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VOLUME 1

COMMITTEE III.2

FATIGUE AND FRACTURE

COMMITTEE MANDATE

Concern for crack initiation and growth under cyclic loading as well as unstable crack propagation and tearing in ship and offshore structures. Due attention shall be paid to practical application and statistical description of fracture control methods in design, fabrication and service. Consideration is to be given to the suitability and uncertainty of physical models. The work shall be coordinated with that of Committee V.2.

COMMITTEE MEMBERS

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KEYWORDS

Fatigue, Fracture Mechanics, Materials, Steel, Aluminium, Titanium, Composites, Improvement, Inspection, Repair.

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CONTENTS

1. INTRODUCTION

2. LIFE PREDICTION: CURRENT STATE-OF-THE-ART
   - 2.1 Cumulative Fatigue Damage (CFD) Approaches
     - 2.1.1 Stress-based (S-N) Approaches
     - 2.1.2 Multiaxial Fatigue
   - 2.2 Fatigue Crack Propagation (FCP) Approaches
     - 2.2.1 Crack Growth Rate Curve
     - 2.2.2 Calculation of the Fatigue Crack Driving Force
     - 2.2.3 Various Special Phenomena Relating to Fatigue Crack Propagation
     - 2.2.4 Fatigue Crack Propagation in a Corrosive Environment
     - 2.2.5 FCP Theory Applied to Ship and Offshore Structures
   - 2.3 Relationship Between CFD and FCP Theories
   - 2.4 Probabilistic Treatment
     - 2.4.1 Model for Probabilistic CFD Approach
     - 2.4.2 Model for Probabilistic FCP Approach
     - 2.4.3 Data for Probabilistic Models
   - 2.5 Fatigue Testing of Components
     - 2.5.1 Large/Full Scale Testing
     - 2.5.2 Load Sequence Effects
     - 2.5.3 Structural Details: Effect on the Fatigue Life.

3. REFERENCE STRESS
   - 3.1 Numerical procedures and extrapolation methods
   - 3.2 Stress Determination Procedures
     - 3.2.1 Finite Element Analysis
     - 3.2.2 Integral Method
     - 3.2.3 Measurement of the Structural Stress
   - 3.3 Hot-Spot S-N-curves
   - 3.4 Misalignment and fabrication tolerances
   - 3.5 Illustrative Example
     - 3.5.1 Finite Element Models
     - 3.5.2 Results
     - 3.5.3 Discussion of Results

4. FATIGUE LIFE IMPROVEMENT
   - 4.1 Factors in Design
     - 4.1.1 Weld Quality
   - 4.2 Factors in Operation
     - 4.2.1 Burr Grinding
     - 4.2.2 TIG Dressing
     - 4.2.3 Hammer, Needle and Shot Peening
     - 4.2.4 Other methods introducing Compressive Stresses at the Weld
   - 4.3 Code Development

5. IMPACT OF DEVELOPMENTS IN MATERIALS ON FATIGUE & FRACTURE
   - 5.1 Material Developments
   - 5.2 New Materials & Applications
     - 5.2.1 Titanium

5.2.2 Aluminium
5.2.3 Composites

6. CONCLUSIONS

REFERENCES

1. INTRODUCTION

The Fatigue and Fracture Technical Committee of the ISSC has made a major contribution to the work of ISSC over the decades. This report of the current committee describes recent activity of the international ship and offshore industry and the researchers that support it, with specific regard to current pertinent issues and trends relating to fatigue and fracture. It is important to remember that the subject area is vast, and that this report should be seen not only in the context of the entire ISSC 2003 proceedings but also as a continuation of past ISSC reports. In addition, the committee choose to focus on areas commensurate with the expertise of the committee members to build on the vast knowledge base generated by previous committee III.2 reports. With this in mind, the present report develops current topical issues such as reference stress, improvement/repair and non-steel marine materials, in addition to developments in fatigue analysis techniques. Environmental issues are distributed throughout the report and not dealt with as a separate topic.

ISSC 2000 dealt in detail with developments in fracture, multi axial fatigue and residual stresses. For this reason they have not been give the same degree of attention and instead are mentioned as sub sections of specific topics. Another area that is important in the field of fatigue and fracture is that of high/low temperature effects. Although these conditions exist, for example in flow lines, they have not been specifically addressed in this report due to the highly specialist nature of these applications. Inspection and Monitoring is dealt with in detail by Specialist Committee V.2 (Inspection and Monitoring) and for this reason has been omitted from this report.

In the last two ISSC committee reports (ISSC1997 and ISSC2000), progress in fatigue life prediction methods was presented in one specific chapter. This format is repeated again as it allows this important topic to be clearly presented in its own right. In this Section, the progress in fatigue life prediction methods relating to metal structures in last three years from 2000 to 2002 is reviewed while the fatigue of composite structures is dealt with in Section 5.

Section 3 deals with the reference stress issue and aims to build on the findings of the comparative study carried out in ISSC2000. Instead of conducting a comparative study, it was thought useful to provide an illustrative example of the implementation of the relevant guidance available for the calculation of hot spot stress. Again it is important to note that ABS, GL and DnV are the classification societies represented on the committee, and whereas every effort was made to include the rules of others, invariably committee members will be more familiar with the rules of their own organisation. Section 4 considers developments in the highly active area of fatigue life improvement in terms of design, operation and its treatment in guidance documents and codes. Section 5 looks specifically at non-steel marine structural materials, focussing on Titanium, Aluminium and Composites.

An important element of ISSC work is to provide an expert opinion on the subject matter reported. Section 6 summarises the main features of the report and makes specific observations on the topics studied particularly with respect to where further work is needed.

2. LIFE PREDICTION: CURRENT STATE-OF-THE-ART

Although metal fatigue has been studied for more than 160 years, many problems still remain to be solved due to the complexity of the subject area. A state-of-the-art review of fatigue life prediction methods for metal structures was recently carried out by Cui (2002a).

According to Cui (2002a), the whole process of fatigue failure for a component can generally be divided into five stages: (1) crack nucleation ($a<a_m$); (2) microstructurally small crack propagation ($a_m<a\leq a_p$); (3) physically small crack propagation ($a_p<a\leq a_l$); (4) long crack propagation ($a_l<a\leq a_c$); (5) final fracture; where a is the characteristic dimension of an equivalent crack in a component, a_m is the smallest crack length detectable by current technology which is about 0.1μm; a_p is the smallest crack length for physically small cracks which is about 10μm, a_l is the smallest crack length for long cracks which is about 1 mm, a_c is the critical crack length at which component fracture occurs. Depending on the initial crack length in a component, some of the early stages may be skipped. These five stages of the fatigue process only exist in "defect free" metal components.

These boundary divisions are subjective and depend on the ability of crack measurement systems. Traditionally, the stages before long crack propagation come under the term "fatigue crack initiation" while long crack propagation is called "fatigue crack propagation". This division is very rough and cannot be expected to provide an accurate model of fatigue life but is simple and is still used in many references (e.g. Lynn and DuQuesnay, 2002).

Factors, which affect the fatigue lives of metal structures, are numerous and it is impossible for a mathematical model to consider all influencing parameters. Simplifications have to be made in order for models to be of practical use. Many models were developed in the past 160 years and they can be grouped into two categories: Cumulative fatigue damage (CFD) theory and fatigue crack propagation (FCP) theory. At present, models conforming to these two categories are widely applied and continue to be developed.

2.1 Cumulative Fatigue Damage (CFD) Approaches

Fatigue damage is a result of material structural changes at the microscopic scale such as dislocations of atomic structures. While bridging microscopic quantities and macroscopic experimental observations is still a long-term endeavour, it is reasonable to believe that microscopic parameters governing fatigue damage have an inherent relationship with the macroscopic stress and strain quantities based upon continuum mechanics concepts (Hao et al, 2000). These macroscopic quantities can be used to account for crack nucleation and early growth. By choosing different macroscopic quantities such as stress, strain, energy density or a combination of these, different cumulative fatigue damage formulas can be derived. They can be categorized into stress-based approaches, strain-based approaches, energy-based approaches and continuum damage mechanics (CDM) approaches (Cui, 2002a). Although strain-based approaches and energy based approaches were proposed for some time (ISSC1997), few references were found in the last three years concerning these aspects (Roessle and Fatemi, 2000; Lynn and DuQuesnay, 2002). Several references were found promoting the use of CDM to predict fatigue life (Dhar et al, 2000; Li et al, 2001; Memon et al, 2002; Cusumano and Chatterjee, 2000), but their application to marine structures is not presently obvious. Therefore the following review is mainly confined to stress-based approaches, which dominate in Ship and Offshore Structures applications.

2.1.1 Stress-based (S-N) Approaches

The Stress-based approach is the earliest and simplest approach for fatigue life prediction. In this approach, the fatigue life (number of cycles N) is related to the applied stress range ($\Delta\sigma$ or S) or stress amplitude (σ_a). The most fundamental assumption is the Palmgren-Miner linear cumulative damage law that ignores load sequence effects. Strictly speaking, the effect of initial defects and final failure state could be accounted for if exactly identical components or structures are tested under actual service conditions and the resultant S-N curves are used. Obviously this is impossible. Thus the S-N curves

that are obtained from simple component are different from the actual fatigue performance of the component assessed. In order to take account of this, the hot spot or notch stress approach is recommended instead of the nominal stress approach (section 3). Therefore, three main processes are involved for the use of stress-based approaches: (1) definition of the long-term fatigue loading which is usually described as a probability distribution such as Weibull distribution; (2) choice of the S-N curves from an existing testing database which most closely reflects the component to be assessed; (3) calculation of the stress concentration factor (SCF) for the component.

The S-N approach has been adopted by all ship classification societies for fatigue strength assessment of ship structures. These were compared by the previous ISSC Fatigue and Fracture Committee (Fricke et al, 2001), which showed that large differences exist between the predicted fatigue lives for the same detail by different classification society rules. Determination of hot spot stress and/or notch stress still remains a key issue in the use of S-N curve based approaches. This problem is addressed in Section 3.

2.1.2 Multiaxial Fatigue

S-N curves are generally based on test results from uni-axial loading. The stress state in real structures at fatigue critical locations is typically multi-axial in nature. Fatigue damage accumulation under multi-axial cyclic stresses have often been modelled by using parameters such as principal stress range, maximum shear stress range, effective stress range or stress state at different crack initiation planes. However, none were proved to be decisively better than others.

Multiaxial fatigue of weldments has continued to be an important area of research in the last three years (Yousefi et al 2001; Sonsino and Kueppers 2001; Dang Van et al 2001; Li et al 2001). Backstrom and Marquis (2001) conducted a review of the topic. A survey of biaxial (bending or tension and torsion) constant amplitude fatigue of welded connections is presented. Re-analysis of 233 experimental results from eight different studies were performed based on hot spot stresses and three potential damage parameters: maximum principal stress range; maximum shear stress range; and a modified critical plane model for welds. Of the three methods, the critical plane model was most successful in resolving the data to a single S-N line.

Recently Kueppers and Sonsino (2002) reported tests on welded aluminium welded joints, performed on the same geometry as for steel welds, a plane flange fillet welded to the end of a tube specimen. They report that aluminium does not show a loss in fatigue life when subjected to loads with changing principal stress directions. It is difficult to explain this difference in fatigue behaviour by use of ordinary theories. Pitoiset and Preumont (2000) presented computationally efficient frequency domain methods for estimating the high-cycle fatigue life of metallic structures subjected to a random multiaxial loading. They showed that the multiaxial rainflow method, initially formulated in the time domain, can also be implemented in the frequency domain. Kawabe and Shibazaki (2001) discussed the combination of fatigue damages produced by several wave-induced loads based on correlation coefficient method. A simple combination formula for the combined fatigue damage caused by two stress components is provided.

Biaxial fatigue behaviour of a box-welded joint in JIS SM 400 B was studied by Takahashi et al (2000) using a multiaxial fatigue test facility. Residual stress measurements and finite element analyses (FEA) were also carried out. Fatigue tests were performed under both uniaxial and biaxial cycle loads, and the results were comparatively examined. In the biaxial fatigue tests, special concerns were focused on effects of biaxial load range ratio and compressive cyclic loads in the lateral direction. It was observed that the direction of fatigue crack propagation under biaxial cyclic tensile loads, which have a phase difference, changes according to the biaxial load range ratio.

2.2 Fatigue Crack Propagation (FCP) Approaches

One of the significant deficiencies of the CFD theory is that load sequence effects are very often neglected. A simple hypothesis of cumulative fatigue damage taking into account the load sequence effect is proposed by Kosut (2000a; 2000b) for engineering purposes. An approach using immediate and history damage factors are used to simplify the application of the hypothesis. The method satisfactorily approximates constant amplitude fatigue lives and fatigue lives in H-L (high-low) and L-H (low-high) loading and even general complex loading cases. Approaches based on fracture mechanics can easily consider load sequence effects and many other effects such as initial defects and the state of the failure. Therefore, recently an increasing number of authors advocate the use of FCP theory to unify fatigue life predictions (e.g. Newman 1998; Miller 1999; Cui 2002b, Cui 2002c).

2.2.1 Crack Growth Rate Curve

In the use of FCP theory for fatigue life prediction, the most fundamental requirement is to establish an appropriate crack growth rate curve for the particular problem. The simplest crack growth rate curve is the so-called Paris law but it is well known that this curve only covers the middle region (linear elastic) of the crack propagation. A complete crack growth rate curve would be nonlinear starting from threshold then to the linear Paris region and finally approaching unstable fracture. Recently Cui (2003) proposed a general constitutive relation for fatigue crack growth analysis of metal structures based on the extension of McEvily and Ishihara's model (McEvily and Ishihara 2001) while Soboyejo et al (2001) proposed a multiparameter approach to the prediction of fatigue crack growth in metallic materials using a generalized empirical methodology. Both relations show good agreement with experimental data.

Another physically-based model is proposed by Shademan et al (2001) for the prediction of fatigue crack growth in Ti–6Al–4V. The model assumes that the crack extension per cycle is directly proportional to the change in the crack-tip opening displacement, during cyclic loading between the maximum and minimum stress intensity factor.

Ramsamooj and Shugar (2001a) applied a local energy criterion to the problem of quasi-static extension of a sub critical crack embedded in an elasto-plastic matrix. The derived expression for the fatigue crack growth rate is approximated by:

$$\frac{dc}{dN} = \frac{0.041}{EY}\left(\Delta K_1 - \Delta K_{th}\right)^2 \frac{1}{1-\left(K_{1\max}/K_{1c}\right)^2} \tag{1}$$

where ΔK_1 is the stress intensity factor (SIF) range, K_{1max} is the maximum value, K_{1c} is the fracture toughness, ΔK_{th} is the threshold SIF, E is Young's modulus, and Y is the yield strength. The new analytical model for fatigue crack growth governs the sub critical growth of the crack up to the point of gross instability. It is a continuous process that covers the growth rate from threshold to failure, and has the capability of predicting the behaviour of full-scale structures from small-scale laboratory tests. An extensive amount of published fatigue data for a wide range of metals and metal alloys is used to validate the new analytical expression for crack growth rate. The agreement between the predictions of the new model and the experimental data ranges from fair to excellent. This model has also been used to predict the life of rigid connectors for a mobile offshore base under random loading by wave action from eight sea states (Ramsamooj and Shugar 2001b). Recommendations are made for the design stresses and for selecting the metal to be used for the design of the connectors for fatigue.

An Experimental investigation into the fatigue crack growth in welded tube-to-plate specimens of StE 460 steel under bending, torsion, and combined in-phase and out-of-phase bending/torsion loading was carried out by Amstutz et al (2001). The tests were performed at stress ratios of R = -1 and R = 0. The residual stresses were reduced using a thermal stress relief method. The fatigue crack development is compared with the prediction of crack growth rates using the Paris Law. Individual stress intensity factors for the semi elliptical surface cracks in the tube-flange specimens are approximated using a weight function analogy making use of published solutions.

While a continuous crack growth rate curve covering the whole fatigue crack process would be much easier for application, this may suffer from inaccuracy because the crack growth rate is different in different crack regions. Miller (1999) proposed to use three crack growth rate curves to describe the crack growth in the micro fracture mechanics (MFM) regime, the elastic-plastic fracture mechanics (EPFM) regime and the linear elastic fracture mechanics (LEFM) regime. Furthermore, different thresholds are found in different regimes. It is however, unclear how a crack graduates from one regime to other. As far as application of the proposed approach is concerned, much research is needed to understand and measure the model parameters.

2.2.2 Calculation of the Fatigue Crack Driving Force

Implicit in the definition of the crack growth rate curve is the quantity to be chosen as the fatigue crack driving force. Strictly speaking, three independent parameters (maximum stress value, stress range or amplitude, crack length) should all be important influences on fatigue crack growth. Paris was the first to identify the importance of the stress intensity factor range in defining crack growth rate but had difficulty in explaining the load ratio ($R=K_{min}/K_{max}$) effect. In order to explain this effect, Elber introduced the concepts of crack closure and the effective cyclic stress intensity factor ΔK_{eff} as the dominant driving force for fatigue. This concept received much attention in the 1980s and 1990s but now is subjected to some challenge [e.g. Hertzberg et al 1988]. Particularly many people have agreed that the physical effects of crack closure were greatly over-estimated in the past (e.g Vasudevan et al 1994). A partial crack closure model (Donald and Paris 1999; Kujawski 2001a; 2001b) was proposed to overcome the overestimation of closure. Later, Kujawski (2001c; 2001d) reported a new explanation of the stress ratio effect. He demonstrated that his ΔK^* defines well the effect of loads ratio, however Cui (2002c) suggested that this single quantity could not account for something that fundamentally involves three independent parameters. Vasudevan et al (2001) discusses that in order to *unify* the damage process, ΔK, K_{max} and the *internal stress* contribution to K_{max} are required to describe the overall fatigue process. Thus, it comes back to the argument of three parameters again. This is an area requiring further research.

Although the stress intensity factor K is the dominant parameter used for fatigue crack analysis, others can also be used e.g. J-integral (J), the strain energy release rate (G), the crack tip opening displacement (CTOD or δ) or the crack tip opening angle (CTOA).

If using K, the accuracy of any fracture mechanics model for the prediction of fatigue crack growth will depend very much on the accuracy of the stress intensity factor solution used. It is known that some factors are important in this process. One of these is the crack aspect ratio, which represents a major source of uncertainty in fatigue crack growth prediction. Etube et al (2000) presented a new approach for the prediction of stress intensity Y correction factors for welded tubular joints. The proposed method accounts for crack aspect ratio evolution during crack propagation. The method is based on a statistical model used to quantify and account for the deviation of experimental results from previous semi-empirical solutions and the modified Newman and Raju flat plate solution.

A new computational method is proposed by Sumi et al (2000) for the calculation of stress intensity factors of cracks in two- and three-dimensional elastic bodies subjected to arbitrary loading. This is based on the weight function method. The weight function is defined as the displacement field induced by a force couple acting on the crack faces near a crack front for a general three-dimensional crack problem.

The fatigue growth of an edge flaw in a round bar under cyclic tension or bending loading is examined by Couroneau and Royer (2000). Different assumptions relating to the crack front are successively considered, and their validity is discussed from the results of a numerical model using finite element analyses.

Structures with multiple load paths experiencing either isolated cracking, widespread fatigue damage or repairs to multi-site damage can display changes in the load path resulting from changes in stiffness due to either the cracking or the associated structural repair. To account for this effect, Peng et al (2002) developed a new 3D hybrid formulation capable of representing this change in stiffness, thereby enabling an accurate analysis of multiple load path structures containing three-dimensional flaws. This procedure was validated by comparison with results available in literature and with results obtained using the alternating finite element technique. For the surface crack problems considered it was found that, if symmetry considerations were used, then accurate results could be obtained with only 65 elements, including the "hybrid element".

Martinez-Esnaola and Martin-Meizoso (2001) analysed the influence of the discretisation of the crack front on the fatigue propagation prediction of semi-elliptical surface cracks. A simple method based on closed-form solutions for the stress intensity factor is used to discuss the effect of the discretisation. It is concluded that the analysis based on just two points along the crack front is sufficient to predict crack shape and fatigue life.

2.2.3 Various Special Phenomena Relating to Fatigue Crack Propagation

The quantitative analysis of fatigue crack growth requires that a constitutive relationship of general validity be established between the rate of fatigue crack growth, da/dN, and some functions of the range of the stress intensity factor, ΔK. McEvily et al (1999) suggest that the general constitutive relationship should be able to explain at least the following six phenomena:

(1) Anomalous fatigue crack growth
(2) Fatigue crack growth under compression-compression cycling
(3) Delay due to an overload
(4) Two step cyclic loading
(5) The effect of mean stress on fatigue life
(6) Small fatigue crack growth

The general constitutive relationship of McEvily et al (1999) and an extension of this (Cui 2003) attempt to explain all six phenomena.

Sinha et al (2000) investigated the short and long fatigue crack growth behaviour of Ti–6Al–4V. Differences between the long fatigue crack growth rates at positive stress ratios ($R = K_{min}/K_{max} = 0.02$–0.8) are attributed largely to the effects of crack closure. Microstructurally short fatigue cracks are shown to grow at stress intensity factor ranges below the long crack fatigue threshold. Anomalously high fatigue crack growth rates and crack retardation are also shown to occur in the short crack regime.

Differences between the long and the short crack behaviour at low stress ratios are attributed to lower levels of crack closure in the short crack regime.

Vasudevan and Sadananda (2001) analysed the fatigue crack growth behaviour under compression–compression loading. Their analysis indicated that to characterise accurately the entire crack growth region of loading from R<0 to R>0, one must include both the *internal stresses* and the applied stresses. It is observed that there is a unique *internal stress gradient* that can be represented for the entire regime of crack growth. The basic criteria for a crack advance would then be the total driving force of both ΔK and K_{max} has to exceed the corresponding threshold values for a long crack. In certain cases, there can be a deviation from this uniqueness of the *internal stress gradient* due to additional contribution from plasticity.

The effect of plastic zone size on the fatigue threshold was studied by Sevillano (2001). The plastic zone size effect was found to be related to the increasing importance of the plastic strain gradient inherent in the plastic zone. This would explain the existence and value of an intrinsic threshold for crack propagation by fatigue of metals. A normalized value of the intrinsic fatigue threshold was found to be only slightly dependent on the nature or microstructure of the metal.

2.2.4 Fatigue Crack Propagation in a Corrosive Environment

Marine structures operate in a corrosive environment. Fatigue behaviour in corrosive environments is quite different from that in air. Corrosion fatigue is well recognised as a principal mechanism for material damage during service. In order to reduce the damage effect on the static and fatigue strengths, corrosion protection systems (CPS) such as paint coatings and cathodic protection are often applied. An approach for risk assessment of the ultimate strength of an aging ship hull structure subjected to corrosion and fatigue is developed by Akpan et al (2002). Time-dependent random function models for corrosion growth, fatigue cracks and corrosion-enhanced fatigue cracks that weaken the capacity of a ship hull are presented. This is indeed a topical issue and will be the subject of a Specialist Committee for ISSC 2006 (V.6 Condition Assessment of Aged Ships).

Bolotin and Shipkov (2001) applied the theory of fatigue crack growth based on the synthesis of fracture mechanics and continuum damage mechanics to the prediction of crack growth under cyclic and/or sustained loading in the presence of the aggressive environment. The final results are presented in the form of diagrams illustrating the history of crack sizes, damage measured, stress concentration factors near the tips, and the crack growth rates as a function of the principal load and environmental parameters.

Corrosion fatigue crack propagation is strongly influenced by weld-geometry (weld-toe undercut), which plays a significant role in reducing the fatigue life and fatigue strength of butt-welded structures, and accelerates the time to propagate to failure. From the limited experiments performed by Wahab and Sakano (2001), it was found that the threshold stress intensity factor of butt-welded structures attains a much lower value in corrosive environments than in air this needs to be included in any fatigue assessment. It is observed that a more rigorous mathematical model can be determined only when relevant important parameters (such as those relating to stress ratios, stress concentrations caused by weld-joint geometry variations, type and rate of loading, residual stresses and threshold properties of the material strength) are known.

Fridman and Zyczkowski (2001) considered the optimal design of non-prismatic columns in a corrosive environment under concentrated axial forces. The initial volume of a column is the design objective whereas the constraint refers to elastic buckling at a certain prescribed lifetime taking into account

corrosive wear of this column. Plane-tapered and uniformly spatially tapered columns are optimised under the conditions of plane or spatial corrosion.

2.2.5 FCP Theory Applied to Ship and Offshore Structures

A fatigue design method for ship structural members based on fatigue crack growth analysis was also proposed by Terai et al (2001). The method is applicable to initial fatigue design, residual fatigue life prediction and fatigue crack damage analysis. The new procedure is derived based on (1) the concept of a fatigue crack growth analysis (the Paris law), (2) a new storm model for the stress time history, and (3) a new sailing model replacing the all headings model. To demonstrate the proposed fatigue design procedure, the effect of the following factors on fatigue life is examined: (1) an initial surface crack at a weld toe; (2) a mean stress corresponding to full and ballast loading conditions; (3) a stress time history; and (4) relative angle (the angle at which a ship encounters a wave).

Peeker and Niemi (1999) introduced a new fatigue crack propagation model based on a local strain approach. The new model is able to predict the fatigue behaviour of details made of structural steel that subjected to any load history, of any geometry, and containing any distribution of manufacture-introduced residual stress. Both the crack initiation and stable crack growth stages are considered. The model takes into account the influence of many fatigue-related aspects, such as crack closure, small crack behaviour, the specimen thickness effect, fatigue threshold and fatigue behaviour under cyclic compression.

Robles et al (2002) developed a method to calculate the fatigue life of submarine pressure hulls using the Paris equation. By assuming an initial crack size the crack size after a given number of load cycles, defined by the number of submarine dives, is obtained.

2.3 Relationship Between CFD and FCP Theories

There is underlying interest in establishing relationships between CFD theories and FCP theories. It is generally agreed that the crack growth approach is more accurate for fatigue life prediction but it is not commonly used for fatigue design in industry because of the two main difficulties: (1) the initial crack size a_0 is often unknown; (2) da/dN vs. ΔK data are expensive to obtain.

One important measure to reduce the scatter in experimental results for so-called "identical" specimens is to consider the initial crack size and distribution explicitly. As crack inspection systems improve, initial crack size and distribution information will become easier to obtain.

To resolve the second difficulty, methods were proposed by Lam and Topper (1999) to derive crack growth rate vs. effective stress intensity factor range curves from effective strain fatigue life data. If the same failure definition is adopted, then both S-N curves and crack growth rate curves reflect the fundamental material behaviour under fatigue loading. Some relation must exist between them although they were tested separately. Based on the general formats of an S-N curve and a crack growth rate curve, a formal relation is established by Cui (2002d) between the two types of curves. This indicates that only one type of curve needs to be tested and the other can be derived from the existing test results. An example of a centre crack in a plate of finite width is used to demonstrate how to convert one set of material parameters to another.

2.4 Probabilistic Treatment

For dealing with scatter, two approaches are generally adopted. One is to use a probabilistic approach to explicitly express uncertainty in results and this approach will not deepen our understanding on the actual mechanism. The other is based on the deep study of failure mechanism and includes more factors in the theoretical model to reduce the scatter. The latter approach is a more positive attitude for scatter. Miller (1999) appealed to the fatigue community that in the 21st century serious attempts have to be made to put scatter in a proper perspective. Nevertheless, it cannot be denied that a lack of precise information always exists in predicting fatigue life of marine structures and probabilistic treatments will always be necessary and useful. But this should not prevent further study to better understand fatigue failure mechanisms and fatigue life prediction methods (Cui, 2002b; 2002c).

2.4.1 Model for Probabilistic CFD Approach

Karadeniz (2001) presented a procedure for modelling uncertainties in the spectral fatigue analysis of offshore structures with reference to reliability assessment. Uncertainties within fatigue damage predictions are generally attributable to stress response characteristics and the damage-model used.

A method of fatigue reliability evaluation for structures loaded by a random process sigma (t) is proposed by Kliman and Jelemenska (2001). They construct a probabilistic fatigue diagram, giving a relationship between the parameters of random loading process and probabilistically interpreted fatigue life of the structure.

Fatigue tests under constant-amplitude loading (CAL) and variable-amplitude loading (VAL) were carried out by Yan et al (2000) on notched friction welded (FW) joints of 45 (0.45%C) carbon steel, which is similar to the AISI 1045 steel. Statistical and regression analysis on the fatigue test results under CAL shows that the fatigue life of 45 steel notched EW joints with small size can be expressed as the function of the equivalent stress amplitude, and the values of the fatigue resistant coefficient and threshold are thus obtained.

2.4.2 Model for Probabilistic FCP Approach

Typical sources of uncertainties in fatigue calculations include variability in material properties, initial flaw size and shape, geometry, loads, and other environmental factors. Probabilistic fatigue crack growth models that are suitable for the assessment of long fatigue cracks were developed and applied by several researchers. The case for short fatigue crack growth, however, has not received the same level of attention. Zhao and Orisamolu (2001) presented a robust probabilistic model for short fatigue crack growth, which accounts for the effects of crack aspect ratio, stress ratio, as well as crack closure and retardation. Advanced fast probabilistic integration techniques in conjunction with the response surface methodology are used for the probability and sensitivity computations. The results obtained from these methods are compared and successfully verified using the direct Monte Carlo simulation scheme, thereby confirming the robustness of the techniques employed.

Shen et al (2001) proposed an approximate approach to efficient estimation of some variabilities caused by the material microstructural inhomogeneities. The approach is based on the results of a combined experimental and analytical study of the probabilistic nature of fatigue crack growth in Ti–6Al–4V. A simplified experimental fracture mechanics framework is presented for the determination of statistical fatigue crack growth parameters from two fatigue tests. The experimental studies suggest that the variabilities in long fatigue crack growth rate data and the Paris coefficient are well described by the log-normal distributions. The variabilities in the Paris exponent are also shown to be well characterized

by a normal distribution. The measured statistical distributions are incorporated into a probabilistic fracture mechanics framework for the estimation of material reliability. The implications of the results are discussed for the probabilistic analysis of fatigue crack growth.

A probabilistic fracture mechanics theory is proposed by Nicholson et al (2000) for fatigue life prediction in which a mixed-mode fatigue crack growth model is combined with extreme value probabilistic methods. The Sih-Barthelemy fatigue crack growth criterion based on strain energy intensity factor under uniaxial loading was slightly modified and extended to multiaxial loading including biaxial loading and torsion. A probability density function is computed for the number of cycles to failure, and scaling relations are also computed. Crack number, length, and orientation at the onset of fatigue are treated as random variables whose probability distributions are known. Numerical results are presented to demonstrate dependence on plate size, on the variance of the crack length distribution, on the multiaxial loading factors, and on the parameters of the fatigue model.

Based on fracture mechanics and theory of random processes, a probabilistic approach is proposed by Lei and Zhu (2000) to analyse fatigue crack growth, fatigue life and reliability of degrading elastic structural components in nonlinear structural systems. Both the material resistance to fatigue crack growth and the time-history of stress are assumed to be random. The effect of slow degradation of structural stiffness due to fatigue crack growth is taken into account.

Lukic and Cremona (2001) presented a probabilistic reliability assessment procedure for steel components damaged by fatigue. The crack growth model is based on the principles of fracture mechanics theory. It is compared to experimental results and gives a good prediction. Zhang and Mahadevan (2000) proposed a Bayesian procedure to quantify the modelling uncertainty, including the uncertainty in mechanical and statistical model selection and the uncertainty in distribution parameters. The procedure is developed first using a simple example and then is applied to a fatigue reliability problem, with the combination of two competing crack growth models and considering the uncertainty in the statistical distribution parameters for each model. This Bayesian failure probability analysis can be incorporated with information from non-destructive inspections performed on the structure to derive more realistic reliability estimates. The procedure for updating the mechanical model, probabilistic model, distribution parameter statistics and reliability is illustrated for the fatigue reliability problem.

Rahman (2001) evaluated the adequacy of current J-estimation models commonly used in probabilistic elastic-plastic analysis of ductile cracked structures. A newly developed probabilistic model based on elastic-plastic finite element method was used to evaluate the J-estimation model.

2.4.3 Data for Probabilistic Models

In order to predict fatigue life of structures under random loading, the probability distribution of parameters of random load states of structures should be determined, given that the material endurance is known and a proper damage rule is chosen. A statistical dependency of two parameters of random load states (the amplitude and the mean of load cycles) is estimated by Klemenc and Fajdiga (2000) by means of the multivariate rainflow load cycle pdf that are represented as vectors (Sa,Sm). The multivariate load cycle pdf is modelled with a mixture of multivariate normal functions. A comparison of different methods for an estimation of the unknown parameters of the normal mixture is carried out. Agreement of numerically modelled and experimentally obtained data is checked by comparison of corresponding marginal probability distributions of load cycle amplitudes and means. The maximum likelihood method was recognized to be the most appropriate for the determination of the multivariate load cycle pdf.

A statistical method for the prediction of the number of initial cracks based on sample size is introduced by Makkonen (2001). The method is tested on eight sets of experimental data of cylindrical specimens made of 34CrNiMo8 steel. The mean fatigue limit tends to decrease and the scatter increases in proportion to increasing material thickness. If these effects can be accounted for, as attempted in this paper, the constant amplitude fatigue limit can be very accurately predicted. The error of the calculated estimates is within -3% to +6% compared to experimental results.

For service life prediction and stochastic reconstruction of load histories, rainflow matrices were recently predominately used to describe the scatter of loading. Typically, only limited data are available due to the cost of measurements. As a consequence of this, discrete rainflow matrices have to be modelled and extrapolated. So far non-parametric methods have most frequently been used to transform discrete matrices into smooth functions. Two appropriate parametric models: a mixture of joint Weibull–normal distributions and a mixture of multi-variate normals, as well as two algorithms for parameter estimation: the EM algorithm and the algorithm developed by Nagode and Fajdiga are thoroughly discussed and compared by Nagode et al (2001). Finally, a method to describe the scatter of rainflow matrices is presented.

2.5 Fatigue Testing of Components

Fatigue and Fracture Mechanics are empirically based disciplines. Materials and Fatigue testing are central to the numerous models used to predict fatigue and fracture behaviour. Many different approaches to testing are applied due to the high cost of large-scale (sometimes full scale) fatigue tests. Invariably simplified testing methods are used to verify elements of numerical analyses. FE simulations are effective when the fatigue behaviour of a structural detail is well known and the aim of the test is to compare different geometries; small scale experiments allows the testing of material and welding performances in controlled environment (e.g. temperature and chemical aggressiveness). In this context great importance is given to the fatigue crack propagation monitoring techniques, many developed by automotive and aeronautic industries and then used in shipbuilding and offshore applications.

2.5.1 Large/Full Scale Testing

Fricke and Wernicke (2001), Paetzold et al. (2001), Dijksstra et al. (2001) and Berge et al. (2001) carried out studies based on large-scale components, all concluding that large-scale specimen tests are important due to the presence of three-dimensional stresses and manufacturing variations such as misalignment and fabrication tolerances. These studies are described in section 4.

Biot et al. (2001) studied the fatigue behaviour of a large scale typical marine structural detail and a series of numerical analyses was performed making use of different finite element models (shell and brick elements). A good agreement between shell element model and experimental measurements of geometric stress concentration factor in the hot spot area was shown. Also the factor value determined according to DNV guidelines for similar details matched the experimental results.

Jang et al. (2001) performed fatigue tests of welded joint for T- joint and double plate of ship structures. S-N curves were obtained for various crack lengths by the HSS (Hot Spot Stress) approach including geometric stress concentration. Also in this case life of fatigue crack growth predicted by numerical analysis shows good agreement with the tests results. By comparing test results, the total fatigue life of double plate is longer than that of a T-joint.

The effect of plate width and free edges on the initiation and propagation of fatigue cracks in plate to plate welded T-joints was shown by Turner et al. (2000) and the fatigue testing of tendon girth welds that are ground flush with the parent pipe material is described by Buitrago and Zettlemoyer (2001).

2.5.2 Load Sequence Effects

The influence of the applied load sequence is generally and implicitly neglected assuming the Miner law. In this hypothesis the time distribution of the load cycles is not an influencing parameter. The suitability of this assumption is still an area of research.

Fatigue tests were carried out by Marquis and Mikkola (2001) on high and very high strength steel I-beam type structures using constant amplitude loading and three spectra considered as representative for ships. Comparison of the spectrum loading test data showed that nominally compressive portions of the loading cycles were non-damaging. It is noted that up to now the influence of the application of large amplitude loads at the beginning or at the end of the structure life still remains to be clarified. Efforts towards a better understanding of this issue should be carried out. Mean stress effects including also residual stresses are highlighted in the same paper. The fatigue life of welded structures is normally assessed on the basis of stress range, regardless of the nominal applied stress ratio, because the presence of residual stresses may result in local tensile stresses near the weld toe where failure is likely to occur. This concept is clearly outlined by Atzori (2000).

The lack of studies on loading sequence effects highlights the extreme difficulties in performing this type of test. Therefore load sequence effects are usually taken into account by conservative safety factors or properly increasing the load conditions. On the other hand these effects exist but also the definition of the loads acting on ship's structures implies a statistical model based on sea state conditions data and ship's mission profile which cannot in any case give an accurate and comprehensive description of the applied loads.

2.5.3 Structural Details: Effect on the Fatigue Life.

Park et al (2001) analysed two different details of side longitudinal stiffener crossing web frame of a VLCC (an inverted angle supported by a soft-toed backing bracket (A) and a T-type stiffener supported by a flat bar web without backing bracket (T)) using FEA and tests, see Figure 1. T-stiffener shows a larger fatigue performance. Scallops create hot spots where the cracks start.

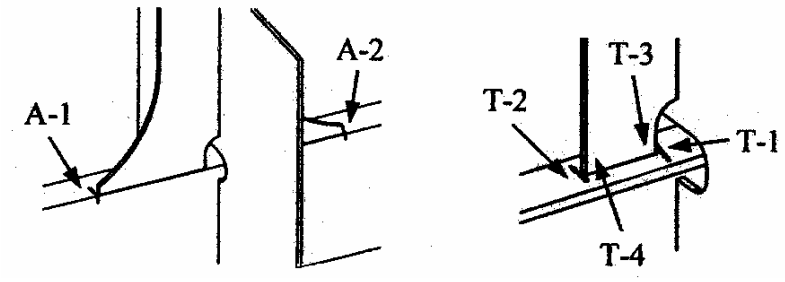

Figure 1: structural details tested (from Park J. et al. (2001))

Rizzo and Tedeschi (2002) tested to complete failure large-scale components manufactured according to standard shipyard fabrication practice. The geometries were a T-section stiffener intersecting a deep web girder, similar to the Park specimens. The main differences between the studies were the tight patches without scallops. This structural detail is important not only as a tight connection but also because of the increased use of automatic welding. The stresses were monitored by means of a strain gauge technique. Dimitraki and Lawrence (2001) suggested some way of

greatly improving the fatigue resistance of fillet weld terminations by a specially designed "stress-concentration reducing part". These stress diffusers are very effective in improving the fatigue resistance of weldments with longitudinal attachments. Of course there is an associated increase in cost and this solution may be used only in very important details.

The fatigue performance of designed and repaired details is studied by Petinov (2001). This looks at the principle of pre-fabricated details to provide parent material in the areas of stress concentration and avoid coincidence of high stress and weld ends in one location. An application of the local strain approach for the evaluation of the necessary configuration of critical location is also provided.

3. REFERENCE STRESS

The term reference stress is otherwise known as the geometric, structural or hot spot stress. It refers to an approach used primarily in the shipbuilding and offshore industries for the fatigue strength assessment of welded joints. The approach is based on the assumption that the stress concentration at the weld toe can be divided into two different components, one relating to the increase in stress due to the geometric effect of the structural detail, and the other due to the increase in stress of the weld itself (or notch factor). The fatigue assessment is made using the geometric component, which is the structural stress at a so-called 'hot spot', together with an appropriate S-N curve. A typical S-N curve considers the notch factor implicitly, and is valid for a certain class of weld shapes and materials. Although the approach is often criticized, it is also considered a very practical one, offering advantages when compared to the traditional nominal stress approach for the assessment of individual joint geometries, which vary from detail to detail, depending on the different scantlings and geometric configurations.

A lot of research work related to the reference stress approach has been reported during the past three years. Most of the focus has been on extrapolation methods and stress determination procedures, but there has also been important efforts regarding misalignment and fabrication tolerance considerations and S-N curves. A literature survey on the subject is given in Sections 3.1 to 3.4 of this report. An illustrative example of the implementation of the reference stress approach according to four different classification society rules is given in Section 3.5.

3.1 Numerical procedures and extrapolation methods

Niemi (1999) gives in an IIW guideline a general design overview of the topic. Definitions are given for the stress direction and weld joint types. A distinction is made between full- and partially-load carrying joints. Hot spot details are classified as either type 'a' for joints on plates or flat members, or type 'b' for joints on plate edges. For fatigue analysis, the greater of the principal stress in ± 45° to weld or the nominal stress perpendicular to the weld is used. For type 'a' details the extrapolation is carried out using points at 0.5 t and 1.5 t or 0.5 t, 1.5 t and 2.5 t. For fine meshes the results at points 0.4 t and 1.0 t or 0.4 t, 0.9 t and 1.4 t should be used in the extrapolation. A quadratic extrapolation is preferred when the stress gradient is non-linear since a linear extrapolation can result in 10-15% lower hot spot stresses. For type 'b' details the extrapolation points shall be at 4, 8 and 12 mm in front of the weld toe.

Doerk et al. (2002) gives the definition of three types of weld toes, types 'a', 'b' and 'c'. The type 'a' of Niemi (1999) is spread to weld toes on plate surfaces at the end of attachments and the weld toe along the weld of an attachment. These are defined as type 'a' and 'c'. Type 'b' is the same as in Niemi (1999), the weld toe being at a plate edge. Comparative studies for four different examples are described. Extrapolations were carried out using stress results at points 0.4 t and 1.0 t, 0.5 t and 1.5 t,

and at points a fixed distance of 4, 8 and 12 mm, with element lengths of 2-4 mm element length, and 5 and 15 mm, with an element length of 10 mm, but with higher order elements. The scatter due to the different mesh sizes and extrapolation points was found to be between ±5 % and ± 10 %.

Fricke and Bogdan (2001) have achieved a good correlation between fine and coarse mesh results on gusset details using linear extrapolation at 0.5 X and 1.5 X, where X = 10 mm, the element length. Comparisons to the BE-results show variations of the relation between the effective notch stress and the hot spot stress, depending to the degree of load being carried by the gusset. Paetzold et al. (2001) presented the results of an analysis of a web frame corner and bracket connection. 20-noded solid elements were used, and the hot spot stress was determined by means of a parabolic extrapolation of element stresses at points 0.5 t, 1.5 t and 0.5 t, where t is the thickness of the web flange.

Poutiainen and Niemi (2000) used linear extrapolation in their investigation of gusset details. For both very fine and coarse FE meshes good correlations for the hot-spot stresses were obtained using points at 0.4 t and 1.0 t and 0.5 t and 1.5 t in front of the weld toe. Wernicke (2001) investigated the axial misalignment on cruciform joints on large web frame corners. For the FE analysis, 20-noded solid elements with reduced integration order were used. A quadratic extrapolation of element stresses at points 0.5 t, 1.5 t and 2.5 t in front of the weld toe were used to calculate the hot spot stress.

Petershagen (2000) carried out a quadratic extrapolation on weld slot details. Element stresses corresponding to points 0.5 t, 1.5 t and 2.5 t were extrapolated to the weld toe. Stresses at the element Gaussian integration points were used. For the determination of the SCF on circular hollow section joints Karamanos et al. (2002) obtained the stress gradient by means of a parabolic extrapolation. From that the hot-spot stress was derived by a linear extrapolation. As the primary stress for the evaluation of the normal stress component to the weld had been utilised it was found to be in accordance with observed crack fronts normal to this stress.

Ulleland et al. (2001) derived the hot-spot stress on longitudinal-web frame joints by means of a linear extrapolation using the stresses on 0.5 t and 1.5 t and the stress directly obtained at 0.5 t in front of the weld toe. Stressed at the Gaussian points were used. From the Gaussian points the stresses were extrapolated to the element side, then to the cut out edge and further to the hot spot at the weld. Principal stresses were calculated from all extrapolated components. The extrapolated hot-spot stresses rather than nodal stresses obtained at 0.5 t were preferred. Rucho et al. (2001) calculated hot-spot stresses on side longitudinal web frame connections by means of a linear extrapolation at points 0.5 t and 1.5 t in front of the weld toe. Measured strains and results of the stress calculations from comprehensive FEA were used. For some cases significant differences are shown. It is concluded that one should extrapolate to the weld toe for measurements and when solid elements are used, and to the intersection line when shell elements are used. For the assessment of edge cracks it was found to be more accurate to apply the stresses not directly from the edge but 0.5 t away.

Using measured stresses, Lotsberg et al. (2001) used extrapolation to obtain hot spot stress on side longitudinal web frame connections. Measurements were taken at points 6, 19 and 28 mm in front of the weld toe. In areas with high stress gradients, a strain gauge strip was applied starting 2 mm away from weld toe. Allessandri et al. (2000) define point locations for hot-spot stress extraction on cruciform joints with fillet- welded plates. These locations were defined using procedures based on the characteristics of the stress gradient. From these procedures the distances X1 and X2 in front of the weld are given in relation to the plate thickness ratio and to the weld thickness.

In Naiquan et al. (2001) an interesting alternative is presented for defining hot spot stresses. Here the stress gradient is expressed as an analytical function, its formulation being based on an FE analysis of

the detail. The analytical function can be obtained by means of an approximation using a second order-polygon. Singularity effects can be identified and excluded by a linear-logarithmic presentation of the stress versus the distance to the weld. A disadvantage of the procedure is the necessity to use fine FE meshes. An investigation of lap joints on a box-stiffener using 20-noded solid elements with size of $t/2 \times t/2 \times t/2$ was carried out. Good agreement between calculated and full-scale test results is demonstrated.

Berge et al. (2001) found, based on large-scale tests on FPSO longitudinals, some scatter in way of the hot spots between the calculated and measured stresses. The calculated stresses tend to underestimate the gradient. These stresses were calculated using linear extrapolation at 0.5 t and 1.5 t points, as per the DNV rules. The calculated stress range obtained was found to be 77% of that measured. Actual weld geometries were not included in the FE model. Park et al. (2001) present the results of a study on hot spot stress calculations for angle-type and T-type connections using a linear extrapolation of stresses at points 0.5 t and 1.5 t.

Bouet-Griffon et al. (1999) give guidelines for the numerical extraction of hot spot stresses for the assessment of aluminium structures. An approach using solid elements and a linear extrapolation on points 0.4 t and 1.0 t is recommended, but a quadratic extrapolation approach is suggested as an alternative. Mesh refinement was applied to eliminate singularity effects and the weld geometry was also modelled. Guideline for modelling the weld as shell elements is given and the use of rigid links to simulate the stiffness of the weld is also discussed.

Fricke (2002) presented comparisons between the analysis and measured stresses near the weld toe using three different stress extrapolation techniques i.e. linear extrapolation over reference points 0.5 and 1.5 times the plate thickness, linear extrapolation over reference points 0.4 and 1.5 times plate thickness and no extrapolation, considering the stress value at 0.5 times the plate thickness. It is shown all three methods can be used with current IIW design S-N curves. Most significantly, it was concluded that the method involving no extrapolation is an attractive alternative, and one that will provide significant saving on analysis during design.

In the Det Norske Veritas rules (DNV (2001)) two definitions of the hot spot stress are given: (1) the stress obtained by extrapolation to the weld toe (or intersection lines); and (2) the stress at 0.5 t from the considered hot spot. The hot spot stress is to be calculated by finite element (FE) analysis. When using the first definition, the hot spot is to be calculated by an extrapolation on points at 0.5 t / 1.5 t in front of the detail. Depending on the element type the hot spot is situated at the weld toe (if included) or at the intersection line. All stress components have to be extrapolated and from them the principal calculated and applied for the assessment. The stress components are to be taken from the Gaussian points of the elements.

In the Germanischer Lloyd rules (GL (2002)) welded joints are normally classified into detail categories, considering particulars in geometry and fabrication, and including subsequent quality control and definition of nominal stress. As an alternative to this detail category and nominal stress approach, the rules allow for an approach based on the hot spot stress. This stress is defined as the stress extrapolated to the weld toe excluding stress concentration in the local vicinity of the weld. The hot spot stress can be determined either by measurement, or numerically, by FE analysis. A linear extrapolation to the weld toe at 0.5 t / 1.5 t points is required. Alternatively quadratic extrapolation can be carried out for details with high bending effects. A procedure using 5mm and 15mm points is not explicitly given but would be used in assessing a detail.

The American Bureau of Shipping rules (ABS (2002)) provide a designer oriented approach to fatigue assessment based on the use of stress concentration factors. When no specific value for a SCF is available, it must be determined by FE analysis. In the case of welded joints this involves the calculation of the hot stress from an extrapolation of elements stresses to the weld toe. The rules require a linear extrapolation to the weld toe of stress components at distances 0.5 t and 1.5 t from the weld toe. The stress components at these two points are obtained by third order Lagrange interpolation of element centriodal stresses.

The Level 3 fatigue assessment (FDA3) procedure in the Lloyd's Register of Shipping rules (LR (2002)) incorporates a full spectral direct calculation procedure based on first principal methods. The rules require a FE analysis to obtain the hot spot stresses in way of critical location fatigue check areas. Here the hot spot stress is the stress evaluated at 0.5 t from the structural intersection. The procedure is based on using shell elements of a mesh size t x t, and the element centroidal stresses. Since the hot spot is taken as 0.5 t, no extrapolation to the weld toe or intersection point is required.

3.2 Stress Determination Procedures

3.2.1 Finite Element Analysis

Niemi (1999) recommends the use of shell or solid elements for FE analysis. Only the linear stress representation has to be taken into account. This linear representation has to be extracted if low order elements or higher order elements with reduced integration are not used. If the weld is neglected the interpolation shall be carried out to the intersection points. The use of relative coarse meshes of about t×t element size is recommended. Hot spot details are classified as a type 'a' for joints on plates or flat members and type 'b' for joints on plate edges. For type 'a' details, either shell or solid elements can be used, but the latter are preferred. Examples of relative coarse meshing are shown together with some guidance for shell and solid meshing. Recommendations for mesh fineness and extrapolation procedures are given. For shell elements an extra average stress is suggested when the weld was taken into account. For type 'b' details, either 8-noded shell or 20-noded solid elements can be used. An element size of 10×10 mm at the gusset weld toe is recommended. A reduced element integration order is required. The stresses are to be extracted at the element mid points. Two detailed case studies are presented, one for a box beam of a railway wagon and the other for an inserted container ship hatch corner. Comparisons between experimental and FE results are given.

Fricke and Bogdan (2001) present the results of an investigation with an aim to define a reference length X for a linear extrapolation from 0.5 X and 1.5 X points. Here X was defined as the element length. The supporting analyses were conducted on gusset plate connections with various geometric configurations and multiple load cases. Comparisons were made to the effective notch stress. Stresses computed by means of the boundary element (BE) method are also given for comparison. For the FE analysis 8-noded shell elements were used. The calculated stresses were found independent of the throat thickness. A good agreement between fine and coarse meshes was found in the case of using linear extrapolation at 0.5 X and 1.5 X and X = 10 mm. Comparisons with the BE results show variations in the relation between the effective notch stress and the hot spot stress depending on the degree of load being carrying by the gusset.

Doerk et al. (2002) give a comparison of the extrapolation methods and the equilibrium method described in Dong (2001 and 2002). Explanations for element types and modelling techniques are described. In four examples the influence of the mesh density and the singularity effect was studied using extrapolated structural stresses and those calculated using the equilibrium method. The examples

considered are a plate lap fillet weld, a one side doubling plate, a bracket toe on a web frame corner and a fillet weld around a plate edge.

Paetzold et al. (2001) performed numerical studies and full-scale specimen tests of web beam connections with different types of brackets. The tests were carried out with bending loads resulting in tension stresses at the investigated details. To evaluate the tests FE models were made using 20-noded solid elements. Very good agreement with measurements was obtained provided the actual weld geometry is taken into account in the FE-model. The mesh density was chosen to have the extrapolation points at 0.5 t, 1.5 t and 0.5 t distances from the weld toe.

In Poutiainen and Niemi (2000) the results of calculations on the detailed analyses of a longitudinal stiffener-gusset connection, a gusset plate on a double-T-beam and a gusset plate on a hollow section were reported. For the FE models very fine as well as coarse meshes ranging from 0.08 t to about 2.0 t element size were generated. Shell and solid elements of higher order were used. Comparison of the results for these mesh types show fairly good agreement. However, less scatter is found when solid elements are used.

Wernicke (2001) investigated axial misalignment on cruciform joints and its influence on fatigue life. Nominal stress, hot spot stress, notch stress and LEFM were considered. The details investigated were full-scale web corners with interrupted flanges, connected by fillet welding with tolerances of a t/3-misalignment of the butting plates. Meshes were made of 20-noded solid elements with reduced integration. Petershagen (2000) reports the FE analyses and testing of a cruciform joint with weld slot detail. A FE analysis using 20-noded solid elements with reduced integration was performed. Because of the geometry of the detail a correlation of the element size to plate thickness is not applicable. Comparative studies were performed using the notch stress approach. The respective characteristic nominal stress ranges for each mesh type was calculated. A notch stress factor for a standard weld with 45° weld angle was applied. Both coarse and fine meshed FE models were used. Only small variations were found for the different mesh densities. Further analyses were conducted using 8-noded solid elements and a 1 mm notch effective radius. Results were found to be about 30% higher. It is concluded that this is probably due to an overestimation of the hot-spot stress because of the steep stress gradient in front of the weld toe.

A report on fatigue testing of panels and specimens with a T-joint and cruciform joint and partially load carrying fillet welds is given in Latorre et al. (2002). A FE analysis with an extremely fine meshed FE model, including the weld transition radius with smoothed contour, was performed. Typical problems in calculating the stress concentration factor are stated. A linear extrapolation from 0.25 t in front of the weld gives a geometric notch factor k_t of 1.20, which is comparable to that of 1.30 for doubler plates.

Karamanos et al. (2002) presented the results of a parametric study of brace-chord circular joint geometries subjected to bending loads. Here the aim was to study the carry-over effect, that is the interaction between two adjacent braces. 20-noded solid elements were used instead of the more common thick shell elements; no difference in hot-spot stress were found when using reduced (2×2×2) or full integration (3×3×3) order for the elements. A mesh density of 1/32 to 1/70 of the weld length around the pipe member was used. It was found that the stress results are influenced by the weld profile and mesh density. In general, a satisfactory correlation to FE-results was achieved. Formulas for the stress concentration factors for chord-brace connections are proposed. Uncertainties are automatically accounted for.

A longitudinal profile to web frame connection was investigated by Ulleland et al. (2001). The profile is directly connected to the web frame via its flat side. A lug was fitted on the other side overlapping the web frame plate. Several types of bulb and flat bar longitudinals were investigated. For FE analysis, 20-noded solid element meshes consistent with the DNV were generated. In general a mesh size of t×t with two elements through the plate thickness was used. The welds were taken into account and were modelled without connection to other members. This was found to be significant only for the lug-web frame connection but not at the longitudinal. An influence of the load application on the local model was also found. To derive the SCF, a nominal stress was defined based on reaction forces and outer load. The SCF at the structural details of the joint are given. Differences in the SCF at the weld toe and at 0.5 t in front are documented. The authors indicate the necessity for different S-N-curves if the DNV procedures of DNV are applied.

Similar investigations of longitudinal-web frame connections are reported in Rucho et al. (2001). Three types of bulb- and one T-profile connection to FPSO-web frame were investigated using FE analysis to extract the hot-spot stress. Comparisons to full-scale specimen tests were made. Inner and outer pressure conditions representative of ballast and applied load were formulated. In fatigue testing the through thickness crack was used as the failure criterion. Both shell and solid element models for the T-profiles were used. In general, 8-noded shells were used, but one model using 4-noded shells was generated for comparison purposes. For the solid element models, 20-noded solid elements were used. All bulb profiles were converted into equivalent T-profiles when using shell elements. For shell elements the element length equivalent to the plate thickness t was chosen. For solids a t/2-mesh size was applied. In general the welds were not modelled apart from in two models the weld of the bracket connection on the profile flange were taken into account by an element thickness equal to the weld foot line. Details with and without weld were verified. For three models the load rigs of the test arrangement were incorporated. Solids elements are shown to give more representative stress results in the weld area, since variations of the physical geometry can be taken into account more accurately.

In Berge et al. (2001), an investigation using higher strength steel materials (for reduced maintenance over the FPSO service life of 20 years) is investigated. Specimens of longitudinal stiffener to web connections were tested with the outer pressure being simulated by two single loads and adjusted based of FE calculations. Numerical investigations were carried out by means of 4-noded shell element models with a mesh fineness considered necessary to extract the hot-spot stresses. Spherical profiles were included, but the eccentricities of lugs and welds were not considered. The computed nominal and overall stresses compare very well to measurements. Because of fabrication tolerances, computed results in the lug-web-connection area were somewhat lower than expected. The calculated hot spot stresses do not fit the scatter of measured data, and the stress gradient tends to be underestimated.

In Naiquan et al. (2001) a comparative study on a box-stiffener with a lapped joint is presented. Assessment procedures pertaining to the nominal, hot spot and the notch stress approaches were carried out. Detailed FE analyses using 20-noded solid elements with size of $t/2 \times t/2 \times t/2$ were performed for structural stress determination. The significance of using either a gap or contact between stiffener and lap joint is investigated. In the case of full contact, about 15% lower hot spot stresses were obtained compared to those obtained for a fully open gap. The hot-spot stress was extracted by extrapolation but using the logarithmic plotted stress gradient. For full scale tests the results of the three approaches were found to be close when using the procedure for the hot-spot stress evaluation.

Allessandri et al. (2000) reported investigations carried out on cruciform joints with fillet-welded plates. These joints are loaded via a butting plate. The stress gradient in front of the weld was found to be independent of weld thickness and plate thickness. It is noted that singularity effects at the weld toe radius influence the gradient in a region up to 2.5 mm in front of the weld. For the calculation of the

hot-spot stress, three extrapolation procedures were applied which take into account both concave and convex weld transition radii. It was found that for small stress gradients the underestimation of micro geometry of the toe is avoided. When comparing to test results the method was found to be conservative. Dijkstra et al. (2001) report the results of fatigue tests conducted on different hopper knuckle configurations subjected to both constant and variable amplitude loading. The hot spot stresses were measured at 6 mm in front of the weld toe. Considering crack propagation with respect to the hot spot stress, a very conservative estimation for these large-scale specimens was obtained, even when long crack growth was permitted.

In Park et al. (2001) the results of an investigation on longitudinal stiffeners are given. It looks at angle-type L-profiles with soft toe stiffener and soft toe backing bracket connection and a T-profile type with ordinary flat bar on top. A large shell FE model of tanker side shell longitudinal bulkhead and web frames was generated. Three longitudinals were incorporated into the model. Welds were not included. External pressure was applied. The hot-spot stresses of the T-type joints were found to be 30% higher than for the angle type. When applying the measured hot-spot stresses and a criterion of 50 mm crack length, the T-type connections were shown to have a 2 - 4 times longer life.

In Huther et al. (1998) a guidance and complement to the rules of Bureau Veritas is given. General definitions as well as rules for the determination of long term stress distribution and loading conditions for the fatigue assessment are indicated. A comprehensive catalogue of SCF for typical structural details based on FE analysis is given. Correction factors to account for structural irregularities are given.

The fatigue assessment procedure based on hot-spot stress ranges and FE analysis is discussed in detail in DNV (2001). Stress concentration factors represent the ratio of the hot-spot stress-range to nominal stress range. SCFs for many structures (plated, pipes, tubular joints, with misalignment) are presented. For welded connections other than tubular joints, shell or solid elements can be used. For tubular joints, thick shell elements must be used. For tubular joints the weld itself is not to be included. For non-tubular joints the weld may be included if the solids are used. During the FE analysis the mesh fineness and the mesh density effects have to be evaluated. It is recommended that a verification of the analysis result be performed using a S-N classified detail similar to that being investigated. Then, if necessary, a corrective factor for the stress concentration factor should be derived to minimise the mesh effects.

GL (2002) requires the application of either shell or solid elements. If elements with higher order are used, a reduced integration is to be used to take into account only the linear stress distribution in the plate.

ABS (2002) suggests two approaches for FE analysis. One involves the use of a conventional beam element idealization including the end bracket connection, and the other involves the use of a fine mesh FE idealization. Except in special cases, the fine mesh approach is required. The importance of establishing rules regarding element size is addressed. These rules must account for the fact that the calculated stress distribution can be unduly affected by both the employed mesh size and the uniformity of the mesh adjacent to the weld toe. Also, since the area adjacent to the weld toe may be experiencing a large and rapid change in stress, it is also necessary to provide rules that allow a fairly accurate description of the stress at the location where the fatigue assessment is to be made. When plate or shell elements are used in the modelling, it is recommended that each element size is equal to the plate thickness.

The local zoom FE modelling approach is used in LR (2002). This involves the investigation of separate detailed local FE models that are loaded with enforced displacements obtained from the global FE model, or, alternatively, incorporated directly into the global model. The fine mesh zones are to cover all potential fatigue check areas to be examined. The fine mesh zone is to be taken as close to t x t as possible. The extent of the fine mesh, in the principal direction of the stress leading to maximum stress concentration is to be 10 to 15 times the plate thickness. All local structural details in close proximity to the area of interest are to be modelled explicitly with shell elements. Although the use of 4-noded quad-shell elements in way of the fine mesh zone is recommended, an alternative approach using higher order elements, such as 8-noded shell elements, with a mesh size of 2 t x 2 t is mentioned.

3.2.2 Integral Method

Dong et al. (2001) describes a procedure involving the equilibrium of the nodal forces in front of the weld to generate an equivalent stress distribution in the crack plane. This procedure minimises annoying singularities and mesh-dependent effects. The equivalent stress is used to obtain plane solutions of stress intensity. Alterations in the stress distribution in thickness direction due to crack propagation can be taken into account. For comparison to the notch stress concept, the use of a SIF that can be directly obtained from the crack surface pressure is suggested. This SIF is then valid for the actual notch situation. Validation calculations for several types of welded joints are shown (T-fillet, lap-, cruciform- and longitudinal stiffener joints). A smaller scatter of fatigue data was obtained using the procedure. Also, a procedure to take into account crack closure for short cracks is proposed. Validations on several typical notched specimens show good results.

In Dong (2002) a detailed explanation and extension of the above procedure is given. To find a through-thickness stress distribution in front of the weld notch an equivalent linear stress distribution is derived. The stress distribution is defined in a reference plane near the weld toe. FE mesh dependent singularity effects in this reference plane can be minimised or excluded using the nodal forces in the equilibrium equations. The procedure is also usable for partial through thickness cracks. In case of non-monotonic stress distributions a bilinear equivalent stress distribution is suggested. Examples are given for a plate lap joint with fillet weld, a double plate lap joint and a hollow section joint. For monotonic stress distributions, element sizes up to multiple plate thickness were found to be possible, while for non-monotonic stress distributions, a maximum 0.5 t for the element size is advised. Comparisons of the procedure to other approaches based on surface extrapolation procedures show a lower scatter of the S-N-data of several fatigue test results.

3.2.3 Measurement of the Structural Stress

Niemi (1999) recommend the measurement of stresses for a structural stress extrapolation at points 0.4 t and 1.0 t for a normal weld configuration and at 0.4 t, 0.9 t and 1.4 t for configurations with stiff elastic foundations below the weld. Interpolations may have to be carried out between the measuring points to arrive at the proper stress gradient. For joints of type ‘b’-joints (plate edge joints) extrapolation points do not depend on the plate thickness. It is recommended that points 4, 8 and 12 mm in front of the weld be used.

The results of an investigation of side shell longitudinal connections using the hot spot approach are given in Lotsberg et al. (2001). Full-scale fatigue testing of five specimens of FPSO side longitudinals was carried out. Typical FPSO connections of higher tensile strength steel were used. General stresses and hot-spot stresses were extracted by measurements. Stresses at points 6, 19 and 28 mm in front of the weld toes were used. In areas of high stress gradient, a strain gauge strip was applied starting 2 mm away from weld toe.

3.3 Hot-Spot S-N-curves

In the recommendation of Niemi (1999) the S-N-curves for steel design are given as lower bound curves by reducing the mean value by two standard deviations. The curves are valid up to 150°C, in a non-corrosive environment. A bonus factor for post weld treatment may be applied. Three S-N-curves are given: FAT 112 for butt welds in special quality; FAT 100 for standard butts, non-load carrying fillet welds, load carrying partial penetration and gusset connections with $L \leq 100$ mm; and FAT 90 for load carrying fillet welds and gusset plates $L > 100$ mm. A FAT-class for hollow-section-joints is not specified. For a thickness correction above $t = 25$ mm, exponents for the respective FAT-class in relation to the weld geometry are given. From case studies in Doerk et al. (2002) the FAT 100 and FAT 90 S-N-curves were confirmed for application in the structural stress approach for different details such as plate lap fillet weld, one side doubling plate, big bracket toes and fillet weld on edge plates.

During tests on large web frame corners Paetzold et al. (2001) found unexpected root cracks occurring after a short period of time. Due to this, the results are not on the safe side of the hot-spot design curve FAT 100. On the other hand nothing unexpected was observed in the case of toe cracking.

Wernicke (2001) observed a good correlation to the FAT 100 S-N-curve of fatigue tests on large web corners when taking misalignments into account. For initiating cracks of 1 to 2 mm, all results fell below the mean curve. Applying a crack length more realistic to inspection in service of 50 mm length, all results are well covered by mean curve.

In Berge et al. (2001), it is reported that cracks were observed between the lug and profile and web and profile on large scale FPSO longitudinals. Using the DNV S-N-curves the results are shown to be non-conservative when using cycles to crack initiation. The fatigue life of through thickness cracks show a better fit to the design curve than to the mean curve. The time to complete cracking was found to be factor of ten higher than that given by the design curve. Crack growth occurred for 90% of the complete fatigue life. An “end-of-fatigue-life” criterion is discussed.

Park et al. (2001) presented the results of investigations on longitudinal stiffeners where S-N-curves were established by a best-fit approach. Using the calculated hot spot stresses the equivalence of the S-N-curves was found for angle-type and L-type connections. Considering the results for a crack length of 50 mm, a FAT of about 100 can be estimated for the bracket toe on the profile flange. Thus the size of the detail is shown to be important. For the investigated details the crack has just passed through the complete flange thickness. It is stated the in small profiles, the half of the web may be cracked.

An overview of guidelines and recommendations for the assessment of aluminium structures is given in Bouet-Griffon et al. (1999). For general details a S-N-curve of class FAT 40 with a slope $m = 4{,}3$ is proposed. For root failures the same FAT, but with $m = 3{,}0$, is proposed. The equations are confirmed by test results.

In DNV (2001) the use of the UK DEn D-curve is recommended for the assessment procedure of general weld details. But the C-curve should be applied if the welds are ground. For tubular joints the UK DEn F-curve has to be applied. This correlates to the thick shell elements for calculation purposes and the exclusion of the weld.

GL (2002) requires the use of the FAT-class S-N curves for the hot spot approach. The FAT 100 curve has to be applied for partial penetration welds or such fillet welds that are non- or partially load carrying. The FAT 90 is to be used for fully load carrying fillet welds. For butt welds the FAT-class

for the nominal stress approach are to be applied. In the case of a non-linear extrapolation and high bending stress the FAT-value may be increased by 15%.

In ABS (2002) S-N curves for 8 different fatigue classes of structural details are given. When the ABS recommended hot spot procedure using the FE fine mesh approach is applied, the use of the E class S-N data is considered to be acceptable.

For the hot spot approach, LR (2002) both a reference mean and a reference design S-N curve are defined. The reference design curve, to be used for the assessment, represents two standard deviations below the mean curve. Not included in LR (2002), but in fact used in FDA3, is a correlated mean S-N curve, Voilette (1998). This correlated S-N curve is derived using a comparative FDA3 analysis, whereby the welded material reference S-N curve is revised, based on the computed fatigue damage index and the actual in-service fatigue damage index.

3.4 Misalignment and fabrication tolerances

According to Niemi (1999) misalignment should be taken into account by decreasing the fatigue class by a factor k_m. Also the calculation may take into account a supposed misalignment. Parametric formulas are given for this misalignment for several standard joints. It is advised to include typical fabrication tolerances, for which specific values of k_m are recommended. For simplified calculations, the misalignment can also be taken into account by using modified nominal stresses. References are listed for parametric formulas of structural discontinuities. In Wernicke (2001) it was shown, for a web corner detail, how to take into account fabrication misalignments using the hot spot stress approach. The additional stress magnification at the hot spot due to axial misalignment was found to be smaller on full-scale specimens than on small-scale specimens with free shrinkage. The GL hot-spot-S-N-curve FAT 100 fits well test results when the misalignment is taken into account.

Based on test results for weld slot details, Petershagen (2000) studied the influence of weld quality. The assessment of the results raises some uncertainties for evaluation using both the hot spot and notch stress approaches. It is clearly illustrated that the weld quality is an influencing parameter in fatigue. Rucho et al. (2001) found a significant influence of the weld geometry when comparing measured and calculated stresses and consequently the SCF. It was found that small differences resulted in significant inaccuracies. By taking into account actual weld angles the correlation can be improved. The fatigue life results in the test were found to be highly dependent on the residual stress state. The requirement for probabilistic and worst case studies in the structural stress approach is emphasized.

Park et al. (2001) in the fatigue testing of angle-type and T-type joints, found that the measured stresses were up to 45% higher than the calculated stresses. Welds were not incorporated into the large shell element model for the numerical investigations. Also, no information on misalignments on the original connections was given. It is stated that fabrication tolerances are probably the main cause of the anomalies. Petipas et al. (2000) reports a state-of-the art assessment of welds by means of local analysis. Various influencing parameters are listed and explained. A main conclusion of the paper is the requirement for the consideration of misalignments and variations of the weld geometry. Variations of weld transition radius for butt welds were investigated and are given in the report. For the weld toe of butt welds a stress concentration factor $k_t = 1.2$ was found for an ideal alignment, while a value of $k_t = 1.7$ was found for a typical misalignment.

Fricke and Wernicke (2001) reported on the probabilistic considerations for the fatigue tests on the large web corners described in Wernicke (2001). A misalignment to the base plate thickness ratio, e/t, is chosen as a stochastic variable. It is used as a constant K in the fatigue equation $N = K \cdot \sigma^{-m}$. Using a

simulation of K in a normal distribution the maximum permissible misalignment e_p/t is obtained. The required production accuracy e_p/t can thus be estimated to have a certain probability of failure.

In DNV (2001) misalignment is taken into account by the correction of the calculated SCF. Correction factors for weld joints are given.

In GL (2002) a reduction factor for the FAT reference value is given. It is used in situations where misalignments are greater than those always included in the S-N-curves. The additional stress resulting from the actual misalignment has to be determined separately.

In LR (2002) existing procedures for simple details with misalignment are to be used. For complex details where existing procedures are not applicable, additional FE analysis must be performed. In such an analysis, the structural detail with a perfect alignment and with the misalignment is to be individually modelled. The additional stress concentration factor is to be obtained as the ratio of the hot spot stress with the misalignment to that with a perfect alignment.

3.5 Illustrative Example

In Sections 3.1, 3.2 and 3.3 of this report, extrapolation methods, FE analysis procedures and S-N curves associated with the reference or hot spot approach were summarized. Of special and perhaps most relevant interest is the information readily available in the classification society rules DNV (2001), GL (2002), ABS (2002) and LR (2002). This section of the report presents the results of a fatigue analysis conducted by the Committee in accordance with the guidelines set out in these four documents.

The problem analysed is the relatively simple I-beam with gusset plate detail shown in Figure 2. The detail has the following geometric characteristics: outer dimension = 200mm x 200mm; length = 2000 mm; flange thickness = 15 mm; web thickness = 10 mm; gusset plate length = 200 mm; gusset plate height = 200 mm; gusset plate thickness = 15 mm; and weld throat (at flange to gusset joint) = 5.0 mm. The I-beam is loaded with an axial load of 770 KN, resulting in a nominal stress of 100 MPa. A pinned boundary condition at the neutral axis at the ends of the I-beam is assumed. The hot-spot region for this analysis is indicated by line A-B in Figure 3, the hot-spot being at the weld toe.

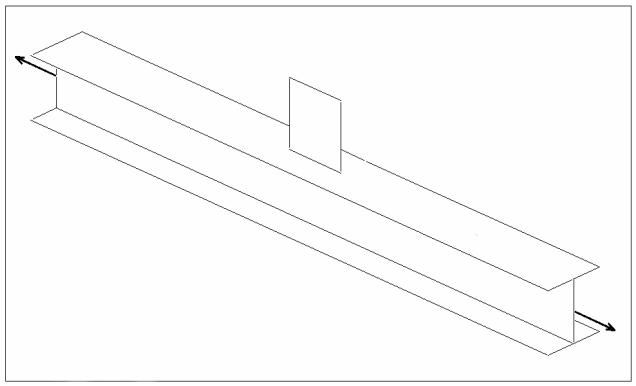

Figure 2: I-Beam and Gusset Plate Configuration

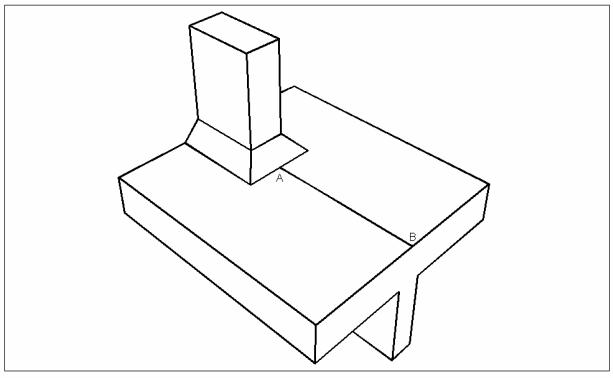

Figure 3: Hot Spot Region

3.5.1 Finite Element Models

Finite element models with four different element types and/or mesh densities were used in the analyses. Quarter symmetry was assumed, and multi-point constraints were used to simulate the pinned boundary condition. A typical finite element mesh in the region of interest is shown in Figure 4. A four-noded shell element model with a t x t mesh was used for the analyses according to LR (2002) and ABS (2002). An eight-noded shell element model with a t x t mesh was used for the analyses according to DNV (2001) and GL (2002). Two models using 20-noded solids, one with a t x t mesh and one with a 0.5t x 0.5t mesh, were used for the analyses according to DNV (2001).

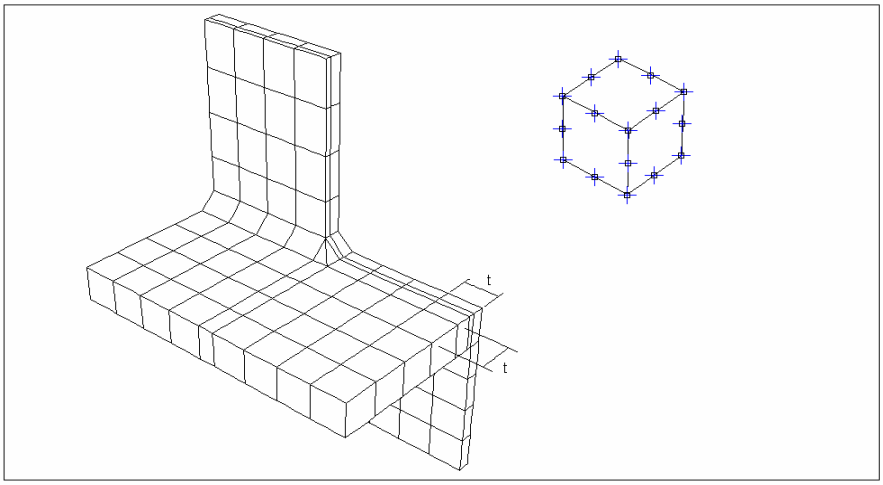

Figure 4: Typical Finite Element Model

3.5.2 Results

In the hot-spot region, the stresses vary in both the longitudinal direction (along line A-B) and the transverse direction. Both ABS (2002) and LR (2002) call for the use of stresses at the element centroids. Since there are no element centroids on line A-B, the use of centroidal stresses will not give the maximum stresses. ABS (2002) and LR (2002) do not provide procedures for the transverse interpolation needed in situations like this. However, for the illustrative study, results with and without transverse interpolation are presented, the latter being a simple linear interpolation over two elements transverse to the line A-B.

Various element integration orders were tried for the 8-noded shell and 20-noded solid. Differences in stresses of less than 1% and 3% were seen between these. In all cases, the higher the order of integration, the higher the stresses. The results presented are for shell elements with 2x2x2 integration and for solid elements with 3x3x3 integration.

The results for 20-noded solid element models without a gap between the flange and gusset are presented. The analyses were also performed with the gap modeled. For t x t meshes, stresses were less than 1% higher with gap modeled. For 0.5 t x 0.5 t meshes, stresses were less than 2% higher with the gap modeled.

Table 1 below provides a summary of hot-spot stress calculations and fatigue life predictions according the four different rules. The procedures followed for each of the rules are explained below.

TABLE 1: SUMMARY OF HOT-SPOT STRESS CALCULATIONS AND FATIGUE LIFE PREDICTIONS

Rule	Case	Element Type	Mesh Density	Stress (MPa)	Life (N)
LR	1	4-noded shell	t x t	129.8	713,900
LR	2	4-noded shell	t x t	140.2	566,000
LR	3	4-noded shell	t x t	129.8	572,100
LR	4	4-noded shell	t x t	140.2	453,500
ABS	1	4-noded shell	t x t	123.9	547,400
ABS	2	4-noded shell	t x t	130.8	464,700
DNV	1	8-noded shell	t x t	160.2	354,800
DNV	2	20-noded solid	t x t	182.6	239,600
DNV	3	8-noded shell	t x t	142.2	507,700
DNV	4	20-noded solid	t x t	163.4	334,100
DNV	5	20-noded solid	t/2 x t/2	164.9	325,500
GL	1	8-noded shell	t x t	155.3	533,500
GL	2	8-noded shell	t x t	165	444,800

3.5.2.1 LR (2002)

In the LR procedure, the crack plane is assumed to be perpendicular to the free surface of the plate. For a given stress check point location, a principal critical fracture plane is defined. When the local stress field exhibits a bi-axial stress behaviour, or the finite element does not have one of its local axes perpendicular to the principal crack plane, the maximum fatigue damage may occur at an angle from the principal fracture plane. In such cases a range of critical crack planes must be investigated by sweeping –40 to +40 degrees about the normal to the principal critical fracture plane in increments of 10 degrees.

The finite element model with 4-noded shells and t x t mesh was used to perform the hot-spot stress calculation. The life predictions were made using both design and correlated S-N curves. In Table 1, the results using the design S-N curve are given as Cases 1 and 2, the former without transverse interpolation and the latter with. The results using the correlated S-N curve are given as Cases 3 and 4, the former without transverse interpolation and the latter with.

3.5.2.2 ABS (2002)

The recommended algorithm for obtaining the extrapolated stress at the weld toe was used. The algorithm proceeds in the following way. Four points, P1 to P4, are defined as the centroids of four neighbouring elements, the first of which is adjacent to the weld toe. Stress components at these four points, obtained from finite element analysis, are then used to obtain (using third order Lagrange interpolation), estimates for the stress components at two points, t/2 and 3t/2 from the weld toe. The stress components at these two points are then linearly extrapolated to the weld toe. The extrapolated stress components are then used to compute the principal stress, or hot-spot stress, which is used for fatigue evaluation.

The finite element model with 4-noded shells and t x t mesh was used to perform the hot-spot stress calculation. The results for two different cases are given in Table 1. In Case 1 there was no transverse interpolation, the stress components for four elements adjacent to line A-B being used for

the hot-spot stress calculation. In Case 2 there was a linear interpolation of stress components involving eight elements. The E Class S-N curve was used for life prediction.

3.5.2.3 DNV (2001)

The DNV rules require the use of either 8-noded shell or 20-noded solid elements for finite element analysis. The mesh density in the hot-spot region is to be t x t for shell elements and t x t or t/2 x t/2 for solid elements. In the latter case, only one element is to be used through the plate thickness. Also, when using solid elements, the modelling of the weld itself is allowed.

The DNV rules allow for one of two different methods to be used: (1) the hot-spot stress is derived by extrapolating the stress to the weld toe, if the weld was included in the model, or the intersection line, if the weld has not been included; and (2) the hot-spot is derived directly from the finite element at a distance t/2 from the weld toe using solid elements, or t/2 from the intersecting line using shell elements. For the I-beam gusset plate detail, the intersection line is the point where the edge of the gusset joins the beam flange.

The finite element models with 8-noded shells and 20-noded solids with t x t meshes were used for both Method 1 and 2 analyses. The finite element model with a 0.5 t x 0.5 t mesh was used for a Method 2 analysis only.

For Method 1 analysis, the stresses are first extracted from the element integration points to the plate surface. A further extrapolation to line A-B is then conducted. Since these stress are based on integration point coordinates, a further interpolation along line A-B must be performed in order to calculate stress at a distance t/2 an 3t/2 from the weld toe, if modeled, or the intersection line, if not. A second order polynomial is recommended for this calculation. Finally, a linear extrapolation of the stresses at t/2 and 3t/2 to the hot spot (weld toe or intersection line) is performed. The stress components at the hot-spot are used to calculate principal stress, which are then used for the fatigue evaluation. The results from the Method 1 analysis are shown in Table 1 as Cases 1 and 2, Case 1 using the 8-noded shell element model and Case 2 using the 20-noded solid element model with a t x t mesh density.

For Method 2 analysis, the stresses are taken directly from the finite elements at a point t/2 from the hot spot. These are the values used in calculating the hot-spot stress. In this analysis, the element node stresses were used. The results from Method 2 analysis are shown in Table 1 as cases 3, 4 and 5, case 3 using the 8-noded shell element model, case 4 using the 20-noded solid element model with a t x t mesh density, and case 5 using the 20-noded solid element mesh with a t/2 x t/2 mesh density.

3.5.2.4 GL (2002)

For the illustrative sample analysis, the model using 8-noded shells was used. Stresses at the element corner nodes were used in the hot spot stress calculations. Only the first three elements in the I-beam flange along line A-B were included in nodal averaging across adjacent elements. The S-N curve design category 100 was used for life prediction.

Two extrapolation procedures were considered. First, the analysis was carried out using Von Mises stresses extrapolated from element stresses calculated at two points t/2 and 3t/2 from the weld toe. The results are shown in Table 1 as Case 1. Second, the analysis was carried out using Von Mises stresses extrapolated from element stresses calculated at two points 5mm and 15mm from the weld toe. The results are shown in Table 1 as Case 2.

3.5.3 Discussion of Results

Fatigue life predictions ranged from 239,600 to 713,900 cycles. The shortest predicted life was in the case of DNV rules using 20-noded solid elements and a t x t mesh density. The longest predicted life was in the case of LR rules with no transverse interpolation and the design S-N curve. The shortest predicted life using LR rules is 454500 cycles, obtained using transverse interpolation and the correlated S-N curve. The shortest predicted life using ABS rules is 464700 cycles, obtained using transverse interpolation. The predicted life using GL rules and extrapolation points 5 mm and 15 mm is 444800 cycles, which is very similar to the LR and ABS values of 454500 and 464700 cycles. In general, the predicted lives using the DNV rules are low compared to the other rules. The one exception is DNV Case 3, where 8-noded shell elements are used, and the stresses are taken directly from the finite element model at 0,5 t from the weld toe. In this case the predicted life is 507,700 cycles, which compares rather well with the LR, ABS and GL values of 454,500, 464,700 and 444,800 cycles. The results DNV Cases 4 and 5 show very little difference between a t x t and a t/2 x t/2 mesh when 20-noded solids are used.

4. FATIGUE LIFE IMPROVEMENT

Fatigue of structures is due to propagation of cracks under cyclic loads, the main driving force being the stress range $\Delta\sigma$, Miller (1999). Depending on crack size there are material based barriers giving rise to critical stress levels to overcome for the crack to grow. A crack may initiate as a shear crack within one grain, Stage I shear crack. At sufficiently high stresses, it is possible for the crack to reorientate and move into neighboring grains. As the crack grows it will successively be more insensitive to micro-structural barriers, like grain boundaries, and finally grow by tensile stresses perpendicular to the crack face, Stage II crack. For some manufacturing processes, like welding, the joining process itself will create cracks that have grown into the Stage II regime. The cracks are then normally longer than 10 grains, before the component is even put into service.

Improvement methods can be applied to structures in general, although many of the cases referred to in this report concern welds, as welding is a very common joining process used in ship and offshore structures. In general, improvement methods may include design considerations taken to more accurately calculate the stress levels in critical positions, like joints or at stress concentrations, and also to possibly reduce the nominal stress levels in these areas. The fatigue life of welds may also be improved by controlling the weld process, and thus reduce the number and extent of weld defects. One may also choose specific weld materials, which during cooling after welding will introduce favorable residual stresses. Finally, there are many post manufacturing treatments available with the potential to improve fatigue resistance.

To improve the fatigue life, the stress range driving the crack growth must be reduced, or to be precise, the part of the stress range that is positive, meaning a lowering of $\Delta\sigma$ and or the mean stress value. Hence, improvement may be achieved by:

- Lowering the stress concentration (or rather the fatigue notch factor) or by lowering the local mean stress, and also stress range, acting at the weld.

- Introducing compressive stresses at the weld thus lowering the mean stress at the weld. This is because the welding process generates residual stresses at the weld that are assumed (which is

also often the case) to reach the yield stress level in tension, which means that the stress at the weld during operation will vary from σ_Y to (σ_Y - $\Delta\sigma$). This is a worst-case scenario (which design codes for welded structures are based on) and means that the local R- ratio is high with tensile stresses acting on the crack tip during the entire load cycle.

An alternative method to improve the fatigue life may be to change the environmental conditions, by use of painting or coating. These methods will not be discussed further.

The nominal stress method used in many design codes may be used to quantify the effect of fatigue life improvement methods. Design codes for welded joints are normally based on elastically determined nominal stress ranges at the weld joint, $\Delta\sigma$. This stress range should be less than the fatigue resistance, denoted f_{rk}, possibly corrected by a safety factor. The fatigue resistance f_{rk} for a welded joint is determined from full-scale tests on welds (at constant amplitude), giving each weld geometry a certain fatigue class FAT. The fatigue class FAT includes the weld geometry, that is the fatigue notch factor K_f and the effect of the welding residual stress field. The FAT class is defined as the applied stress range $\Delta\sigma$ that for a given welded joint gives a fatigue life of $2x10^6$ cycles. Methods improving the weld profile will reduce the stress concentration factor and thus the fatigue notch factor, which will increase the FAT class whereas methods introducing compressive stresses in the weld will lower the mean stress level in the weld and thus also the positive part of the stress range acting on the crack. For the case where the new residual stress level is known, a mean stress correction factor is introduced which increases the allowable stress range. Normally these improvement methods will result in compressive residual stresses with unknown magnitude. The positive effect achieved may then be interpreted as an increase of the fatigue class.

For ship structures, it has been argued that post manufacture treatments are seldom cost-effective, i.e. they are too expensive and the scatter in the quality of achieved results is too large, Violette (2001). However, in two large investigations, post manufacture treatments suitable for ship applications were studied, Haagensen and Maddox (2001) and Kirkhope et al. (1999a).

IIW's Commisison XIII studied fatigue life improvement methods for several years. The results from this interlaboratory testing program on weld improvement methods is described by Haagensen and Maddox (2001), see below. The main objective of the programme was to assess the reproducibility of burr grinding, TIG dressing, hammer and needle peening. Based on the results achieved recommendations are now given for the improvement of the fatigue strength. Note though, that the methods used are applied to the weld toe. One must therefore separately consider fatigue failures initiating from other points (i.e. the weld root).

In a parallel Canadian investigation, Kirkhope et al. (1999a), a comprehensive survey of twenty fatigue life improvement methods is presented. Advantages and disadvantages and the relative life improvement are listed. Three methods, believed to be feasible and suitable for practical use in ship applications are studied and tested in detail in a separate paper Kirkhope et al. (1999b). This considers a specific test assembly consisting of a plate with a stiffener containing a scallop in the middle subjected to grinding, TIG dressing and hammer peening respectively. For these three methods guidance is given on inspection and quality control procedures, relative costs as well as effects of corrosion conditions.

4.1 Factors in Design

In Bull et al. (2000) a technique is introduced to design a welded joint to obtain the minimum stresses in a base plate, cover plate and the weld. In this way, a specified fatigue life can be obtained. This

technique links finite element adaptive techniques, error estimators and stress trajectories, together with a self-designing structures software and is applied to the case of cover plates welded to base plates.

Chaperon et al. (2000) presents a methodology for the optimal design of structural components with fracture and fatigue constraints. For the case of a cut-out geometry in a square plate subjected to a 4:1 and a 2:1 biaxial stress field, the shape of the cut-out is determined considering constraints on crack growth. It was hypothesized that the optimum shape would be such that all locations around the cutout would be equally fatigue critical. The methodology includes use of an initial "near optimum" shape be used in conjunction with the alternating finite element method, for multiple cracks, which builds on existing CAD based finite element models and the resultant formulation then linked to available optimization codes.

Norman and Lotsberg (2001) used four different hot spot stress approaches to accurately calculate the structural stress in a three perpendicular plate intersection containing a scallop. Different scallop geometries were found to give roughly the same estimated fatigue life, whereas use of weld toe grinding will increase the fatigue life.

Das (2002) reports finite element analyses performed to redesign a naval experimental manned observatory spherical acrylic submersible to increase its fatigue life when operating at 914 m ocean depth. A new design was proposed for the interfaces of the submersible in order to reduce the high stresses and high relative displacements calculated for the initial design.

4.1.1 Weld Quality

One problem experienced with fillet welds is that of cold laps, that is lack of fusion in the weld toe. Cold laps destroy the weld profile, giving reduced fatigue performance. Samuelsson (2002) discusses the application of a weld class system and how to interpret weld classes. The existence of cold laps in experimental results from the literature is studied. A parametric FE-analysis is reported that shows that the toe radius is the geometrical parameter with the highest influence on the fatigue life. The addition of the toe radius in acceptance limits in the weld class system is discussed.

In Martinsson (2002) several batches of non-load carrying fillet welds (using different weld data) were tested. A majority of the test pieces contained cold laps. Experimental results from present and earlier investigations were compared with FE-based fracture mechanics fatigue life predictions showing good agreement. It was seen that cold laps occurred frequently in the specimens and that they decrease the fatigue life.

Nguyen et al (1996) performed numerical analyses to predict the combined effect of a weld toe undercut, residual stresses and misalignment on the fatigue strength of butt-welded joints. The reduction of fatigue life, in comparison to a flush-ground welded plate, caused by an introduction of weld toe undercut is twice that due to a welded joint without any undercut. Fatigue life can be decreased by up to 10 and 100 times compared to perfect stress-relieved conditions of aligned and misaligned joints respectively, once high tensile residual stresses of yield stress magnitude are present. Kim et al (2001) also investigated the welding residual stress issue. Stress distribution and re-distribution by were studied analytically and experimentally. The study showed that welding residual stresses near the weld toes decreased under pre-load. Robels et al. (2000) suggested a method for the evaluation of the fatigue life of submarine pressure hulls applying linear elastic fracture mechanics principles based on the Paris law.

4.2 Factors in Operation

Dimitrakis and Lawrence (2001) studied fillet weld terminations - ubiquitous weld details having a notoriously poor fatigue resistance. A specially designed stress-concentration-reducing part was incorporated in the wraparound welds at the ends of fillet-welded longitudinal attachments. The incorporation of this part at the terminations of the fillet-welds substantially decreased the weld toe stresses in those locations where fatigue cracks customarily start, reducing weld toe residual stresses and promoting increases in the weld-toe notch-root radius. In the long-life regime the incorporation of these small added parts increased weldment fatigue life by 300% and fatigue strength by 30%. It was found that the full benefit of the added part could only be achieved when welding processes were employed that avoided the production of cold-lap weld-toe defects.

The effect of weld repair was studied by Shankar and Wu (2002) for the case of aluminium alloys used for high-speed marine vessels. The propagation in the weld line (of welded plates) was numerically calculated for both the as –welded case and for a weld repair case. The weld repair was found to significantly increase the grain size and the size of defects, resulting in only a small improvement of the fatigue life.

Lopes et al. (2002) studied the effect of a single overload on a flash welded chain link used for offshore moorings. Based on crack growth measurements on CT-specimens it was found that the fatigue life could be improved mainly because of an improved microstructure. It is also suggested to apply the overload after a period in operation.

4.2.1 Burr Grinding

The primary aim of grinding is to remove or reduce the size of weld toe flaws (flaws of the size of a few tenths of a mm are often present after welding) from which cracks may propagate. At the same time the stress concentration factor is reduced by smoothly blending the transition between the plate and the weld face. Haagensen and Maddox (2001) describe different burr grinding procedures including methods for inspection and control. It is reported that for certain fatigue classes, that is weld geometries where weld toe crack propagation is the failure mode, the benefit corresponds to an increase in allowable stress range of 1.5 corresponding to a factor of 3.4 in fatigue life. Figure 5 below shows the weld classes (classified by the FAT-number) for which a benefit can be claimed and the maximum benefit allowed for burr ground aluminium weldments

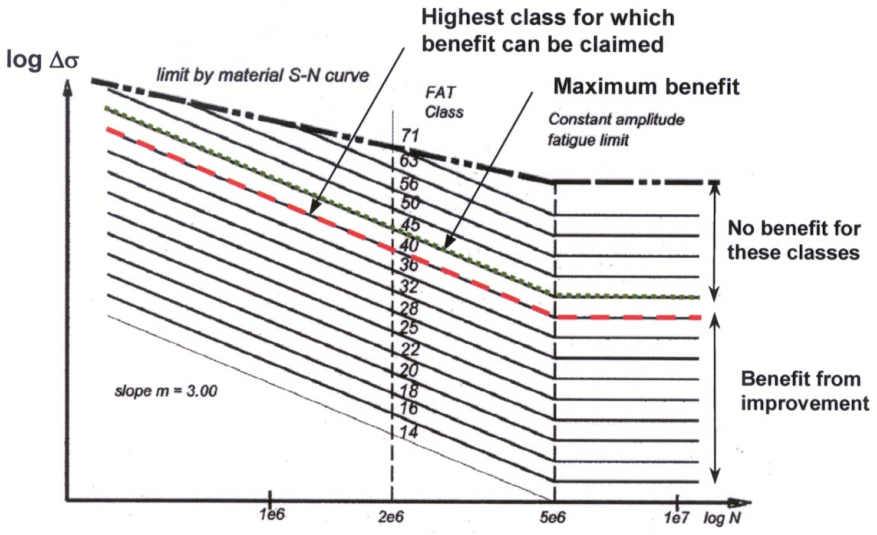

Figure 5: Benefit and limitation of improvement for burr ground aluminium weldments. S-N curves from IIW Fatigue design recommendations (Hobbacher, 2002). From Haagensen and Maddox (2001).

Kirkhope et al. (1999b) notes that burr grinding is not recommended for welded joints that are loaded in a direction parallel to the weld. Moreover, as the method improves the weld toe, where crack initiation can be expected from the weld root will get no improvement, examples are partial penetration welds.

Grinding was used to repair a platform with the objective to extend service life by 20 years (the platform had been in service for 15 years), Haagensen et al. (2000). The burr grinding operations were performed according to IIW recommendations, see Haagensen and Maddox (2001) and were preceded by a course and training program for inspectors and operators. To obtain sufficient quality under tight time constraints it was believed necessary to motivate and instruct operators previously unfamiliar with the improvement methods. A separate test program was set up using butt-welded and ground specimens. It was found that proper grinding could raise the fatigue strength up to almost that of the unwelded case.

4.2.2 TIG Dressing

The aim of TIG-dressing is to remove weld toe flaws by remelting the material at the weld toe. Providing a smooth transition between the plate and the weld face can also reduce the local stress concentration effect at the weld toe. Haagensen and Maddox (2001) describe the equipment and procedure used. The same improvement as for burr grinding is observed, that is an increase in allowable stress range by 1.5. Kirkhope et al. (1999b) reports that TIG dressing is sensitive to weld contaminants more than other methods, and that the quality of the treatment is dependent on the combination of dressing parameters and the skill of the operator.

Lebaillif et al. (2002) carried out design experiments to determine optimal parameters for TIG dressing with regard to maximal fatigue life improvement. Two different steel grades are included in the study. Dahle (1998) evaluated the improvement of fatigue strength due to TIG dressing by comparing experimental data with that of the mean regression curve and proposed TIG dressed design S-N curve.

4.2.3 Hammer, Needle and Shot Peening

In peening operations, compressive residual stresses are introduced in the weld region by mechanically induced plastic deformation. With these operations the mean stress level in the weld is lowered, and the normally high tensile welding residual stresses is relaxed. One may note, that the beneficial effect of peening is dependent on the mean stress of the operating load. In general, these techniques are not suitable for structures operating at an applied external stress ratio of more than $R = 0.5$ or a maximum applied stress of $0.8\ \sigma_Y$. Note also, that for a variable amplitude loading case, occasional peak loads may mechanically relax induced compressive stresses as well as the peaks in the welding residual stress field. This fact is well known for welds subject to variable amplitude loading. In Bogren and Lopez Martinez (1993) a non-load carrying fillet welded plate was subjected to a load spectrum with a major part having a low magnitude. It was found from X-ray measurements that very early in the test the residual stress field at the fillet weld was relaxed to about half its original magnitude. One would therefore assume that compressive and tensile peaks in the load spectrum will redistribute the residual stresses built in by the hammer peening. Kirkhope et al. (1999b) noted that although one could ensure that the weld area is covered by the peening, it is not possible to verify that hammer peening was

carried out correctly. In order to do this, residual stresses in the weld region must be monitored after peening and during service life.

For the initiation of cracks, that is for the so-called stage I shear crack within one grain, it has been argued that in peening, it is rather the crystallographic distortion that gives a beneficial effect creating more barriers for the crack to overcome, Miller (1993). This would apply for improvement of other joints or details with lower fatigue notch factors than welds.

In Haagensen and Maddox (2001) hammer peening (where the weld toe is repeatedly hammered with a blunt nosed chisel) and needle peening (where a bundle of round-tipped rods are used) equipment and procedures are described. For both cases, the improvement is quantified as an increase in the Fatigue Class for the component although one must be aware of the stress ratio sensitivity, which limits cases where a benefit can be expected. For the hammer peening case it is also observed that fatigue on large scale structures indicate a lower benefit than for small-scale specimens. For structures with thickness larger than 25 mm it is recommended that the benefit for hammer peening is assumed to be the same as for burr grinding or TIG-dressing.

Hammer peening treatment has been shown to have a good potential to significantly extend the fatigue life of side shell longitudinal / web frame connections on TAPS-tankers operating on the US west coast, Blackstone and Basu (2000). Use of this technique, which is for the tankers studied was found to be very cost effective, has reduced the number of fatigue cracks observed considerably. The possible shake down of the compressive residual stresses introduced is discussed. For the operating conditions present, the experience seems to indicate that the compressive residual stresses remain, or at least shake down / relax to the magnitudes of the operating stresses. Thus, provided that hammer peening will transform tensile welding residual stresses to compressive stresses, there will be a period in time during which the fatigue crack growth will be lower than for a corresponding unwelded joint. When the peening induced stresses have relaxed, due to overloads in the operating load spectrum, the cracks grow by operating stresses only.

Hassan (2001) investigated the effect of air-hammer peening on enhancing the fatigue strength of welded steel plates experimentally and analytically. Air-hammer peening was applied to the weld toe area for two cases: a cracked weld toe and an un-cracked weld toe. Test results demonstrated that air-hammer peening is an effective method for enhancing the fatigue strength of welded details especially when subjected to the non-cracked condition. An analytical model was developed using linear elastic fracture mechanics to estimate the fatigue propagation life. Three-dimensional finite element analysis was performed to obtain the stress concentration factor at the crack propagation path. The model was successful in predicting the fatigue life of test specimens.

Ochi et al. (2001) studied the effect of shot-peening on the fatigue strength of ductile cast iron (ferrite-pearlitic ductile cast iron, FPDI, and pearlitic ductile cast iron, PDI) experimentally. The shot-peening treatment was found to give high-level work hardening and high-level compressive residual stress near the surface layer thereby improving the fatigue strength. In addition, it can reduce the number of casting defects that initiate the fatigue cracks near the surface. In this report, the fracture morphology and the fatigue properties were investigated in terms of crack behaviour and residual stress change. Therefore, the initial residual stress distribution and its change during the high cycle fatigue test of the SP-treated specimen were investigated.

Torres et al (2002) evaluated the fatigue life of AISI 4340 steel under four shot peening conditions. It was demonstrated that the shot peening intensity that produces best results in fatigue life is influenced by several factors: relaxation of induced compressive stresses during the fatigue process;

surface conditions created by shot peening; and the possibility of the compressive residual stress field to push the crack source beneath the surface.

The fatigue life improvement of airframe parts by use of shot peening was studied by Sharp et al. (2002). The procedure includes the removal of a thin layer of material which may contain defects from manufacturing processes as well as the introduction of compressive stresses at the surface.

Shot peening in combination with surface treatments (vacuum carburizing and contour induction hardening) to decrease the grain size were used by Ando et al. (2002) to improve the fatigue life of automotive components subject to pulsating loads. Using these methods the fatigue limit of gears could be increased considerably.

Shot peening by use of lasers is still under laboratory development but may be used in production in the near future. O'Hara (2002) reports results using lasershot peening. One could then introduce a compressive residual stress field to a larger depth with virtually no roughening and no decontamination. Montross et al. (2002) reviews the current status of laser peening and also gives some applications.

4.2.4 Other methods introducing Compressive Stresses at the Weld

The fatigue life improvement of critical details of bridges was studied experimentally by Fisher et al. (2002). From tests on full size girders and full size rolled web girders it was concluded that Ultrasonic Impact Treatment (or ultrasonic peening) was superior to other peening processes in terms of fatigue life improvement. This method also operates at lower noise and vibration levels than other peening methods tested.

In Ohta et al. (2002) a positive effect of using low transformation temperature electrodes was observed in tests of lap welds. This effect is due to the introduction of compressive stresses at low temperatures due to a volume expansion during the final solid-state phase transformation in the weld metal. An increase in fatigue strength of 40 – 70% compared to using ordinary electrodes is reported.

Two existing improvement techniques based on introducing compressive stresses are compared in an experimental investigation (Huo et al.) 2001. Ultrasonic peening and use of low temperature transformation electrode (LTTE) was employed on transverse butt weld joints and plates with longitudinal fillet weld gussets. Ultrasonic peening was found to give a much higher fatigue life improvement, although use of LTTE may be justified for the case of plates with longitudinal fillet weld gussets where it can be cost effective as no additional post weld treatment is carried out.

In Huo et al. (2002) ultrasonic peening is compared with TIG-dressing in an experimental investigation on fillet welds subjected to constant or variable amplitude loading. For high-cycle fatigue loading levels the ultrasonic peening method was found to give a better fatigue life improvement although this improvement was smaller for variable amplitude loading.

Eckerlid et al. (2002) also reports major improvements in allowable stress ranges for a given fatigue life when using low temperature transformation weld filler metals in out-of-plane gusset fillet welds.

Cold expansion of holes in structures is another method used to introduce a favorable compressible residual stress field in areas where fatigue cracks may initiate and propagate. Lacarac et al. (2001) studied the effect of cold expansion of holes in aluminium alloys at two different temperatures (20°C and 150°C). Based on the experiments they conclude that the fatigue life may be increased by a factor of 1 – 10 at room temperature.

4.3 Code Development

The IIW issued Recommendations for fatigue design of welded components in 1996. An updated revision is now under discussion, Hobbacher (2002). The experimental findings from Haagensen and Maddox (2001) is then included in the recommendations. Guidance is given for four post treatments: burr grinding, TIG-dressing, hammer peening and needle peening. These methods may be used in connection with repair or upgrading of existing structures, not for general use in the design in order to obtain a longer fatigue life than an ordinary use of standard design curves would give. Moreover, improvement applies only to the weld toe, and care should be taken to consider other possible crack initiation points, i.e. weld roots or weld imperfections. The recommendations are valid for steel with a yield stress σ_Y < 900 MPa and aluminium alloys used for welding, for operating temperatures below the creep range and for cases when High Cycle Fatigue (HCF) conditions prevail, that is the applied stress ranges are low.

Currently the recommendations are developed for the nominal stress method whereas more work is needed to include the improvement recommendations for the structural stress method. For burr grinding and TIG-dressing, following procedures outlined in Haagensen and Maddox (2001), IIW discusses an increase in the allowable stress range with a factor 1.5 (50% increase), see also Figure 5 above. This benefit does not apply for higher FAT-classes, as they are valid for classes where failure is not governed by weld toe failure. For hammer and needle peening, it is suggested to upgrade FAT-classes below 90 to the FAT-class 125. To ensure that compressive overloads will not relax the residual stresses induced by the peening operation, there are limitations on the service load spectrum.

Det Norske Veritas (2001) in their recommended practice for fatigue strength of offshore structures state that the fatigue life may be increased a factor of 2 for grinding and TIG-dressing. For hammer peening the corresponding increase factor is 4 provided restrictions in compressive peak loads in the load spectrum are met.

Rudolph et al. (2002) presents fatigue assessment methods for post weld treated pressure vessel components. These assessment methods are based on a local strain approach and are demonstrated for cylinder-to-cylinder intersections and butt welded joints in typical pressure vessel structures.

5. IMPACT OF DEVELOPMENTS IN MATERIALS ON FATIGUE & FRACTURE

Materials are normally presented by their characteristics in terms of elastic modulus, yield strength, tensile strength, hardness and ductility, toughness, fatigue strength, creep deformation and fracture, oxidation and corrosion, friction, abrasion and wear. Whether a material is attractive or not to be applied in marine structures depends very much on the material resistance to possible failure modes, e.g., failure by elastic deflection, failure by extensive yielding at ordinary temperatures or elevated temperatures, and, failure by fatigue and fracture. Failure by fracture and fatigue can be categorized by sudden fracture of brittle material, fracture of cracked or flawed members, fatigue/progressive fracture and fracture with time at elevated temperatures. Some materials are brittle. The brittleness of the material is measured by its capability of resisting loads under static conditions until the material breaks rather suddenly with little or no evidence of plastic deformation. A structural member made of ductile material and subjected to uniaxial stress rarely fractures under static load, except at regions of abrupt change in section, at edges, from defects, or when very low temperatures are encountered. Another type of fracture may occur at elevated temperatures under a static load that is applied for a long period of time. Therefore, resistance to temperature can also be a measure of material strength. Fatigue

strength is another important measure of structural failure resistance due to repeated cycles of reversed stress. In addition, good corrosion resistance can reduce structure failure due to fatigue and fracture.

5.1 Material Developments

While steel is by far the most widely used material in Ship and Offshore applications, the industry is facing challenges from new concepts and deep-water offshore developments. Therefore, there are increasing needs to take advantage of other materials, e.g., titanium, aluminium and composites. Previous ISSC reports have concentrated on reporting research and development of steels used in marine environments, in particular high strength weldable steels in more recent reports. This Section reports on recent application and research into non-steels.

Titanium has been used for some special applications within the naval and offshore industry for some time, notably for sub-marine hulls and for piping and heat exchangers for sea water systems. There is also increasing interest within the offshore industry to use Titanium as a structural material in highly loaded components, e.g. for risers and riser components. Such components are usually subjected to large deflections and significant fatigue loading. The main reasons why Titanium is of interest are its:

- Excellent corrosion resistance
- High strength
- Low density
- Good flexibility (low modulus of elasticity)

Aluminium is an attractive material as it is light, clean, normally ductile, easily formed and fabricated, and readily available. The material has been widely applied in structures including aircrafts, buildings, bridges, railway and road vehicles. For ship structures, aluminium has mainly been limited to build, e.g., small boats, superstructures of large ships with steel hulls, and minesweepers. Recently, the ship industry has become more interested in fast speed and light craft using aluminium. Aluminium hull structures with lengths greater than 100 meters are also being considered.

The implementation of composites in marine applications is perceived as a promising path forward with composite materials offering many advantages including high specific strength and stiffness, lighter weight, enhanced corrosion resistance, high thermal insulation, improved structural damping and favorable fatigue performance characteristics.

In the following sections focus on titanium, aluminum and composites, reviewing these in terms of their use in marine applications.

5.2 New Materials & Applications

5.2.1 Titanium

5.2.1.1 Experience

Even though Titanium has been studied and considered for structural use offshore for several years there is still a limited number of actual applications.

Conoco chose titanium Grade 23 for the whole Heidrun drilling riser except for the top section, see e.g. Sauer *et al.*(1996a), Sauer *et al* (1996b), Salama *et al* (1998) and Simonsen *et al* (1999). This riser is rated to 300 bar, and the gas and oil extracted are expected to become sour in the longer term. Extruded seamless test pipes and actual riser pipes with 24” OD, 22” ID and 14.6 m (48 ft) pipe section

lengths, were used. Both the OD and the ID of the pipes were machined. The 22" flanges were of compact design and had extended weld necks formed by so called "stalled-off extrusion". The weld method was TIG and a total of 26 joints, with 2 welds per joint. The riser has been in service since 1996.

Cooper Oil Tool designed, manufactured and installed a large titanium Grade 29 taper stress joint (TSJ) for the Placid deep water rigid riser system. The system was installed in the Green Canyon field in the Gulf of Mexico in January 1988. The reservoir was poor and the joint was retrieved in 1989, stored, refurbished and re-installed offshore for Ensearch in 1995. In addition a number of smaller TSJ's were installed.

No specific problems were reported from the use of Titanium in these applications. Titanium has, furthermore been considered for several other riser projects, e.g. the Visund development for Norsk Hydro, Tørstad and Bratfos (1999) and the Åsgard B development for Statoil, Berge *et al* (2002b). In both these projects extensive testing and analyses was carried out. However, the final choice was not Titanium, mainly due to cost and fabrication schedule.

Much of the early work on the use of Titanium for riser applications were summarised at a seminar in Trondheim in 1999, Berge and Lunde, eds. (1999).

5.2.1.2 Candidate Grades for Use in Risers

There are several Titanium Grades that are considered for riser applications. The most interesting are:

Alpha (α) Alloys

The *Grade 9 (Ti-3Al-2.5V)*, containing 3% aluminium and 2.5% vanadium, is a near-alpha alloy containing limited beta phase, but one which exhibits good ductility and fabrication in combination with improved medium strength. The Grade 9 alloy is susceptible to crevice corrosion in chloride or other halide-rich services at temperatures above 75-90°C.

Pd-enhanced alloys of Grade 9 are made to eliminate crevice corrosion at temperatures above 85°C. These alloys are denoted *Grade 18 (Grade 9 + Pd)*. The Ru-enhanced version of Grade 9 is denoted *Grade 28 (Grade 9 + Ru)* and is qualified under the NACE Sour Service Specification MR-01-75. The *Grade 32 (Timetal 5111)* is a near alpha alloy of intermediate strength, designed for high toughness, good weldability, stress corrosion cracking resistance and room temperature creep resistance. The alloy is considered a viable alternative to Grade 23 and will obtain enhanced corrosion resistance by addition of Pd or Ru.

TABLE 2: MECHANICAL PROPERTIES ACCORDING TO ASTM B861 AND B862 FOR SOME CANDIDATE ALLOYS

ASTM Grade	**Common Alloy Name**	**Nominal Composition (wt %)**	**Alloy Type**	**Mechanical Properties**			
				Min. 0.2% YS (MPa)	**Min. UTS (MPa)**	**Elastic Modulus (GPa)**	**Elongation Min. (%)**
Grade 9	Ti-3-2.5	Ti-3Al-2.5V	Near-alpha	483	620	103	15
Grade 18	Ti-3-2.5-Pd	Ti-3Al-2.5V-0.05Pd	Near-alpha				
Grade 28	Ti-3-2.5-Ru	Ti-3Al-2.5V-0.1Ru	Near-alpha				

Grade 32[1)]	Timetal 5111	Ti-5Al-1Zr-1Sn-1V-0.8Mo	Near-alpha	586	689	107	15
Grade 23	Ti-6-4 (ELI)	Ti-6Al-4V (0.13 max o_2)	Alpha-beta	759	828	105	10
Grade 24 (ELI)[2)] (Grade 23+Pd)	Ti-6-4 Pd (ELI)	Ti-6Al-4V-0.05Pd	Alpha-beta	759	828	107	10
Grade 29	Ti-6-4 Ru (ELI)	Ti-6Al-4V -0.1Ru	Alpha-beta	759	828	105	10
Grade 19	Ti Beta-C	Ti-3Al-8V -6Cr-4Zr-4Mo	Beta	759 [3)] (1103) [4)]	793 [3)] (1138) [4)]	96	5 15
Grade 20	Ti Beta-C/Pd	Ti-3Al-8V-6Cr-4Zr-4Mo-0.05Pd	Beta	759 [3)] (1103) [4)]	793 [3)] (1138) [4)]	96	5 15

According to ASTM B348; ' Standard Specification for Titanium and Titanium Alloy Bars and Billet'

The ASTM Grade 24 version is not defined as an ASTM grade, however the mechanical properties are similar with those given for Grade 23.

Properties for material in solution treated condition

Properties for material in solution treated and aged condition

Alpha-Beta (α+β) Alloys

The basic structural alloy of titanium is *Grade 5 (Ti-6Al-4V)*, which has the addition of 6% aluminium and 4% vanadium. Aluminium stabilises the alpha phase whilst vanadium stabilises the beta phase. Introducing beta phase into the matrix produces a duplex-alloy that can be heat treated to give significantly higher strength than the Grade 9 alloy. Grade 5 can be solution treated and quenched and tempered in thickness up to approximately 25 mm to give a fine dispersed beta-phase in an alpha matrix, thereby strengthening the alloy. Grade 5 is more prone to stress corrosion cracking in seawater than other grades, and there is still some uncertainty regarding its hydrogen absorption in well fluids at temperatures above 80°C. However, for riser design Grade 5 itself is not really suitable due to its limited fracture toughness. The toughness and resistance to stress corrosion cracking in the Grade 5 alloy has, however, been improved by limiting the interstitial content, mainly oxygen, to produce the Extra Low Interstitial (ELI) grade, denoted *Grade 23*.

Pd-enhanced (0.05 %) alloys of Grade 5, denoted *Grade 24*, are made to eliminate crevice corrosion at temperatures above 85°C. No measurable influence was found of minor Pd additions on the alloys susceptibility to hydrogen absorption or embrittlement. However, Grade 24 may be susceptible to stress corrosion cracking and sustained load cracking. Thus, Grade 24 is not considered suitable for riser applications and a Grade 23+Pd, so-called *Grade 24 ELI* version, should be chosen in lieu of standard Grade 24. Similar corrosion improvements are achieved by adding 0.1 % Ru. Grade 23 with Ru is currently being installed in geothermal wells to resist the effects of hot brine. The Ru bearing versions of Grade 23 were given the ASTM designation *Grade 29 (Grade 23 + Ru)* and are qualified under the NACE Sour Service Specification MR-01-75.

Beta (β) Alloys

An alloy of special interest in connection with oil and gas production facilities is the *Beta C* alloy, available as ASTM *Grade 19 (Ti-3Al-8V-6Cr-4Mo-4Zr)* and the Pd-enhanced version of Grade 19, denoted *Grade 20*. The alloys are heat-treatable and combine high strength and excellent corrosion properties. It is usually cold formed or hot worked in the lower strength annealed condition, and then solution treated and aged to very high strengths. By virtue of its significant Mo content, this alloys displays superior resistance to hot chloride crevice corrosion for service temperatures exceeding 90°C. The Grade 19 alloy is qualified under NACE MR-01-75 for sour service. The alloys are however expensive with high alloying content, and will only be cost competitive for specific applications.

5.2.1.3 Fatigue Properties

SN testing of both base material and of weldments were performed in several recent investigations, e.g. Berge *et al* (2002a), Berge *et al* (2002b), Horn *et al* (2002) and Torster *et al* ((1999a). Ronold and Wästberg (2002) summarises results from several investigations and performs a statistical analysis of the results both for base material and for weldments. The results from Ronold and Wästberg (2002) are also included in the DNV RP (DNV (2001)). Almost all the data presented in these investigations are from specimens extracted from girth-welded pipes intended for riser applications.

The various investigations suggest different design curves for Titanium welds and there does not seem to be a consensus yet which curve is the most appropriate:

$\log(N) = 19.8 - 6.0 \times \log(S)$
Stolt-RMI curve, Baxter *et al* (1997)

$\log(N) = 17.0 - 5.0 \times \log(S)$
Marintek curve Berge *et al* (2002a)

$\log(N) = 13.1 - 3.4 \times \log(S)$
Ronold *et al* (2002), incl. in DNV (2001)

where the stress range (S) is expressed in MPa.

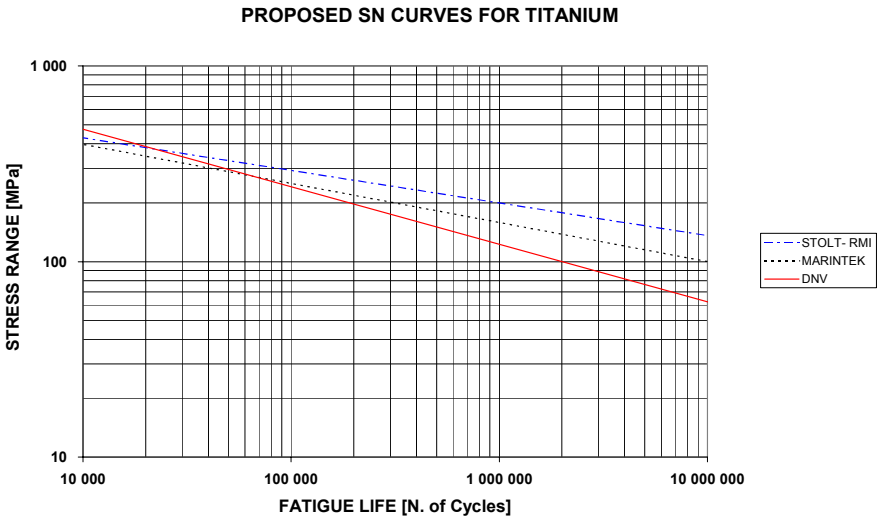

Figure 6: Illustration of the three SN-Curves mentioned above (data beyond 5×10^6 is very scarce)

These curves differ mainly in the "low stress-long life" region where there is limited data available (data for fatigue lives beyond 5×10^6 are very scarce). Ronold *et al* (2002) is the most conservative and the Stolt-RMI curve, Baxter *et al* (1997), the most optimistic. The main reason for the difference between the curves is the populations of test results included. Ronold *et al* (2002) contained the fewest number of results whereas the Stolt-RMI curve contained the greatest number.

It is common practice to machine or grind the welds for highly loaded Titanium applications. This means that the crack initiation site will normally be at locations of internal porosity and the fatigue life depends on the size and location of such porosities, see e.g. Tørstad and Bratfos (1999), Salama (2000) and Berge *et al* (2002b).

These results also clearly show the necessity of stringent quality control during fabrication of Titanium welds in order to avoid onerous weld defects and that qualification testing is still necessary for each development project considering the use of Titanium.

Fatigue crack growth measurements under conditions relevant for riser applications were reported by e.g. Baxter *et al* (1997), Salama *et al* (1998), Salama (2000), Simonsen et al (1999) and Tørstad and Bratfos (1999). The results from these investigations vary considerably, e.g.:

$da/dN = 2.39\times10^{-11}\ (\Delta K)^{2.7}$ (mm/Cycle)
Simonsen *et al* (1999)

$da/dN = 2.8\times10^{-11}\ (\Delta K)^{3}$ (mm/Cycle)
Baxter *et al* (1997)

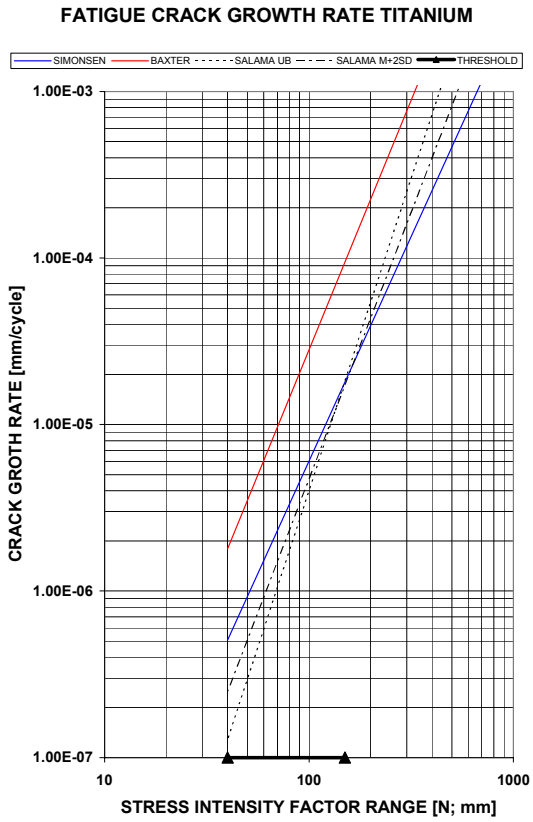

Figure 7: Illustration of fatigue crack growth curves for titanium. Fatigue crack growth thresholds are reported between 40 and 150 $Nmm^{-3/2}$

There is a factor of approximately 5 – 7 between these curves in the area of interest and the results from the other investigations, referenced above, essentially fall between these curves. ΔK_{th}-values are also reported and found to vary between 40 and 150 $Nmm^{-3/2}$ depending on the R-ratio. It is seen, as for SN results, that so far there is no consensus which crack growth values are the most appropriate for design. This again clearly shows the need for further testing under relevant conditions and that qualification testing must be carried out for each development project considering the use of Titanium.

Berge *et al* (2002b) and Babalola and Berge (2002) report results from fracture mechanics analyses of fatigue crack growth from internal porosities and compare the analyses results with SN testing. The agreement between the analyses and test results are strongly dependent on the assumptions made regarding e.g., crack growth properties, threshold values, stress intensity factor solutions and initial crack sizes.

Regarding the initial crack sizes Berge *et al* (2002b) observes that although crack initiation in all cases took place from three-dimensional porosities with near spherical shape and diameter in the range 0.15 – 0.8 mm the calculations suggested that the crack initiation period was very short. This is different from expected behaviour. Fractographic features indicated however that the initial stage of crack growth from areas of porosity might take place in a brittle mode. In that case the porosity size may be an underestimate of the initial defect size.

5.2.1.4 Fracture Properties

The fracture toughness of the most relevant Titanium grades (see Table 2) are relatively low when compared to common structural steels. The fracture toughness, K_Q, is typically in the range 70-100 MPa√m or measured as CTOD in the range 0.05 – 0.10 mm, see e.g. Simonsen *et al* (1999), Tørstad and Bratfos (1999) and Torster *et al* (1999b).

For most offshore applications, the wall thickness range of interest is normally too small for characterisation by K_{IC} and DNV (2001) recommends characterising the fracture resistance by J-R curves instead. There are however still only limited results available from relevant J-R testing. It is therefore common practice to characterise the actual material for the actual conditions for each project.

The desire to fully utilise the high strength of Titanium together with the relatively low fracture resistance places high demands on the fabrication quality and the NDT capabilities both during fabrication and possible in-service inspection.

5.2.2 Aluminium

Aluminium alloys are widely employed in shipbuilding mainly for *high-speed light craft* (HSLC) and for the upper decks of passenger vessels. However, compared with steel, the fatigue behaviour of marine aluminium alloys are less well understood, and increased research in this field is recommended.

Øyvind Wilhelmsen (2000) presents a summary of experience with HSLC over 30 years, as shown in Figure 8. Experience indicates that High Speed Light Craft overall have a low rate of structural hull damage, although higher than for other types of vessels. Among individual craft there may, however, be examples of higher rates of damage. It is important to note that age of the craft does not seem to influence the rate of damage significantly.

The most common structural failure is fatigue cracking due to vibrations in connection with machinery and propulsion units and fatigue cracking in local details after a relatively short period of service.

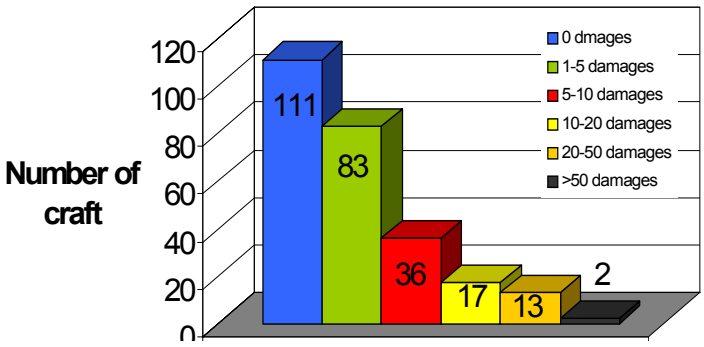

Figure 8: Typical distribution of reported damage, O. Wilhelmsen, (2000)

The research activity on the fatigue behaviour of Aluminium alloys can be analysed taking into account the following items (Dousset and Gallus, 2002, Capasso and Rizzo (2002)):

a) The criteria followed to estimate *fatigue life*
b) The most influential parameters on *crack growth of aluminium alloys*
c) The *vibration* effect on structures
d) The impact of *welding* on fatigue life

With reference to item (a), a general review of the research involved in *fatigue life estimation* can be found in section 2. However, it is important to note that many methods used successfully to predict fatigue damage in steel components seem less efficient when used for aluminium alloys, probably due to the lack of sufficient amount of data (see *W.-S Jeon and J.-H. Song* [2002]).

5.2.2.1 Parameters Affecting Crack Growth of Aluminium Materials

Fonte et al (2001) dealt with the *microstructure* and *environment* influence on fatigue crack growth in 7049 aluminium alloy. They experimented an underaged (UA) and an overaged (OA) alloys, which each have their own particular microstructure. The two materials demonstrated distinct behaviour in the two environments of humid air and vacuum (Figure 7). The overall behaviour relies on a complex relationship between the effect of the environment with microstructure and loading.

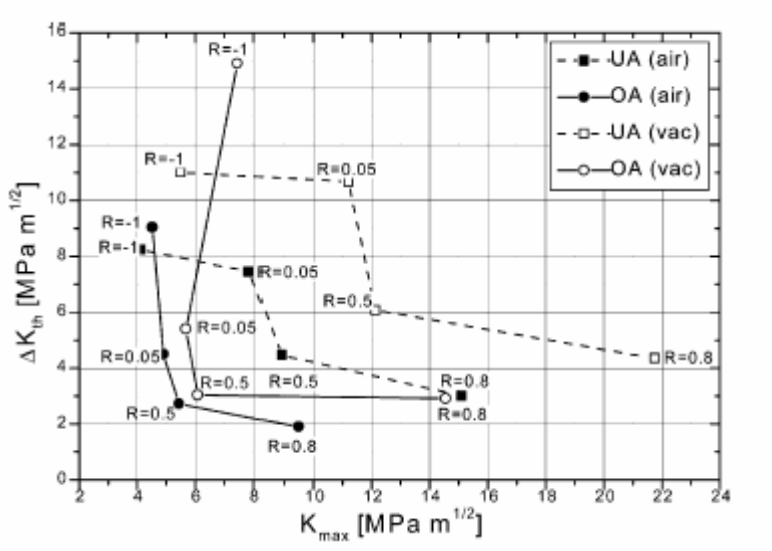

Figure 9: Threshold ΔK_{th} vs K_{max} of UA and OA alloys at different R-ratios in ambient air and vacuum, Fonte et al., [2001]

Borrego et al (2001) carried out an experimental study on fatigue crack growth behaviour, in AlMgSi1-T6 (6082-T6) aluminium alloy under *constant amplitude loading* and *single tensile overload conditions,* at various stress ratios. The Authors assumed that R-ratio had dramatic effects on fatigue crack growth, suggesting crack closure in both crack growth regimes I and II under constant amplitude loading. Moreover, the stress ratio R and other parameters, namely the overload ratio and the baseline level, influence severely the crack growth transients. In addition, experiments showed that the crack closure might be the main factor determining the transient crack growth behaviour following overloads for plane stress conditions.

Bergner et al (2001) measured and analysed fatigue crack growth rates in the Paris regime on thin-sheet heat-treatable wrought aluminium alloys. They split the alloys into two groups: group A (artificially aged materials) and group B (naturally aged alloys). In group A, the crack growth curves converged strongly to one single point and the authors established a relation between *m*, the exponent of Paris law, and a dimensionless material parameter, $\sigma_y \theta B/(K_{mc})^2$. Group B was characterised by: (a) smaller crack growth rates at ΔK_0=10 MPa.m$^{0.5}$, (b) a correlation between these rates and the roughness of crack faces and (c) excessive values of *m*. Thus, according to the authors, the main mechanism responsible for the variability of the Paris exponents of the alloys of group A is constraint-affected plasticity-

induced crack closure, which depends on the materials properties. Concerning group B, an additional mechanism responsible for the reduced growth rates at ΔK_0 is roughness-induced crack closure.

5.2.2.2 Vibration Effects

Shih and Wu (2002) assessed the first-mode vibration and fatigue crack propagation of rectangular plates in aluminium 6063-T5 with an edge crack and evaluated the influence of different load frequencies. The application of ultrasonic frequency (20 kHz) loading to test fatigue and fracture mechanical properties of materials is briefly reviewed and recent investigations on high strength aluminium alloys are reported in Stanzl-Tschegg and Mayer (2001). Very high cycle endurance tests and near threshold crack growth experiments were performed with the 2024-T351 aluminium alloy. The influence of ambient air and distilled water environments were evaluated. Fatigue tests under randomly varying loads showed that the linear damage summation calculation overestimated lives by approximately a factor of two, as shown in Figure 10.

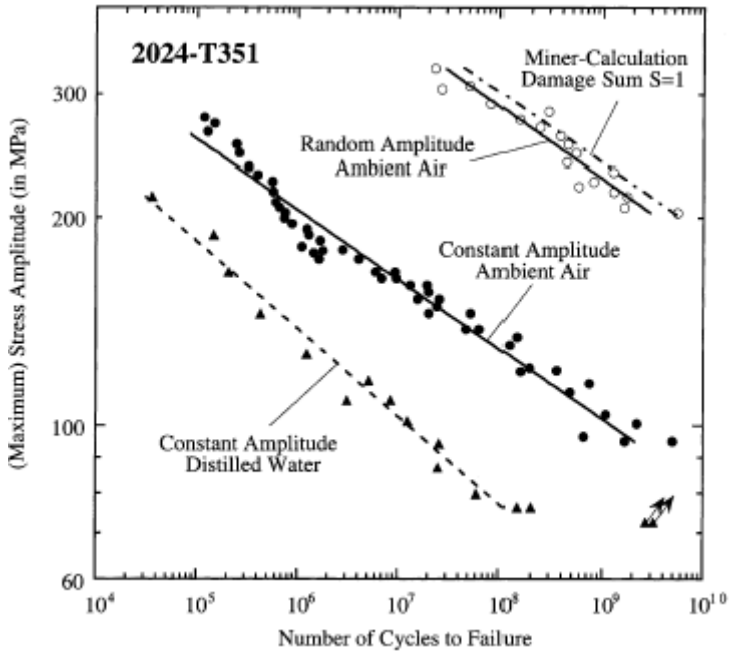

Figure 10: Endurance data of 2024-T351 (Stanzl-Tschegg and Mayer (2001))

5.2.2.3 Weldments

The strong welding effect on the mechanical characteristics (including fatigue) of aluminium alloys were investigated by Pinho da Cruz et al (2000). They studied the fatigue behaviour of an AlMgSi1 alloy lap welded joint and the improvement in fatigue strength due to post weld heat treatment. The prediction of crack initiation life under plane strain conditions was based on the local strain approach using Morrow's modified equation. As life predictions are extremely sensitive to the weld toe curvature radius, the experimental results scatter widely, at least partially attributed to the variation of the minimum curvature radius of the specimens. The experimental and the predicted results agree satisfactorily for r_c=0.1 mm. The T6 heat treatment significantly improved the fatigue strength of the welded specimens. An improvement of about 50% of the stress range was attained for a crack initiation life of 10^6 cycles.

In Lazzarin and Livieri (2001), the fatigue strength of aluminium-welded joints with different geometries and thickness are summarised in single scatter band by using a N-SIF-based approach. The

statistical analysis is carried out taking into account experimental data already reported in the literature, referring to welded joints with a thickness ranging from 3 to 24 mm. Results of steel and aluminium welded joints are then compared. The assessed value of the theoretical exponent quantifying the scale effect penalty was found to be larger than that suggested by Eurocodes (0.326 against 0.25).

An estimation of the fatigue strength of light alloy welds by an equivalent notch stress analysis was carried out by Atzori et al (2002). The Authors propose a relatively simple method to estimate the fatigue strength of a welded joint on the base of the estimation of the fatigue strength of the equivalent V-notch subjected to a remote stress equal to the structural stress that can be regarded as a "hot spot" stress. According to the described method, the scale effect can be taken into account. The fatigue and static behaviour of aluminium box–stiffener lap joints were investigated by Ye and Moan (2002). This type of joint was first analysed numerically by the finite element (FE) method, which investigated the influence of the lap plate and the weld leg length on the stress concentration at the weld toe and root. Secondly, 13 full-scale specimens from a shipyard were tested to evaluate the fatigue strength of this joint. The influence of the weld leg length was evaluated. The test data agreed with those for toe failure given by Eurocode 9.

5.2.3 Composites

The use of composite material laminates in structural applications has increased in recent years and particularly in the marine and aircraft industries. ISSC 1997 for the first time considered in detail the fatigue strength of composites, addressing the phenomenological aspects of fatigue damage mechanics and failure mechanisms. This section will not duplicate that report but aims to update it. Composite materials are defined as a material containing two or more distinct phases on a macroscopic scale. They generally contain a fiber reinforcing material supported by a binder or matrix material and are used as laminates with layers of various composite materials. Glass (GFRP) or carbon (CFRP) fiber reinforced plastic is commonly used for structures selected for weight critical structural applications. The Matrix is usually made from resins (epoxy, polyester, vinyl-ester, etc.). An exhaustive list of composite materials is practically impossible; a large number of fiber and matrix materials exist and can be coupled in different ways for specific applications and many other materials can be selected for particular industries.

Fatigue modelling of FRP materials (load life representation, stiffness and strength degradation, cumulative damage) particularly for structural joints was dealt with in the cited ISSC 1997 report. Although metals like steel and aluminum have many advantages, not least the large service experience available regarding their behaviour, many structural applications in shipbuilding could benefit from materials with low weight/strength ratio and/or particular properties (e.g. magnetic and acoustic emission for naval ships, shaping easiness for fast and pleasure crafts, large deformations for ship superstructures and some particular parts, etc.).

5.2.3.1 Fatigue Behaviour and Fatigue Analysis of Composites

The lack of design experience of composites and their complex characterization hinders their extensive use. Composites are currently mainly used for fast craft, pleasure boats and very specific functions on larger ships. Fatigue is a so-called mesoscopic phenomenon; it starts at a microscopic scale and develops into a macroscopic mechanism. Therefore, due to the different materials used in composites, failure starts microscopically with different behaviour in fibers, the matrix or at their interfaces but crack growth can develop throughout the entire structure. In metals no significant reduction of stiffness is observed in the majority of fatigue processes. In contrast composite deterioration may be detected from the early stages of fatigue by the formation of more or less extended damage areas which contain

a multitude of microscopic defects such as debonding, initial fiber fractures, etc. gradually increasing either in extension and importance of defects.

Hyman et al (2001) studied the extent that sandwich panel behaviour depends on the nature of core material behaviour, and whether the ratio of allowable stress to ultimate strength should depend on the degree of ductility or type of non-linear behaviour. Non-linear finite element modeling was carried out to obtain a thorough understanding of the way ductility in the core influences panel behavior. A series of cores having typical stress-strain relations varying from brittle to extremely ductile were considered. The modelling covered the two extremes of aspect ratio (square and very long panels) and a range of boundary conditions. The case of constant amplitude tension-tension fatigue of fiber-reinforced composites has received considerable attention, but many other standard tests exist. One must be aware of a number of basic characteristics of polymeric matrix composites which may influence fatigue life. Many resin systems display appreciable damping and as a result any temperature rise during testing can effect fatigue life (high frequency testing to be carried out carefully).

Van Paepegem et al. (2001) tests' highlighted that, as metal stiffness remains quasi unaffected during fatigue life and an elastic behaviour can be correctly supposed, in fibre reinforced composites the gradual loss of stiffness in the damaged zone leads to a continuous redistribution of stresses and a consequent reduction of stress concentrations within structural components. Therefore they suggest a residual stiffness fatigue model for life prediction instead of S-N- curves or damage accumulation models, which cannot take into account stress redistribution and stiffness reduction. Experimental results and analytical implementation in FE code using *cycle jump* approach give good agreement. Whitworth (2000) also proposed a residual strength degradation model in graphite/epoxy composite laminates relating the residual strength to the applied fatigue cycles and the maximum applied stress. Based on this model, the statistical distribution of the residual strength was derived and compared with available experimental data. Good agreement is observed between the proposed model and experimental results.

The scantling criterion of composite structures in addition addresses the reproducibility as well as the specimen characterisation. Investigations showed that lifetime prediction methods used for homogeneous materials where degradation occurs with negligible loss of rigidity are ineffective for composites. Any observed preliminary damage should be reported because it is useful in assessing fatigue damage mechanism and in developing fatigue failure models. A review of various problems encountered in 2-D theoretical and numerical modeling of fatigue and failure modes in composite structures was carried out by Muc (2000). Muc (2000) also proposes a simple numerical method, implemented in FE code to evaluate fatigue life starting from mechanical properties obtained during material characterization of plies. This concludes that because of the very complex mechanism of composites failure, special attention should be paid to the following: Fatigue damage is distributed throughout the structure volume in a stochastic manner and is not limited to a single predominant crack (as for isotropic brittle materials); The type of damage is dependent on stacking sequences, materials properties, fiber orientation and loading type; Failure modes can be: matrix cracking, interfacial debonding, delamination, fibre breakage (Figure 11).

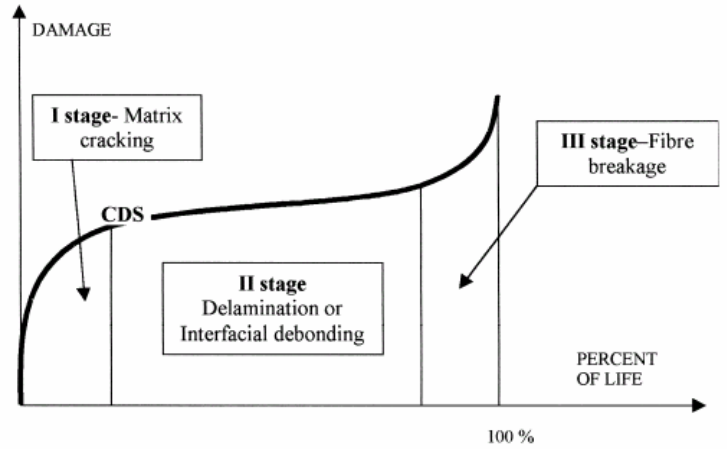

Figure 11: Development of Fatigue Damage (from Tarleja R. (1990))

The behaviour shown in Figure 11 is also confirmed by Chen et al. (2002) by real-time monitoring of damage in composite materials during fatigue loading using acoustography. Results show that damage area growth under constant amplitude fatigue loading occurs in three stages. After an initial small enlargement, damage grows at a constant rate until the last stage is reached when damage grows at an increasing rate until final failure.

Fatigue damage accumulation in engineering materials is usually quantified using a suitable damage parameter that can be used as a reliable descriptor of damage development. The fatigue strength evaluation of the composite laminates is more complex than that of homogeneous materials due to the anisotropy and due to the cited different ways of failure (matrix cracking, interfacial debonding, delaminations and fibre breakage) i.e. a larger number of parameters should be considered.

For unidirectional composite materials two failure modes exist: the fiber and the matrix failure mode. When multidirectional laminates are considered another failure mode, the interlaminar, is encountered. Fatigue damage can take different forms and therefore a clearly stated definition of failure is important, particularly when reporting fatigue life data. Resin micro-cracks can develop without evidence, leading to loss of stiffness and residual strength. A very complex 3-D stress state exists at free edges, leading to delamination. Delamination makes it is difficult to relate simple specimen laboratory results to the behaviour of full-scale structures (scale effect).

Ganesan (2000) developed a computational methodology for modeling analysis of tests data, based on a rigorous stochastic approach. From sample data, the true probability distributions of damage parameters are extracted based on an analytical approach. The correlation properties of the damage development process are also determined in terms of autocorrelation functions. A systematic way of characterizing the damage modes of the material, in terms of the correlation characteristics is also developed. The damage development is modelled as an embedded Markov process. A recursive stochastic matrix equation that characterizes the damage development using the true probability distributions and correlation properties of test data is formulated.

According to Ganesan, major sources of variability are: (i) initial damage state, such as the variability in the initial elastic modulus of composite laminates. Since the fatigue damage evolution is a non-linear process, the changes in initial conditions significantly influence the state of the damage evolution process; (ii) Severity and load sequence effects as well as material damage (including the changes in material parameters) and; (iii) failure criterion. The severity of load cycles and material damage

(including the changes in the material properties) is specified in the model in terms of the probability transition matrix.

A review of the main ideas in fatigue analysis of composites in the context of the application of probabilistic methods, both computational and theoretical, were carried out by Kaminski (2002). The whole variety of mathematical and computational tools shown in the paper makes it possible to analyse ordinary and cumulative deterministic or stochastic fatigue processes efficiently in different composite materials. Some local and global models are mentioned and the deterministic or stochastic techniques together with the approaches which enable randomisation of classical deterministic techniques to obtain at least first two probabilistic moments of the structural response. The application of the perturbation based Stochastic Finite Element Method (SFEM) to fatigue analysis of homogeneous and heterogeneous media also is shown. Considering the stochastic character of the analysis, the reliability tools appropriate to multi-component materials are presented together with the specially adopted brittle and ductile fracture criteria.

Philippidis et al. (2002) studied the effect of a complex stress state on fatigue life of GFRP (glass fiber reinforced plastic) laminates (0° and ±45° layers). Tests at different stress ratio R, on and off-axis loading directions, at constant amplitude and a theoretical formulation are presented highlighting large effect of shear and transverse stresses, even if they are generally smaller with respect to axial normal stresses. The detrimental effect of off-axis loading stress ratio (σ_2/σ_1 and σ_6/σ_1) is dependent on R (more evident for R=0.1 and 0.5 traction). The experimental results are better predicted by a Goodman-Gerber like formulation in on-axis loading but give poor performance for off-axis loading.

Temperature should always be monitored during tests on composites. To this end, Sedrakian et al. (2002) proposed a damage model based on generalized standard material thermodynamics. An updated stress-strain field is essential. Models based on the resistance loss notion appear insufficient particularly in multi axial fatigue whereas models using the generalised standard material thermodynamics related to scale appear more general.

Definition of failure singularly in terms of stress or strain limits at which a component can no longer fulfil cannot consider interaction between failure mechanisms. Petermann et al (2001) proposed energy based fatigue failure criteria incorporating both stress and strain. Microstresses and microstrains are used to generalize different loading modes. Mean stress is implicitly taken into account. It is believed that fatigue of multiaxial and/or multi-directional laminate composites can be successfully addressed using failure energy based criteria.

A decohesive model using a mixed damage scale and using the total fracture energy to simulate the fracture process of composite materials was developed by Chen et al. (2001). The model implemented in a commercial FE software, assumes a bilinear interfacial decohesion function. In comparison with traditional numerical methods in fracture mechanics, this approach can automatically predict the failure load, crack path and the residual stiffness of bodies undergoing the fracture process. A stiffened composite panel and a repaired composite sandwich beam under four-point bending were tested. Good agreement between model predicted and measured failure load, crack path and residual stiffness was demonstrated: the bilinear decohesion model potentially can predict the crack growth and the progressive delamination of composites.

Multiaxial fatigue of composites can also be addressed using a bridging micro mechanic model. Zhen-Ming (2002) studied multiaxial fatigue of plain glass woven fabric reinforced composite defining an elementary cell and assuming its behaviour. The fatigue strength is detected through the constituent fatigue failures (ultimate strength of material using different criteria) irrespective of whether the

material is subjected to uniaxial or multiaxial loads because the S-N curves are drawn out for multiaxial loads simulated using only constituent properties.

The elastic stress field in homogeneous and orthotropic material is a function of geometry of the through the thickness material discontinuities. To obtain the optimum weight/strength ratio in designing laminated plates subjected to fatigue bending loads a method using a linear cumulative damage constraint is proposed by Walker (2000). Design variables are fibres orientation and plate thickness. Several examples are presented using an FE modelling technique.

5.2.3.2 Corrosion Resistance and Repair of Composites

A very important issue for marine structures is their behaviour in a seawater environment. Water is able to diffuse into composite materials and weaken the matrix as well as the fiber matrix interface. The effect of water absorption on the physical and mechanical properties of polyester resins has been known for many years and was reviewed comprehensively by Ishida and Koenig (1978): briefly, the absorption of water causes swelling, plasticisation and a reduction in the glass transition temperature.

Pauchard et al. (2002) applied a stress corrosion model based on initial fibre strength distribution and sub-critical growth of pre-existing flaws to the microscopic analysis of the delayed fiber failure processes occurring within a water-aged unidirectional glass/epoxy composite under static loading (i.e. relaxation, the specimens were loaded at 5 mm/min up to the specified value of the imposed strain. Image acquisition was carried out periodically during the relaxation stage): an SCC (stress corrosion cracking) model was applied. An individual fibre failure within a volume was identified as a time function and strength distribution and sub-critical crack propagation law assessed. Reduction of crack growth rates for fibres embedded in matrix compared with fibres in air were noted. Ying Shan et al. (2002) tested unidirectional glass and glass-carbon fibre reinforced epoxy matrix (hybrid composite) under tension-tension loads either in air or in distilled water at 25°C. While no significant change in fatigue life was observed for both types of specimens tested in air and in water when cyclically tested at 85% of average ultimate tensile strength (UTS), the detrimental effect of water became apparent at a lower stress levels of 65 and 45% UTS. It was also shown that by incorporating an appropriate amount of carbon fibers within a glass fibre composite, a much better performance in fatigue can be achieved for glass-carbon hybrid composites. A simple life prediction model for the hybrid composite was proposed, the results suggesting that the synergistic effect of the reinforcing fibers is critical in governing the fatigue behavior of intra-ply hybrid composite.

Kotsikos et al. (2000) characterized the effect of sea water absorption on fatigue damage accumulation in a glass fibres reinforced polyester laminate of the type widely used in the marine and offshore industries, by means of their acoustic emissions. Pre-exposure was found to reduce the flexural strength and enhance damage accumulation in fatigue by stimulating matrix cracking, fibre debonding and delamination.

An interesting application of composites is in the repair of structures in service. Sometimes hot steel working is not possible and different repair methods are necessary. Bonded repairs are mechanically efficient, cost-effective and can be applied rapidly to produce a damage-tolerant repair. In comparison with metallic patches composite repairs have the advantages of formability, tailor made stiffness, high specific strength and immunity to corrosion and fatigue. Composite patches can be pre-cured and secondarily bonded on to cracked structures or co-cured insitu.

Analysis of repaired structures presents significant difficulties due to the different nature and properties of the materials involved in a composite repair (metals, composites, adhesives). Tsamasphyros et al.

(2001) proposed an analytical and numerical approach for the fatigue life assessment of an isotropic cracked plate that was repaired by a bonded composite patch. A number of cracked plates with different crack lengths and overall dimensions of the composite repair and one or two-sided patches were considered. Results are presented for the stress intensity factor in the patched crack and the maximum stress reinforcement stress and adhesive strain. It was found that for the case of a two-sided reinforcement, the results obtained by both methods were in good agreement. However, for the case of a single reinforcement the accuracy of the analytical method decreased due to the tendency to out-of-plane bending as a result of bonding a reinforcing patch to only one face of a plate, which is ignored in the analysis.

5.2.3.3 Composite Application in Marines Structures

A particular application of composite is in large propellers blades. Some small propellers for pleasure crafts are already on the market and larger propeller blades were installed on naval ships. Vasileiu et al. (2002) proposed an FE model with different meshes and mesh generator codes for this application. The blade deformation as a function of loading pressure, can be optimized to avoid cavitations, as far as possible, but it is also recommended that these should be analysed structurally.

Bolted composite joints are commonly used in aircraft construction and could be useful in several marine applications e.g. offshore platforms, lashing systems, mooring devices, etc. Specimens with a double-lap configuration and six bolts were fatigue tested by Shon et al. (2002) at load ratios R = -0.2 to R= -5. A linear damage rule was used to predict the spectrum fatigue life. The experimental results show that the shortest fatigue life occurs for specimens loaded at R= -1 followed by specimens loaded at R = -0.2. The longest fatigue life occurred for specimens loaded at R= -5. It was found that 50% elimination of load cycles in the spectrum could be used without affecting the fatigue life. The Miner's rule predictions appeared to overestimate the spectrum fatigue life. From bolt failure it was found that the first bolt row transfers the largest amount of load in the specimens.

Several applications are currently being explored to use spoolable composite tubulars including: onshore and offshore pipelines, sub sea injection lines, well workover/intervention services, flowline cleanouts and surveys, well bore completions and coiled tubing drilling. Large-diameter (> 6-inch), long-length, composite pipe is also being considered for future development as flexible risers and sub sea pipelines.

Concepts for fabricating long-length spoolable composite pipe were first introduced in the late 1960's, but the technology was not widely accepted nor applied. The loads and strains imposed on spoolable pipe extend beyond classical boundaries resulting in complex design and mechanics issues. Combined mechanical and pressure loads imposed during spooling causes steel pipe to experience plastic yielding which eventually leads to failure. Although composite pipe has the potential to perform repeatedly at high loads better than steel, it can experience performance-degrading effects as well, which must be addressed in design. The ability to repeatedly spool and deploy composite pipe, even when loaded by high pressure, is a unique characteristic of composites made possible through tailoring the mechanical properties to address specific design requirements. Williams et al. (2000) provides a comprehensive review of spoolable composite tubular products under development for the oil and gas industry, discusses advanced design concepts, identifies current limitations, and describes additional opportunities for application development.

In-situ test results on tensile, compression, flexure and ILSS properties of carbon fiber-reinforced composites in deep water are presented for the first time by Venkatesan et al. (2002). Results revealed that apparent weight gain increases with depth. Mechanical properties are not affected by deep-sea

environment and deterioration or degradation or bio-film formation was not observed. Rudolph et al. (2001) proposed the use of an X-ray refraction technique to scan "free inner surfaces" formed by interface of fibers and matrix, void in the matrix, by incomplete wetting of the fibers. Additional inner surfaces, e.g. fibers de-bonding, fibers cracks and crazes can appear under load.

An interlayer system should also be considered for composite materials. The fatigue crack propagation behaviour in the vicinity of an interface between materials with different yield stress (transition from plastically weaker to plastically stronger and vice-versa) was studied by Pippan et al. (2000) considering the plastic mismatch on the fatigue crack propagation normal to the interface studied. The elastic properties and thermal coefficient are neglected being nearly identical for both materials. Crack propagation rate diminishes at interface from plastically weaker and accelerate from plastically stronger layers. The same behaviour was noted in systems containing more than two layers. A large effect of an extremely small thermal mismatch occurred. Moreover a crack bifurcation close to the interface appeared when cracks approach from plastically weaker material probably by change of near crack tip deformation field when crack tip approaches the interface vicinity.

As offshore exploration and production activities head to deeper water, extensive efforts are focused on mitigating the potential challengers associated with deep- and ultra deep-water systems. As described in Saad et al. (2002), an application of composites to deepwater is the top tensioned riser system. Through numerous field qualification testing programs it was concluded by the authors that current state-of-practice of the composite industry is sufficiently robust to allow reliable design and manufacturing of composite risers.

6. CONCLUSIONS

As described in the introduction, this report reviewed current activity with regard to fatigue and fracture in the ship and offshore industry. Section two deals with trends in fatigue prediction methods and highlighted the need for increased component testing under realistic service conditions. In particular it is important that fatigue tests are carried out under simulated service spectra representative of real conditions. An important parameter leading to scatter fatigue life predictions is that of the calculation of reference stress on which fatigue calculations are based. This subject was reviewed in detail in section three, and a comprehensive illustrative example was presented to highlight the subjective and sometimes ambiguous nature of design guidance for the calculation of hot spot stress. There are inconsistencies between the guidance given by different classification societies. This issue should be addressed.

Section four looked at improvement methods. Post treatments may be applied to welds in order to repair or upgrade structures; they should not be used in the design of new structures. These treatments apply to cracks starting from the weld toe, and to loads in the low stress high cycle regime.

The acceptance of fatigue life improvement methods is related to the level of quality control and the uncertainty in results achieved. Two such methods based on weld toe profiling, Burr grinding and TIG-dressing, are believed to have good potential. Guidance for inspection and quality control of primary variables like geometrical dimensions is given in the literature based on extensive test programs. Post treatment methods based on the introduction of compressive residual stresses in the weld region may give an even higher fatigue life improvement. However, although procedures exist for their implementation, one does normally not have knowledge of the stress levels introduced. Depending on the load spectrum present these stresses may relax with time due to compressive stress peaks, which eventually with time would lead to a welded joint subject to service loads only. To gain a better

understanding of the beneficial effect of these methods more research and development is needed into residual stress measurement systems and practical ways at determining the interaction between post treatment residual stresses and stresses from service loads.

Finally section five looked at the emergence of new materials in ship and offshore structures applications. One of the main obstacles for more extensive use of Titanium as a structural material for the offshore industry is considered to be the lack of relevant and recognised design codes. In order to rectify this DNV recently completed a Joint Industry Project, with participation from both the offshore and Titanium industries, with the objective to develop a recommended Practice (RP) for the Design of Titanium Risers. This work is reported in DNV (2001) and Leinum and Tørstad (2002). Also described in Section 5.3.1.3, the inconsistency regarding SN design curves clearly shows the need for further testing, especially in the "low stress-long life" region, and the need for a better quantitative understanding of the influence of internal porosity and also other possible weld defects.

Aluminium is an attractive material as it is light, strong, clean, normally ductile, easily formed and fabricated, and readily available. It is recyclable and thus environment friendly. It is an excellent alternative to steel for use in ship hulls when justified by required functionality or overall cost for production, operation and maintenance. The accumulated experience of many years shows that aluminium alloys of "marine" grade offer both safety and reliability for use in marine structures. Due to a comparatively low modulus of elasticity, application of aluminium alloys may, in design of larger ship hulls, be challenged in the fields of buckling, fatigue, vibration, deflection and hydro-elasticity. However, these were also the problems the aircraft industry faced decades ago. Yet today, the aircraft industry is among the most reliable and successful. The merits of applying aluminium alloys undoubtedly justify more extensive research and development in building ships for the future.

From the review in Section 5.3.3, it is clear that attempts to evaluate the fatigue behaviour of composite materials are still in progress. Taking into account the different types and applications of such materials, different approaches were used to evaluate their fatigue strength and predict remaining life. For the most common composite ships structures, a test criterion, which considers the loading and the material features, should be suggested. It may be that such approach is pragmatic, but it can help a comparison among different structural solutions focused on to the specific load systems, involving fatigue and preferring large or full scale specimens to avoid the difficult evaluation of the scale effects and of the involved detail. Continued advancements in the testing of composites for offshore applications would further improve the current state of knowledge regarding mechanical and structural integrity characteristics and in-service monitoring techniques, thereby enhancing future prospects for qualification and regulatory approval.

Even though composites were used in both the ship and offshore industries for several years, their application were mainly focused on pleasure crafts, small size ferries, superstructures of ships and offshore units, raiser components. With reference to the offshore field, the lack of practical and generally accepted design codes has limited their application. With the aim to develop generally accepted design standards/practices for composite components in offshore applications, DNV recently carried out two joint industry projects (JIP), which attracted a large number of participation from material suppliers, engineering companies, the oil industry and authorities and upon completion of the projects the participants agreed that the project results should be transformed into a DNV Offshore Standard for Composite Components and a Recommended Practice for Composite Risers. The two documents are reviewed by the industry and are scheduled for publication in 2003, DNV (2003a, 2003b). However, more effort is needed in the area of design code development.

REFERENCES

ABS (2002). ABS Rules for Building and Classing Steel Vessels-2003, American Bureau of Shipping, Houston, 2002.

Akpan, U. O., Koko, T.S., Ayyub, B. and Dunbar, T.E. (2002). Risk assessment of aging ship hull structures in the presence of corrosion and fatigue, *Marine Structures* **15:** 211– 231.

Allessandri, E., Labesse-Jied, F. and Huther, I. (2000). Comparison between different methods to calculate the geometric stress for welded cruciform joints. International Institute of Welding Doc. XIII-1847-00, 2000.

Amstutz, H., Storzel, K., Seeger, T. (2001). Fatigue crack growth of a welded tube-flange connection under bending and torsional loading. *Fatigue and Fracture of Engineering Materials and Structures* **24 (5):** 357-368.

Ando, K, Matsui, K, Ishigami, I, Nasu, K, and Etou, H, (2002). Fatigue fracture process and combined surface treatment to increase fatigue limit, *Proceedings of the Eight International Fatigue Congress held 3-7 June 2002 in Stockholm Sweden*, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 2469-2476.

Ara S., T. B. Zineb, J. L. Billoet (2002), Contribution of industrial composite parts to fatigue behaviour simulation, *International Journal of Fatigue* **24,** 307–318.

Atzori, B. (2002). Moderni metodi e procedimenti di calcolo nella progettazione meccanica, ed. Laterza Bari.

Atzori B., G. Meneghetti and L. Susmel, (2002)*Estimation of the fatigue strength of light alloy welds by an equivalent notch stress analysis,* International Journal of Fatigue 24, 2002, 591-599.

Babalola, O. T., Berge, S., (2002), Fatigue of Titanium Welds – Models for Assessment of Defect Sensitivity, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28578.*

Backstrom, M. and Marquis, G. (2001). A review of multiaxial fatigue of weldments: Experimental results, design code and critical plane approaches. *Fatigue and Fracture of Engineering Materials and Structures* **24(5):** 279-291.

Baxter, C., Pillay, S., and Hutt, G. A., (1997), Advances in Titanium Risers for FPSO's, *Offshore Technology Conference, OTC 8409.*

Berge, S., and Lunde, L., eds., (1999), *International Seminar on Titanium Risers and Flowlines, Trondheim, Norway.*

Berge, S., Eide, O. I., and Maicon, P., (2002a), Fatigue Strength of Titanium Riser Welds; Effect of Materials Grade and Weld Method, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28576.*

Berge, S., Maincon, P., and Hauge, M., (2002b), Fatigue of 28-inch Titanium Riser – SN Data and Defect Assessment, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28577.*

Berge, S., Johansen, A. and Bjorheim ,L.G. (2001). Fatigue strength assessment of hull details for an FPSO, in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), Elsevier Science Ltd., 1071-1079.

Berger, C., Eulitz, K.-G., Heuler, P., Kotte, K.-L., Nauendorf, H., Schuetz, W., Sonsino, C.M., Wimmer, A. and Zenner, H. (2002). Betriebsfestigkeit in Germany – an overview. International Journal of Fatigue 24, 603-625, Elsevier, 2002.

Bergner F., G. Zouhar and G. Tempus (2001) *The material-dependent variability of fatigue crack growth rates of aluminium alloys in the Paris regime,* International Journal of Fatigue 23 (2001) 383-394.

Biot, D., Boote, M., Maestro, A. M. and Tedeschi,R. (2001). An investigation of fatigue damage: numerical approaches and experimental validation. *OMAE Congress*, Rio de Janeiro, 3-8 September, OFT-1034.

Blackstone, W R, and Basu, R I, (2000). Hammer peening – a practical way to extend fatigue life, Proceedings of the ETCE/OMAE 2000 Joint Coinference (Paper OMAE2000/MAT-2394) in New Orleans, LA, USA, 8 pp.

Bogren, J, and Lopez Martinez, L, (1993). Spectrum fatigue testing and residual stress measurement on non-loaded carrying fillet welded test specimen, *Fatigue under spectrum loading and in corrosive environments*, Blom, A F, Editor, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 77-90.

Borrego L.P., J.M. Ferreira and J.M. Costa (2001) *Fatigue crack growth and crack closure in an AlMgSi alloy,* Fatigue & Fracture of Engineering Materials & Structures Volume 24 Issue 4 Page 255 - April 2001.

Bolotin, V.V. and Shipkov, A.A. (2001). Mechanical aspects of corrosion fatigue and stress corrosion cracking. *International Journal of Solids and Structures* **38:** 7297-7318.

Bouet-Griffon, M., Courbière, M. and Ehrström, J.C., (1999). Fatigue assessment of aluminium welded components. Publications of EAEC, 1999.

Buitrago, J. and Zettlemoyer, N. (2001). Fatigue of tendon welds with internal defects. *OMAE Congress*, St. Johns, 11-16 July, MAT-2001.

Bull, J W, Woodford, C H, Christie, WC, Neau, E, and James, MN, (2000). The low stress design of welded plates using the self-designing structures approach, Computers and Structures, 78, 487-496.

Capasso M., Rizzo C. (2002), Ship Structures Fatigue Strength: Importance of Testing, DINAV Report 02CRI04.

Chaperon, P, Jones, R, Heller, M, Pitt, S, and Rose F, (2000). A methodology for structural optimisation with damage tolerance constraints, Engineering Failure Analysis, 7, 281-300.

Chen A.S., Almond D.P., Harris B. (2002), Impact damage growth in composites under fatigue conditions monitored by acoustography, *International Journal of Fatigue* **24**, 257–261.

Chen J., New A. (2001), Application of decohesive model with mixed damage scale in fracture analysis of composite materials, *Fatigue & Fracture of Engineering Materials & Structures* **24,** 761–769.

Couroneau, N. and Royer,J.(2000). Simplifying hypotheses for the fatigue growth analysis of surface cracks in round bars. *Computers and Structures* **77:** 381-389.

Cui,W.C.(2002a). A state-of-the-art review on fatigue life prediction methods for metal structures. *Journal of Marine Science and Technology* **7:1**, 43-56.

Cui, W.C.(2002b). A unified fatigue life prediction method for marine structures. *Proceedings of the 5th national ship mechanics committee conference of CSNAME*, April 19-25, 2002, Mianyang, Sichuan, China; also in *Proceedings of the 2nd national marine steel structures conference*, May 28-June 1, 2002, Wenzhou, Zhejiang, China.

Cui, W.C.(2002c), Towards a unified fatigue life prediction method for marine structures. Accepted by *Journal of Engineering for the Maritime Environment*.

Cui, W.C.(2002d), Relation between crack growth rate curve and S-N curve for metal fatigue. *Journal of Ship Mechanics.* **6:6** 45-65.

Cui,W.C.(2003). A general constitutive relation for fatigue crack growth analysis of metal structures, Submitted to *Acta Metallurgical Sinica*.

Cusumano, J.P. and Chatterjee, A. (2000). Steps towards a qualitative dynamics of damage evolution. *International Journal of Solids and Structures* **37 (44):** 6397-6417.

Dahle, T, (1998). Design fatigue strength of TIG-dressed welded joints in high-strength steels subjected to spectrum loading, International Journal of Fatigue, 20, 677-681.

Dang, Van, Bignonnet, K., Fayard, A. and Janosch, J.L. (2001). Assessment of welded structures by a local multiaxial fatigue approach. *Fatigue and Fracture of Engineering Materials and Structures* **24(5):** 369-376.

Das, P S (2002). Redesign of NEMO-type spherical acrylic submersible for manned operation to 3000 ft (914 m) ocean depth, ASME Journal of Pressure Vessel Technology, 124, 97-107.

Det Norske Veritas (DNV), (2003a), DNV Offshore Standard, *DNV-OS-C501*, Composite Components, to be published in 2003.

Det Norske Veritas (DNV), (2003b), DNV Recommended Practice, *DNV-RP-F202*, Composite Risers, to be published in 2003.

Dhar, S., Dixit, P.M. and Sethuraman, R. (2000). A continuum damage mechanics model for ductile fracture. *International Journal of Pressure Vessels and Piping* **77:** 335-344.

Dijkstra, O.D., Janssen, G.T.M. and Ludolphy, J.W.L.(2001). Fatigue tests on large scale knuckle specimens. in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), 2001, Elsevier Science Ltd., 1145-1151.

Dimitrakis, S. D. and Lawrence, F. V. (2001). Improving the fatigue performance of fillet weld terminations. *Fatigue & Fracture of Engineering Materials & Structures* **24(6):** 429-440.

DNV (2001). Fatigue strength analyses of offshore steel structures – Recommended practice RP-C203. DNV, Høvik, October, 2001.

Doerk, O., Fricke, W. and Weissenborn, Ch. (2002). Comparison of different calculation methods for structural stresses at weld joints. International Institute of Welding Doc. XIII-1919-02, 2002.

Donald,K. and Paris,P.C. (1999). An evaluation of ΔK_{eff} estimation procedure on 6061-T6 and 2024-T3 aluminum alloys, *International Journal of Fatigue* **21:** S47-57.

Dong, P., Hong, J.K. and Cao, Z., (2001). A mesh-insensitive structural stress procedure for fatigue evaluation of welded structures. International Institute of Welding Doc. XIII-1902-01, 2001.

Dong, P., (2002). A Structural definition and numerical implementation for fatigue analysis of welded joints. Centre for welded structure research, Battelle, 2002.

Dousset V., Gallus M., (2002), Technical Report DINAV C730, 2002.

Eckerlid, J, Nilsson, T, and Karlsson, L, (2002). Fatigue properties of longitudinal attachments welded by low transformation temperature welding filler, Design and Analysis of Welded High Strength Steel Structures, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 225-246.

Etube, L.S., Brennan, F.P., Dover, W.D. (2000). A new method for predicting stress intensity factors in cracked welded tubular joints. *International Journal of Fatigue* **22:** 447–456.

Fisher, JW, Statnikov, E, and Tehini, L, (2002). Fatigue strength improvement of bridge girders by Ultrasonic Impact Treatment (UIT), IIW Document XIII-1916-02, International Institute of Welding.

Fonte M.A., S.E. Stanzl-Tschegg, B. Holper, E.K. Tschegg, A.K. Vasudévan (2001) *The microstructure and environment influence on fatigue crack growth in 7049 aluminium alloy at different load ratios,* International Journal of Fatigue 23 (2001) S311-S317.

Fricke, W., Cui, W.C., Kierkegaard,H., Kihl,D., Koval,M., Lee,H.L., Mikkola, T., Parmentier, G., Toyosada, M., Yoon,J.H. (2002). Comparative Fatigue Strength Assessment of a Structural Detail in a Containership using various Approaches of Classification Societies. *Marine Structures* **15(1):** 1-13.

Fricke, W. and Wernicke, R. (2001). Fatigue strength assessment of cruciform joints. in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), 2001, Elsevier Science Ltd., 1061-1069.

Fricke, W. and Bogdan, R. (2001). Determination of hot spot stress in structural members with in-plane notches using coarse element mesh. International Institute of Welding Doc. XIII-1870-01, 2001.

Fricke, W (2002). Recommended Hot Spot Analysis Procedure for Structural Details of FPSO's and Ships Based on Round-Robin FE Analysis, International Journal of Offshore and Polar Engineering, Vol. 12, No. 1, March 2002, 40-47.

Fridman, M. and Zyczkowski, M.(2001). Structural optimization of elastic columns under stress corrosion conditions. *Structural and Multidisciplinary Optimization* **21 (3):** 218-228.

Ganesan, R. (2000). A data-driven stochastic approach to model and analyze test data on fatigue response. *Computers and Structures* **76:** 517-531.

Ganesan, R. (2000), A stochastic modeling and analysis methodology for quantification of fatigue damage, *Computational Methods for applied mechanical. Engineering* **190**, 1005-1019.

Germanischer Lloyd, (2002). Rules for classification of ships Germanischer Lloyd 2002, I-Ships – Part 1 – Seagoing ships – Chapter 1 Ships hull Section 20 Fatigue

Haagensen, P J, Gunleiksrud, Å, Ludvigsen, J A, and Larsen, J E, (2000). Repair and Strength ening of the Veslefrikk B floating production platform, Proceedings of the 119th International Conference on Offshore Mechanics and Arctic Engineering (Paper OMAE2000-2394), New Orleans, LA, USA.

Haagensen, P J, and Maddox S J, (2001). IIW recommendations on post weld improvement of steel and aluminium structures, IIW Document XIII-1815-00, International Institute of Welding.

Hao, S., Liu, W.K. and Chang,C.T.(2000). Computer implementation of damage models by finite element and meshfree methods. *Comput. Methods Appl. Mech. Engrg.* **187:** 401-440.

Hassan, A F, (2001). The effect of air-hammer peening on the fatigue strength of welded steel plates, Journal of Engineering and Applied Science, 48, 121-135.

Hertzberg,R.W., Newton,C.H. and Jaccard,R. (1988). Crack closure: correlation and confusion. In: *Mechanics of Fatigue Crack Closure*, ASTM STP 982. Philadelphia,PA: American Society for Testing and Materials, pp.139-148.

Hobbacher, A (2002) Recommendations for fatigue design of welded joints and components, IIW Document XIII-1593-96/ XV-845-96 (June 2002 update), International Institute of Welding.

Horn, A. M., Hauge, M., Røstadsand, P-A., Bjørnbakk, B., Dahlberg, P. and Fosseholm, T., (2002), Cost Effective Fabrication of Large Diameter High Strength Titanium Catenary Riser, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28445.*

Huo L, Wang D, Wang W, Zhang Y, (2001). Ultrasonic peening and Low transformation temperature electrode used for improving the fatigue strength of welded joints, IIW Document XIII-1894-01, International Institute of Welding.

Huo L, Wang D, Wang W, Zhang Y, (2002). Investigation of the fatigue behaviour of the welded joints treated by TIG dressing and ultrasonic peening under variable amplitude load, IIW Document XIII-1915-02, International Institute of Welding.

Huther, M. and Beghin, D. (2002). A Fatigue strength guidance note for welded ship structure assessment. International Institute of Welding Document. XIII-1742-98.

Hyman B., Hayman P., Mc George D., Noury P., (2001), Non linear core behavior in sandwich panels for High Speed Craft, *Vol. III p. 207, The 6th International Conference on Fast Sea Transportation, Sept. 2001, Southampton.*

Ishida H, Koenig JL. 1978, Reinforcement mechanism of fiber–glass reinforced plastics under wet conditions: a review, *Polymer Engineering and Science*; **18,128**–45.

ISSC (1997). Report of Technical Committee III.2 Fatigue and Fracture, in *Proc. of Int. Ship and Offshore Structures Congress*, ed. T.Moan and S.Berge, Elsevier, Vol.I, pp.285-349.

ISSC (2000). Report of Technical Committee III.2 Fatigue and Fracture, in *Proc. of Int. Ship and Offshore Structures Congress*, ed. H.Ohtsubo and Y.Sumi, Elsevier, Vol.I, pp.323-392.

J.A.M. Pinho da Cruz J.A.M., J.D.M. Costa, L.F.P. Borrego and J.A.M. Ferreira (2000) *Fatigue life prediction in AlMgSi1 lap joint weldments, ,* International Journal of Fatigue 22 (2000) 601-610.

Jang, J. M., Han, J. G., Kang, Y. I., Kim, Y. C., Jeon, H. and Song, C. (2001). Fatigue life assessment of welded joints considering crack propagation based on hot spot stress. *OMAE Congress*, Rio de Janeiro, 3-8 September, MAT-3532.

Jeon W.-S. and J. H. Song (2002), *An expert system for estimation of fatigue properties of metallic materials*, International Journal of Fatigue 24 (2002) 685-698.

Kaminski M. (2002), On probabilistic fatigue models for composite materials, *International Journal of Fatigue* **24**, 477–495.

Karadeniz,H. (2001). Uncertainty modeling in the fatigue reliability calculation of offshore structures. *Reliability Engineering and System Safety* **74:** 323-335.

Karamanos,S.A., Romeijn and A., Wardenier, J. (2002). SCF equations in multi-planar welded tubular DT-joints including bending effects. Marine Structures 15 (2002) 157-173.

Kawabe,H. and Shibazaki,K. (2001). Combination of fatigue damages produced by several wave-induced loads based on correlation coefficient method. in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), Elsevier Science Ltd., 1089-1095.

Kim, I.-T., Yamada, K. and Kainuma, S.(2001). Fatigue behavior of butt welded joints containing inclined lack-of-penetration. *Structural Engineering/Earthquake Engineering* **18(1):** 53s-62s.

Kim, Wha Soo, Doe Hyun Kim, Sang Gab Lee, Yoon Ki Lee (2001). Fatigue strength of load carrying box fillet weldment in ship structure. *PRADS Congress*, Shanghai 16-21 September, 1161-1167.

Kirkhope, K J, Bell, R, Caron, L, Basu R I, and Ma, K-T, (1999a). Weld detail fatigue life improvement techniques. Part 1: Review, Marine Structures, 12, 447-474.

Kirkhope, K J, Bell, R, Caron, L, Basu R I, and Ma, K-T, (1999b). Weld detail fatigue life improvement techniques. Part 2: application to ship structures, Marine Structures, 12, 477-496.

Klemenc,J. and Fajdiga,M. (2000). Description of statistical dependencies of parameters of random load states (dependency of random load parameters). *International Journal of Fatigue* **22:** 357–367.

Kliman, V. and Jelemenska, J. (2001). Fatigue reliability evaluation of structure under random loading using safety criterion - Part I. Methodology. *Kovove Materialy-Metallic Materials* **39(3):** 199-217.

Kosut, J. (2000a). A simple phenomenological hypothesis of cumulative fatigue damage part I. Half-cycle formulation. *Kovove Materialy-Metallic Materials* **38(2):** 96-106.

Kosut, J. (2000b). A simple phenomenological hypothesis of cumulative fatigue damage part II. General formulation and discussion. *Kovove Materialy-Metallic Materials* **38(3):** 178-187.

Kotsikos G., Evans J.T., Gibson A.G. (2000), Hale J.M., Environmentally enhanced fatigue damage in glass fibre reinforced composites characterised by acoustic emission, *Composites: Part A* **31,** 969–977.

Kueppers, M, and Sonsino, C M (2002) Fatigue behavior of welded aluminium under multiaxial loading, *IIW Document XIII-1943-02*, International Institute of Welding.

Kujawski,D. (2001a). Enhanced model of partial crack closure for correlation of R-ratio effects in aluminum alloys. *International Journal of Fatigue* **23:** 95-102.

Kujawski, D.(2001b). Correlation of long- and physically short-cracks growth in aluminum alloys. *Engineering Fracture Mechanics* **68(12):** 1357-1369.

Kujawski, D. (2001c). A new $(\Delta K^{+}K_{\max})^{0.5}$ driving force parameter for crack growth in aluminum alloys. *International Journal of Fatigue* **23:** 733–740.

Kujawski, D.(2001d). A new crack driving force parameter with load ratio effects. *International Journal of Fatigue* **23:** S239-S246.

Labesse, F. and Recho, N. (1998). Local-global stress analyses of fillet welded joints. International Institute of Welding Doc. XIII-1737-98, 1998.

Lacarac, V D, Smith, D J, and Pavier, M J, (2001). The effect of cold expansion on fatigue crack growth from open holes at room and high temperature, International Journal of Fatigue, 23, S161-S170.

Lam, T.S. and Topper, T.H. (1999). Derivation of effective crack growth rate and crack closure data from effective-strain fatigue life data, In *Proceedings of the seventh International Fatigue Congress(Fatigue'99)*, ed. X.R. Wu and Z.G. Wang, Beijing, China, Higher Education Press, pp.415-420.

Latorre, R.G., Herrington, P.D. and Mattei, N.J. (2002). Stress analysis of transversally loaded aluminium weldment. Marine Structures 15 (2002) 175-191.

Lazzarin P. and P. Livieri, (2001) *Notch stress intensity factors and fatigue strength of aluminium and steel welded joints,* International Journal of Fatigue 23 (2001) 225-232.

Lebaillif, D, Buirette, C, Claeys, J, Huther, I, Lieurade, H P, and Degallaix, G (2002). Multiparametric optimization of TIG-dressing for fatigue improvement, IIW Document XIII-1944-02, International Institute of Welding.

Lei, Y. and Zhu, W.Q. (2000). Fatigue crack growth in degrading elastic components of nonlinear structural systems under random loading. *International Journal of Solids and Structures* **37:** 649-667.

Leinum, B. H., and Tørstad, E. H., (2002), DNV RP-F201: Recommended Practise for Design of Titanium Risers, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28474.*

Li, B., Santos, L.T. and De Freitas, M. (2001). A computerized procedure for long-life fatigue assessment under complex multiaxial loading. *Fatigue and Fracture of Engineering Materials and Structures* **24(3):** 165-177.

Lopes, M R, Pereira, M V, Darwish, F A, and Camaro, A F, (2002). Improvement of residual fatigue lire in a flash welded structural steel, Proceedings of the Eight International Fatigue Congress held 3-7 June 2002 in Stockholm Sweden, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 445-452.

Lotsberg, I., Askheim, D.Ø., Haavi, T. and Maddox, S.J. (2001). Full scale fatigue testing of side longitudinals in FPSOs. 11th International Offshore and Polar Engineering Conference ISOPE, Proceedings (2001).

LR (2002). ShipRight Fatigue Design Assessment, Level 3, Guidance on Direct Calculations, Lloyd's Regsiter, October 2002.

Lukic, M. and Cremona, C. (2001). Probabilistic assessment of welded joints versus fatigue and fracture. *Journal of Structural Engineering* **127:** 211-218.

Lynn, A.K. and DuQuesnay, D.L. (2002). Computer simulation of variable amplitude fatigue crack initiation behaviour using a new strain-based cumulative damage model. *International Journal of Fatigue* **24:** 977–986.

Maddox, S.J. (2001). Recommended hot-spot stress design S-N curves for fatigue assessment of FPSOs. *Proceedings of the International Offshore and Polar Engineering Conference* **4:** 97-104.

Maddox, S.J. and Razmjoo, G.R. (2001). Interim fatigue design recommendations for fillet welded joints under complex loading. *Fatigue and Fracture of Engineering Materials and Structures* **24(5):** 329-337.

Makkonen, M. (2001). Statistical size effect in the fatigue limit of steel. *International Journal of Fatigue* **23(5):** 395-402.

Marquis,G.B. and Mikkola,T.P.J. (2001). Effect of mean stress changes on the fatigue strength of spectrum loaded welds. in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), Elsevier Science Ltd., 1113-1120.

Martinez-Esnaola, J.M. and Martin-Meizoso, A. (2001). Modelling fatigue propagation of surface cracks. *International Journal of Fracture* **109(3):** L17-L22.

Martinsson, J (2002). Fatigue Strength of welded cruciform joint with cold laps, Design and Analysis of Welded High Strength Steel Structures, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 155-162.

McEvily, A.J. and Ishihara, S. (20010. On the dependence of the rate of fatigue crack growth on the $\sigma_a^n(2a)$ parameter. *International Journal of Fatigue* **23:** 115-120.

McEvily,A.J., Bao,H. and Ishihara,S. (1999). A Modified Constitutive relation for fatigue crack growth, In *Proceedings of the seventh International Fatigue Congress(Fatigue'99)*, ed. X.R. Wu and Z.G. Wang, Beijing, China, Higher Education Press, pp.329-336.

Memon, I.R., Zhang,X., Cui,D. (2002). Fatigue life prediction of 3-D problems by damage mechanics with two-block loading. *International Journal of Fatigue* **24:** 29–37.

Miller,K.J. (1999). A historical perspective of the important parameters of metal fatigue and problems for the next century. In *Proceedings of the seventh International Fatigue Congress(Fatigue'99)*, ed. X.R. Wu and Z.G. Wang, Beijing, China, Higher Education Press, pp.15-39.

Miller, K (1993). Materials science perspective of metal fatigue resistance, Materials Science and Technology, 9, 453-462.

Montross, C S, Wei, T, Ye, L, Clark, G, and Mai, Y-W, (2002). Laser shock processing and its effects on microstructure and properties of metal alloys: a review, International Journal of Fatigue, 24, 1021-1036.

Muc A. (2000), Design of composite structures under cyclic loads, *Computers and Structures* **76**, 211-218.

Nagode,M., Klemenc,J. and Fajdiga, M. (2001). Parametric modelling and scatter prediction of rainflow matrices. *International Journal of Fatigue* **23:** 525–532.

Naiquan, Y., Moan, T. and Tveiten, B.W. (2001). Fatigue analysis of aluminium box-stiffener lap joints by nominal, structural and notch stress range approach. Proceedings of PRADS 2001, 1053-1060, Elsevier, 2001.

Newman, J.C. Jr. (1998). The merging of fatigue and fracture mechanics concepts: a historical perspective, Progress in Aerospace Sciences **34:** 347-390.

Nguyen, Ninh T and Wahab, M A, (1996). The effect of undercut and residual stresses on fatigue behaviour of misaligned butt joints, Engineering Fracture Mechanics, 55, 453-469.

Nicholson, D.W., Ni, P. and Ahn, Y. (2000). Probabilistic theory for mixed mode fatigue crack growth in brittle plates with random cracks. *Engineering Fracture Mechanics* **66:** 305-320.

Niemi, E. (1999). Structural stress approach to fatigue analysis of welded components. Final draft of designer guide. International Institute of Welding Doc. XIII-WG3-06-99, 1999.

Norman, M, and Lotsberg, I, (2001). Fatigue life improvement of scallops in ships/FPSOs using finite element analysis, Proceedings of the International Offshore and Polar Engineering Conference, 105-110.

Ochi, Y, Masaki, K, Matsumura, T, and Sekino, T, (2001). Effect of shot-peening treatment on high cycle fatigue property of ductile cast iron, International Journal of Fatigue, 23, 441-448.

O'Hara, P, (2002). LasershotSM peening – a production reality, Proceedings of the Eight International Fatigue Congress held 3-7 June 2002 in Stockholm Sweden, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 2477-2484.

Ohta, A, Suzuki, N, and Maeda, Y (2002). Fatigue strength improvement of lap welded joints by low transformation temperature welding wire – superior improvement with strength of steel, IIW Document XIII-1924-02, International Institute of Welding.

Paetzold, H., Doerk,O. and Kierkegaard, H. (2001). Fatigue behaviour of different bracket connections. in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), Elsevier Science Ltd., 1137-1143.

Park, J., Kim, K.B.,Kim, W.S. and Kim, D.H. (2001). An experimental investigation on fatigue behavior of inverted angle and T-type side longitudinals in tankers. in *Practical Design of Ships and Other Floating Structures*, You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds), Elsevier Science Ltd., 1129-1135.

Pauchard V., Chateauminois A., Grosjean F., Odru P. (2002), In situ analysis of delayed fibre failure within water-aged GFRP under static fatigue conditions, *International Journal of Fatigue* **24**, 447–454.

Peeker, E. and Niemi,E. (1999). Fatigue crack propagation model based on a local strain approach. *Journal of Constructional Steel Research* **49:** 139–155.

Peng, D., Jones, R. and Pitt, S. (2002). A hybrid formulation for 3D fracture analysis. *Engineering Fracture Mechanics* **69:** 45-67.

Petermann J., Plumtree A. (2001), A unified fatigue failure criterion for unidirectional laminates, *Composites Part A* **32,** 107-118.

Petershagen, H., (2000). The hot-spot stress concept – a case study. Schiffbauforschung 39, 2000.

Petinov, S. V. (2001). The pre-fabricated hull details for application in design and repair. *PRADS Congress*, Shanghai 16-21 September, 1153-1159.

Petipas, E., Leburn, B. , De Meerleer, S., Fournier, P., Charrier, A. and Pollet, F., (2000). Use of the local appeoach for the calculation of the fatigue strength of welds. International Institute of Welding Doc. XIII-1850-00, 2000.

Philippidis T. P., Vassilopoulos A. P. (2002), Complex stress state effect on fatigue life of GRP laminates. Part I, experimental and Part II, theoretical formulation, *International Journal of Fatigue* **24,** 813–823 and 825-830.

Pippan R., Flechsig K., Riemelmoser F. O. (2000), Fatigue crack propagation behavior in the vicinity of an interfacebetween materials with different yield stresses, *Materials Science and Engineering* ***A*283**, 225-233.

Pitoiset ,X. and Preumont, A. (2000). Spectral methods for multiaxial random fatigue analysis of metallic structures. *International Journal of Fatigue* **22:** 541–550.

Poutiainen, I. and Niemi, E. (2000). The determination of hot spot stress in gusset structures using a coarse element mesh. International Institute of Welding Doc. XIII-1820-00, 2000.

Rahman, S. (2001). Probabilistic fracture mechanics: J-estimation and finite element methods. *Engineering Fracture Mechanics* **68:** 107-125.

Ramsamooj, D.V. and Shugar, T.A. (2001a). Model prediction of fatigue crack propagation in metal alloys in laboratory air. *International Journal of Fatigue* **23:** S287–S300.

Ramsamooj, D.V. and Shugar, T.A. (2001b). Prediction of fracture-based fatigue life of connectors for the mobile offshore base. *Marine Structures* **14(1-2):** 197-214.

Rizzo, C. and Tedeschi,R. (2002). Experimental fatigue tests of a typical structural detail (beam no. 1, 2 & 3). *IMAM Congress* Crete 13-17 May 2002, Paper no. 22.

Rizzo C. (2002), DINAV Internal Report 02CRI03 "FATIGUE STRENGTH OF COMPOSITE MATERIALS MADE SHIP STRUCTURES: MARINE APPLICATIONS OF RECENT DEVELOPMENTS"

Robles, L.B.R., Buelta,M.A., Goncalves, E. and Souza, G.F.M. (2000). A method for the evaluation of the fatigue operational life of submarine pressure hulls. *International Journal of Fatigue* **22:** 41–52.

Roessle, M.L. and Fatemi, A. (2000). Strain-controlled fatigue properties of steels and some simple approximations. *Int. J. Fatigue* **22:** 495-511.

Ronold, K. O., Wästberg, S., (2002), Characteristic S-N Curves for Fatigue Design of Titanium Risers, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28475.*

Rucho, P., Maherault, S, Berstad, A. and Samnøy (2001). Comparison of measurement and Finite Element Analysis of side longitudinals. 11th International Offshore and Polar Engineering Conference ISOPE, Proceedings (2001).

Rudolph, J, Schmitt, and Weiss, E, (2002). Fatigue lifetime assessment procedures for welded pressure vessel components, International Journal of Pressure Vessels and Piping, 79, 103-112.

Rudolph H.-V., Ivers H., Harbich K. W. (2001), Application of X-ray refraction topography to fibre reinforced plastics, *Composites Part A* **32,** 473–476.

Saad, P., Salama M. M., Jahnsen, O., (2002), Application of Composites to Deepwater Top Tensioned Riser Systems, *21st International Conference on Offshore Mechanics and Arctic Engineering, OMAE2002-28325.*

Salama, M. M., Murali, J., Joosten, M. W., (1998), Titanium Drilling Risers – Application and Qualification, *17th International Conference on Offshore Mechanics and Arctic Engineering, OMAE98-2110.*

Salama, M., (2000), Fatigue Crack Growth Behaviour of Titanium Alloy Ti-6Al-4V and Weldment, *19th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2000-2001*.

Samuelsson, J. (2002). Cold laps and weld quality limits, Design and Analysis of Welded High Strength Steel Structures, Engineering Materials Advisory Services Ltd, Cradley Heath, West Midlands, UK, 155-162.

Sauer, C. W., Actis, S. C., Thornton, J. M., and Watkin, B. (1996a), The Use of Titanium for Deepwater Drilling Riser Applications, *Petroleum Engineer Magazine.*

Sauer, C. W., Sexton, J. B., Sokoll, R. E., Thornton, J. M., and Watkin, B. (1996b), Heidrun TLP Titanium Drilling Riser System, *Proc. Of Offshore Technology Conference, OTC, No. 8088.*

Schon J., Nyman T. (2002), Spectrum fatigue of composite bolted joints, *International Journal of Fatigue* **24**, 273–279.

Sevillano, J.G. (2001). The effective threshold for fatigue crack propagation: A plastic size effect? *Scripta Materialia* **44(11):** 2661-2665.

Shademan, S., Soboyejo, A.B.O., Knott, J.F. and Soboyejo, W.O. (2001). A physically-based model for the prediction of long fatigue crack growth in Ti–6Al–4V. *Materials Science and Engineering* **A315:** 1–10.

Shankar, K, and Wu, W D, (2002). Effect of weld repair on crack propagation behaviour in aluminium alloy 5083 plates, Materials & Design, 23, 201-208.

Sharp, P K, Liu, Q, Barter, S A, Baburamani, P, and Clark, G, (2002). Fatigue life recovery in aluminium alloy aircraft structures, Fatigue & Fracture of Engineering Materials & Structures, 25, 99-109.

Shen,W., Soboyejo, A.B.O. and Soboyejo, W.O. (2001). Probabilistic modeling of fatigue crack growth in Ti–6Al–4V. *International Journal of Fatigue* **23:** 917–925.

Shih Y.-S. and G.-Y Wu (2002) *Effect of vibration on fatigue crack growth of an edge crack for a rectangular plate, ,* International Journal of Fatigue 24 (2002) 557-566;

Simonsen, T., Murali, J., and Foss, J. O., (1999), The Heidrun TLP Titanium Drilling Riser – Materials Performance, Properties and Operational Experience, *Interantional Seminar on Titanium Risers and Flowlines, Eds. S. Berge and L. Lunde.*

Sinha, V., Mercer, C. and Soboyejo,W.O. (2000). An investigation of short and long fatigue crack growth behavior of Ti–6Al–4V. *Materials Science and Engineering* **A287:** 30–42.

Soboyejo, A.B.O., Shademan, S., Foster, M., Katsube, N. and Soboyejo, W.O. (2001). A multiparameter approach to the prediction of fatigue crack growth in metallic materials. *Fatigue and Fracture of Engineering Materials and Structures* **24(4):** 225-241.

Sonsino, C.M. and Kueppers, M. (2001). Multiaxial fatigue of welded joints under constant and variable amplitude loadings. *Fatigue and Fracture of Engineering Materials and Structures* **24(5):** 309-327.

Stanzl-Tschegg S.A. and H. Mayer (2001) *Fatigue and fatigue crack growth of aluminium alloys at very high numbers of cycles, ,* International Journal of Fatigue 23 (2001) S231-S237;

Takahashi,I., Takada,A., Akiyama,S., Ushijima, M., Maenaka, H. (2000). Fatigue behavior of a box-welded joint under biaxial cyclic loads (2nd report): Effect of biaxial load range ratio and cyclic compressive loads in the lateral direction, *J. SNAJ* **188:** 599-610.

Tarleja R. (1990), Fatigue of composite materials, *Lancaster:Technomic Publishing*.

Terai, K., Tomita, Y., Hashimoto, K. and Osawa, N. (2001). Fatigue design method of ship structural members based on fatigue crack growth analysis. *Proceedings of the International Offshore and Polar Engineering Conference* **4:** 589-594.

Torres, M A S and Voorwald H J C, (2002). An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel, International Journal of Fatigue, 24, 877-886.

Tørstad, E. H., and Bratfos, H. A., (1999), Qualifying Titanium Risers for the Visund Field, *Stainless Steel World Conference*.

Torster, F., dos Santos, J. F., Hutt, G. A., and Kocak, M., (1999a), Fatigue Properties of Radial Friction Welded Ti-6Al-4V-0.1Ru Risers, *18th International Conference on Offshore Mechanics and Arctic Engineering, OMAE99-2162*

Torster, F., dos Santos, J. F., Kötzig, T., Schaffer, H., Hutt, G. A., Kocak, M., (1999b), Effect of Microstructure on the Fracture Toughness of Radial Friction Welded Ti-6Al-4V-0.1Ru Risers, *18th International Conference on Offshore Mechanics and Arctic Engineering, OMAE99-2163.*

Tsamasphyros G. J., Kanderakis, G. N., Karalekas D., Rapti D., Gdoutos E. E., Zacharopoulos D., Marioli-Riga Z. P.(2001), Study of composite patch repair by analytical and numerical methods, *Fatigue and Fracture of Engineering Materials and Structures* **24,** 631–636.

Turner, D., Lambert, S. B. and Burns, D. J. (2000). Effect of plate width and free edges on the initiation and propagation of fatigue cracks in plate-to-plate welded T-joints. *ETCE/OMAE Congress*, New Orleans, 14-17 February, MAT-2300.

Ulleland, T., Svensson, M. and Landet, E. (2001). Stress concentratiom factors in side shell longitudinals connected to transverse web frames. 11th International Offshore and Polar Engineering Conference ISOPE, Proceedings (2001).

Van Paepegem W., Degriek J., De Baets P. (2001), Finite element approach for modeling fatigue damage in fiber reinforced composite materials, *Composites Part B* **32,** 575-588.

Vasileiu N. V., Tsouvalis N.G., (2002), FE modeling of composite marine propellers, *IMAM 2002 Congress Crete 13-17 May 2002,* paper 111.

Vasudevan, A.K. and Sadananda,K. (2001). Analysis of fatigue crack growth under compression–compression loading. *International Journal of Fatigue* **23:** S365–S374.

Vasudevan,A.K., Sadananda,K. and Glinka, G. (2001). Critical parameters for fatigue damage. *International Journal of Fatigue* **23:** S39–S53.

Vasudevan,A.K., Sadananda,K. and Louat,N. (1994). A review of crack closure, fatigue crack threshold and related phenomena. *Materials Science and Engineering* **A188:** 1-22. Violette, F, (2001). III.2 Fatigue and Fracture, Official discussion by Dr F Violette, Proceedings of the 14th International Ship and Offshore Structure Congress, Eds Ohtsubo, H, and Sumi, Y, Elsevier, Amsterdam, The Netherlands, 113-142.

Venkatesan R., Dwarakadasa E.S., Ravindran M. (2002), Study on behavior of carbon fiber reinforced composite for deep sea application, *OTC 14325 OTC 2002.*

Violette, F. (1998). On the Fatigue Performance Prediction of Ship Structural Details. The Royal Institution of Naval Architects, Spring Meeting 1998, Paper No. 4.

Wahab, M.A. and Sakano, M. (2001). Experimental study of corrosion fatigue behaviour of welded steel structures. *Journal of Materials Processing Technology* **118:** 117-122.

Wernicke, R. (2001). Fatigue strength assessment of cruciform joints with misalignment. International Institute of Welding Doc. XIII-1872-01, 2001.

Wilhelmsen Ø., (2000), *Hull Structural Damage and Repairs, DNV,* DTP851, 2000.

Williams J. G., Sas-Jaworski II A.(2000), Composite spoolable pipe development, advancements and limitations, *OTC 12029, OTC 2000.*

Yan, J.H., Zheng, X.L. and Zhao, K. (2000). Prediction of fatigue life and its probability distribution of notched friction welded joints under variable-amplitude loading. *International Journal of Fatigue* **22 (6):** 481-494.

Ye N. and T. Moan, (2002) *Fatigue and static behavior of aluminium box-stiffener lap joints,* International Journal of Fatigue 24, 2002, 581-589.

Ying Shan, Kin Liao (2002), Environmental fatigue behavior and life prediction of unidirectional glass–carbon/epoxy hybrid composites, *International Journal of Fatigue* **24**, 847–859.

Yousefi, F., Witt, M. and Zenner, H. (2001). Fatigue strength of welded joints under multiaxial loading: Experiments and calculations. *Fatigue and Fracture of Engineering Materials and Structures* **24(5):** 339-355.

Zhang, R. and Mahadevan, S. (2000). Model uncertainty and Bayesian updating in reliability-based inspection. *Structural Safety* **22:** 145-160.

Zhao, Z. and Orisamolu, I.R. (2001). Probabilistic fatigue damage assessment for short crack growth. *Key Engineering Materials* **200:** 57-80.

Zhen-Ming Huang (2002), Fatigue life prediction of a woven fabric composite subjected to biaxial cyclic loads, *Composites Part A* **33,** 253-266.

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