predicting the reliability of hull girder was proposed by Downes and Pu (2002). In this procedure, a Monte Carlo simulation method was used to predict the failure probability, and a Lloyd's register's program, LRPASS, for calculating average stress-strain curves of each stiffened panels was integrated into the program predicting ultimate hull girder strength by Smith's method in such a way that the stress-strain curves could be interactively generated.

Masaoka et al (2000a) reported on reliability analyses of ship hull girders. Smith's method was used to evaluate the ultimate strength of hull girders, in which the average stress-strain curves of structural elements were obtained from a database based on non-linear finite element analysis. The mean value and standard deviation of ultimate strength was estimated by Monte Carlo simulation with 100 samples. The reliability of the hull girder was then calculated by a FORM method. A similar method was applied to a very large floating structure (Masaoka et al, 2000b). The reliability index of the structure under different wave heights was calculated. The sensitivity factors of reliability with respect to yield stress, plate thickness and loading were also presented.

Incecik and Pu (2001) have assessed structural strength of FPSOs by both deterministic and probabilistic methodology. In the context of reliability analysis, the failure probability of FPSOs in three failure modes, namely ultimate strength of the hull girder, initial yielding of the hull girder, and ultimate strength of stiffened plates, was predicted by a first order second moment method.

Yang et al (2001) have applied fuzzy reliability analysis to ship longitudinal strength. Three failure modes, namely initial yielding of the hull girder, torsional/flexural buckling of stiffeners, and ultimate bending strength of the hull girder, were considered. The ultimate bending strength was predicted by an empirical formula. The reliability analysis was carried out by using the first order second moment method. Fuzziness in both resistance and load effects was included in the analysis.

Sun et al (2000a,b) have carried out a reliability analysis of hull girder strength considering corrosion and fatigue. Ultimate hull girder strength was used as the measure of ships' strength. Corrosion is assumed as a random process with a constant mean value. Coating life is modelled by a Weibull distribution. Crack propagation is evaluated by Paris-Erdogen equation. Only global vertical bending moments were considered in the prediction of crack propagation. A response surface method was used to generate the limit state function and a Monte Carlo simulation-based method was adopted for predicting failure probability. This methodology was applied to a bulk carrier in this paper and further applied to a FPSO in Sun and Bai (2000). A similar procedure was applied to ships used in the ISSC-2000 benchmark study by Sun and Bai (2001). The differences from the previous methods are: (a) the hull girder ultimate strength was predicted by a recently derived analytical formulation which agrees well with other methods, and (b) a three-stage process was introduced to model the corrosion, in which the coating effectiveness was considered. Further work on reliability of corroded and fatigue damaged ships was presented by Guedes-Soares and Garbatov (1999a,b).

The reliability analysis of damaged ships due to collision and grounding was carried out by Qi et al (1999). The ultimate residual strength of a hull girder was predicted by an analytical formulation, in which the damaged sections were removed. The reliability was calculated by an importance sampling method.

A structural system reliability approach was applied to predict the reliability of ultimate hull girder strength and sensitivity factors by Okada et al (1999). Both plate and beam elements were used to model the midship cross section. The dominant failure path was identified by this approach.

Two reliability analyses of structural strength are discussed by Hess (2002) in support of quantitative measurement of ship structural performance. The first analysis is the Monte Carlo simulation prediction of the reliability of a composite, sandwich panel subjected to a dynamic, lateral pressure load, with failure defined as first-ply failure. Coupon test data for glass-reinforced polyester from five different fabricators were used to develop the basic variable uncertainty information to demonstrate the impact of fabrication choices and subsequent material property characterization on the performance of the structure. The second analysis is the advanced second moment method reliability prediction of a combatant hull girder against ultimate strength and subjected to vertical, wave bending moments from an extreme mission. The hull girder bending strength prediction was performed using the US Navy code ULTSTR, and a 10% coefficient of variation was applied based on Monte Carlo simulations.

Reliability analysis of composite plates under uniform lateral pressure and a central point load was carried out by Lin (2000). Stochastic finite element method, first order second moment method and Monte Carlo method were used, and first-ply failure was considered as failure for the composite plates. Four different failure criteria were adopted for deriving limit state functions in the analysis. It was concluded that both stochastic finite element method and FORM can predict reliability with reasonable accuracy. The same stochastic finite element method was applied to a composite plate under uniform lateral load by Lin and Kam (2000).

Monte Carlo simulation was applied to predict the reliability of a simply supported composite plate under lateral pressure, Jeong and Shenoi (2000). The first-ply failure was treated as the failure of the plate. Different failure criteria, such as maximum stress and Tsai-Hill criteria, were used in the reliability analysis. In addition, sensitivity analysis was also carried out to identify the importance of each variable. This work was further extended to use both first order second moment method and Monte Carlo simulation method to predict the failure probability of a composite plate, Jeong and Shenoi (2002). The accuracy of these two methods was compared.

For a redundant structure, the failure of a component does not necessarily lead to collapse of the whole structure**,** so structural system reliability methods should be ideally used. This is particularly true for offshore structures, such as jacket platforms, which have quite high redundancy. Structural system reliability methods for offshore structures have been reviewed by Onoufriou and Forbes (2001). The major uncertainties in predicting resistance of offshore platforms are identified. The areas, which need further development, are recommended.

A comparative study was reported by Dier et al (2001) on the reliability predictions of representatives of jacket and jack-up platforms. It was found out that the predicted reliability index was significantly affected by the adopted foundation modelling. The reliability index was reduced if the foundation failure was considered by a refined method. The jacket and jack-up platforms have a similar level of reliability. Morandi et al (2001) have pointed out the implicit and explicit safety reserves in various design codes for jack-ups and their impact on the reliability. The effects of other important factors on the reliability of jack-ups, such as environmental loading prediction, loss of air gap and deck inundation, etc, were also discussed. The author believes that some inherent features of jack-ups, which were not considered in the reliability analysis, make them safer than what is reflected in the predicted reliability index.

Talavera et al (2001) have proposed a procedure for reliability analysis of very large floating structures. A simplified hydroelastic approach was used to predict the dynamic stresses in the structure. Reliability of the structure was then evaluated by a first order and second moment method. In the analysis only the buckling and ultimate strength of deck or bottom were considered.

Structural reliability analysis was performed on a very large pontoon-type floating structure together with a surrounding gravity-type breakwater by Fujikubo et al (2001). Failure modes considered in the analysis include ultimate bending and shear strength of the floating structure and overturning of the breakwater. The ultimate bending strength and shear strength were evaluated by both the idealised structural unit method and finite element method.

6.3 Ultimate Strength Reliability-Based Design And Optimisation

Reliability-based design of five ships was reported by Xu and Cui (2001). Both ultimate strength of hull girder and stiffened panels were considered in reliability analysis. The ultimate strength of hull girder was evaluated by an empirical formulation, which is based on the prediction of the ultimate strength of stiffened panels. The reliability analysis was carried out by the first order second moment method. Partial safety factors of five different ships were derived. These ships were redesigned to achieve the target reliability index.

7. TUBULAR MEMBERS AND JOINTS

7.1 Tubular members

A number of papers have been published related to ductile collapse of members and girders. Most relate more to a civil engineering application than to ship and offshore structures. Nevertheless some of the conclusions should be applicable in both fields.

An overview of Eurocode 3 Part 1.5 Design of Steel Structures is given by Johansson et al. (2001), focusing on tall girders and planar plated structures without transverse loading, typically applied in steel bridges and similar structures. The paper presents the background and justification of some of the design rules with focus on the ultimate limit states. Lindner (2000) discusses stability formulae for structural members, comparing theoretical solutions according to second-order theory with simplified formulae in Eurocode 3 and DIN 18 800. Special attention is given to the support conditions of the members and to lateral–torsional buckling. Alternative beam-column interaction formulae based on second-order in-plane elastic theory are proposed by Boissonnade et al. (2002), showing an extensive comparison with more than 15,000 results of finite element numerical simulations. Hasham and Rasmussen (2002) present a study of the strength of thin-walled I-sections in combined compression and major axis bending. Nonlinear finite element analysis is used to produce interaction curves for four cross-sections covering the range from slender to compact. For each cross-section, interaction curves are produced for four overall slenderness values including short and long beam-columns. The interaction curves are compared with design strengths obtained using the AS 4100, AISC LRFD, and Eurocode 3. The design strengths are shown to be generally conservative, particularly for slender cross-sections. Improved design interaction curves are proposed.

Chung and Lawson (2001) discuss the design of beams with large rectangular and circular openings. This paper presents the design method in the format of Eurocode 4, and presents general information on sizing of openings as a function of the utilisation of the shear and the bending resistances. The effect of these openings on deflections is estimated by a simple factor that is dependent on the size and the location of the openings. Typical design tables for composite beams with large rectangular openings are presented. Chung et al. (2001) examine steel beams with circular web openings based on analytical and numerical studies, and suggest an empirical shear moment interaction curve for practical design of steel beams with circular web openings.

Kwak et al. (2001) present theoretical formulations for geometrically nonlinear analysis of three-dimensional beams with thin-walled open sections. The displacement field is described based on a total Lagrangian formulation, and the warping degree of freedom is taken into consideration to simulate the structural behaviour of slender or curved beams with an arbitrary shape. Static condensation is used to reduce the warping degree of freedom from the global stiffness matrix, and an improved arc-length method is used to overcome numerical instability in snap-through buckling analysis. Finally, correlation studies between analytical results and other previous numerical studies are presented to establish the validity of the proposed numerical approach.

Ronagh et al. (2000a, b) present a theoretical formulation for the nonlinear analysis of thin-walled beam-columns whose cross-section is tapered. An expression for the first variation of the Total Potential is derived, that may be used in a nonlinear equilibrium analysis, and an expression for the second variation of the Total Potential is derived, that may be used in a stability analysis. These variations are used as the basis for a finite element formulation. The resulting finite element formulation is then used to investigate the linear stiffness behaviour of a tapered beam subject to a torque, classical stability analyses of tapered members and the stability of tapered members when subjected to the effects of initial bending curvature. Where possible, comparisons are made with other solutions in the literature, and it is shown that the numerical model presented in this paper is very accurate.

Elchalakani et al. (2002a) present a theoretical formulation to predict the moment-rotation response of circular hollow steel tubes of varying D/t ratios under pure bending. The formulation includes the effect of ovalisation along the length of the tube, plasticity and local buckling of the tube wall. Two local plastic mechanisms are studied to model the local buckling behaviour, especially during the unloading stage. The theoretical predictions are compared with experimental results (Elchalakani et al., 2002b). Good agreement is found between the theoretical predictions and experimental moment-rotation responses. A closed-form solution is presented, suitable for spreadsheet programming. Ovalisation effects of tubular members is also considered by Karadeniz (2001), who presents a simple method for including ovalisation effects into the stiffness matrix of 3D FE analyses.

The dynamic behaviour of tubular steel members subjected to impact damage is investigated by Zeinoddini et al. (1998, 1999, 2000). They present results from numerical studies, closed analytical solutions and experimental tests showing that axial pre-loading has a marked effect on the lateral collapse load of the member, and on the level of energy that the member can absorb prior to collapse. Experiments are done on the tubes impacted by a dropped object with a velocity of about 7 m/s at their mid-span. Ruggieri and Ferrari (2002) present an experimental and numerical investigation of the structural behavior of a dented tubular member under lateral load.

Langhelle and Amdahl (2001) present results from an experimental investigation of the behaviour of AA 6082 alloy aluminium columns at elevated temperatures. Particular emphasis is put on high temperature creep effects. Tensile tests provide information for the material model of aluminium applied in the nonlinear finite element programs. 31 column buckling tests are performed for validation of the material models in nonlinear finite element programs and for evaluation of design rules. The column buckling tests are compared to numerical analyses and design rules predictions.

Watanabe et al. (2000) present an experimental study of multi-directional earthquake loading on rectangular hollow steel columns. Earthquake loading is in reality complex and multi-directional, as opposed to the conventional uni-directional approach. Thus, the experimental study investigated the effects of multi-directional load histories on the response of tubular columns commonly used in the construction of elevated highways and building structures. Test results indicate that, in comparison with uniaxial displacement paths, multi-directional displacement patterns lead to significant degradation in stiffness, strength and ductility of tubular columns.

Brooker and Ronalds (2001) present a continuum damage mechanics (CDM) model to represent ductile failure in nonlinear FE analyses. The model uses a CDM based relation to describe the dependence of the failure strain on stress state, and simulates element failure via material softening. The applicability of the model in presenting the first onset of failure is demonstrated by comparing finite element predictions with experimental results taken from the literature.

Kim and Kang (2002) present results from large-scale testing of a 3D, two-story, single-bay, and sway allowed frame subjected to non-proportional vertical and horizontal load. Details of the test frame, test instruments, set-up and test procedures and the load–displacement curve of the test frame are presented. Non-linear numerical analysis is also performed, and the results compared with the experimental results. It was observed that the load carrying capacity calculated by the AISC-LRFD method is 28% conservative when compared with that by the experiment, due to inelastic redistribution of moments in the frame.

Avery and Mahendran (2000) present test results and numerical methods for steel frame structures comprising non-compact sections. A series of large-scale tests are reported to provide experimental verification of the analytical models. The test frames exhibited significant local buckling behaviour prior to failure. The paper presents details of the test program including the test specimens, set-up and instrumentation, procedure, and results. Al-Shawi (2001) investigates the behaviour of circular hollow sections under large rotations, which cause ovalisation of the cross section and reduction of the plastic section. It is found that the reduction in the theoretical plastic moment of resistance can be significant, and this is confirmed by experimental evidence. Earls (2001) studies the structural ductility of high-performance steel I-shaped beams. It is observed that current cross-sectional compactness and flange-bracing limitations may not be directly applicable to these types of high-performance steel flexural members.

A number of other papers have been published on non-linear formulations and analyses of frame structures. More details can be found in Hsiao and Lin (2000), Liew and Tang (2000), Liew, Chen, Shanmugam and Chen (2000), Chen, Liew and Shanmugam (2000), Tomka (2001), Kim, Park and Choi (2001), Kim and Choi (2001), Kim, Park and Choi (2001a, b), Kim, Choi and Ma (2003), Huh, Kim and Kim (2001), Rodrigues and Jacob (2001), Srirengan, Chakrabarti and Ghosh (2002), and Pinna and Ronalds (2002).

7.2 Joints

MSL Engineering (2000) has carried out a major Joint Industry Project on assessment criteria, reliability and reserve strength of tubular joints. Phase I of the JIP has dealt with two aspects of joint technology (Dier and Lalani, 1998). Firstly, it has produced assessment criteria for joints under uni-axial loading, with better reliability than previous codes. Implicit in this is the effect of chord loading which was not well captured in previous criteria. The results of this part of the work has been included in ISO 13819-2. Secondly, Phase I concentrated on the development of complete non-linear load-deformation formulations for joints under uni-directional loading. The load-deformation characteristics are given by closed-form equations for the complete P-δ or M-θ curves for T/Y, DT/X and K/YT joints subjected to axial, IPB or OPB loads. The equation coefficients, for a given joint classification, are simple functions of the non-dimensional joint parameters β, γ, θ, g etc.

Phase II of the JIP (MSL Engineering, 2000; Dier and Hellan, 2002) has extended the previous developments by establishing yield and ultimate failure envelopes for multi-directional loading, also incorporating chord load interaction. The resulting formulations have been codified into a generic joint module for use in non-linear frame analysis packages adopted in the offshore industry. The joint module has been developed and integrated as part of the USFOS system.

8. PLATES AND STIFFENED PLATES

8.1 General

Plates and stiffened plates are the dominating structures in all ship and offshore applications and steel is the dominating material used. Consequently the ultimate strength of these structural elements has also been actively studied and all ISSC reports give specific emphasis on this topic. The recent developments in non-linear numerical analysis methods enable nowadays fairly accurate analysis of the collapse behaviour of local structural elements. The main topics under active research are: modelling of post-weld initial imperfections, effect of end conditions such as rotational restraints and torsional rigidity of support members, and the effect of combined loadings such as biaxial compression/tension, edge shear and lateral pressure. In chapters 3 to 5, the analytical, experimental and numerical analysis are discussed in general, whereas here the emphasis is summarising the work related more on the practical applications developed for plates, stiffened panels and steel sandwich panels.

Paik and Thayamballi (2002b) give a comprehensive review of the present state-of-the-art concerning ultimate limit state design of steel plated structures. This text book forms an extensive handbook for researchers, practical engineers and students covering the following chapters: principles of limit state design, ultimate strength behaviour of beams, columns and beam columns, elastic, inelastic and post-buckling behaviour of plates, elastic, inelastic and post-buckling behaviour of stiffened panels and grillages, ultimate strength of plate assemblies, ultimate strength of ship hulls, impact mechanics and structural design for accidents, fracture mechanics and ultimate strength of cracked structures. In addition the present knowledge on semi-analytical and numerical analysis methods are summarised.

Also the classification societies are developing their design models for ultimate strength assessments of stiffened panels and hull girder. Steen et al. (2001) present a new computerised design model based on an orthotropic version of Marguerre's nonlinear plate theory. The stiffened panel is treated as an integrated unit, allowing for internal redistribution of membrane stresses between component plates while preventing overall buckling and permanent deformations. Bureau Veritas (2000) has specified a calculation procedure for hull girder ultimate strength. Class NK (2001, 2002) has also specified procedures to calculate hull girder ultimate strength as well as ultimate strength of the panels. Also a new edition for the API Bulletin for design of flate plate structures has been published (Serrahn et al, 2002) with the main emphasis in the areas of bi-axial compression with lateral pressure and bi-axial compression with and without edge shear. Similar approaches can also be found for civil engineering applications such as bridges as specified in Eurocode 3 (Johansson et al 2001).

8.2 Unstiffened plates

Paik et al (2000b) have developed closed form solutions for ultimate strength and effective width formulations for ship plating subjected to combined axial load, edge shear and lateral pressure. The formulations are compared with FEM calculations and experiments with satisfactory agreement.

Fujikubo et al (1999, 2000c) and Khedmati et al (2000) have estimated the ultimate strength of ship bottom plating under combined transverse thrust and lateral pressure by applying a simplified method that was developed based on a series of elastoplastic large deflection FEM analysis. The results are compared with DnV formulations, and the design values according to DnV have been found conservative.

Teixeira et al (2001a) have conducted a parametric study applying FEM analysis to quantify the effect of lateral pressure on the collapse of square and rectangular plates under a predominantly compressive load.

Yao et al (2001a) study the post-ultimate strength behaviour of long rectangular plate subjected to uniaxial thrust with special emphasis on the localisation of plastic deformation and resulting elastic unloading beyond the ultimate strength to evaluate the effect of initial deflection shape on the ultimate strength. These studies are based on elastoplastic large deflection analysis by FEM. Generalization of a simplified method for predicting ultimate compressive strength of ship panels is developed by Cui and Mansour (1999). Mateus and Witz (2001a, 2001b) have conducted parametric studies of post-buckling behaviour of steel plates including also the effect of thickness variations on the post-buckling behaviour of corroded steel plates.

8.3 Stiffened plates

Paik and Thayamballi (2002b) present a new book with a comprehensive set of formulas and analysis results for ultimate limit state design of structures (ex. ships) built of stiffened panels and grillages. Ultimate strength of stiffened panels under combined loads (biaxial, edge shear, lateral pressure) for various failure modes is presented including geometric and material properties as well as post-weld initial imperfections. The validity of the formulations are verified by comparisons with non-linear finite element solutions and mechanical collapse tests.

As suggested in the recommendations of previous TC III.I ISSC 2000, some work has been addressed to the evaluation of load combination. Cui, Wang and Pedersen (2000) proposed a simplified method to deal with a combination loading of stiffened panels on ships. The paper by Roberts and Shahabian (2001) has pointed out an interaction formula for the ultimate resistance of slender web panels to combined bending, shear and patch loading, whose results have been also validated by experimental tests.

Fujikubo et al (2000a, 2000b, 2002) and Kaeding and Fujikubo (2001) have developed ISUM rectangular plate element with new lateral shape functions and have applied the element to conduct elastoplastic large deflection ISUM analysis for offshore structures under longitudinal and transverse thrust. The proposed stiffened plate model consists of ISUM plate elements and beam-column elements. The new stiffened plate model can cope with buckling of a stiffener as well as a local panel.

A number of non-linear FEM analysis have also been conducted. Pasqualino and Estefen (2001) have applied FEM analysis (ANSYS) to study the effect of initial geometric imperfections, boundary conditions and applied loads (biaxial) on structural capacity of a stiffened panel. Comparison with IACS and DNV recommendations are conducted and the lack of specific biaxial loading formulations by IACS are criticized. Miller et al (1999) have conducted comparative analysis of the compressive strength for longitudinally stiffened panels fabricated with three different welding methods. The ultimate strength of panels constructed using continuously welded stiffeners, intermittently welded stiffeners and intermittently welded serrated stiffeners are studied. Testing results and analysis of the failures showed that the use of serrated stiffeners introduces a different failure mechanism, which can lead to a significantly earlier failure. Sheikh et al (2002) have studied the stability of steel plates stiffened of T-shape section under uniaxial compression and combined uniaxial compression and bending using FEM-analysis. A comparison of the numerical analysis results with API and DnV design guidelines indicates that the guidelines lack the potential interaction-buckling phenomenon between various failure modes i.e. plate, stiffener or overall buckling, which can cause a sudden loss of capacity.

Belenkiy and Raskin (2001) have estimated the ultimate load on structural members subjected to lateral loads applying FE-analysis (ANSYS) for beams, stiffened panels and grillages and the results are compared with analytical formulations.

8.4 Steel sandwich panels

Laser-welded metallic sandwich panels offer a number of outstanding properties which allow the designer to develop light and efficient structural configurations for various applications to replace the conventional stiffened platings. These panels have been under active investigations for the last 15 years in the US and Europe as summarised by Kujala and Roland (2002). The standard buckling control calculations for thin plates can be applied also for steel sandwich panels as summarised by Romanoff et al (2002) and Kolster (2002). For sandwich panels, local denting of the cover plate under high local point or wheel loads is an important failure mode due to the typically fairly thin cover plate thickness as studied by Romanoff (2001) and Romanoff and Kulala (2001, 2002), see Figure 4 and 5.

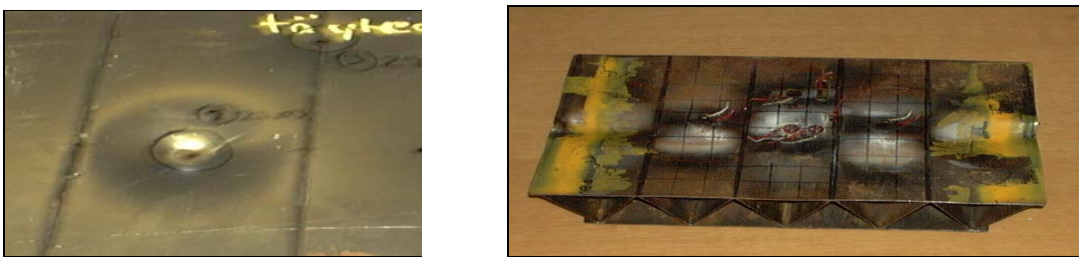


Figure 4. Typical failure modes for all steel sandwich panels (Kujala et al, 2002)

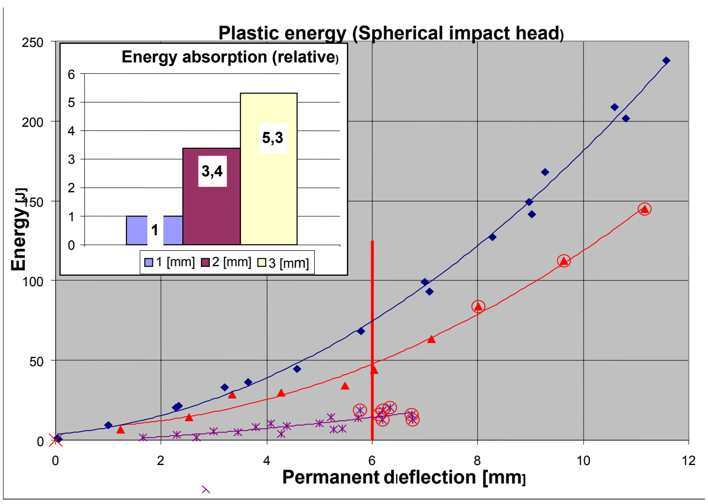


Figure 5. Required plastic energy in the impact as a function of the permanent deflection on the steel sandwich panel with distance between core 120 mm and top plate thickness varying: 1mm (yield strength 180 MPa), 2mm (yield strength 430 MPa) and 3 mm (yield strength 380 MPa), the diameter of the ball is 25 mm (Kujala et al 2002)

9. SHELLS

Examples of theoretical and experimental investigations on GRP shells can be found in the papers by Ross et al (2001a) and Spagnoli et al (2001). The former is applied to oblate dome shell, while the latter highlights the results of a numerical simulation of plastic cylinders under axial compression, carried out by FEM analysis, comparing them with the experimental results obtained in previous investigations. It was shown that design against buckling may be carried out by using geometrically non-linear analysis with due consideration of initial imperfections and thickness irregularities. Finally, steel and aluminium alloys have been studied by Skallerud et al (2001) in a theoretical approach on the non-linear response of shell structures. The aim was to demonstrate that in collapse response of slender structures, the straining of the material may be moderated but the motion may be governed by large rigid body translations and rotations.

Starting from test results involving unstiffened steel conical shells in compression, an interesting analysis on the collapse strength has been performed by Chryssanthopoulos and Poggi (2001); they have proposed a theoretical expression for plastic mechanism approach and finally have reported some comments regarding the existing shell buckling codes.

In the recent past, crash effects, corroded structures and buckling propagation have received more attention by researchers in the ultimate strength of shells. It is known that the presence of cracks can considerably reduce the buckling loads of a shell structure; Estekanchi and Vafai (1999a) have first studied the overall behavior of plates and shells as affected by the presence of a through crack, analyzing various parameters such as the order of mesh refining the crack tip, the effect of boundary conditions, crack length and shell curvature. Then, the same authors have proposed in a second work, Estekanchi and Vafai (1999b), a general finite element model able to perform the buckling behavior of cracked cylindrical shells, taking into account crack length and orientation.

The buckle propagation problem in deepwater pipelines has been analysed by Pasqualino and Estefen (2001a). They have proposed a theoretical explicit formulation for the numerical simulation of the phenomenon, validated by experimental data from small-scale laboratory test.

The phenomenon of buckle propagation in pipe-in-pipe systems under external pressure has been studied by Kyriakides S. (2002) and Kyriakides and Vogler (2002) through a combined experimental and analytical approach. In the part I of this two-part report, the authors have shown the results of extensive experimental tests, where the initiation of collapse in carrier pipes and the evolution of events that follow are studied for a wide range of pipe parameters. In part II, they examine and evaluate the performance of three levels of models for estimating the propagation pressures, showing that they can be predicted with great accuracy, when the geometric and material characteristics of the pipes are properly represented in the models.

An interesting and effective empirical method applicable in a practical engineering to evaluate the ultimate strength of two way grid shells has been proposed by Yamashita and Kato (2001). The method is based on the column strength concept in which the key measure is the modified Dunkerley equation in terms of a generalized slenderness and knock-down factor to reflect imperfection sensitivity.

Prousty and Satsangi (2001) presents a numerical analysis of stiffened shells and illustrate some of the important issues related to the modeling of the shell/stiffener connection.

Cylindrical shells have been always an important and attractive topic in the ultimate strength members. Pasqualino and Estefen (2001b) have presented the results of a numerical and experimental study on the behavior of stiffened cylindrical shells, contributing to the design of submersible vehicles. They have adopted the FEM analysis taking into account large displacements, plasticity and the arc-length control in the post-buckling regime. Finite element analysis have been carried out by Lennon and Das (2000) on ring and stringer stiffened cylinders, in order to investigate the effects of stiffeners on post buckling behavior in torsion; the analysis has also involved the combination of axial and surface pressure loads on the resistance to plastic collapse in torsion. A parametric study on the influence of thickness imperfections on the non linear buckling of cylinders under uniform external pressure has been analyzed by Conbescure and Gusic (2001) by using the COMI finite element and taking into account geometry and thickness imperfections. The buckling of cylindrical shells under a dynamic shear load has been examined by Michel et al (2000); FEM calculations are presented in order to investigate the effect of geometric imperfections and a preload. Starting from a paper by Ross et al (1998), a series of experimental works on thin-walled cylinders have been published by Ross and Sandler (2000), Ross and Waterman (2000), in order to produce design charts which could be used for designing against the occurrence of elastic and inelastic shell instability. The study is extended to cover circular corrugated cylinders by Ross et al (2001b).

Finally, the third edition of API bulletin by Balint et al (2002) presents new formulations for local buckling whose results are compatible with test data for the material elastic and the elasto-plastic behavior, simplifying use with more design flexibility and more sensitivity of various parameters affecting design decisions.

10. SHIP STRUCTURES

10.1 Strength analysis of ship structures

For a long time, it had been common to consider three strengths for the strength assessment of ship structures, which are longitudinal global strength, transverse strength and local strength. In earlier times, the three strengths were calculated separately applying different methods. For the longitudinal strength analysis, *Beam theory* was applied, whereas for the transverse strength analysis, *Slope Deflection Method* or *Moment Distribution Method* was used modelling the transverse cross-section of a hull girder as a plane frame. With the developments of the FEM and the computers, it has become possible to calculate all the strengths at the same time by applying the FEM. However, this is not for a collapse analysis but for an elastic stress analysis in general. For the collapse analysis, it is still common to distinguish longitudinal, transverse and local strength analyses.

10.2 Ultimate hull girder strength

Longitudinal strength of a ship's hull is the most fundamental strength for ship structures, and many papers have been published after the last ISSC regarding the ultimate hull girder strength. From the viewpoint of the applied method of analysis, they can be classified into three, which are an application of the FEM or the ISUM, that of the Smith's method and approximations by analytical methods.

In relation to the Smith's method, Yao *et al*. (2000a) discussed the influence of local pressure loads on ultimate hull girder strength. Hu *et al*. (2001a) used newly developed average stress-average strain relationships in the Smith's method and assessed the ultimate longitudinal strength of bulk carriers. He and Wan (2001) also developed a new method of analysis in the framework of the Smith's method. Rigo *et al*. (2001) and Pradillon *et al*. (2001) discussed the influences of the shape of average stress-average strain relationships as well as the ultimate strength of elements on the moment-curvature relationship of a hull girder applying the Smith's method.

Ikeda *et al*. (2001) dealt with the strength assessment of aged single hull tankers on the basis of the calculated results by applying the Smith's method and the FEM. For the FEM analysis, the explicit FEM code, LSDYNA-3D, was applied, which was specially customised by taking into account the rupture of structural members for the collapse analysis of ship structures. It was found that the ultimate hull girder strength decreases linearly with respect to the reduced section modulus due to corrosion. Detail of this FEM analysis was introduced by Yao *et al*. (2002a). The implicit FEM code, MARC, was also applied by Meinken and Schluter (2002) to calculate and assess the hull girder strength of inland push-barge.

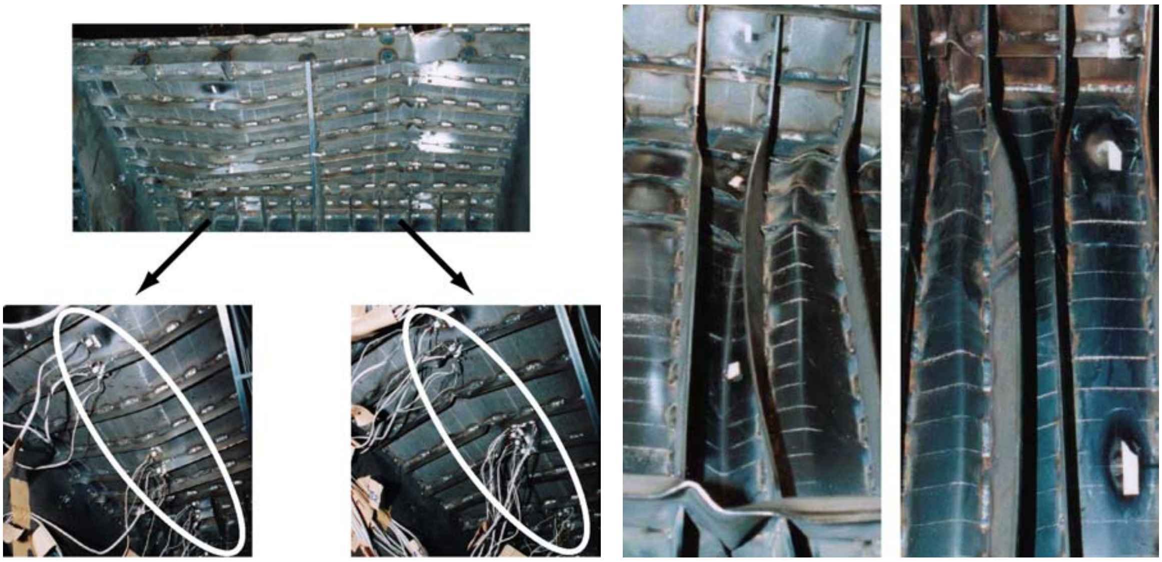
On the other hand, Wang *et al*. (2002) applied the ISUM to assess the influences of accidental damage on the ultimate hull girder strength of sixty-seven commercial vessels. Paik *et al*. (2002) also applied the ISUM to simulate the collapse behaviour of ten typical merchant ships. According to the calculated results, bulk carriers and some container ships showed higher ultimate strength in sagging than in hogging. This is opposite to all the results reported up to now. Although no concrete explanation for this can be seen, the ultimate limit state design format was addressed on the basis of the calculated results.

Paik *et al*. (2001a) simulated a post-ultimate strength behaviour of a hull girder on the basis of simple calculations utilising empirical formulas for ultimate strength of stiffened plating. Paik and Thayamballi (2002a) investigate the ultimate strength of ageing ships (corrosion and fatigue damage) and discuss the possibility of damage tolerant vessel design. Simple formulas in a closed form were developed by Egorov and Kozlyakov (2001) to evaluate the ultimate hull girder strength on the basis of the improved formulas to predict ultimate strength of stiffened plates in compression. Applying the newly developed formulas, influences of various factors on the ultimate hull girder strength were described. Chuang *et al*. (2000) discuss the ultimate hull girder strength criteria in the rules for high speed craft by analysing the possible collapse modes and estimating the ultimate longitudinal strength by a simple method.

Reliability analysis on the ultimate hull girder strength is very important when the safety of a ship structure is assessed as discussed by Das and Dow (2000), Masaoka *et al*. (2000a), Sun *et al*. (2000a,b), Qi *et al*. (2000), Sun and Bai (2001), He *et al*. (2002), and Guedes-Soares and Garbatov (1999a,b).

Another important hull girder strength is the torsional strength in the case of a hull girder with large openings such as container ships. Hu and Chen (2001b) performed the limit state analysis, and the evaluated torsional strength was compared with the design loads given by the classification society rules. Ultimate hull girder strength in torsion is discussed also by Paik *et al*. (2001c).

As for experimental work, Yao *et al*. (2002b) carried out the sagging collapse tests on 1/10-scale welded steel hull girder models of a chip carrier. It was observed that the buckling collapse is concentrated at two adjacent frame spaces accompanied by overall flexural buckling and stiffener tripping of the deck plating as well as local panel buckling of the upper side shell plating between side frames. Such collapse modes are shown in Figure 6.



(a) Collapse of deck plating (b) Collapse of Side shell plating

Figure 6. Buckling collapse modes of 1/10-scale chip carrier model in sagging. Yao et al (2002b)

10.3 Ultimate strength of partial structure

(1) Bulkhead

From the viewpoint of bulk carrier safety, the strength assessment of the transverse bulkhead with corrugation against flooding load is quite important. Teng and Li (2000) applied the nonlinear FEM code, ABAQUS, to simulate the buckling/plastic collapse behaviour of corrugated bulkheads. On the basis of the calculated results, influences of various factors on collapse strength were discussed.

On the other hand, Ji *et al*. (2001) propose simplified formulas to calculate the ultimate strength of corrugated bulkheads applying the *Beam-column theory*. The influences of shear force and the constraints from adjoining structures are taken into consideration in the proposed formulas.

(2) Double bottom

Double bottom of an empty hold of a ship hull girder in hogging is subjected to lateral water pressure from the bottom as well as longitudinal and transverse thrust. To simulate the collapse behaviour of double bottom structure, Abe *et al*. (2000) propose a new system for structural analyses. This system enables one to assess the strength of plated structures by considering the influence of buckling. In this system, a linear stress analysis is performed with simple plate elements, but the influence of buckling is considered by reducing the in-plane rigidity of the buckled plate elements.

Fujikubo *et al*. (2002) developed new ISUM elements to analyse the collapse behaviour of double bottom structures. Large plate elements and beam-column elements were used for inner and outer bottom plating with bottom longitudinals, whereas Timoshenko beam elements are used for webs of girders and floors. All the elements can undergo buckling/plastic collapse. With these elements, fundamental collapse modes and localised failures in double bottom structure were obtained under pressure loads as indicated in Figure 7.

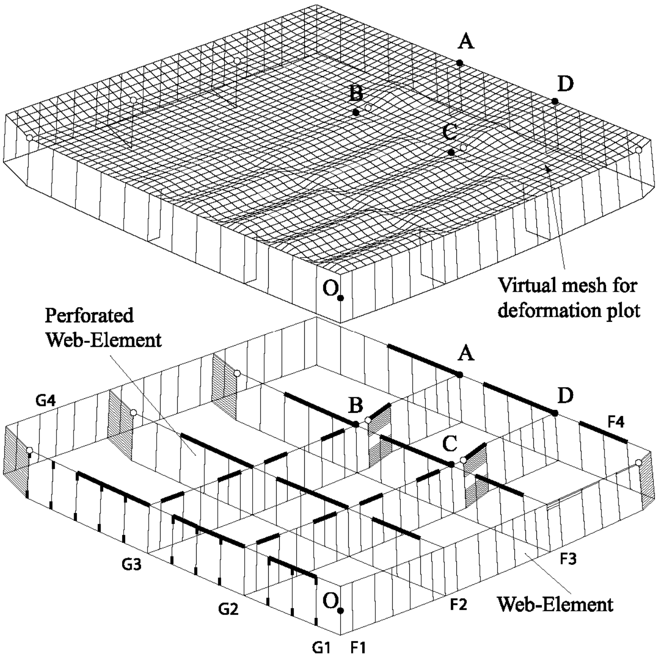


Figure 7 Collapse mode of double bottom under pressure loads (ISUM analysis)

(3) Hatch cover

Yao *et al*. (2000b, 2001b) performed a series of elastoplastic large deflection analysis on hatch covers of Handy size, Panamax and Cape size bulk carriers by applying the computer code ULSAS. For each type, two hatch covers were analysed, one designed by the 1966 ICLL rule, MTJ (1967), and the other by the 1997 IACS unified requirement, IACS (1997). Two cases were considered for each hatch cover, which are with and without corrosion margin. It had been found that buckling/plastic collapse of the top panel as a stiffened plate subjected to combined thrust and lateral pressure becomes the trigger of the collapse of a whole hatch cover.

On the basis of the observed collapse behaviour, a simplified method was proposed to evaluate the collapse load of the hatch cover. The predicted collapse loads showed good correlations with those by the FEM analyses.

(4) Girders

Olaru *et al*. (2001) performed a series of the FEM collapse analysis on existing plate girder specimens and double bottom girders subjected to shear/bending and the applicability of classical theories to evaluate the ultimate strength was confirmed.

11. OFFSHORE STRUCTURES

11.1 Jacket structures

Nonlinear frame analysis provides a better understanding of the overall structural system compared with traditional design practice, which typically focuses on individual components with load effects determined from a linear frame analysis. At present, nonlinear analyses are used most frequently to reassess existing structures, but there are a number of publications addressing the use of nonlinear analyses in the design of new structures.

Skallerud and Amdahl (2002) have published an extensive textbook on nonlinear analysis of offshore structures. The book addresses three main aspects of nonlinear analysis of offshore structures: 1) basic nonlinear continuum mechanics and numerical procedures implemented in state of art computer codes;

2) modelling alternatives for simulation of tubular members and tubular joints; 3) system behaviour and reassessment of offshore structures, including accidental effects such as fire, collision, explosion, cracks etc. Although focus is placed on offshore applications (e.g. jacket structures and pipelines), the methods described may just as well apply to other structural applications. The discussion on how to utilise redundancy and redistribution of forces within a structure is quite general.

The book includes many of the recent developments in assessing the capacity of offshore structures. Many new results were obtained during the 1990s. The book gives a balance between theory, practical modelling and engineering applications. Some of the test results presented may be employed in finite element code validation.

The ULTIGUIDE project (DNV, 1999), carried out by DNV, SINTEF and BOMEL, presents best practice guidelines for nonlinear frame analyses of offshore structures. The aim of the ULTIGUIDE is to provide guidance for an engineer to select parameters and interpret results from a nonlinear analysis. The guide focuses on jacket structures, as these are the most common type of existing offshore platforms. Nevertheless, the recommendations will also be valid to some extent for other types of structures. The guideline does not specify a recommended safety level, but is intended for use with existing codes and specifications. The topics dealt with in this guide address the questions arising in connection with reassessment of existing structures, but the recommendations will be valid also in other design situations.

Bolt (2000) describes a series of ultimate strength tests of a large-scale jacket type structure as part of the Tubular Frames project, phase III. The project followed earlier phases of 2D frame tests which had indicated that components behave differently within the confines of a frame than in isolated tests on which engineering practice has been based (Bolt, 1995). Furthermore, both analyses and previous tests have shown that structural systems exhibit significant reserve strength beyond design load levels.

The purpose of phase III of the Tubular Frames project was therefore to demonstrate the validity of these findings for 3D jacket type structures, and to examine aspects absent from earlier plane frame tests. Specific objectives were:

- To establish the effects of nonlinear joint/member behaviour on three-dimensional behaviour and collapse mechanisms
- To quantify the reserve and residual strength of three-dimensional frames and to investigate the redundancy and load shedding characteristics.
- To investigate the static performance of members and joints within tree-dimensional frames and to develop procedures for the exploitation of available component data.

The results were used in an industry-wide benchmarking exercise to evaluate the capabilities of existing 3D nonlinear frame analysis software. Basic load cases are illustrated in Figure 8. Unfortunately, little data has yet been made available in the public domain.

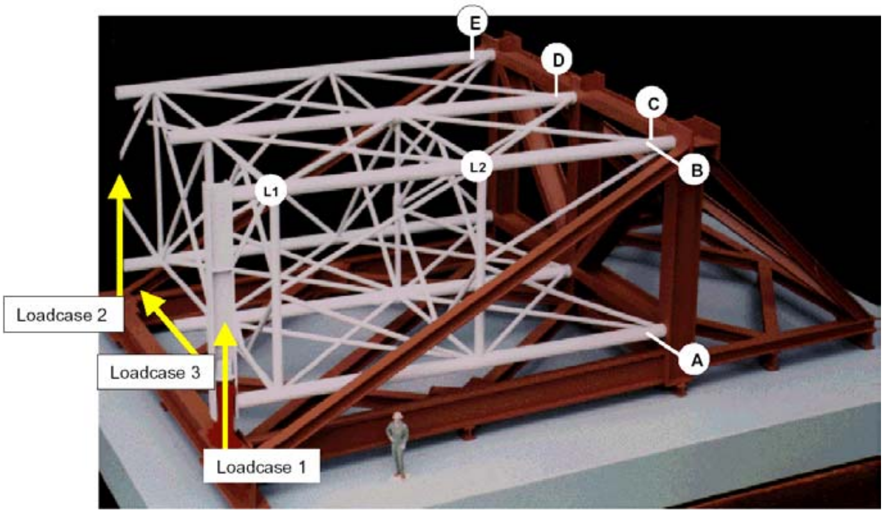


Figure 8. Model of 3D test structure within purpose built reaction rig

11.2 Jack-up Platforms

Two special issues on Jack-up Platforms edited by D´Mello et al (1999, 2001) have been published by Marine Structures.

Jack-up drilling platforms are used for the exploration and operation of offshore oil and gas fields, as well as for the servicing of fixed structures. Originally designed for shallow waters, they have the major advantage of being re-usable with special application for marginal field development. The two conferences held in London in 1999 and 2001, for which papers are presented in Marine Structures issues, focused in a number of areas of interest to the jack-up platform industry, including site assessment procedures, reliability, acceptance, hydrodynamic loading, dynamic behavior of platforms, foundation fixity and platform instrumentation. In this section the papers related to the ultimate strength of jack-up platforms will be reviewed.

Spud-can foundations are usually modeled as pinned or spring supports of a flexible jack-up structure. The simplest approach is to select linear vertical and horizontal springs and a nonlinear rotational spring stiffness consistent with acceptable foundation reactions. However, as this model does not capture spud-can sliding and/or penetration failure, it does not allow a full jack-up ultimate strength assessment. The work presented by van Langen et al (1999) demonstrates that it is possible to formulate a robust and accurate model for the assessment of jack-up foundation response. It takes into account pre-failure nonlinearity in rotation as well as spud-can failure, both sliding and bearing, and can be used in an integrated nonlinear structural analysis.

In order to establish the significance of the leg sliding 'failure mode' a nonlinear time-domain dynamic finite element analysis procedure has been developed by Hoyle and Snell (1999) which allows the sliding phenomena to be simulated. The results show that the nominal annual probability of occurrence associated with a Recommended Practice for sliding utilization check of the unit is in excess of one order of magnitude greater than that associated with the dynamic initiation of sliding and about one and a half orders of magnitude greater than that associated with the onset of structural failure after sliding has occurred.

Analysis of full-scale measurements obtained from a jack-up platform with a skirted spud-can operating in the North Sea is described by Karunakaran et al (1999). Comparison between measured and simulated platform response by application of a nonlinear time domain analysis is performed.

Implications with respect to procedures and assumptions employed for design of the platform are addressed.

High strength steels, generally defined as steels with minimum yield strengths of 450 MPa, are widely used in jack-up construction. However, information on the properties of these materials is limited compared with that for conventional offshore steels and consequently recommendations on the use of these materials are limited in current codes and guidance. The paper by Sharp et al (1999) identifies research in this area and reviews results in light of current code and guidance requirements, with emphasis on fatigue, fracture, static strength, fire and blast performance of jack-up steels.

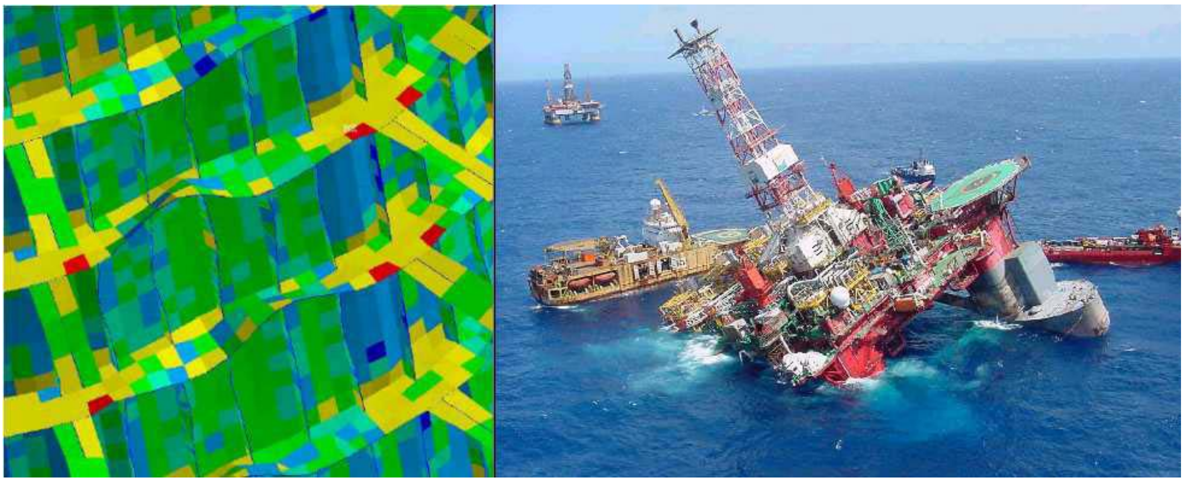
In 1991, the Health and Safety Executive - UK (HSE), commissioned a review of the resistance of jack-ups to boat impact. A resulting conclusion was that jack-ups offer only limited resistance to severe damage in such events. Subsequent safety case assessment in the period 1993-1995 highlighted a significant range in the predicted impact resistance of jack-ups, which assessors believed to be more dependent on the approach followed rather than on the basic design. As a result further work was considered necessary to identify key factors that duty holders should be considering as part of the analysis undertaken to demonstrate the case for safety. The paper by Gjerde et al (1999) is intended to disseminate the findings of a study carried out by Det Norske Veritas (DNV) on behalf of the HSE. A significant part of the collision energy is dissipated as strain energy and, except for global deformation modes, the contribution from elastic straining can normally be neglected. Key aspects such as dynamic effects are often ignored, sometimes to the detriment of the final calculated energy absorption capacity of the jack-up. A number of approaches were received and identified by the HSE as typical approaches for design of jack-ups in the North Sea. In order to assess and compare the approaches a case study based on a typical jack-up design with three legs was used. The results obtained from different approaches are compared and discussed.

The risk management of high-strength steels used for the leg of production jack-ups, with no opportunity for dry dock inspection, requires careful attention to several factors, such as design, materials selection, fabrication and corrosion protection in service. The performance of such steels in seawater is reviewed by Sharp et al (2001). The use of jack-ups for production, with limited opportunities for in-service inspection, has introduced new requirements for risk management of high-strength steels in seawater. In recent years, there have been considerable developments in steel metallurgy, leading to improved combinations of properties in terms of strength/toughness and welding performance. Materials selection plays an important role in minimizing the effects of using high-strength steels in seawater. A key part of this process depends on the use of tests that appear to have some limitations in practice. Improved tests are required.

11.3 Accident with the Semi-Submersible Platform P-36

On March 15th 2001, the semi-submersible platform P-36 operating at Campos Basin in 1360 meters of water depth, offshore Brazil, had a serious accident which led to the sinking of this floating unit six days later. Workshop on the Accident with P-36 Platform, organized by PETROBRAS and COPPE (2001), presented different aspects of the accident obtained by the technical working groups under the co-ordination of the PETROBRAS Inquiry Commission responsible for the investigation of the accident. The procedures adopted and the conclusions emitted by the Commission were verified by DNV.

The final report of the Inquiry Commission mentioned three main events: burst collapse of the emergency drainage tank (EDT); gas explosion; and flooding and sinking. A series of operational errors were identified as the main cause of the first event and also ultimately responsible for the sinking. A graphical animation of the whole process that originated the first event and then the chain of intermediate events up to the sinking is included in the Workshop CD proceedings, see also Figure 9.



(a) Structural analysis of EDT burst collapse (b) P-36 sinking

Figure 9 Accident with the Platform P-36

Of particular interest to the Technical Committee on Ultimate Strength is the first main event associated with the burst collapse of the EDT under internal pressure. A nonlinear static analysis was performed by Cyranka and Videiro (2001) using the software ANSYS 5.7. Considering the symmetry conditions, half tank was modeled by shell and beam plastic elements associated with the treatment of geometric nonlinearity by the full Newton-Raphson approach. It was conservatively modeled as a perfect cylindrical shell, orthogonally stiffened with longitudinal stiffeners and ring frames. Internal pressure increments were applied up to the tank structural collapse at 1 MPa.

Additional analyses performed by other authors of the gas explosion and dispersion as well as the platform sinking were also presented in the Workshop. Design guidelines for semi-submersible production platforms were discussed and a review of PETROBRAS technical specifications was proposed based on the lessons learned from the P-36 accident. Finally, actions to be implemented by the company regarding operation, maintenance and personnel training were presented.

Additional papers on the subject were published later on. The analyses confirmed that the first event in P-36 accident was the structural rupture of EDT due to internal overpressure. With the tank rupture, equipment and piping on a column floor were damaged, causing the flooding of the platform's pontoon with water, raw oil and gas that ignited and exploded causing the second event, now an actual explosion (Videiro et al, 2002). The detailed description of the events which took place from accident initiation until sinking, the main causes, conclusions and recommendations of the Inquiry Commission as well as the new PETROBRAS operational program were addressed by Barusco (2002).

11.4 FPSO

FPSOs (floating, production, storage and offloading unit) are being increasingly employed for oil and gas production in deep waters. Some FPSOs were converted from tankers which had been designed using a traditional Class Rule type approach, while purpose-built FPSOs are being designed using advanced techniques to simulate hydrodynamics and structural behavior. The traditional design procedures are based on simplified component approach that may underestimate the loading but provides a larger factor of safety on the structural capacity. Results from studies based on some FPSOs located in the North Sea (Hamdan et al, 2002) indicated that the safety factor for the two approaches is similar, since the advanced approach tends to result in higher loadings but also in higher capacities. Another issue also addressed is the apparent variation in reserve strength against hogging and sagging bending moments. This is particularly true for double hull FPSOs which tend to have a higher capacity at the hull bottom in comparison to the deck. The ratio of sagging to hogging ultimate strength ranges from 0.72 to 1.0 for converted tankers, which is in contrast to the ratio of sagging to hogging wave induced vertical bending moment which tend to have a value above unity. This indicates that safety factors against sagging and hogging failure are expected to vary widely.

Van der Cammen et al (2002) have discussed the application of reliability based analysis for the determination of the ultimate strength of the hull girder of an FPSO. The method is based on a simplified approach to calculate the ultimate bending capacity of the hull girder in hogging and sagging. Eldho et al (2002) have proposed a procedure for the estimation of the ultimate longitudinal capacity and probability of failure of FPSOs by dividing the cross section of the hull girder into beam column elements considering the different loads acting on the hull. The analytical method used in this study for the calculation of ultimate strength, presented by Paik and Mansour (1995), assumes that the ship's hull collapses when both collapse of the compression flange and yielding of the tension flange occur.

12. COMPOSITE STRUCTURES

Composite structures are increasingly being considered and used for lightweight, advanced applications, in areas with high corrosion, and in areas requiring the integration of the structure with other ship systems. Mouritz et al (2001) describe recent applications of fibre-reinforced polymer (FRP) composites applied to ships and submarines. Uses described include composites for naval vessels, i.e. patrol boats, minecountermeasure vessels, and corvettes; composite substructures; composite masts; composite propulsion systems, i.e. propellers, propulsors and shafts; composite secondary structures and machinery-fittings; and composite submarine structures, i.e. pressure hulls, control surfaces, and masts.

This chapter reviews ultimate strength research in composites for marine applications and generally centers on FRP or glass-reinforced polymer (GRP) materials and their resulting size or scale effects, stiffened, unstiffened shell and sandwich panel strengths, environmental aging and damaged strength due to fire and impact.

Material characterization of the nonlinear, viscoelastic stress-strain behavior of a rubber-toughened, carbon/epoxy composite is assessed by Bocchieri and Schapery (2000) and compared to a similar glass/epoxy composite. A quasi-elastic model is developed to predict the time-dependant stress-strain relationship and compared to experimental coupon tests.

Khan et al (2000) discuss the mechanical behavior of a ship structure GRP composite, reinforced by glass fibers under increasing compressive strain rates as might be encountered by naval mine countermeasure surface ships. Solid cylinders and cubes were tested in through-thickness (normal) and in-plane compression at strain rates ranging from 0.001 to 10 s^{-1}. The in-plane elastic-modulus and strength are shown to first increase with increasing strain rate then quickly decrease. Under normal compression, the strength increased with increasing strain rate, but the elastic modulus and maximum strain appeared insensitive. Fracture toughness was measured for loading rates between 2 and 1000 kN/s, with fracture toughness increasing with increasing loading rates. Khan and Simpson (2000) report in greater detail on the GRP cubes tested in compression.

Random field theory is used in Wu et al (2000) to account for strength variability in a lamina. Monte Carlo simulation of laminate strength variability is found to compare favorably to experimental variability for carbon/epoxy, uni- and multi-directional laminates. The normal distribution is recommended as an appropriate probabilistic model for the laminate strengths predicted by both experiment and numerical analysis. The coefficients of variation in the strength of the experimental tests was found to range from 1.5% to 3.1% for unidirectional laminates, but went to 7.7% for the multi-directional $[0/45/90\text{-}45]_{2S}$ laminates.

The size or scale effect is the influence of specimen size on test results and how the larger structure may or may not exhibit the same behaviour. Bazant (2000) reviews the literature on the size effect on structural strength, including composite materials for design of ships. The focus is on quasi-brittle size effect in material fracture, with general background into statistical size effects as embodied in Weibull fracture analysis, plasticity, linear-elastic fracture mechanics, and energetic size effects. Davies and Petton (1999) report on 13 hand-layup, GRP panels that were constructed of different thicknesses and used to determine elastic and strength material properties. Small specimens are shown to be adequate for determining the properties of larger structures except in the case of thin specimens that do not have the same fiber content or resin impregnation as larger structures, and in the case of shear strength obtained from a 45° tensile test, which is highly dependent upon specimen cross-sectional area. A new theory is presented in Tabiei and Sun (2000) for addressing the strength size effect associated with the length, width and thickness of a laminate under tensile loading. The predictive equations are developed assuming the Equal Load Sharing Rule ELS Rule with sequential multi-step failure of lamina material. The developed model is compared favourably to test results from literature and implemented in the ABAQUS FEA code.

Roberts and White (1999) discuss the testing of rectangular unstiffened, sandwich and hat-stiffened composite plates under in-plane compression and out-of-plane pressure loads to produce buckling failure for comparison to analytical and numerical predictions. The orthotropic FRP laminate panels were clamped on loaded ends, with simply supported long edges on the unstiffened and sandwich panels, and free edges on the hat-stiffened panel. Three panels were tested for each load-case and panel design.

Boyle et al (2001) present experimental in-plane compression buckling and post-buckling test results for orthotropic, glass/vinylester skinned, sandwich panels with comparison to numerical and analytical predictions using the same test fixture as used in Roberts and White (1999). Predictive models overpredicted buckling strength by 5 to 8 % for balsa core and 15 to 23% for PVC foam core. Possible reasons are cited for poor agreement in the post-buckling behavior. Panels with balsa core were found to have greater strength than that of panels with a foam core of density 69.5 kg/m^3. Mines and Alias (2002) used 3-point, beam bending, experimental tests to determine material properties to support numerical analysis of GRP sandwich beams typical of high performance marine vehicle hull structures. Wadee (2000) examines the sensitivity of axially-loaded, sandwich panels with various shapes of localized and periodic imperfections. It is found that this structure exhibits highly unstable snap-back behavior in the perfect case and that combined with localized imperfections, it would never attain its linear critical buckling load. Localized imperfections are identified as the most severe for the majority of load cases.

Muc and Zachara (2000) predict the buckling strengths and natural frequencies of simply-supported, graphite-epoxy, sandwich composite plates using three analytical approaches (higher-order, shear-deformable theory, first order shear deformable theory and Love-Kirchhoff classical theory) which are compared to a NISA II FE analysis. Agreement is shown to increase with increasing order of applied theory. Four different FE modeling techniques were also applied to discern modeling effects. Normal strength behavior at the interface between the core and skin for orthotropic models was shown to heavily influence the local stability of the faces or the core in a sandwich panel. As a result, the authors recommend the inclusion of all 3-D components of the stress tensor in failure criteria.

An exact analytical, three-dimensional, elasticity solution for buckling of simply-supported orthotropic laminate plates is presented by Gu and Chattopadhyay (2000) and compared to predictions by classical laminate theory and the refined third order shear deformation theory for thin, moderately thick and thick materials. Predictions diverge with increasing thickness.

Mouring (1999) summarizes experimental results of testing of GRP laminate plates stiffened with preform frames under in-plane uniaxial compressive loads with three different frame fiber orientations (0,90), (+45,-45,0) and (0,90,+45,-45). The laminates making up the frame skins are non-symmetrical combinations of Trevira and chopped-strand mat (CSM). The panel laminates consisted of five layers of CSM (90/0). Two samples of different frame skin thicknesses were constructed for each orientation. Boundary conditions were fixed at the loaded ends. The panels initially buckled locally at the free edge before compression failure of the frames at approximately twice the local buckling load. The tri-axial layup provided the best overall strength. Blake et al (2002) numerically and experimentally analyze the strength of a top-hat, GRP stiffener with a viscoelastic polymer insert, under three point bending, representative of UNDEX effects on a ship's hull. The limited discount, or stiffness reduction approach, is used to model progressive damage. One experiment was conducted to determine accuracy of FE modeling techniques and understand failure progression.

Dvorak et al (2001) explore the use of tongue and groove geometry for joining thick, woven E-glass/vinyl ester composite laminated plates to steel or other composite plates, with applications in naval ship structures. Numerical and experimental studies are reported for tensile loading. Joint strength is found to increase with increasing thickness, providing an efficiency as high as 60% for joining steel and composite members.

Leotoing et al (2002) present analytical criteria based on a linear-elastic model to predict local symmetric and antisymmetric (wrinkling) buckling and global buckling of sandwich composites, and compare the predictions to linear FE results. Post-buckling behaviour is assessed using geometrically non-linear FEM with elastic and elastoplastic materials. A very high sensitivity towards imperfections is demonstrated, though the significance of this is downplayed. The results of a microbuckling analysis by Rosen are rederived by Niu and Talreja (2000) using a new generalized Timoshenko beam model. A new mechanism is proposed for kink band formation based on matrix shear sliding deformation and fiber microbuckling, allowing predictions to be based on constituent properties.

Carvelli et al (2001) present a procedure to predict the collapse pressure of medium thick GRP composite shells as would be used for an underwater vehicle, namely cylinders, cones and hemispheres. Numerical and analytical prediction techniques are employed to determine the weakest structural member, which is then assessed using a numerical nonlinear analysis with inclusion of geometric imperfections. Correlation to the one at-sea experiment showed the prediction to range from a 6.1% overprediction to an 11% underprediction of the collapse strength of the cylindrical section. Ross and Little (2001b) compare numerical predictions to experimental testing of a carbon fiber prepreg, corrugated circular cylinder, subjected to external hydrostatic pressure, and tested to destruction. The prediction was approximately 20% higher than the test strength, a difference mainly attributed to the lack of imperfections included in the numerical model. A plastic knockdown factor was developed and applied which reduced the discrepancy to "within a few percent."

Elghazouli at al (1998) discuss axial buckling tests on six laminated composite cylinders made from hand lay-up, woven-roving GRP. Chryssanthopoulos et al (2000) and Spagnoli et al (2001) use these tests to validate linear and nonlinear FE modeling approaches to predict buckling behavior of thin-walled (R/t > 70), GRP composite cylinders under axial compression. Messager (2001) considers the influence of winding-induced thickness imperfections on laminated, thin-walled, carbon/epoxy cylinder buckling strength under external, hydrostatic pressure. Such imperfections were found to significantly reduce the buckling strength. A linear, analytical, Saunders-type model was developed, which compared favorably to a linear FE model.

Huang and Zeng (2000) conducted numerical and experimental analysis of a layered wood, submarine missile nosecone, under axial tension, compression and internal pressure. A theoretical and an experimental investigation was carried out by Ross et al (2001a) on seven hemi-ellipsoidal oblate domes, which were tested to destruction under external hydrostatic pressure. 4 domes were GRP, 3 were SUP (solid urethane plastic). FE modelling, which accounted for nonlinearities in geometry and material properties, gave good agreement with the test results. The paper explains how the domes were manufactured and tested, and describes the buckling failures of the domes.

Ferreira and Barbosa (2000) present a FE model for geometric non-linear analysis of composite laminate shell structure buckling, using a layered formulation of the Marguerre shallow shell element. The buckling behavior of composite shells is analyzed as a function of the material orientation and laminate stacking. Isotropic and orthotropic laminated shells were analyzed.

Dao and Asaro (1999) describe the effects of fire degradation on the strength of single-skin, glass-reinforced vinylester composite panels and propose design criteria. Panels were tested under in-plane compressive loads and out-of-plane loading under ASTM E119 fire conditions.

Mouritz and Mathys (1999) investigate post-fire, tensile and flexural, mechanical properties of thin marine-grade glass reinforced polyester, vinyl ester and resole phenolic composites after exposure to heat fluxes ranging from 25 to 200kW/m2 for 325 s or 50 kW/m2 for 1800 s. Curves useful for the design of composite skins to meet post-fire requirements are proposed for thicknesses up to 50mm. Mouritz and Mathys (2001) focus on the post-fire mechanical properties of glass-reinforced polyester composite skins with and without thermal barriers, of which four were considered. Flexural, tensile, and compressive strengths and stiffnesses, and interlaminar shear strength, were assessed. Proposed predictive models are shown to be within 10-20 percent of the experimental result and are considered suitable for use in preliminary design. Koo et al (2001) describe research and development of advanced fire safe polymeric materials for structural applications inside the pressure hull of submarines, and conducted testing of 9 glass-reinforced and one carbon-reinforced composites to determine ignitability, heat release and tensile, flexural and impact mechanical properties. The phenolic/silicone resin system was found to be a good candidate for future analysis due to its low cost and good mechanical properties.

Mouritz and Thomson (1999) study shear, flexure, and compression properties of GRP skins over a poly vinyl chloride foamed core intact and with interfacial cracking and impact damage to the skin. The effect of specimen size for intact sandwich structure was considered for increasing specimen lengths, and it was found that the failure mechanism changes from compressive fracture of the skins to shear crimping of the core when specimen length reaches ~100mm. Five crack lengths and four damage lengths were investigated, with the defect covering the full width of the specimen. The laminate skins were constructed using woven-roving and chopped strand mat glass with cold-curing vinylester resin. Small specimen tests were conducted with full width defects, making scaling to full size difficult due to defects being more isolated on larger panels. Interfacial cracks only reduce sandwich strength if there is a change in failure mechanism. For in-plane compression of a sandwich panel with interfacial cracks, the failure mechanism changes from core shear crimping to skin buckling, and for shear loading changes from localized skin buckling to core shear cracking, where the shear loading was shear through the section, not in-plan shear. Strength, but not stiffness, is shown to decrease rapidly for these loads for flaws greater than 30mm in length. Flexural strength remained unaffected. Stiffness and strength decrease with increasing damage energy except when damaged area is in bending-tension. Degradation is most pronounced when damaged area is placed under compression.

The influence of delaminations on buckling loads under in-plane compressive loads for laminate plates is assessed by Kouchakzadeh and Sekine (2000) using Mindlin plate elements in a linear FE analysis. Results show that the buckling load decreases with increasing number or size of delaminations, and is also affected by the orientation of the delamination. It is also shown that the use of a through-thickness hole is inappropriate for modelling the effects of delaminations on the buckling strength. Experiments were conducted by Netto and Estefen (2002) to analyze the onset of damage due to free edge delamination in GRP panels under quasi-static and fatigue tensile loads. The laminate stacking sequence was varied and recommendations given. Grenestedt (2001) describes the advantages and testing of two types of peel-stopper devices for eliminating the risk of catastrophic skin debonding in GRP sandwich hull structures of high-speed ships. Four-point bending tests were conducted. Peel-stoppers in conjunction with panel joints are shown to be as strong as regular sandwich structure, but do not fare as well in the presence of shear dominated loading.

Gellert and Turley (1999) examined the aging behavior which accompanies the seawater immersion of four glass-reinforced, composite laminates. Four resin-systems were considered: an isophthalic polyester, a developmental resole phenolic and two vinylester glass-fibre reinforced polymer systems. The effects of static loading while submerged on water uptake and mechanical properties are addressed. Flexural strength degraded as water uptake approached saturation 15 to 21 % for unloaded polyester and vinylester GRP's and 25% for unloaded phenolic GRP, with loading increasing the strength reduction of the phenolic GRP to 36%, but no effect on the others. Interlaminar shear strengths fell by 12 to 21 % for saturated phenolic GRP and 80 to 90 % saturation for the other GRP's. Creep was significantly higher for immersed vs. control (atmospheric) specimens.

13. ALUMINIUM STRUCTURES

Aluminium is increasingly being used in load-carrying structures like ship hulls, offshore structures and bridges. Compared to steel, relatively little experience has been accumulated for large aluminium structures. The existing design recommendations for aluminium panels are to a large extent based on experience from steel structures. This approach immediately seems natural but there are a number of differences between steel and aluminium, which call for specific analysis of aluminium:

- Aluminium can be extruded into stiffeners or combined plate-stiffener configurations with very fine tolerances and possibly high material anisotropy.
- Welded aluminium connections in general have rather poor fatigue properties.
- Welding distortions can be relatively large for aluminium structures.
- The heat of the weld generates a weak zone (normally called the Heat Affected Zone, HAZ) next to the weld. The reduction of strength in this zone may be up to 50%.
- The corrosion characteristics of aluminium are quite different from steel.

These differences make it difficult to immediately transfer experience from steel to aluminium with regard to design, construction and maintenance. Therefore, it is very important that more research is conducted in this area in line with that referenced below.

There are many different aluminium alloys available, refer to Violette et al (1998) or the report of ISSC TC III.1, Kaminski et al (2000) for typical material properties. A number of codes can be used for design of welded aluminium structures, for example:

- Classification Society Rules, for example: DNV High Speed Light Craft Rules (1996) or "Germanischer Lloyd, Bureau Veritas, RINA (2002)".
- Eurocode 9, European Committee for Standardization (1998),
- British Standard 8118 (1999)
- NORSOK (1998) (can be used as discussed by Zhu and Moan (2001))

The papers by Zha et al (2000,2001) and Aalberg et al (2001) supplement each other well in giving a comprehensive set of experimental data for axial compression of longitudinally stiffened aluminium panels. Both series of tests were carefully designed with regard to load and displacement boundary conditions.

The study by Aalberg et al (2001) is concerned with open (L-sections) as well as closed (hat) sections stiffeners made of AA6082-T6. The observed failure modes are regular flexural buckling of the entire panel and also stiffener tripping for some of the panels with L-stiffeners. Comparison of the test results to predictions of EuroCode9 shows that EuroCode9 gave conservative predictions in all considered cases. The ratio of the ultimate strength in the tests to that of the prediction by EuroCode9 varied from 1.13 to 1.77 (both for closed section, flexural buckling). The analysis by Zha and Moan (2001) is concerned with panels with flat-bar stiffeners. The considered materials are AA5083-H116 and AA6082-T6. Tripping of the stiffeners turns out to be the dominating failure mode. Welded aluminium structures may show significant welding induced distortions and residual stresses and the paper discusses how well these imperfections can be predicted by the so-called tendon force approach. A finite element program is used to investigate the effect of initial deflections, welding residual stresses and HAZ. It is shown that the strength may be reduced by 15% when the loss of material strength in the HAZ is 50%. This reduction should not be considered as an upper bound, however, as only a limited number of configurations – and not worst-case – were considered. For example, no welds were considered in the direction transverse to the loading direction. Comparison of the measured ultimate strengths to the EuroCode 9, DNV's Rules for High Speed Light Craft (1996) and NORSOK (1998) revealed that the latter gave the most accurate prediction of the strength corresponding to the tripping failure mode.

Hopperstad, Langseth and Tryland (1999) report on an experimental program to study the stability and ultimate strength of aluminium alloy outstands. Two tempers (T4 and T6) of the AA6082 alloy are tested and the structural configuration is an axially compressed cruciform. The experimental results are compared with theoretical predictions using the Stowell theory for plastic buckling with the effective width approach to account for post-buckling capacity. The agreement between theory and experiments was found to be quite satisfactory, the mean values of the ratio of measured to predicted strength were 0.97 and 1.11 for temper T4 and T6 respectively and the corresponding standard deviations were 0.09 and 0.15.

Abildgaard et al (2001) investigate the effect of welding on axially loaded as well as laterally loaded aluminium plates. For the axially loaded plates it turns out that a weld entirely across the plate reduces the strength by the same amount as the yield strength in the HAZ. Since the considered plates were relatively thick (designed to buckle and yield simultaneously) this result could be expected but it still demonstrates how detrimental the effect of the welding can be. For the laterally loaded plates it was shown that a 35 % reduction in yield stress in the HAZ around the boundary reduced the load at a deflection of one plate thickness by 20%.

Hutchinson and He (2000) consider the ultimate strength of axially loaded curved aluminium sandwich panels, i.e. both the face sheet and core are made of aluminium. The paper determines the face sheet thickness, core thickness and core density that minimizes the weight of the geometrically perfect shell with a specified load carrying capacity. Imperfection sensitivity is then assessed to determine if load knockdowns are larger for these types of structures than for elastic shells.

Chan and Porter Goff (2000) studied the ultimate strength of aluminium plates joined by fillet welding with particular focus on the effect of the reduced-strength zone next to the weld. The effect of this weakened zone was investigated for welded cruciform specimens in tension, experimentally as well as numerically. By their choice of this configuration the study is mainly concerned with aspects of termination of an axially loaded stiffener welded to a plate. The paper discusses how the ultimate strength is affected by welding direction, weld configuration, and tapering of the stiffener. Moreover, the paper compares the measured ultimate strength to predictions made using British Standard BS 8118 (1999) and shows that BS8118 does not consistently produce conservative predictions of the strength.

14. BENCHMARK

14.1 Introduction

The goal of this benchmark is to study the collapse behaviour of axially compressed stiffened aluminium panels (including extruded profiles). The main objectives are to compare codes/models and to perform a detailed and quantitative sensitivity analysis of the ultimate strength of a welded aluminium panel.

Two phases were carried out. *Phase A:* All members analyse the same structure with a defined set of parameters and using different codes. It was expected that all the codes/models used in the Phase A would predict the same results. In *Phase B*, to boost the scope of the analysis, the different members perform with their own model FE analyses for a range of variation of different parameters providing a sensitivity analysis. More detailed information on the sensitivity analysis will be submitted for publication in Marine Structures.

Compared to steel panels, the ultimate strength of aluminium structures is sensitive not only to residual stresses and initial deformations, but also to deterioration of mechanical strength in heat-affected zones (HAZ). Numerical analyses of aluminium panels have been carried out in several studies, using different approaches.

The present results of nonlinear finite element simulations can be considered as complementary to the laboratory experiments in the development of design codes for structural applications.

14.2 Reference panel description

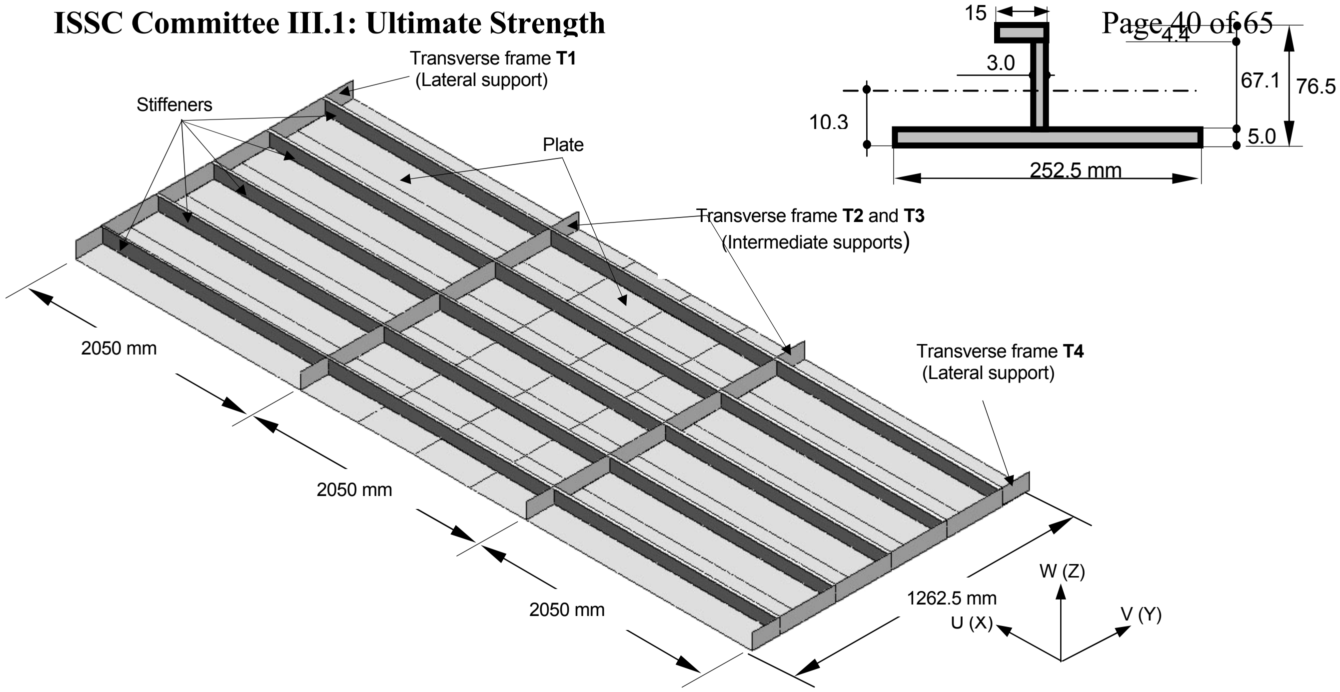


Figure 10: The three spans model (3 x 2050 mm, column slenderness of 1.80)

Geometry: A three span panel with L-shaped stiffeners, fabricated from extruded aluminium profiles in alloy AA6082 temper T6, and joined by welding, was defined for the finite element analyses. The dimensions of the initial model are presented in Figure 10. The slenderness ratio (square root of yield squash load for the cross-section over elastic column buckling load) was 1.8.

Loads: Only axially compressive loads are applied at the initial neutral axis at both ends (no shift is assumed). Lateral load, shear force and bi-axial in-plane stresses are not applied. Deadweight is not considered and a uniform temperature is assumed.

Material properties: The material is assumed to be isotropic with Poisson's ratio = 0.3 and Young Modulus = 70.475 N/mm^2. Material properties were based on the Aalberg (2001) experiments. True stress vs. true strain properties derived from engineering values were input into the model for plate and stiffeners. The same material properties are considered for the intermediate plates supports. The aluminium material strength in the heat-affected zone is reduced by the high temperature during the weld thermal cycle. A reduced yield stress (50–60% reduction) was considered in the HAZ.

Boundary conditions: The following assumptions were made: the boundary conditions for the stiffened panels are simply supported along the two longitudinal edges (unloaded), and are kept straight. The stiffener cross section remains plane at the panel edges as it would for a stiffened panel supported by heavy transverse frames and longitudinal stiffeners. The frames are modelled by transverse plates at each end of the panel (T1 and T4). Their dimensions are 1262.5 x 71.8 mm and 10 mm thick. The two loaded ends are clamped [W=V=0 with U=0 on one side and U=U* on the other side]. The axial displacement (uniform), U*, is imposed at one loaded end. The two end plates are assumed rigid.

At the intermediate support locations, transverse plates are considered, T2 and T3. Their dimensions are 1262.5 x 71.8 mm and 3 mm thick. The five stiffeners are supported by two intermediate support plates (T2, T3) and two end plates (T1, T4). In order to simulate stiff transverse frames, the (w) displacements along Z of these 4 transverse plates are not allowed. W = 0 is assumed for all the nodes at the intersection between the main plate and the four transverse support plates.

<u>*Initial imperfections:*</u> Plate and stiffener imperfections were considered using the following procedure: a uniform lateral pressure is applied (on the opposite side of the stiffener – tip of stiffener in tension) on the overall structure (on the 3 spans model). The pressure was calibrated in order to obtain a linear elastic deflection *w* of 2 mm at the central point of the central panel (Figure 11). Even if it is not a standard procedure, this procedure has been selected to ease and simplify the modelling work of the participants.

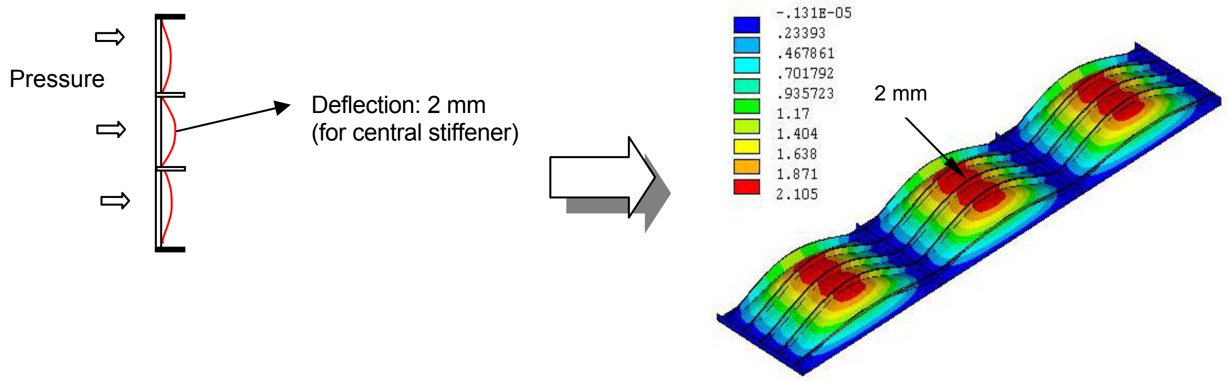


Figure 11: Procedure for initial imperfection

The shape and amplitude of the initial imperfections (plate and stiffeners) are assumed to be exactly the deflections induced by this uniform lateral pressure. The displacements at each node were captured and used to define the initial configuration (geometry of the FEM model). It is assumed these imperfections do not induce stresses.

<u>*HAZ modelling:*</u> In the first stage, the numerical analyses were conducted using a HAZ width of 2 x 25.0 mm along stiffener/plate junction lines in the stiffener web and plate, at the intersection between the five extruded elements and transversally in the plate only (Figure 12). The following WELD configurations were considered:

- 5 longitudinal welds at the junction between the plate and the 5 stiffeners,
- 4 longitudinal welds at the intersection between the 5 extruded elements,
- 2 transverse welds between plates,
- 2 transverse welds at the junction between transverse frames and the plate,

14.3 Finite element modelling

Information concerning the codes and meshes used by the participants are presented in Table 1.

Lehmann-Catalin: The commercial finite element code MSC Marc was used. The nonlinear equation system is solved with the Newton-Raphson approach, in about 350 steps. Elasto-plastic formulation with piecewise linear workhardening is used for the material. The yield surface is von Mises, and the hardening law is isotropic.

Philippe-Radu: The stiffened plate panel was modelled and analysed using the commercial finite element code ANSYS. The SHELL43 element was used to mesh the whole geometry. An elasto-plastic model with von Mises yield criterion and multi-kinematic strain hardening was used to model the material constitutive behaviour. Axial compression was simulated by an imposed displacement in the x-direction, applied in small enough increments to ensure that the analysis will closely follow the structure's load-response curve. In order to help the problem to converge, optional features as line search, automatic load stepping and bisection were activated.

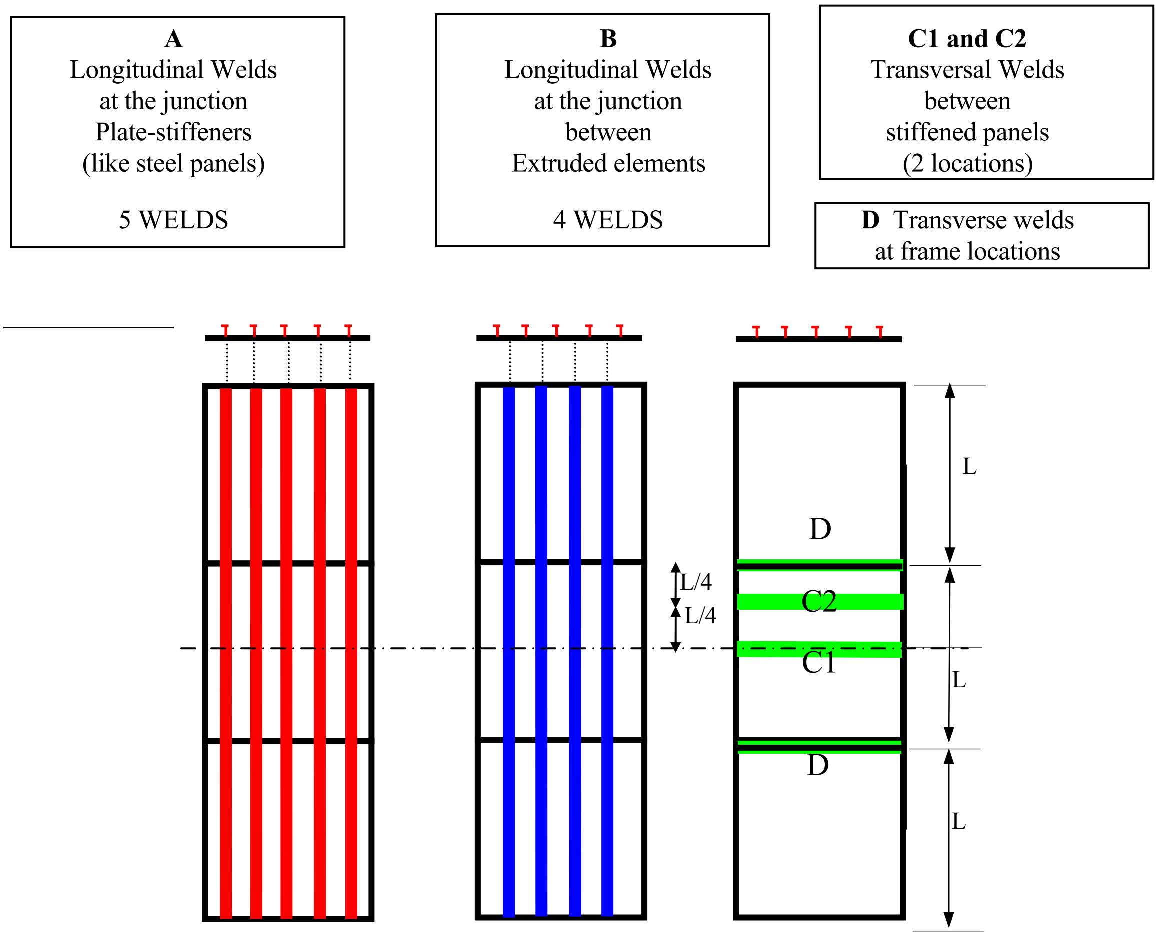


Figure 12: Weld Positions
(HAZ width = 2 x 25 mm in plating and 25 mm in webs)

Pasqualino-Estefen: The model was developed with the aid of the finite element program ANSYS release 5.3. The continuum was discretized with the four noded plastic shell element SHELL43, with six degrees of freedom per node (three rotations and three displacements). The finite element mesh was set in order to properly define the HAZ regions and keep good aspect ratio for the elements. The refinement of the L stiffeners could be further improved along its transverse section but it would generate an extremely heavy model.

Yao-Higashiyama: ULSAS is a homemade code, which enables one to simulate collapse behaviour of structural members and systems considering the influences of yielding and ultra-large deflection. Both shell and beam-column elements are used in ULSAS. As for a shell element, an isoparametric shell element with four nodal points is used. An element of the same type with two nodal points is used as a beam-column element. These elements are characterised as degenerated elements with a linear displacement field and reduced integration. Both material and geometrical nonlinearities are considered.

Wan: The FEA of the stiffened plate with HAZ effects was completed using ANSYS with different mesh sizes. The model includes 1866, 2790, 4242, 7150 and 8672 elements of ANSYS SHELL143. The multi-isotropic strain hardening law and von Mises yield criterion are applied.

Bo-Ulrik: The analysis was carried out using the explicit finite element code LS-DYNA. The material behavior is modeled with a multi-linear elastic-plastic model. The input to this model is true stress vs. plastic true strain. The axial compression was simulated by an imposed displacement in the x-direction at the end of the plate.

TABLE 1

SOFTWARE USED BY THE CONTRIBUTORS AND MESHING FEATURES

	FEM Software	Mesh		Number of elements on a single ligne (or row)				
		Type of element	Total number of elements	Number of elements along X in one span of 1025mm (or 2050mm)	Number of elements along Y (between 2 stiff.)	Number of elements for the web (stiff)	Number of elements for the flange (stiff)	Number of elements on the plate HAZ's width
Lehmann-Catalin	MSC Marc	shell	8520	40	8	3	1	2 for weld A 2 for weld B
Philippe-Radu -Standard mesh	ANSYS	shell43	6588	16	13	4	2	5 for weld A 4 for weld B
Philippe-Radu-Fine mesh	ANSYS	shell43	13656	42	13	4	2	5 for weld A 4 for weld B
Pasqualino-Estefen	ANSYS	shell43	10320	40	12	3	1	4 for weld A
Wan (Coarse mesh)	ANSYS	shell143	1866	10	6	3	1	2 for weld A
Wan (Standard mesh)	ANSYS	shell143	7150	30	10	4	1	4 for weld A
Wan (Fine Mesh)	ANSYS	shell143	8672	32	10	5	1	4 for weld A
Yao - Phase A (coarse mesh, M2)	ULSAS	shell/beam	4160/480	96	20	4	Beam-Column Element	no
Yao - Phase A (fine mesh, M4)	ULSAS	shell/beam	14400/960	192	40	6		no
Yao - Phase B (final mesh)	ULSAS	shell/beam	8880/480	96	50	6		2 for weld A 2 for weld B
Bo - Ulrik	LS-DYNA	shell	7850	32	13	4	2	5 for weld A 4 for weld B

14.4 Finite element analyses

The first model (3 spans of 2050 mm) was analysed by all the contributors. It was found in Phase A that the model is not sensitive to HAZ which is anticipated due to the high slenderness ratio of 1.8. Subsequently, a second model was proposed with a slenderness ratio of 0.9 (3 spans of 1025 mm). As parameters in the sensitivity analyses the committee selected:

- effect of the welding joint types (longitudinal, transversal, extruded and no extruded components). Several configurations are studied - *Phase B1*,
- effect of the HAZ width (25 to 100 mm) - *Phase B2*,
- effect of initial panel deflection (amplitude and shape) - *Phase B3*,
- effect of the residual stress - *Phase B4*,
- effect of the plate thickness - *Phase B5*.

14.4.1 Phase A - Calibration Assessment.

The aim of Phase A was as a calibration between members. A three-span stiffened panel, of 3 x 2050 mm, was considered. This phase was divided in two steps: *PHASE A1* without the effect of the HAZ and *PHASE A2* with the effect of the HAZ.

The effect of the heat-affected zone (HAZ) is considered only in PHASE A2. In Phase A, members participating in the sensitivity analysis (actually 5 contributors) had to perform an identical analysis. The model includes initial deflections (plate and stiffeners) and non-linear material properties. The effect of residual stresses was not considered in PHASE A.

Additional analyses with HAZ effects (PHASE A and welds A) were completed by Wan with different mesh sizes. The model includes respectively 1866, 2790, 4242, 7150 and 8672 shell elements (Table 1). The results show that the convergence of the ultimate stress is quite good. However, the convergence rate slows down when the number of elements increases. For the present collapse analysis of stiffened aluminum panels, the optimal mesh size seems require about 8000 elements.

14.4.2 Phase A2 – Calibration with HAZ

The following 4 configurations of HAZ were initially proposed for Phase A2 (Figure 12):

- Configuration 1: Welds A, situated at the plate–stiffener junction,
- Configuration 2: Welds B, situated between extruded elements,
- Configuration 3: Welds B + C1, where welds C1 are situated at 1/2 of the central span,
- Configuration 4: Welds B + C2, where welds C2 are situated at 1/4 of the central span.

The analysis results of each participant at this phase are presented in Table 2. There are no significant differences between results, the general behaviour and ultimate load of the different models being quite similar. All the models are seen to fail in flexural buckling, with the middle field in Z negative direction, and the other two fields in positive direction. The first drop in the average stress/average strain curve corresponds to the flexural buckling, while the second drop corresponds to the stiffener tripping in the middle of the test piece.

The first phase showed that the behaviour of the panel stays elastic until the collapse (Table 2). It was then impossible to get any information about the influence of the HAZ with this model. Therefore a new model was considered for Phase B.

TABLE 2

RESULTS OF THE PHASE A1 AND A2 ON THE THREE SPANS MODEL 3 x 2050 mm

	Lehmann-Catalin			*Philippe- Radu*			*Wan*			*Estefen-Pasqualino*		
	Maximum average stress		Average strain	Maximum average stress		Average strain	Maximum average stress		Average strain	Maximum average stress		Average strain
	[N/mm^2]	Difference to reference	[%]	[N/mm^2]	Difference to reference	[%]	[N/mm^2]	Difference to reference	[%]	[N/mm^2]	Difference to reference	[%]
Without HAZ (reference)	96.57	ref	0.1372	98.14	ref	0.1392	100.49	ref	0.1452	95.61	ref	0.1353
WITH HAZ												
Welds A	96.33	-0.25%	0.1367	97.34	-0.82%	0.1398	100.02	-0.46%	0.1421	95.52	-0.10%	0.1353
Welds B	96.47	-0.10%	0.1369							95.57	-0.05%	0.1353
Welds B + C1	96.47	-0.10%	0.1369	97.91	-0.23%	0.1392				95.57	-0.05%	0.1353
Welds B + C2	96.47	-0.10%	0.1369							95.57	-0.05%	0.1353
Mean value	**96.43**	**-0.14%**	**0.137**	**97.62**		**0.139**	**100.02**		**0.142**	**95.55**		**0.135**

14.4.3 Phase B1- Weld Types

At the end of Phase A, the organizers became confident that the quality of the results allowed the start of the next phase, where each contributor studied alone, one or multiple parameters.

For Phase B, a modified model was proposed to assess the effect of the HAZ on the ultimate strength. This new panel with 3 spans of 1025 mm was obtained from initial model by halving the total length of the plate. The column slenderness of the new model becomes 0.90 instead of 1.80 for the 2050mm model used in Phase A. The geometric imperfections are determined the same way as with Phase A, by imposing a lateral pressure that induces a displacement of 2 mm at the center of the panel.

Two new weld configurations were also added for the analyses: configuration 5, *welds A + welds C2* and configuration 6: welds A + welds D where Welds D are situated in the frames and at junction frame-plate (Figure 12).

An analysis without HAZ was additionally performed as a reference case. The results presented in Table 3 show the differences between the collapse modes of the different studied cases.

TABLE 3

EFFECT OF THE HAZ ON THE NEW MODEL - 3 X 1025 mm SPANS

	Philippe-Radu (Shape 2 [*])			Lehmann-Catalin (Shape 1)			Yao-Higashiyama (Shape 1)		
	Maximum average stress		Average strain	Maximum average stress		Average strain	Maximum average stress		Average strain
	[N/mm^2]	Difference to reference	[%]	[N/mm2]	Difference to reference	[%]	[N/mm2]	Difference to reference	[%]
Without HAZ (reference)	173.46 171.92 (if shape 1)	Reference	0.321	169.88	Reference	0.031	160.80	Reference	0.300
WITH HAZ									
with HAZ Welds A	150.22	-13.40%	0.300	144.48	-16.71%	0.292	136.15	-21.51%	0.301
with HAZ Welds B	171.21	-1.30%	0.324	161.47	-6.91%	0.296	157.70	-9.09%	0.302
with HAZ Welds B+C1	151.61	-12.60%	0.269	141.94	-18.17%	0.246	146.28	-15.67%	0.230
with HAZ Welds A+C1	129.12	-25.56%	0.232	125.81	-27.47%	0.259	126.10	-27.30%	0.245
with HAZ Welds A+C2	132.93	-23.37%	0.241	132.25	-23.76%	0.244	135.09	-22.12%	0.240
with HAZ Welds B+C2							142.05	-18.11%	0.239
with HAZ Welds A+D(frames)	146.43	-15.59%	0.302						
Mean value	**146.92**	**-15.30%**	**0.278**	**141.19**	**-18.60%**	**0.267**	**140.56**	**-18.97%**	**0.259**

[*] Shape 2 was used by Philippe-Radu and Shape 1 by the other contributors. This may explain the difference, namely for analysis with Weld B.

14.4.4 Phase B2 – HAZ width (η)

This phase of the sensitivity analysis deals with the effects of the HAZ width. Four HAZ widths (Welds A) were studied: η_1 = 25 mm, η_1 = 50 mm, η_1 = 75 mm, η_1 = 100 mm (see Figure 15). Figure 13 shows the results of these analyses compared with the reference case (without HAZ).

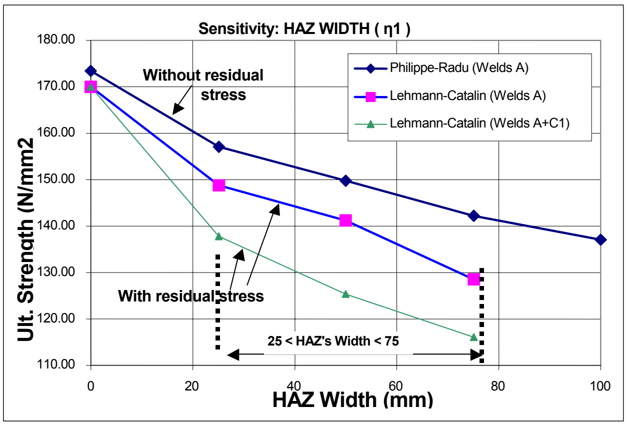


Figure 13: Sensitivity of the HAZ width

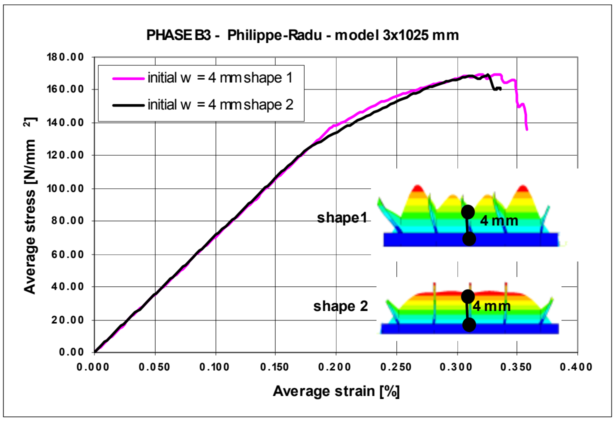


Figure 14: Influence of the initial imperfections shape

14.4.5 Phase B3 – Initial Imperfection

The influence of the amplitude and shape of initial imperfection was studied in this phase. The amplitude is considered at the reference point in the centre of the panel (Figure 11) where it is different from the maximum value. Two shapes of initial deflection were considered in the analyses (Figure 14).

Concerning the effect of initial deflection amplitude, Table 4 shows that the ultimate strength varies significantly with the amplitude (for identical shape). By increasing the lateral deflection amplitude from 4 to 8 mm, the ultimate strength is reduced approximately 4% (Table 4).

TABLE 4

SENSITIVITY ON INITIAL DEFLECTION AND SHAPE – WELDS A, MODEL 3 X 1025 mm

	Maximum average stress		Average strain
	[N/mm²]	**Difference to reference (4mm - shape 2)**	[%]
Sensitivity of the deflection amplitude (2, 4 and 8 mm) - Shape 2			
Initial deflection w = 2 mm - shape 2	173.46	+2.70%	0.321
Initial deflection w = 4 mm - shape 2	168.89	ref	0.313
Initial deflection w = 8 mm - shape 2	162.11	-4.02%	0.317
Sensitivity of the deflection Shape (amplitude = 4 mm at the reference point - centre of the panel)			
Initial deflection w = 4 mm - shape1	169.71	+0.49%	0.322
Initial deflection w = 4 mm - shape2	168.89	ref	0.313

14.4.6 Phase B4 - Residual Stresses

In this phase, *Lehman-Catalin* analysed the effect of the residual stresses due to welding in the HAZ, on the ultimate strength of the panel (Table 5). The distribution of the welding residual stresses is presented in Figure 15. Checking the effect of welding is, of course, a very difficult task. The simulation of welding itself is beyond the scope of work of this Committee. Simplified distributions of residual stresses were assumed and a parametric study was done.

The stresses defined in Figure 15 were considered as initial stresses. The convention for the tensile initial stresses that extend over the entire HAZ width is that they are constant over the width and through the thickness. Their direction is parallel to the welding seam and the magnitude is equal to the flow limit of the material of the HAZ, that is 130 N/mm^2. This is valid for the stresses in the plate, as well as for the stresses in the stiffener.

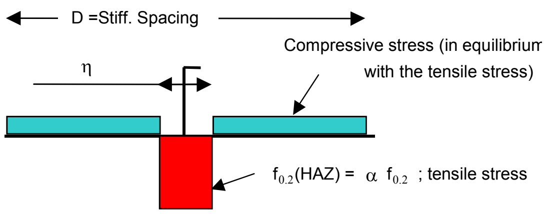


Figure 15: Residual stress across the HAZ

For the transverse welds, the residual stresses are acting perpendicular to the residual stresses of the longitudinal welding seams. The width of the field of compressive stresses in the plate is a problem, as it cannot be the entire length of the model. Therefore, they are considered to act only in the middle area of the model, between the transverse beams (1025 mm). The magnitude of the transverse residual stresses is determined in the same way as for the longitudinal ones.

Weld position influence: similarly, as with Phase B1, this effect is studied by a combination of longitudinal and transverse welding seams. The tendency is the one already expected such that the panel has a higher ultimate strength for welds B (extruded element) than for welds A.

Table 5 groups the values of the ultimate strength in two categories, *with* and *without* residual stresses. By comparing the two categories, the same pattern can be observed with a slight reduction of the ultimate strength in the case *with residual stresses*.

TABLE 5

SENSITIVITY TO RESIDUAL STRESSES – MODEL 3 X 1025 mm

Lehmann-Catalin	Maximum average stress		Average strain
PLATE of 5 mm	[N/mm^2]	**Difference to reference**	[%]
Without HAZ	169.88		0.312
With HAZ: η = 50 mm			
WELDS A			
- without residual stresses	144.48	Ref	0.292
- with residual stresses	141.20	-2.27%	0.280
WELDS B			
- without residual stresses	161.47	Ref	0.296
- with residual stresses	164.77	2.05%	0.280
WELDS A+C1			
- without residual stresses	125.81	Ref	0.259
- with residual stresses	125.42	-0.31%	0.228
WELDS A+C2			
- without residual stresses	132.25	Ref	0.244
- with residual stresses	128.92	-2.52%	0.234
WELDS B+C1			
- without residual stresses	141.27	Ref	0.246
- with residual stresses	148.94	5.43%	0.258

14.4.7 Phase B5 - Plate Thickness

Additional analyses were done to check the coupled effect of the plate thickness and the welding residual stresses (Table 6). The thickness of the plate was increased to 7 mm, keeping the rest of the geometry unchanged. The material properties and residual stresses correspond to welds A, where the width of the HAZ is η_1 = 50 mm.

TABLE 6

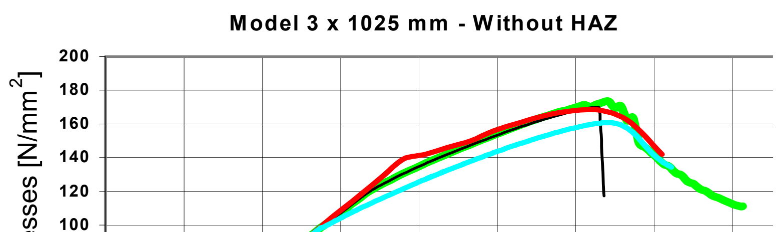
SENSITIVITY ON PLATE THICKNESS – WELDS A, MODEL 3 X 1025 mm

	Maximum average stress		Average strain
	[N/mm^2]	**Difference to reference**	[%]
Plate thickness 5 mm	144.48	ref	0.292
Plate thickness 7 mm	180.12	24.66%	0.288
Plate thickness 5 mm	141.20	ref	0.280
Plate thickness 7 mm	171.57	21.51%	0.259

According to Table 6, the ultimate strength of the considered stiffened panel is increased by 11-12% due to an increase of 20% in plate thickness. This is an important conclusion with regards to the thickness uncertainty due to corrosion. It confirms that the plate thickness is one of the most important parameters related to ultimate strength.

14.5 Explicit Dynamic Analysis

When a quasi-static problem is solved as a wave-propagation problem, as is the case in explicit analysis, it is very important to carefully consider the load history. The loading rate should be sufficiently low to prevent inertia effects from dominating the solution. On the other hand, a long loading time increases the calculation time and also the numerical errors, as more time steps are needed to reach the final configuration. Figure 16 compares the results of implicit FEM analyses with the results of an explicit analysis using a total loading time of 0.1s. It is seen that the agreement between explicit (*Bo-Ulrik*) and implicit analyses is very good.



Contributors (Shape 1)	σ_u [N/mm2]
Philippe-Radu	171.92
Lehmann-Catalin	169.88
Yao-Higashiyama	160.80
Bo-Ulrik Explicit Model	168.00

Figure 16: Implicit analysis versus explicit analysis.

14.6 Discussion

The conclusions given below are only valid for the considered structure. The analysis showed the following sensitivities:

a) Welds types (HAZ effect):

- The reduction of ultimate strength varies from 0% to 30.0%
- Configuration with Welds B (extruded elements) is less sensitive to HAZ than with Welds A (Stiffeners welded on the plate), respectively, 13.0-17.0% and 1.0-6.0%.
- Most sensitive configuration concerns configuration with welded stiffeners (Weld A) and transverse weld (Weld C1/C2) : 23.0-27.0%,
- A transverse weld induces (C1, C2), alone, a reduction of about 11.0-12.0%.
- Transverse weld (Weld D) at the junction between the plate and the frame has aninsignificant effect: about 2.0%

b) HAZ width: The variation of ultimate strength is not proportional to the HAZ's width. The first 25 mm of the HAZ width are the most significant and has the largest effect on the ultimate strength. For the considered model with Welds A, we observed:

- for the first 25 mm of HAZ width ($\eta_1 \approx 25$ mm), the reduction is approximately 9%,
- for the second and third increments of 25 mm of HAZ width ($\eta_1 \approx 50$ and 75 mm), the additional reduction of ultimate strength is about 4.5%%,
- then (η_1=100mm), the additional reduction of ultimate strength becomes smaller (3.0%).
- Similar behaviour is recorded when the residual stress is added. The effect of the first 25 mm is even much bigger (12% instead of 9%).
- For WELDS A+C1 (with residual stress), the reductions are 19%, 7% and 5%.

c) Initial imperfection: About 1% of reduction of the strength is recorded for each mm of initial deflection measured at mid span of the central stiffener.

d) Residual stress: The strength variation induced by the residual stresses is about –2.5% (plate of 5mm thick). This variation depends significantly on the weld types, for instance from a reduction of -5.0% to an increase of strength of +2.0 % (Weld B = extruded element). Such increase has to be confirmed by more advanced analysis and experiments. Effect of residual stresses with a plate of 7 mm thick is twice the effect with a plate of 5 mm.

e) Explicit analysis: An explicit analysis can be performed as an alternative to standard implicit FEA. It requires a very careful consideration and extensive parameter studies of the loading rate to assure that non-physical dynamic effects are not dominating the solution.

f) Convergence: Coarse meshes are not suitable to study collapse analysis of stiffened aluminum panels. For the concerned model, an optimal mesh size seems to require about 8000 elements.

15. CONCLUSIONS

This report has reviewed published work related to ultimate strength, covering the period 2000-2003. The report clearly demonstrates that the field is very active in academia as well among practicing engineers. The constant strive for more cost-effective structures at required levels of safety drives the work towards a better understanding of the connection between ultimate strength, loads, initial design and in-service degradation. Many of the important real-life configurations show such a complex dependence between those aspects, that there are plenty of opportunities for significant advances in the years to come. One of the challenges to be addressed is how to efficiently deal with coupling between micro- and macro-mechanics, for examples in the case of ductile fracture in large-scale structures or in the case of micro(material) failure in a composite structure.

<u>Empirical and Analytical Methods</u>
Empirical and analytical methods are useful at the initial stage of structural design. From this aspect, developments of empirical and analytical methods to evaluate the buckling/ultimate strength are still necessary even if it has become common to perform the FEM analyses considering both material and geometrical nonlinearities. In this connection, some useful formulations have been reported since the last ISSC. One of the important remaining subjects in the analytical formulation may be that for combined local/overall buckling/post-buckling behaviour of stiffened plating under general combined loads.

<u>Numerical Methods</u>
With the significant development of commercial FEM software, FEM has moved towards becoming a standard analysis tool for the prediction of ultimate strength. As computational power decreases in cost, the requirements to larger and finer models grow. Therefore, future research efforts will focus on the development of robust element models and effective solution procedures in order to enhance accuracy, convergence and capability. As an alternative to the FEM, the so-called mesh-free method has received a good deal of attention and several references are discussed. The combined approach based on coupling of the FEM and the mess-less or particle method is expected to give cost-effective procedures for practical application.

The Idealized Structural Unit Methods (ISUM) had been classified into two, which are the ISUM of the first generation, which is based on the empirical formulations, and the ISUM of the second generation, which is based on mathematical approximations. These ISUMs, however, cannot simulate actual collapse behaviour of the structural systems accompanied by localisation of the deflection and yielding beyond the ultimate strength. To address this situation, a new ISUM is proposed similar to that of the second generation but with the ability to simulate localized effects owing to new shape functions and a little smaller discretization compared to old ISUMs. It is hoped that the applicability of the new ISUM to the collapse analysis of ship and other structures is demonstrated in a near future.

<u>Experimental Methods</u>
Due to the complexity of material and structural behaviour under ultimate conditions, experiments become an inevitable part of the ultimate strength assessments or at least of the validation of prediction methods. The report lists several rather new experimental methods relevant for ultimate strength. A new, efficient method for plate thickness measurement may become important for in-service assessment of the current strength of a vessel.

<u>Reliability Analysis</u>
Reliability analysis techniques have been continuously applied to different types of ships and offshore structures, such as oil tankers, FPSOs, jack-up platforms, large floating structures, etc. Efforts have been made to investigate the uncertainties in the process of predicting ultimate strength of hull girders

using progressive collapse analysis. Monte Carlo simulation has been integrated into progressive collapse analysis so that a more accurate estimation of failure probability of hull girders could be obtained. More work, especially experimental study, need to be carried out to quantify the uncertainties in progressive collapse analysis.

Response surface methods have been applied to unstiffened and stiffened plates when numerical methods are used to assess the ultimate capacity of panels. These methods are considered as good candidates for implicit limit state functions. Reliability analysis of composite panels has also been reported.

The effects of corrosion and fatigue on the reliability of ultimate hull girder strength were investigated. The through-life reliability of ships can be calculated by time-dependent reliability analysis.

Structural system reliability analyses were carried out on jack-up and jacket platforms. The results are very sensitive to the theoretical models of foundations, and to other structural features, which were not considered in the reliability assessment. These effects need to be further investigated.

Tubular Members and Joints

A number of papers have been published on nonlinear formulations and analyses of frame structures. Some novel formulations are presented, extending the nonlinear formulations to thin-walled open sections and to beam-columns with tapered cross-section. Some work is presented on the influence of cut-outs in girders. Also, important contributions are given on low-cycle fatigue and shakedown of members. However, few sources are available relating specifically to ship structures, interaction between frames and plating, redundancy of plate / frame structures, etc.

Closed-form solutions have been developed for the complete nonlinear P-δ or M-θ curves for joints subjected to uni-directional loading (axial and bending loads). In the present ISSC period, the formulations have been extended to multi-directional loading, also incorporating chord load interaction, and codified into a generic joint module for use in nonlinear frame analysis packages.

Plates and Stiffened Plates and Shells

Plates and stiffened plates are the dominating structures in all ship and offshore applications and steel is the dominating material used. The recent developments in nonlinear numerical analysis methods enable nowadays fairly accurate analysis of the collapse behaviour of these local structural elements. The main topics requiring additional work are: gathering full-scale data on the real post-weld initial imperfections on various types of stiffened panels, effect of combined loadings and especially studies related to the interaction phenomenon between various failure modes. The amount of real residual stresses in ship structures is also a topic requiring further development work, but the main problem is the lack of full-scale data of the residual stresses and lack of knowledge of how these stresses will change under fluctuating wave loadings.

There is also a continuous need for development of light structures for marine applications. New types of innovative solutions such as laser-welded metallic sandwich panels have emerged requiring careful and detailed analysis to develop sound ultimate strength analysis methods for these panels having typically very thin cover and core plates.

Ship Structures

Many papers have been published since the last ISSC regarding the buckling/ultimate strength of ship structural members and systems. These papers deal with ultimate hull girder strength under longitudinal bending, buckling/plastic collapse strength of bulk carriers bulkheads subjected to flooding load, double bottom structure subjected to pressure load and bulk carrier hatch covers under blue sea water. Most of them are discussed on the basis of the results of nonlinear FEM analyses and ISUM analyses, but some are based on experimental results. In some papers, simplified methods were developed to evaluate the collapse strength. It is hoped that sophisticated and accurate, but simple methods, are developed on the basis of rational formulations to evaluate the buckling/collapse strength and to simulate collapse behaviour of ship structures.

Offshore Structures

Jackets, jack-ups and floating units employed in the oil and gas offshore activities are very sensitive structures to accidental collision of supply boats. Although the structural consequences on the ultimate strength have been studied during the last two decades, additional studies are recommended, especially those related to experimental programmes, to adjust the available analytical and numerical simulation tools. For storage units, with emphasis on the FPSOs, the possibility of an environmental disaster associated with a huge amount of oil spill following a collision should be better understood and prevented, at least partially in the design stage. The burst collapse of the emergency drainage tank (EDT) of the semi-submersible platform P-36, offshore of Brazil, led to its sinking few days later. Analyses have been performed to investigate the different aspects of the main events, which initiated and escalated the accident. Lessons learned from this accident certainly will generate new design procedures and safety measures for floating production units.

Composite Structures

Recent ultimate strength research in composites for marine applications has generally centered on FRP or glass-reinforced polymer (GRP) materials and their resulting size or scale effects, stiffened, unstiffened shell and sandwich panel strengths and stiffnesses, seawater immersion effects, damaged strength due to fire impact, and manufacturing defects. Experimental testing of panels and cylinders continued in support of analytical and numerical analysis to perfect predictive capabilities. Linear approaches continue to be used to gain an approximation of the onset of buckling while nonlinear approaches are developed to increase accuracy, and address the post-buckling regime. Modelling the imperfections in the material is shown to be important as one might expect, though knockdown factors continue to be employed to skew predictions closer to test results in cases where imperfections are not explicitly considered in the analysis. Closed form, three-dimensional analytical solutions for panel buckling are introduced and compared to higher-level predictions and tests. Formulations and curves are proposed for use in the design of composite skins against fire with recommendations made about material choice.

Aluminium

Aluminium is increasingly being used in load-carrying structures like ship hulls, offshore structures and bridges. Compared to steel, relatively little experience has been accumulated for large aluminium structures. The existing design recommendations for aluminium panels are to a large extent based on experience from steel structures. This approach immediately seems natural but there are a number of differences between steel and aluminium, which call for an analysis approach specific to aluminium:

- Aluminium can be extruded into stiffeners or combined plate-stiffener configurations with very fine tolerances and possibly high material anisotropy.
- Welded aluminium connections in general have rather poor fatigue properties.
- Welding distortions can be relatively large for aluminium structures.
- The heat of the weld generates a weak zone (normally called the Heat Affected Zone, HAZ) next to the weld. The reduction of strength in this zone may be up to 50%.
- The corrosion characteristics of aluminium are quite different from steel.

These differences make it difficult to immediately transfer experience from steel to aluminium with regard to design, construction and maintenance. This report has discussed a number of studies related to the ultimate strength of welded, stiffened aluminium panels. However, the work on aluminium is still rather limited compared to steel so for the reasons given above it is very important that more research is conducted in this area.

Benchmark

The aim of the benchmark was to predict the ultimate strength for a stiffened aluminium panel using different finite element models and codes and variations of the most uncertain input parameters. A comparison of the results of various codes for the same configuration showed good agreement. An extensive sensitivity study - varying the most uncertain parameters, such as width of heat-affected zone, geometric imperfections and residual stresses – revealed that the ultimate strength is indeed quite sensitive to quantities which are typically considered of secondary importance in a steel structure. For example it was shown a 50% reduction of the yield stress around a transverse weld might reduce the ultimate strength by 30%.

In the future, such sensitivity assessment has to be continued with the study of other parameters and panel configurations. The results could be completed by a comparison with rules, codes (Eurocode 9) and experimental results given by the literature.

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