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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.

## COMMITTEE MEMBERS

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## KEYWORDS

Fatigue, Fracture Mechanics, Probabilistic Methods, Materials, Rules and Guidelines, Fitness for Services, Inspection and Life Extension

# CONTENTS

# 1. INTRODUCTION

Over the decades, the ISSC committee “Fatigue and Fracture” has been a major contributor to address the impertinence of good science work within the field. Fatigue and fracture mechanics have been an area with high focus on research the last 50 years with several books, publications and conferences covering these topics. Fatigue failure of structures has caused fatalities. The first known and highly addressed accident, which caused loss of several human lives, was the Versailles Railway accident in 1842. Almost 110 years after this accident, a meeting was held in London, U.K., with the most distinguished fatigue specialists at that time. They concluded that even in 1956 it was not a practical proposition to present a detail overview of the topics of metal fatigue since there was already “at least 4 books in the English language” addressing this topic. It is important to notice that the subject is vast and the committee can therefore not cover all topics related to fatigue and fracture. Hence, the topics in the current report have been selected based on the knowledge and interest of the members of the committee. The report is an overview of recent activities within the offshore and ship industry with focus on the latest research on fatigue and fracture. More than 270 publications have been reviewed and referenced. The committee has been in contact with several of the other committees in order to prevent duplications of work within ISSC.

Fatigue failure is an extremely complex physical process which is governed by a great number of parameters related to, for example, local geometry and material properties of the structural region surrounding the crack growth path. There are different approaches and methods which can be used in fatigue life predictions. Section 2 presents an overview of these approaches and methods, both from a local and global perspective, covering the stress-based, strain-based and fracture-mechanics based approaches.

Since the past two decades probabilistic approaches for fatigue have become more common, and both S-N curve with Miner’s damage accumulation rule or fracture mechanics based approach have been discussed in section 3. In addition, the influence of multi-axial fatigue design procedures which has taken steps forward in the ship industry by adopting new criteria in the fatigue life prediction models have been evaluated.

In Section 4, some of the factors that influence the fatigue life of structures are discussed such as mean and residual stresses, thickness effect, corrosive environments and fabrication. Some methods which have been developed for improving the fatigue performance are also evaluated.

Today, it is anticipated that about 25% of the unknown oil and gas resources are located in the Arctic areas. In order to exploit these resources, considering also the wish and future needs for year-round navigation in ice-covered waters in these areas, ships and offshore structures have to be made of materials which have properties that can sustain the loading conditions in this environment. In addition, exploitation of oil and gas in deep waters under high pressure and low temperature and sour service, materials have to have properties which over time sustain these challenges cost-effectively. Section 5 focuses on new developments and applications of materials seen in the offshore and shipping industry from a fatigue point of view.

In Section 6, fatigue design methods for ship and offshore structures are discussed. For ships, rule-based-methods for fatigue evaluation are proposed by classification societies, and a comparison of the different fatigue methodologies provided by BV, DNV, GL, KR, LR and NK are summarised in Table 6. The IACS Common structural rules (CSR) for Oil Tankers and Bulk Carriers Hull structure, published in January 2006, has been effective for new-builds since the 1st of April 2006 and it has been evaluated extensively. In addition, new revisions of different offshore codes and alternative fatigue design management methods are also discussed in this section.

The understanding of fatigue is mainly based on observations from experiments or structural failure and the interpretation of these events. Section 7 reviews and discusses some significant work in this area. In addition, a benchmark study is presented, performed by the committee, in order to validate hot-spot stresses assessed from different models. The details discussed are: HHI hopper corner model (135 deg.), the MHI right angle joint model and the VLCC bilge knuckle model.

Inspection, maintenance and repair strategies provide the means to ensure safe operations during the life of vessels and offshore structures; these topics are discusssed briefly in Section 8.

Finally, Section 9 summarises the main features based on the committee’s expert opinions. Since the topic is vast, and because the current report cannot touch upon all aspects related to fatigue and fracture issues related to ship and offshore, recomandations with respect to further work is highlighted.

## 2. STATE OF THE ART OF LIFE PREDICTION METHODS

It is commonly recognized that it is impossible for a physical model to account for all fatigue influencing parameters, thus a lot of approximate models have been conceived for practical fatigue assessments.

A global approach is a valid tool for design and statistical quality control of typical structural details, where guidelines are provided in design rules and codes. A local approach is, by its very nature, the most suitable for research and calibration purposes, and, being more onerous than a global approach, it is enforced in codes only for unconventional fatigue analyses. In Figure 1 a tentative classification of the basic variants of the approaches for fatigue evaluation is shown: proceeding from the left-hand-side to the right-hand-side, methods become more exact and more demanding.

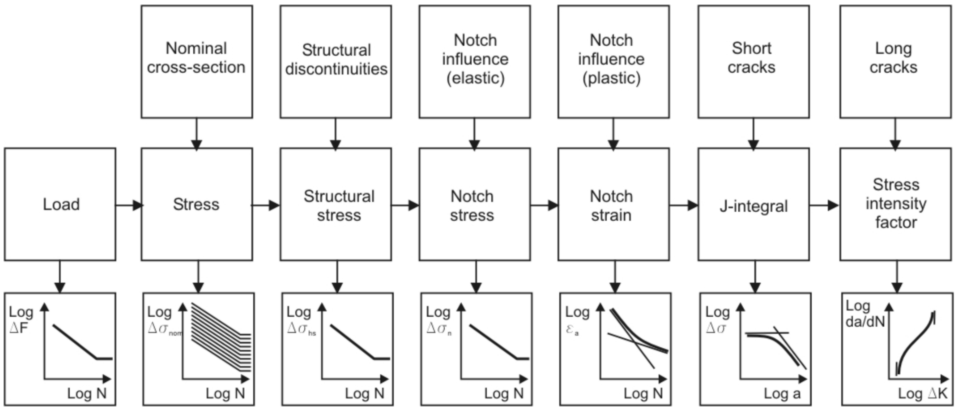


Figure 1: Approaches for fatigue life calculations (Radaj and Sonsino, 1998)

A number of investigations are addressed to the review of the state of art of life prediction methods. Based on the important review of fatigue assessment procedures of welded joints by Radaj *et al* (2006), the concept of nominal stresses, structural stresses, notch stresses or deformation criteria are described in details. Second edition of the book is focused on methodologies, which were developed rapidly during the last decade, like the hot-spot structural stress approach, the notch stress or strain concept applicable to thin-sheet structural components and the crack propagation methods. Some other studies are particularized for a type of welded joint in order to describe current design methods, their background and relevant experimental data. This is the case of the comprehensive work by Maddox (2006), where procedure for fatigue performance of steel fillet welds with respect to failure in the weld throat is examined, see section 7.1 for further detail of this study.

International Institute of Welding (IIW) provides fatigue recommendations of welded components and structures, including the effect of weld imperfections with respect to fatigue. The codes cover all current methods of verification, as e.g. component testing, nominal stress, structural stress and notch stress methods, as well as fracture mechanics assessment procedures. The safety philosophy covers the different strategies, which are used in various fields of application and gives a specified choice for the designer, see Table 1. The main areas of update are the structural hot-spot stress concept, which now allows for an economic and coarser meshing of finite element analysis, the extension of the effective notch stress concept to welded aluminium structures and numerical assessment of post weld treatments for improving the fatigue properties. Hobbacher (2007) presents the update of the recommendations.

Table 1
Strategy for the fatigue assessment (Hobbacher, 2007)

| Type | Stress raisers | Stress determined | Assessment procedure |
|---|---|---|---|
| A | General analysis of sectional forces using general theories e.g. beam theory, no stress risers considered | Gross average stress from sectional forces | Not applicable for fatigue analysis, only for component testing |
| B | A + macrogeometrical effects due to the design of the component, but excluding stress risers due to the welded joint itself. | Range of nominal stress (also modified or local nominal stress) | Nominal stress approach |
| C | A + B + structural discontinuities due to the structural detail of the welded joint, but excluding the notch effect of the weld toe transition | Range of structural hot-spot stress | Structural hot-spot stress approach |
| D | A + B + C + notch stress concentration due to the weld bead notches<br>a) actual notch stress<br>b) effective notch stress | Range of elastic notch stress (total stress) | a) Fracture mechanics approach<br>b) effective notch stress approach |

### *2.1 Low-cycle, High-cycle and Ultra-high-cycle Approaches*

Life prediction methods which presume homogeneous material (free from cracks, inclusions or defects) at the outset of the investigation can be divided into strain-based (low-cycle fatigue) and stress-based (high-cycle fatigue) methods. Low-cycle fatigue is characterised by repeated plastic strains during cyclic loading conditions where fatigue failure occurs after relative low number of load cycles (in the order of $10^4$ cycles). This design approach is normally used in fatigue assessment of local areas where high stress concentrations exist and the material response locally is repeated plastic deformation. In addition, stress-based approaches use the elastic stress range (or amplitude) as the governing load parameter. At a sufficient load level, which may result in a fatigue life of approximately $10^7$ cycles, a threshold referred to as the fatigue or endurance limit can be seen for many materials. Maddox (2008a) carried out S-N fatigue tests of strips cut from girth welded steel pipe under constant and variable amplitude loading in order to investigate the effect of stresses below the constant amplitude fatigue limit. Based on the results obtained, Miner's rules overestimated the fatigue life compared to fatigue life obtained under spectrum loading.

Stress-based approaches which result in fatigue lives in the order of $10^4$ to $10^7$ are referred to as high-cycle fatigue approaches. However, Murakami (2002) discusses ultra-high-cycle fatigue which is a stress-based approach but for stress levels lower than for those in the high-cycle regime (i.e. below the first fatigue “limit” threshold). The resulting fatigue life is in the order of $10^9$ cycles where another and lower fatigue threshold can be observed. Murakami explains the existence of several fatigue thresholds by internal barriers (inclusions, defects, slip planes, orientation and size of microcracks) which are activated depending on e.g. the magnitude of the applied load and existence of geometric constraints.

Lotsberg *et al* (2006) give a description of the methodology developed by DNV in the Recommended Practice DNV-RP-C206 (DNV, 2007) for fatigue design of FPSO units (see also ch. 6.1.3). In the paper the main topics of the methodology are described with a special regard to the hot-spot structural stress evaluation method and to the calculation of low-cycle fatigue damage from loading and unloading. With reference to the latter, due to large stress cycles implying local yielding at the hot spot, hot-spot stresses calculated from a linear elastic analysis are modified by a plasticity correction factor and by a redistribution factor before the S-N curve is entered. In screening the structure of a ship to identify the most critical hot spots, the hot-spot structural approach may be advantageously applied, even if considerable plastic local deformations occur, Garbatov *et al* (2007).

Boge *et al* (2007) present the results of laboratory tests carried out on tubular joints with the aim of investigating the stress life curve in the low-cycle fatigue region. The main purpose of the study is to generate more data for the low-cycle fatigue region of tubular joints and to investigate the effect of mean stress, or R-ratio, on fatigue strength in this region. The data, analysed and compared with published data and with current fatigue design criteria for tubular joints, show a common scatter band in the cycle range of $10^4 \sim 10^5$. At the same time, the two S-N curves evaluated separately in the low-cycle range ($10^3 < N < 10^5$) and in the high-cycle range ($10^5 < N < 10^7$) exhibit different slopes. Authors explain such a slope discrepancy with a transition from high to low-cycle fatigue. See section 6.4.2 for Damage Calculation due to combined Low and High Frequency loads.

### *2.2 Cumulative Fatigue Damage based on S-N Curves*

New findings, limitations, suitability and uncertainty of physical models associated with different fatigue approaches and practical applications, can be found in the following chapters. It will appear evident that, even if the accuracy of the various approaches is not the same (i.e., they do not guarantee the same fatigue damage estimation), “the best approach” is just the most suitable one for each single case. Nevertheless, steps towards improved harmonisation, especially for the classification design codes would be welcomed, see Chapter 6.

### *2.2.1 Nominal Stress Approach*

The nominal stress approach is based on far-field stresses due to forces and moments at the potential site of cracking or the stresses not containing any stress increase due to structural details or welds. Extensive experience has been acquired over the years in the use of such a very practical approach, to such an extent that it continues to be the primal method for fatigue assessments. The method has certain intrinsic limitations to be ascribed to a poor tracing of the decisive fatigue-strength influencing parameters. On the other hand, its formal simplicity makes it the right method for design codes and guidelines. It is replaced by the structural stress approach only when a high demand of accuracy is needed, as well as in the case of complex structures. Nominal stress in simple component is evaluated by resolving to general theories (e.g., the beam theory) based on linear-elastic behaviour, for more complex structures, if no analytical solutions are available, it may be calculated resorting to simple and coarse FE mesh models.

Research activities within the nominal stress approach concerns to improve fatigue codes for different structural components and derive S-N curves for these new fatigue class designations. More comprehensive strength-curves compendia are being elaborated, as test validations from which S-N curves are drawn tend to be carried out by controlling more parameters. On the other hand, some factors affecting fatigue strength are usually taken into account by introducing approximate and empiric corrections like the; influence of mean and residual stresses, effect of stress multiaxiality, effect of plate thickness and impact of treatments for stress relaxation, in addition to exposure to corrosive environments and elevated temperatures. Contemplation of such effects is of fundamental importance for the sake of reducing safety factors and providing reliable service life curves.

### *2.2.2 Structural Stress Approach*

In the structural stress approach, the fatigue strength of any structural detail is assessed by making reference to the intensity of the stress or strain field measured or calculated in the area where crack initiation most likely will occur, usually denoted a “hot spot”. The structural stress (also referred to as geometric stress) takes into account the local stress concentration which is related to the structural geometry or discontinuity (i.e., the structural effect) and not to the local weld geometry (i.e., the weld toe effect). Local weld geometry is either captured in the different S-N curves or by the Mk (stress intensity magnification) factor used in fracture mechanics analyses.

In plate-type structures, the structural stress is commonly defined as the sum of membrane and bending stress components at the hot spot, so the local nonlinear stress peak at the notch is excluded ref. Niemi *et al* (2004) and Fricke, (2006a). At the same time, effects of the local notch at the weld toe or root are included in S-N curve, thus reducing the number of curves in comparison to the nominal stress approach.

Accordingly, stress S-N curves need to be specific for each hot-spot local configuration, depending on the welding process, the weld characteristics and the attachment type. Classifications of type of attachments have been defined for tubular joints and for plate-type structures. The decisive issue in the structural stress approach is how to obtain a significant structural stress value, that is a stress neglecting the notch effect but, at same time, effective in describing the macrostructural behaviour of the structural component.

The definition of a procedure as unambiguously as possible for separating local configuration effects from the notch effects is the subject of today's investigations and the following procedures have been developed to derive the reference structural stress at the hot spot:

- the extrapolation of surface or through-thickness stresses to obtain a hot-spot stress
- the equilibrium searching in a small volume at the hot spot to obtain an equilibrated structural stress, as in the Dong's method (also referred to as Battelle's method)
- the evaluation of an effective structural stress at a read out point properly located in the vicinity of the crack initiation point. In the method proposed by Xiao and Yamada (2004) the stress is measured 1 mm below the surface on the expected crack path; in the method proposed by Haibach (1970), the stress is determined on the surface 2 mm apart from the weld toe

In Figure 2 the structural stress extrapolation at the weld toe of a bracket on a plate surface is shown (σk is the notch stress, $\sigma_s$ the structural hot spot stress, $\sigma_n$ the nominal stress and $K_s$ is the structural stress concentration factor). The hot-spot stress is derived from the stresses both at plate surface and in the weld toe section.

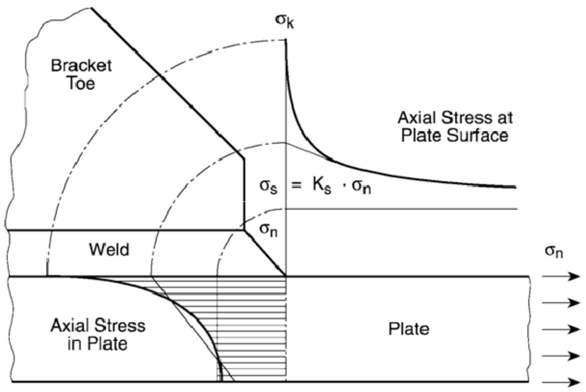


Figure 2: Stress types at a typical hot spot of a plate-type structure (Fricke *et al*, 2007a)

Surface stress extrapolation is based on stresses located relatively far from a weld in order to avoid the weld-notch effect, but sufficiently close to the potential crack site to catch the influence of the geometry. There are several proposals for location of those points and in most cases the plate thickness is a suitable parameter to position the evaluation points. However, sources of uncertainty are related to the position of the evaluation points, to the availability of Gaussian stresses in FEA and to the fitting procedure (usually performed by a second-order function). Specific techniques have been defined for structural modelling. From a practical point of view, procedures based on low-density mesh shell-element FE models are to be preferred, provided that their accuracy and consistency is compared with solid-element models. Comprehensive guidelines for calculation and measurement of structural hot-spot stresses are given by Hobbacher (2007). Another open question is how to deal with multiaxial stress-strain conditions.

Tveiten *et al* (2007) carried out a set of full scale fatigue tests of an aluminium ship structural detail. The test detail was also analyzed by FE method, using several modelling techniques and element types. Basing upon the results from both experimental tests and FE analyses, recommendations on the procedure of fatigue assessment of aluminium ships including S-N curve to be used were presented. Authors concluded, that the hot-spot stress from FE analysis could be taken at a point 0.5 $t$ from the weld toe, or by linear extrapolation on the read out points located at 0.5 $t$ and 1.5 $t$ (being t the plate thickness) which is one of the commonly recommended extrapolation techniques. The overall recommendation from this work is to use a hot-spot stress defined at 0.5 $t$ from the weld toe and a FAT 32 design curve for this type of welded aluminium details.

Xu and Barltrop (2007) investigated stress singularities with the aim to allow for the classification of details to a limited number of classes. According to elastic stress analysis, structural sharp corners are singularities and may be classified by type and strength. Authors pointed out that, once a correspondence has been determined between these characteristics and the structure under consideration, this provides guidance both on the mesh size needed to analyse a structure and on the size-dependent stress concentration factors.

The uncertainties in calculation and measurement of structural stress concentration factors are stressed by Lotsberg *et al* (2007c), who compared the results obtained by FE analyses with those derived by on-site measurements. Two different measurement techniques were applied; the standard strain gauges and detections of the stress field based on the magnetostriction effect. Comparison between the data measured by the two methods gives evidence of the accuracy of the new method. Comparison between measured and calculated structural stress concentration factors shows that only the results of the most accurate solid-element FE models fall into the same region of results obtained by measurements. In order to capture real geometry of a welded toe, three-dimension laser scan technique is a useful tool, Hou (2007). The digitalized geometry can then be used in finite element analyses in order to exact represent the geometry and calculate the stress concentration factor.

The structural stress approach based on the hot-spot stress concept is a compromise between accuracy and ease of use, its weakness is to neglect the stress distribution in the cross section of the plate at the notch. However, in every local-stress-based approach for plate-type structures, the knowledge of the stress gradient from the notch to the back side of a plate should be of major concern, since it controls the crack propagation. In the Dong's method the fatigue-effective stress gradient over the cross section is considered by the sum of a structural stress due to the external load and a self-equilibrating stress due to the notch effect and accounted for by increasing the structural stress by a notch factor based on fracture mechanics concepts. The definition of simple procedures for the evaluation of the stress distribution through the thickness of a plate at a weld toe is still under consideration; see ch. 6. Gotoh *et al* (2006) present a simple estimation method in providing accurate stress distributions normal to the cross section at a notch.

The results of the study carried out by Ha (2006), as reported in the paper of Kim *et al* (2007), show the superiority of the Dong's approach with respect to the hot-spot approach, due to both the highly mesh-insensitive computation of the structural stress component and the need of a single "master S-N curve" for the evaluation of the endurable structural stresses. The proposed master S-N curve has been determined by processing the results of over 2000 existing fatigue tests, which performed on different welded joints under various loading conditions. The structural stress as proposed by Dong and the hot-spot stress obtained by a common extrapolation technique have been used by Kim *et al* (2007) to perform a comparative fatigue strength assessment for a side shell connection of a container vessel. The results, both in terms of stresses and damage ratios, are found to be similar. A comparison of different procedures, based on different effective structural and notch stresses are given by Poutiainen and Marquis (2006). An original method based on the structural stress approach is compared to the structural stress approach proposed by Xiao and Yamada (2004) and to the effective notch stress approach based on the rounding of the weld toe or root by a fictitious radius equal to 1 mm. The results of the study confirm the soundness of the proposed structural stress methods based on crack propagation considerations.

Osawa *et al* (2007a) proposed a procedure to carry out hot-spot stress calculations making use of the less expensive shell models properly calibrated on mixed shell/solid elements FE models based on the 'perpendicular shell coupling method" (PSCM), deeply discussed in Chapter 7. Lotsberg *et al* (2007a), define a procedure to adjust such stresses with the purpose of considering all the bending effects that shell elements cannot capture. In the proposed procedure, the hot-spot stress gained from a shell-element FE model is modified to take into account the bending effects due to both the bending load and the incorrect local bending stiffness caused by neglecting the fillet weld. The latter effect is accounted for by resorting to a structural stress read out on a point properly shifted away from the intersection line, which is then magnified by the so called β factor. A formulation for the β factor is given with reference to cruciform joints of different geometries based on FE analyses with solid element models, where weld geometry was included.

Fricke (2006a) and Fricke and Doerk (2006b) present procedures for fatigue assessment of weld root cracking of fillet-welded structures. The first configuration studies a loaded fillet-welded attachment end where a structural averaged stress at the end of the welded attachment is calculated. This local nominal stress is including macro-geometric effects, however neglecting the weld toe effect. The second topic investigated is the assessment of fillet and partial penetration welds subjected to local throat bending, based on the calculation of a linearised structural stress as a combination of membrane and bending stress, where each stress component is derived by integration of the internal nodal forces in the leg plane just in extension of the non-welded root faces (Figure 3). Fatigue tests carried out on different structural configurations suggest that the modified nominal stress approach needs more adjustments in order to improve its consistency, while the results of the structural weld stress approach are in good agreement with those given in codes and guidelines.

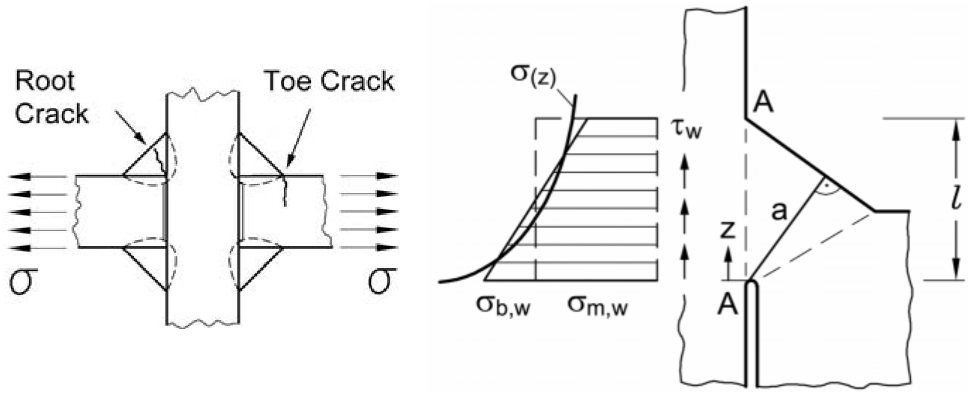


Figure 3: Possible fatigue cracks in fillet-welded cruciform joints and the linearization of stresses in the leg section of a partial-penetration fillet weld (Fricke, 2006a)

The structural-stress based approach is well suited for performing qualitative and comparative assessments, with the aim of optimizing the detail shape parameters. A case study where the structural stress approach has been successfully performed is reported by Eylmann *et al* (2005) where a comprehensive fatigue test program has been carried out on a ship structural component of a truck deck stiffened by trapezoidal profiles. The structural-stress based FE analysis (performed by shell and solid-element FE models) has been implemented to predict the location and the direction of the cracks on the tested specimens and has been proved to be a robust procedure for the classification of new structural details or components.

A precise definition and the numerical calculation of the structural stresses are difficult, which has resulted in the development of different methodologies discussed and compared in the paper of Fricke and Kahl (2005). They are the structural hot-spot stress approach according to the IIW, the structural stress approach according to Dong and the structural stress approach according to Xiao and Yamada (2004). The applications to three examples show the differences in the analysed stresses and predicted fatigue lives, and are compared with fatigue tests data. In spite of different structural stress definitions, the fatigue lives predicted with the three approaches are not too distant from each other and, generally, the fatigue life predictions are conservative in comparison to fatigue tests.

### *2.2.3 Effective Notch Stress Approach*

Any fatigue assessment of a structural component, in order to be an absolute assessment, needs to represent the notch effect in an explicit form. The fatigue-effective elastic notch factor (also called "fatigue notch factor") gives account of the reduction, with respect to the un-notched parent material, in the endurance limit of a notched structural member. It is worth stressing that fatigue notch factor depends, among other, on the absolute notch sharpness and specimen size. An advantage of the effective notch approach is that technically one S-N curve is sufficient for representing the fatigue properties of the base material in the HAZ, since the weld notch effects are included in the calculated stresses. For fracture mechanics assessments, the local effect from the toe is captured in the Mk factor ref. BS7910, for further information see section 2.4.1. On the other hand, the method it is not suitable for code or guidelines procedures because it involves very fine FE mesh models.

Neuber's rule is used to convert an elastically computed stress or stain into the real stress or strain when plastic deformation occurs. The notch stress may be defined as the total local stress at the root of a notch, taking into account the stress concentration caused by the component geometry and local notch, and calculated assuming ideal-elastic material behaviour. Methods for averaging elastic stresses at the notch are still under consideration. The critical distance approach, the high stressed volume approach and the fictitious notch rounding approach are regarded as sound references. In the fictitious notch rounding approach the real weld contour is replaced by an effective one. Different proposals for reference radii exist, e.g. by Radaj (2006) who proposed a fictitious radius of 1 mm to consider microstructural support effect for steel and aluminium. In the guidelines proposed by Fricke (2008a) different proposals for reference radii and associated S-N curves are given, in addition to FE recommendations for the notch stress. Fatigue classes to be used for effective notch stresses calculated as the first principal stresses introducing a fictitious radius of 1 mm are based on FAT 225 for steel and FAT 71 for aluminium (valid for plates with $t > 5$ mm). Despite that the validity of fictitious notch rounding approach has been well proved and is a valid engineering approach, some important questions are still open, regarding the proper value of the fictitious notch radius for shear loading, the effect of mean and residual stresses, the influence of local hardness changes at the notch root and the range of applicability with reference to the extent of the plastic deformation.

A round robin was carried out within the Network of Excellence MARSTRUCT (Fricke *et al*, 2007a) with the objective to quantify the uncertainties related to modelling, stress evaluation and identification of sources of scatter, in order to provide design recommendations for effective notch stress calculation. The study concerns the fatigue strength assessment of a one-sided fillet weld root with non-fused root faces, performed by applying the notch support hypothesis in terms of stress averaging approach and, specifically, by rounding the weld toe or root by a fictitious radius. In Figure  the structure is shown. Two interesting considerations were made: the first one is that, although different modelling techniques were used, the scatter of the results is fairly small; the second is that the element size for reliable notch stress analysis should at least be a quarter of the weld toe or root radius.

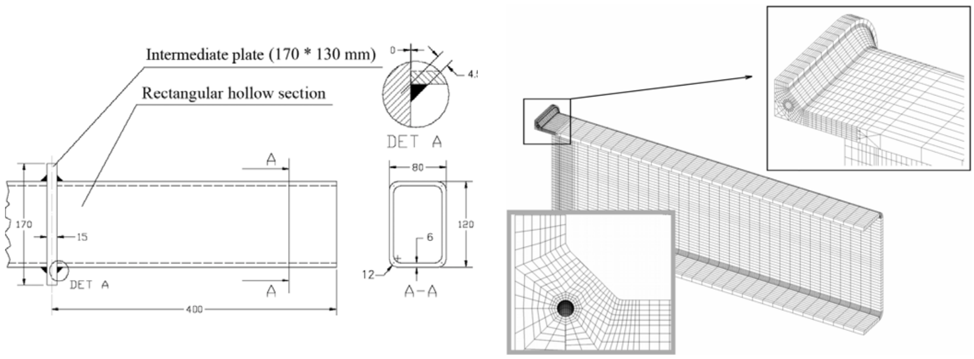


Figure 4: Test specimen geometry and a typical FE model (Fricke *et al*, 2007a)

Park and Miki (2008) investigated the applicability of the effective notch stress approach to fatigue assessment of existing large-size specimens for cruciform joints, diaphragm joints and out-of-plane gusset joints, by considering fatigue crack initiation points, stress distributions and fatigue strengths. By using the maximum principal stress, they show that it is possible to assess whether fatigue cracks will initiate at the weld toe or at the weld root. Fatigue strengths of the existing test results using the effective notch stress approach are above the S-N curve of FAT 300. For out-of-plane gusset joints, the effective notch stresses along the weld root line depend significantly on weld size and weld penetration size.

Fricke and Kahl (2007b) presented fatigue life prediction results on different bracket connections whose fatigue strength is known from tests based on notch stresses. The notch stresses are computed by using coarse-mesh global FE models and 3D and 2D submodels, where the weld profiles have been idealized  or have been derived from the scanned geometry using the laser-based sheet-of-light system as measurement technique. In both cases a fictitious notch rounding has been performed leading to a radius enlarged by 1 mm in the realistic model and a radius equal to 1 mm in the idealized model (worst case approach). The most significant outcome is that the scatter of the endured load cycles is not reduced when using realistic weld profiles, therefore more investigations are necessary to go deeply into the recognition of the effective notch stress. On the other hand, the study confirms that the idealized weld profile is conservative in relation to S-N design curve IIW (FAT 225).

Atzori *et al* (2008a) summarised the guidelines of the notch stress intensity factor

(NSIF) approach and utilised the NIFS to evaluate the averaged strain energy density *W* in a finite size volume surrounding the fatigue crack initiation points as the uniform reference fatigue life parameter. After revision of about 650 fatigue data they present a ΔW-N single scatter band for welded joints made of structural steels, with failures originated both from the weld toes and the weld roots. By using the mean value of the strain energy density in an area surrounding the critical points, they showed that fatigue data from failures originated from both weld roots and weld toes can be summarised in a single scatter band. This was also proven for a complex welded structure (Atzori *et al*, 2008b). Lazzarin *et al* (2007) modelled plane and three-dimensional welded joints under uniaxial loading conditions. FE analysis by using coarse meshes was carried out in order to evaluate mean value of the strain energy density (SED) over a circular sector centred at the weld toe. Evaluation of the NSIFs needs a much more refined FE mesh in order to obtain good accuracy. The maximum difference between the NSIF values obtained from models with very refined meshes and those from coarse meshes was about 5 %.

The demand of a more accurate calculation of the notch stresses based on the real micro and macro local geometry of the welds is pointed out in the study of Farajian-Sohi *et al* (2006), with the purpose of improving the link between weld quality classes and fatigue codes. In the paper a procedure is outlined for digitizing a weld specimen, for converting the unstructured set of points into a surface representation, and for creating a 3D solid element FE model. With reference to two different weld specimens, the stress concentration factors obtained by these procedure have been compared with those calculated by 2D models on the basis of the weld geometry captured by a traditional plastic replica technique. The comparison shows that there is a marked difference between the stress concentration factors and the authors conclude that such result confirms the necessity of an unambiguous definition of the reference notch stress, especially in view of the application of the accurate modern digitizing methods.

### *2.3 Notch Strain Approach (Initiation Phase)*

Like the notch stress approach, the notch strain approach includes weld shape and material parameters. However, unlike the former, it is able to take into account the macrostructural support effect which arises when an considerable local plastic deformation occurs at the notch. Basically, strain based procedures have a better formal consistency and very clearly explain the elastic-plastic mechanism which takes place around a notch root when the elastic constraint of the surrounding material controls the deformations inside such a zone. The notch-strain based assessment shows the same advantages discussed in relation to the stress-based approach. However, inhomogeneity in material and the difficulties in defining suitable models to include the micro- and macro-structural notch support effect can be challenging. With reference to the latter, the highly stressed volume criterion has been successfully applied in plastic-strain conditions. On the other hand, the macrostructural notch support formula has been modified for considering multiaxiality fatigue and for application in case of complete plasticisation of the net section.

Wang *et al* (2006) proposed a fatigue damage prediction method for welded joints in the low-cycle fatigue regime in ship structures. In the paper, a literature review of material behaviour under low-cycle large stress range investigated, and the possible approaches to obtain the strain-life curve are discussed. In the outlined procedure, the hot-spot stress is used and the pseudo hot-spot stress range is derived based on elastic hot-spot stress range and material stress-strain curve with the application of Neuber's hypothesis. A suitable design S-N curve has been derived from tests carried out on non-load-carrying fillet joints under strain control condition. Tateishi *et al* (2007) discuss a local strain based approach to predict the fatigue strength of welded joints in extremely low-cycle fatigue region. Low-cycle fatigue tests were conducted on T-shaped welded joints in order to locate crack initiation sites and to obtain the fatigue life. The local strain field around the welded toe was analyzed by elasto-plastic FE analysis, and the local strain amplitude at the cracking point was quantified. Extensive research on low cycle fatigue has revealed that the strain amplitude at the cracked point, the so called local strain, dominates the low-cycle fatigue life.

### 2.4 Fracture Mechanics Approach (Propagation Phase)

Commonly used Paris and Erdogan fatigue crack propagation law assumes a power relationship between the crack growth rate da/dn and the stress intensity range $\Delta K$. A robust fatigue life assessment is based on proper calculation of $\Delta K$. As long as the crack propagates in a homogeneous stress field, $K$ can be assessed with good accuracy basing upon mathematical solutions. However, for complex stress fields, formulae for $K$ can be difficult to obtain.

#### 2.4.1 Crack Growth Rate Models

To have more accurate calculation of the crack growth rate ($da/dN$) as a function of a single parameter, $\Delta K$, is considered as inadequate. Therefore the idea to express it by two governing forces, $\Delta K$ and $K_{max}$, called "unified approach" is proposed and verified to provide better agreement with experimental data than the single parameter approach, Sadananda and Vasudevan, (2003), Sadananda and Vasudevan (2004), Bukkapatnam and Sadananda (2005), Maymon, (2005), Stoychev and Kujawski (2005).

Stoychev and Kujawski (2008) performed analytical and numerical simulations of the crack-tip stresses and presented two-parameter, $K_{maxTH}$ and $\Delta K_{TH}$, describing the threshold condition for fatigue crack propagation. Vasudevan *et al* (2005) discussed conventional approach assuming reduction of $\Delta K_{th}$ with load ratio $R$ which has been interpreted in terms of crack closure arising from plasticity, oxide or crack surface roughness. The decrease of $\Delta K_{th}$ with $R$ is more dependent on the environmental effects on fatigue crack growth (FCG) than oxide/roughness-originated closure which may be generated by the mechanical-chemical process such as fretting. There is a critical $K^*_{max,th}$ that advances the crack so the criterion for crack propagation is when the applied $K_{max} > K^*_{max,th}$. Noroozi *et al* (2005) predicted the fatigue crack growth by modelling the stress-strain characteristics in the material areas close to the crack tip. Zhang *et al* (2005) observed microscopic fatigue crack growth in the ultra fine grain aluminium alloy IN 9052 and concluded that fatigue crack propagation is caused by the shear band decohesion around the crack tip and proposed a new stress-based parameter d*a*/d*S*. Ma *et al* (2006) analyzed the effect of load angle on crack growth rate and on crack bifurcation angle. On the basis of the experimental data, a mixed-mode crack growth model is proposed to evaluate numerically fatigue crack growth rate, in which the effects of the loading mode and of the residual stresses due to weld are considered.

Nykänen *et al* (2007) investigated the influence of weld toe radius, flank angle and weld size on the fatigue strength of the non-load-carrying cruciform fillet welded joints. They concluded that local geometrical variations of the weld and weld throat size have only a minor effect on the fatigue strength, if the depth of an initial toe crack is greater than 0.2 mm. The local geometrical effects disappear as the depth of the initial toe crack increases. In the analytical study it was assumed that for the as-welded condition, the tensile residual stresses caused by welding are high enough so the crack remains open during the entire loading cycle. For this reason the stress intensity factor range corresponding to the nominal stress range is effective and independent of the R-ratio of nominal stresses. Based on this investigation, a simple equation which expresses welded joint fatigue strength to the weld toe radius/plate thickness ratio was proposed by Nykänen *et al* (2008).

It has been observed that components in service spend approximatly 80% of its life time in the region of short crack growth where the crack length is less than 1 mm. Since flaws of this size are difficult to detect, it is important to understand the high-cycle fatigue in order to prevent small cracks to grow into failure. Several authors have been investigated the phenomena in order to estimate total fatigue life of welded structures. Taylor and Hoey (2008) propose two methods; crack modelling method (CMM) and the theory of critical distances (TCD) for prediction of high-cycle fatigue failure in welded joints. Notches of large root radius could be analysed simply by using the maximum elastic stress range whereas notches of small root radius could be analysed by assuming them to be cracks of the same length. TCD is a method which uses a material constant with units of length, the so-called critical distance L, to predict a variety of phenomena such as the effect of notch root radius, the short fatigue crack effect and other size and scaling effects for bodies containing stress concentration features, described previously by Taylor (2005). Crupi *et al* (2005) carried out a comparison study of different methods for predicting high-cycle fatigue behaviour of welded joints. The methods were, the notch stress intensity factor and crack modelling methods, the critical distance methods (CDM) based on a stress averaging approach with fictitious radius concept and the direct CDM approach commonly known as hot-spot approach. Verification of experimental data from the literature shows, that all four methods give reasonable predictions of endurance limits for a range of weld types in both aluminium alloys and steels. The explicit use of CDM and the point method with FEA was found as an easy method with high accuracy.

The effective driving force applied to a crack can be defined as the difference between the total applied driving force and the material threshold for crack propagation. The fatigue limit of a structure depends on the resistance of the materials microstructural barriers that have to be exceeded in order for a crack to initiate. Chapetti (2008) performed analysis of high-cycle fatigue behaviour of structures containing notches by applying a fatigue crack propagation threshold curve reflecting the short crack influence. Chapetti's model is used to estimate the threshold for crack propagation by using the plain fatigue limit, ΔσeR, the threshold for long cracks, $\Delta K_{thR}$, and the microstructural characteristic dimension (e.g. grain size). The model was compared with published experimental results and showed good agreement.

Smooth specimens cannot be used to predict fatigue life of a notched component. Verreman and Limodin (2008) studied the high-cycle fatigue behaviour of V-notches. Empirical formulas are available to predict the fatigue notch factor $k_f$., depending on the notch tip radius. If the notch tip has a large radius the fatigue notch factor become similar to the stress concentration factor $k_t$. The authors concluded that blunt notches are controlled by crack initiation ($k_f = k_t$) while for severe notches ($k_f < k_t$) short crack propagation was dominating the fatigue limit. Based on the results they proposed a method requiring two S-N curves for a given material; one based on fatigue life of a smooth specimen (material resistance to crack initiation) and a second one containing V-notch effect (material resistance to short crack propagation). Stress singularities are a problem at the tip of a sharp V-notch, Tovo and Livieri (2007). By using implicit gradient approach they could overcome this problem using a linear elastic hypothesis alone. The implicit gradient approach defines an effective stress which assumes a finite value over the whole volume. The implicit gradient approach provides high accuracy of fatigue life prediction and definition of geometrical stress extrapolation at the weld toe (hot spot stress) is not necessary. They also provided a simplified equation to relate the NSIF of mode I to the effective stress opening angle for sharp V-notches. For complex structures, the implicit gradient approach can be used to directly obtain the maximum value of effective stress range and the location of the point where a fatigue crack initiates. As continuation they evaluate the fatigue behaviour of complex structures on the basis of the non-local effective stress defined by an inhomogeneous Helmholtz equation, Tovo and Livieri (2008). They concluded that the implicit gradient approach can reduce the assessment of fatigue strength in mixed objects to simple estimation of the peak value of an effective stress obtained by implicit gradient over all the components.

Kim (2005a) investigated fatigue propagation and fatigue life of weld root cracks under mixed mode I and III. Depending on the initial mode I stress intensity factor (SIF) range branch and/or co-planar crack propagation was observed. The observed fatigue life for branch type crack propagation was longer than that of co-planar one, Kim and Kainuma (2005b).

In order to combine normal and shear stresses, Kim and Yamada (2005c) proposed to use an equivalent stress range, Δσr cos αfor fatigue life evaluation. They extended the

Paris's law to include both Mode I and Mode III loading in order to derive an equivalent stress intensity factor. The results were compared with three types of published fatigue data and their proposed approach, irrespective of the principal stress direction, resulted in appropriate fatigue evaluation. The proposed equivalent stress range can therefore be applied for fatigue life evaluation when normal and shear stresses are combined.

Noroozi *et al* (2006, 2007) developed a fatigue crack growth two-parameter driving force model , $\Delta k = K^{p}_{\max,\mathrm{tot}} \Delta K^{1-p}_{\mathrm{tot}}$ which account for residual stress and stress ratio effect on fatigue crack growth. The maximum stress intensity factor and the stress intensity range are combined, and with some correction of applied stress intensity factors due to due to the effect of plasticity induced residual stresses near the crack tip, a master fatigue crack growth curve was derived. Three different crack driving force models were proposed and compared and verified using fatigue crack growth data obtained for an aluminium alloy, a steel alloy and a titanium alloy with load ratios, R, ranging from -1 to 0.7. The driving force model that best fitted the results was $\Delta k = K^{p}_{\max,\mathrm{tot}} \Delta K^{0.5}_{\mathrm{tot}}$.

### *2.4.2 Various Special Phenomena relating to Fatigue Crack Propagation*

Anami and Sause (2005) performed FEM analyses and simple crack propagation analyses which only considered I-mode of crack propagation in a web-flange weld of corrugated web girders in order to estimate the fatigue strength. They studied the relationship between different locations of point of initiation and fatigue properties. They found interaction between presence of longitudinal folds on webs and relationship between radius of bend and fatigue properties and proposed some simplified formulas for fatigue-life assessment of such geometries. However, since these formulas are based on limited number of analyses only, they should be fully validated for other design cases in order to be applied. Susmel and Tovo (2006) tested under uniaxial fatigue load a cylindrical stiffener on a plate and a tube through a hollowed plate, both circularly welded. They observed that crack initiation sites changed their position as the number of cycles to failure increased. The observed phenomena of the investigated welded joints was then theoretically assessed from a multiaxial fatigue point of view by applying the Modified Wöhler Curve Method in terms of hot-spot stresses and good precision in estimate both crack initiation sites and fatigue lifetime was reached.

It is often a challenge for designers that analytical models available for stress concentrations factors used for fatigue or crack growth analyses are conservative and often do not represent the geometry in question, therefore an effort has been taken to carry out comparison studies. Yang *et al* (2007) analysed fatigue crack growth of a square hollow section (SHS) T-joint, using the 3D boundary element method. The numerical results were compared with previous experimental crack growth data, the results showed good agreement where the numerical results were slightly on the conservative side. Fatigue life was estimated using the Paris' law where the numerical and experimental crack growth data was applied, The results were compared with standard S-N curve approach. The S-N curve showed conservative estimation of life and the authors recommend using the 3D boundary element model to simulate crack growth under the weld toe of the SHS T-joint. Bellett and Taylor (2006) carried out work on fatigue behaviour of complex, three-dimensional stress concentrations which cannot be modelled as simple two-dimensional notches. Previous work by Bellett *et al* (2005) had concluded that errors arise when two-dimensional geometries are applied to certain type of three dimensional geometries. Therefore experimental methods based on four different 3D welded and machined geometries were compared with the Point method and the Line method. The comparison showed for some of the cases these methods were conservative and a factor of 2 on predicted fatigue limit stress range were seen. The authors proposed correction factors in order to reduce some of the conservatism, however they could not completely eliminate the difference from experimental and the predicted results.

Fatigue cracks normally initiates from the weld toe for non-load-carrying joints where for load-carrying joints the initiation can start from both the toe or the root for filet welded cruciform joints. Kainuma and Mori (2007) carried out a study on fatigue crack initiation site where they investigated the effect of stress range, residual stresses and weld size. They concluded that initiation site depends on the magnitude of the stress range, e.g. with large stress ranges the initiation often started at the root, where for lower stress range the initiation site is the toe when the residual stress were taken into account. The residual stress is tensile in the toe area and compressive in the root area. Test data also showed that the critical leg size ratio of a load-carrying fillet welded cruciform joint was 1.2, above this value the failure occurred at the weld toe.

### *2.4.3 Unstable Crack Propagation*

Unstable crack propagation is the final stage of the Paris crack growth curve and known for the rapid unstable growth of a crack. Mahmoud and Dexter (2005) have studied propagation of large cracks from five half-scale welded stiffened panels under cyclic tension fatigue tests. The details were typical ship details and the goal was to investigate the propagation of the cracks as they interacted the stiffeners. To simulate the crack propagation, stress intensity factor ($\Delta K$) determined with either a finite-element analysis or an analytical model at increments of crack length was applied in a linear elastic fracture mechanics analysis. Residual stress measurement was conducted and included in the analysis. Numerical calculation gave reasonable agreement with the experiments and show little sensitivity to stiffener type. The models developed in this project can be used to assess the remaining life of stiffened panels where large cracks are present. Holtam *et al* (2008) investigated the crack growth in sour service environment and found that shallow cracks can grow with a speed of 130 times the growth in air. They also noticed that once rapid unstable crack propagation starts, hydrogen can no longer keep pace with the growing crack. Therefore the resistance to rapid crack propagation increases with increasing propagation rate.

## ***2.5 Fracture Mechanics Evaluation for Strains larger than 0.5 %***

Current fracture mechanic assessment procedures, e.g. BS 7918, R6, API 579 and API 1104 are not specifically developed to handle strain > 0.5%. The industry has used a longitudinal tensile strain limit of 0.5 % in order to prevent fracture initiation and plastic collapse from circumferential weld flaws small enough to have been accepted by specifications like workmanship criteria or results from engineering critical assessments (ECA). However, pipelines have been designed for strain in the magnitude of up to 4 % due to reeling or environmental loads such as e.g. grounding, ice scouring and gouging, seismic loading and bottom snaking. The design demand is displacement controlled, e.g. the design allows the pipeline to displace/move such that the pipes operate in the plastic region. Due to safety issues high pressure gas pipelines are recommended to be buried, however due to soil movements the pipe will see large displacements, and the design criterion is to prevent failure for such conditions.

There has been a tremendous effort the last years, especially within the offshore industry where several strain based pipeline projects have been constructed or are under planning, in order to develop guidelines and procedures that handles high strain. Two projects that have been run in parallel are PRCI and Sintef/DNV/TWI and the output from the last one was the basis for the DNV-RP-F108 "Fracture Control for Pipeline Installation Methods Introducing Cyclic Plastic Strain" (DNV, 2006). This recommended practise can be used for reeling applications where high strain is introduced, however it does not cover/include the effect of bi-axial stresses from e.g. internal pressure. The latest edition of CSA Z662 allows for up to maximum 2.5 % permissible installation strain in the pipe wall.

Frequently, degradation of the pipe capacity has been discovered and addressed due to the internal pressure, Tyson *et al* (2007), Gioielli *et al* (2007) and Østby (2007a). Sintef and DNV started up a phase 2 of the Fracture Control JIP in 2008, in order to cover the operational phase and including the effect of biaxial stresses. The PRCI (Pipeline Research Council International) was initiated in 2006 to examine the effect of internal pressure on tensile strain capacity. The objective of both programs has been to validate numerical models with results from full-scale test data and to develop future predictive models. The projects concluded that the reduction of tensile strain capacity came from the increase in crack driving force when internal pressure is applied and that ductile crack growth resistance does not change with the application of internal pressure. The strain capacity observed from full scale tests has been reduced by a factor of up to 2 when internal pressure is assumed for pipelines that have circumferential planar defects.

Lately there have been several pipeline projects that have been designed for high strains. Several methods have been applied in order to validate the different concepts, e.g. finite element models, small scale tests, wide plate tests and full scale tests, Hukle *et al* (2005). Test programs proposed in order to carry out engineering critical assessments for strain >0.5% are comprehensive and costly. Therefore a simplified strain based fracture assessment model was proposed by Østby *et al* (2007a), based on an assumed linear relationship between the increment in the CTOD and the applied strain. This model has been verified by small and large scale experiments and compares well with the results from these. However, the model does not account for Lűder plateau in the material stress strain curve, nor does it explicitly account for embedded defects. Østby (2008), presented results from experimental investigations and numerical modelling of strain capacity of SENT specimens with defects in both the base material and weld metal. Two techniques were compared; multiple specimen technique (resistance curve is obtained by loading 6 specimens to different load levels) and a silicone replica technique (at different load levels the loading is stopped, and a new silicone replica is made). They concluded that for the notch geometry studied, the silicone technique appeared to give a more accurate representation of the CTOD vs. the crack extension, compared to the multiple specimen technique. From the study they concluded that weld metal overmatch can lead to increased strain capacity for defects located in the middle of the weld metal. Fusion line was not tested. From the FE study they saw that non-conservative predictions of strain capacity could occur when the effect of ductile tearing was not accounted for in the fracture assessment. The same effect was reported by Gioielli *et al* (2008). They monitored local tearing at notches in two full scale pressurized pipes (40 % SMYS and 80 % SMYS) in combination with finite element analysis in order to predict stable tearing. They observed that ductile tearing typically initiated at around 50-60 % the strain capacity of the test samples. Tearing initiated at lower strain levels when higher internal pipe pressure (80 % SMYS vs. 40 % SMYS) were applied. Tearing analysis was carried out by Minnaar *et al* (2007) in order to estimate the strain capacity of a welded pipeline. There have been discussions within the industry, regarding the need to perform tearing analysis as opposed to use a more traditional critical toughness value, such as, critical Crack Tip Opening Displacement ($CTOD_{critical}$), as the failure criteria. However, Gioielli *et al* (2008) suggested that accurate accounting of stable tearing should be included in future efforts to develop stain capacity prediction methods.

Østby *et al* (2006) presented finite element results that showed a significant effect of biaxial loading on the crack driving force, this force was also seen to be influenced by yield stress mismatch and misalignment. A set of simplified strain based fracture mechanics equations were presented which transfer the biaxial loading, yield stress mismatch and misalignment to an equivalent case with a homogeneous pipe. Full scale strain testing was conducted on 12” pipes with and without pressure to evaluate the analytical results of internal pressure, Østby and Hellesvik (2007b). Artificial surface flaws (aimed size 3x100 mm) were introduced in the pipe. The results show that internal pressure reduces the failure strain significantly. This is due to the increased driving force due to biaxial loading. The same effect was seen by Gioielli *et al* (2007).

Sandvik *et al* (2006) carried out probabilistic assessment for ductile tearing calculations for a strain based pipelines with surface defects. To establish the critical strain, the tangency criterion was used for the ductile tearing analyses. The author concluded that FORM gave more conservative results than SORM, however the difference was marginal

The PRCI projects tested 8 full scale 12.75”, t = 0.5” API 5L X-65 pipes, 4 including girth welds, Wang *et al* (2008). The results showed a reduction in strain capacity of approximately 2 comparing pressurised pipe to non-pressurised pipes, see Table 2.

Table 2
Summary of the tensile strain capacity determined from full-scale tests

| Test Specimen | Tensile Strain Capacity (%) | | Strain Capacity Reduction Factor by Pressure |
|---|---|---|---|
| | No Pressure | High Pressure | |
| High Y/T Plain Pipe | 2.0 | 0.9 | 2.2 |
| Low Y/T Plain Pipe | 2.8 | 1.6 | 1.8 |
| High Y/T Pipe, Weld Centerline Flaw | 4.8 | 1.7 | 2.9 |
| High Y/T Pipe, HAZ Flaw | 8.6 | 4.9 | 1.7 |

Gordon *et al* (2007) present the results of a finite-element study of pipeline girth welds subjected to high strain in order to evaluate the effect of biaxial loading on the crack driving force response of fusion line surface flaws. The FEA results confirmed that biaxial loading (due to internal pressure) can have a significant effect on crack driving force and the results indicated that the maximum biaxial effects occur at a pressure induced hoop stress of approximately 50% of the (SMYS). It was also seen that the effects of the biaxiality diminish when the pressure induced hoop stresses increased above 50% SMYS. Based on the analyses, they advised that HAZ softening should be minimized by placing limits on maximum weld heat input and parent pipe chemistry.

Girth welds are the weakest link in strain-based design pipelines since they contain natural defects and contain less resilient microstructures compared to linepipe steel. In addition there are local stress concentration factors due geometric eccentricities like high-low misalignment and the weld geometry itself. In order to obtain high strain resistance, weld metal with high tearing resistance is crucial and generally increases with decreasing grain size and oxygen content. Welding processes using low heat input also provides better strain properties than high heat input processes that involves fluxes in the consumable and/or $CO_2$ in the shielding gas. However, high heat input is often chosen since fluxes are typically associated with high productivity. Fairchild *et al* (2008) studied the effects of different welding process on X80 girth welds in order to achieve high strains. They concluded that typical SMAW electrodes should be enhanced for high-strain X80 applications. The effect of overmatching the welds in order to obtain good strain properties is a known phenomenon however; with increasing strength in the base material the demand for higher weld strength decreases the tearing resistance of the weld metal. Motohashi and Hagiwara (2007), investigated the yield strength (YS) matching on the strain capacity of miss-matching girth welded pipelines subjected to uniaxial strain, based on finite element of CWPT in order to clarify the strength matching dominating the strain capacity. They concluded that the tensile strength (TS) matching was a more important factor than the YS matching on the CTOD crack driving force.

### *2.6 Relation ship between S-N and Fracture Mechanics Approaches*

The S-N approach is a suitable method for fatigue assessment of welded components or structures when fatigue life may be defined as a crack not exceeding a physically short crack (i.e. maximum 10 grains long). Fracture mechanics may, however, always be applied presumed that all necessary material data is available to carry out a micro-structural fracture mechanics analysis, elasto-plastic fracture mechanics analysis and/or a linear-elastic fracture mechanics investigation. The former two fracture mechanics based approaches are not practically to apply on ship and offshore structures in the design phase, and hence, they will not be discussed further here. Instead, two examples of models that attempt to link the S-N and linear-elastic fracture mechanics approaches are mentioned.

Inspection planning and maintenance can successfully be designed by means of fracture mechanics approaches if the length of the crack used in the assessment is known at the outset. If, however, this crack length is unknown and has to be assumed, the inspection planning will be very uncertain. Serror *et al* (2007) have therefore proposed a methodology called SAPHIRS which links the S-N and linear-elastic fracture mechanics approaches in the fatigue evaluation. The S-N approach is applied to assess where in the structure the most fatigue damage is accumulated during fatigue loading conditions. It is referred to here as multi-crack initiation and can be performed using a local approach, Petitpas *et al* (2000) taking into account the residual stress fields, notches and plastic corrections. When the criterion for fatigue failure according to this approach is fulfilled, a linear-elastic fracture mechanics analysis follows. In this analysis, the displacements of the crack lips are assumed to determine the conditions and factors governing crack propagation. If used in numerical procedure using the FE method, the technique does not need successive re-meshing along the crack path. A "line spring method", Desvaux (1985), is used to calculate the stress intensity factors and it allows for taking into account the stiffness variation during crack propagation, which is impossible for analytical solutions, without re-meshing. The methodology proposed by SAPHIRS has the capacity to make predictions of arbitrary crack path growth and predictions made by the methodology have been validated by experiments made on an industrial welded structure, Lebaillif *et al* (2005). A similar methodology called the two-phase model (TPM) was proposed by Lassen and Recho (2009) who carried out fatigue analyses of fillet welded joints. A period of crack occurrence is represented by a deformational approach using the Coffin-Manson equation with Morrow's mean stress correction and Ramberg-Osgood cyclic strain curve. The crack propagation period is modelled by integration of the Paris law with a simplistic representation of the stress intensity factor for mode I crack growth. The TPM approach has been compared with some test data. The non-linear S-N curve obtained from the TPM coincides with the conventional S-N curve predictions at high stress levels, but fits the experimental data near the assumed fatigue limit far better than a traditional bi-linear S-N curve. As a result, the authors conclude that their model contribute to more precise fatigue life predictions, especially at low stress levels.

### *2.6.1 Fracture Data by Testing*

A reliable and accurate fracture mechanics evaluation requires detailed knowledge of the material in question like the yield and tensile stress, the amount of residual stress and the material toughness. The fracture toughness is the material's ability to absorb energy in the plastic range and it increases with increasing temperature and decrease with increasing strain rate or rate of loading. For designers, the goal is to select material with sufficient toughness measured by e.g. (CvN, CTOD, SENT, J-R, Kmat) when subjected to service loads and environments in order to ensure that the component does not fail in brittle behaviour, see section 5.1.1. The fracture toughness is strongly dependent of the geometry and loading conditions. The standardised toughness specimens as Charpy and SENB have high clamping forces at the crack tip (constraint) and will give low fracture toughness values, see Figure 5.

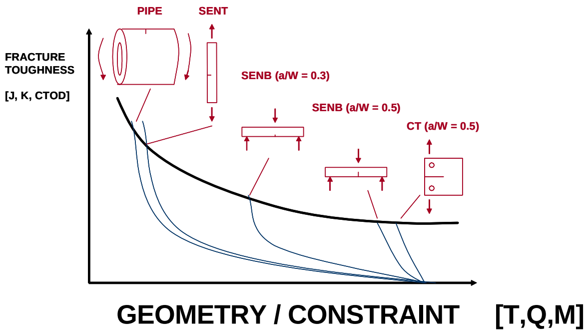


Figure 5: Facture toughness compared by the constraint level for different specimens, Nyhus *et al* (2001).

The fracture toughness tests are normally small scale tests, and conventional fracture mechanics assumes that the structural component containing a flaw exhibit the same fracture resistance as small scale laboratory fracture toughness specimens. It will therefore always be a discussion of how small scale tests can be considered to represent the component or structure in question. Minami *et al* (2007) present a procedure which account for the constraint loss when transferring the CTOD fracture toughness obtained from a small scale specimens to an equivalent CTOD value for the structure.

SENT (single edge notch tension specimen) is known to display a similar ligament deformation pattern and constraint level as found for cracks in pipes. According to Nyhus *et al* (2003) the test is popular especially if the strains are introduced due to reeling of a pipeline, see Section 2.5. However, there is still no common guideline on how to measure CTOD from SENT and further research is needed. Cravero *et al* (2008) investigated if the crack tip constraint in pipes subjected to external load and internal pressure could be based on SENT specimens. They made several finite element models and carried out several finite element analyses and found only small differences in the results and concluded that the resistance curve from uniaxial loading also can be applied for biaxial loading.

Fracture behavior of ferritic steel is dependent both on temperature and specimen size. Brittle fracture occurs at low temperature as a cleavage mechanism while at higher temperature ductile mechanics of voids nucleation. Increasing the thickness of the test specimens decreases the fracture toughness value, Rathbum *et al* (2006). Cleavage fracture toughness can be analyzed based on the Master Curve concept also incorporated into ASTM E1921-97. The master curve is a normalized curve of median fracture toughness of 25 mm thick deeply cracked specimens versus temperature in the ductile-to-brittle transition region, further details and validation of the curves are provided by Wallin (2002). The curve is based on macroscopically homogeneous materials, a bimodal distribution was proposed by Wallin *et al* (2004) which can be used for HAZ fracture toughness.

Statistical procedures have been derived lately in order to estimate the probability of cleavage fracture as a function of temperature, specimen thickness and ductile crack growth. Sumpter and Kent (2006) carried out fatigue tests at cold temperatures (-50°C) in order to investigated the probability of cleavage fracture when a fatigue crack is propagating thorough a structure under cyclic loading. They concluded that the results did not show an increased probability of fracture compared to standard monotonic loaded tests which could be due to limited number of tests, constraint effect and load effect. Rathbum *et al* (2006) carried out experimental study to systematically measure constraint loss on different specimen thicknesses and width in order to investigate the effect on the measured cleavage initiation fracture toughness in the transition regime. An empirical analysis showed that high constraint toughness scaling with the thickness (B) is reasonable consistence with ASTM E1921. Trondskar (2004) carried out two case studies on pipeline weld flaws using deterministic and probabilistic fracture mechanics analysis using constraint correction. By introducing constraint modification for the pipe, the probability of failure decreased significantly.

A probabilistic model of cumulative failure by cleavage based on the weakest link model was applied in order to anlayse experimental toughness data based on SENB specimens, Faleskog *et al* (2004). They concluded that the probabilistic model captured the fracture toughness data scatter in addition to constraint effect and predicted a fracture toughness threshold value.

Wide plate tests have been applied for several decades in order to assess weld defects, since the late 70-ties the curved wide plate tests (CWPT) have been popular in order to asses pipeline girth welds defects. The specimen is pulled in tension until failure occurs; the size of the plate shall be large enough in order represent the structure itself. Around the 90-ties the CWPT was used to address the capacity for girth welds subjected to loads in the plastic region, this was carried out at the University of Gent. However, the first publication of strain based design based on CWPT was published in 2002 by Denys *et al* (2002). Fairchild *et al* (2007) carried out 26 CWPT with girth weld for X80, X100 and X120 steel. Previous to the tests, the size of the CWPT geometry had been optimized to a ratio of 3:1, see figure below for test set up.

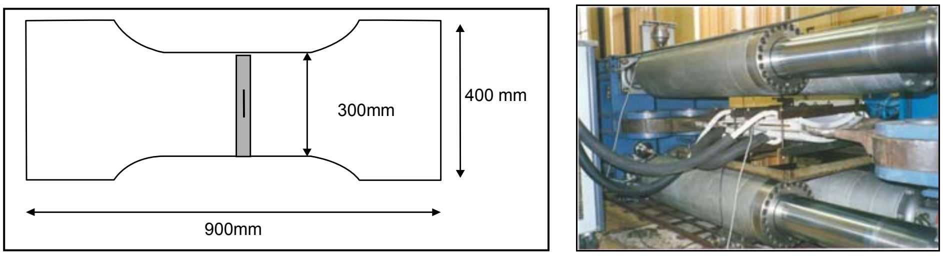

Figure 6: CWPT specimens geometry and test machine (Fairchild *et al* 2007)

The CWPT's were carried out at -20°C, compliance measurement, in combinations with FEA, were used to quantify crack growth tearing resistance in the CWPT specimens. The tearing resistance results from the CWPT and small scale test showed a large difference, where the SENB (single edge notch bend specimen) provides to be more conservative. Unloading compliance and finite element analysis were used to assess crack growth and tearing resistance in the CWPT and the tests showed that the cyclic loading did not affect measured strain capacity.

In ASTM E1820 a procedure for crack growth measurements based on small scale testing are given, however no standard procedures are available for large scale test. Minnaar *et al* (2007) presents an unloading compliance methodology to measure ductile crack growth of flaws machined in full scale structures deformed to large plastic strain. The method converts experimental measured compliance history to crack growth history and FEA analyses were used to develop compliance transfer functions. It is recommended that a standard procedure is developed in order to derive crack growth from large scale testing.

## 3. PROBABILISTIC APPROACHES AND MULITIAXIAL FATIGUE

### *3.1 Probabilistic Approach*

Since the past two decades probabilistic approaches for fatigue have become more common. Two different approaches are often considered to describe the fatigue limit state; S-N curve with Miner's damage accumulation rule or fracture mechanics based approach. In the probabilistic analysis the uncertainties of all the influencing parameters for fatigue are taken into account by treating them as basic variables in the analysis. One of the main challenges is to obtain the necessary statistical information of these variables. Additionally, the probabilistic analysis requires reliable mathematical models to describe the statistical variation of the parameters, which are often based on a limited amount of measured data.

For both probabilistic S-N and fracture mechanics approaches, the appropriate modelling of the structural response due to fatigue loading is an important issue.

Schmidt *et al* (2008) presented the methodology for the evaluation of the slamming loads and the fatigue lives for stiffened panels of an offshore structure subjected to random wave slamming. Time histories for the air gap, relative velocity, angle between the surface of the water and the bottom plating of the fairlead support structure were generated with the use of the RAOs from the motion analysis of the offshore unit within a particular sea-state and simulation. When a slam was detected, the semi-empirical method, calibrated with model tests on ocean basin was used to predict the peak slamming pressure. The fatigue lifespan was estimated in a complete stochastic method. Olagnon and Guédé (2008) focused on the calculation of fatigue damage due to large numbers of different load spectra. According to the mathematical definition of rainflow and statistical properties of the Gaussian process, they provided theoretical formulas to estimate the fatigue damage from spectral parameters. The presented methods contribute to the damage modelling in the case where the load spectra are composed of one or several narrow-band low-frequency and high-frequency loads. Practical demonstration of the developed formulas was carried out, and the results were compared to the results obtained by the existing formulas. Gupta *et al* (2006) studied fatigue damage in randomly vibrating jack-up platforms under non-Gaussian loads, where the wave excitations were modelled as a stationary with a specified power spectral density function. Morison's equation and theories of random vibration were adopted to calculate acting loads and the structural response, respectively. The proposed method used the simple peak counting method to estimate fatigue damage, and it was presented as an alternative and computationally cheaper technique in comparison to the Monte Carlo simulation procedure.

### *3.1.1 Probabilistic S-N Approach*

Probabilistic S-N fatigue assessment methods for offshore structures were reviewed by Muhammed and Stacey (2008). They examined the factors affecting the uncertainties in the fatigue life prediction of welded joints. The study reviewed state of the art references, and gave recommendations on appropriate statistical distributions for probabilistic fatigue S-N analysis. The reanalysis of the existing data showed that fatigue life predictions for offshore structures are mainly dominated by uncertainties in the estimation of nominal stress and stress concentration factor. Other influencing variables are related to the modelling of the fatigue strength with S-N curve and Miner damage summation. Zhao and Yang (2008) reviewed different approaches to determine the probabilistic value of fatigue limit. Limitations of different approaches were discussed with respect to their supporting theoretical background. The studied approaches did not strictly match the primarily condition for probabilistic fatigue limit i.e. a given fatigue life. A new approach based on the maximum likelihood method was developed and validated with test results of two different steel grades. Koller *et al*. (2009) presented the experimental validation of a statistical model for S-N curve corresponding to any stress level and amplitude. The proposed model originally proposed by Castillo *et al*. 2009 is based on sound physical and statistical properties. Their validation results seem to confirm the applicability of the model providing linear and non-linear trends for S-N curves, including the percentile curve shapes. Pollak and

Palazotto (2009) compared different probabilistic models to support fatigue design in the ultra high-cycle fatigue range. The random fatigue limit model and two simplified models with bilinear and hyperbolic S-N curve shapes were fitted to the experimental data of a titanium alloy, and probabilistic stress-life curves were presented. The bilinear and hyperbolic models were recommended for materials, which exhibit a sharp transition between constant slope and horizontal fatigue limit behaviour with relatively constant fatigue strength scatter over the testing range.

### *3.1.2 Probabilistic Fracture Mechanics Approach*

Fracture mechanics models are commonly applied to assess the effect of an inspection and repair strategy of structures degrading due to crack growth. One of the main challenges is that the probabilistic fracture mechanical approaches often need to be calibrated based on the S-N curves. This is due to the crack initiation and because initial stages are subjected to uncertainties which are difficult to quantify. Ayala-Uraga and Moan (2007) studied various alternative S–N and fracture mechanics formulations for welded joints in ship and offshore structures. They included both linear and bi-linear crack growth laws. The calibration of the fracture mechanics approaches was based on the crack initiation time, initial crack size and the crack aspect ratio. They recommended that both segments of crack growth are highly correlated with each other in order to be conservative, when the bi-linear crack growth law is applied. The definition of reliable initial crack size for fracture mechanics-based life prediction was studied by Liu and Mahadevan (2009). They proposed a new methodology to calculate the equivalent initial flaw size distribution. Their methodology was based on the Kitagawa-Takahashi diagram applying only the fatigue limit and the fatigue crack threshold stress intensity factor. Thus, the proposed methodology was independent on applied load levels unlike the commonly used back-extrapolation method. The developed methodology was illustrated with probabilistic crack growth analysis, and the predictions were compared with experimental observations for various metallic materials. Harlow *et al* (2006) presented a crack-growth-based probability model for fatigue life prediction for the ultra-high-cycle fatigue range covering two distinct mechanisms for the nucleation and early growth of fatigue cracks. The traditional S–N and fatigue crack growth approaches were related through one plausible explanation of the damage evolution processes. The proposed approach was assessed through comparisons with an extensive set of fatigue life data for SUJ2 steel. The connection between the crack growth model and S–N curve, the impact of residual stresses, and the distribution between external and internal nucleation sites were examined, and discussed. Grooteman (2008) presented a stochastic life approach as an alternative to the current deterministic and partially stochastic approaches. The proposed approach based on the constructed failure distribution form experimental or service data. The determined failure distribution was applied to reverse crack growth analysis to obtain the initial inspection time and corresponding crack length distribution. Then the forward crack growth analysis was utilised to determine a schedule for repeated inspections. The methodology was illustrated with an aircraft component, and results were compared to the results of the deterministic analysis. The method contributes to economical inspection planning.

### *3.2 Multiaxial fatigue*

The influence of multi-axial fatigue design procedures has taken steps forward in the ship industry by adopting new criteria in the fatigue life prediction models. With existing commercial computer softwares, different interpretations of the critical plane concept (i.e. the material plane which accumulates the most fatigue damage during load cycling and where crack occurrence and initial growth is assumed to take place) has been implemented and are widely used and adopted in multiaxial fatigue assessments.

In Susmel *et al* (2005) several multi-axial fatigue criteria were reviewed with respect to their definition of accounting for mean stress effects and interpretation of the critical plane concept related to the physics behind crack occurrence and growth. Susmel (2008) reformulated the so-called “modified Wöhler curve method” (MWCM) in order to more efficiently account for the detrimental effects of non-zero mean stresses perpendicular to the critical planes. Correction factors for various materials sensibility to mean stress effects on critical planes were denoted as “mean stress sensitivity index” and assumed to be material constants that can be obtained by appropriate experiments. The MWCM was applied and its accuracy was studied in estimations of multi-axial high-cycle fatigue damage under non-zero mean stress and under non-proportional loading conditions. It was also applied to study the high-cycle fatigue strength of notched samples tested under in-phase bending and torsion with superimposed tensile and torsional static stresses. It was shown that this new method correctly predicted high-cycle fatigue damage in the presence of stress concentration phenomena.

Shariyat (2008) proposed a fatigue damage model applicable to multi-axial stress-based fatigue design based on a new numerical algorithm to identify the critical plane. The model is examined for general cases in particular with non-proportional random loadings and complicated geometries. Experimental results were presented for validation against both proportional and non-proportional loading cases. In addition, Ninic *et al* (2007) present a multi-axial fatigue damage function that incorporates an algorithm for search of the most critical plane. Numerous load cases incorporating variations in mean stress were evaluated using the Gerber criterion on the critical plane. The fatigue damage function proposed showed accurate high-cycle fatigue strength prediction compared to methods proposed by Gough and Pollard, Carpintieri and Spagnoli, and McDiarmid. Jen *et al* (2008) assessed the fatigue life of butt-welded joints under oblique loading by using local approaches. Finite element calculations were carried out to obtain the local stress at the weld toes. Four multi-axial fatigue prediction models were utilised to evaluate the fatigue life of the butt-welded joint, where the Findley criterion produced the best prediction.

Reis *et al* (2006) studied several proportional and non-proportional loading paths with different intensities and the same ratio between shear stress and normal stress, concerning the goal of same von Mises equivalent stress. Experimental tests were carried out on a biaxial testing machine and specimens were made of three materials:

CK45 normalized steel, 42CrMo4 quenched and tempered steel and the stainless steel AISI 303, with six different biaxial loading paths. Meanwhile a numerical method was implemented in a spreadsheet using several multi-axial fatigue methods, such as the critical plane models and also the energy-based critical plane models, in order to determine the critical plane orientation for each different loading path, respectively. After specimen failure, fractographic analyses of the fracture surface, on the plane of the stage I crack propagation, were carried out and once identified the local of crack initiation, crack orientations were measured using optical microscope. Comparisons of the predicted orientation of the damage plane with the experimental observations show that the shear-based multi-axial fatigue models give good predictions for stage I crack growth for the ductile materials presented.

## 4. FACTORS INFLUENCING FATIGUE

Fatigue damage is one of the most important failure modes in structures such as ship and offshore structures, which are subject to dynamic variable amplitude loading. A large number of factors affect the fatigue damagelike:

- Mean stresses and their redistribution
- Residual stresses
- Loading of the structure including load sequences
- Thickness of the structural joints
- Corrosive environments and temperature of the surroundings
- Design
- Fabrication and methods for improving fatigue performance
- Sensitivity of the material

Each of the above factors will be discussed in the following sections. In general, the description of fatigue strength of structures can be divided into fracture mechanics-based (fatigue crack growth behaviour) and S-N based approaches (stress-life behaviour). This division is therefore introduced in the following when appropriate.

### *4.1 Residual and Mean Stress Effect*

The mean stress in offshore and ship structures is composed by residual stresses from fabrication and mean stresses introduced by loading from e.g. eigen-weight and prevailing sea-state conditions. The actual level of mean stress affects the fatigue life, i.e. fatigue strength decreases as the mean tensile stress increases. Under compressive mean stress the fatigue life of the structures is increased, see e.g. Zhang and Moan (2006). In McClung (2007), a broad and extensive literature survey is presented which addresses among others the stability of surface and near-surface residual stress fields during fatigue, including redistribution and relaxation due to static mechanical load, repeated cyclic loads, thermal exposure and crack extension. Primary attention is given to residual stresses resulting from manufacturing operations. In section 6.1.2.1 the residual and mean stress effects included in the ship rules are discussed.

### *4.1.1 Fracture Mechanics-Based Approach*

It has been shown that crack growth constants applied in the Paris equation differ for various *R*-ratios even for the same material, which makes it troublesome to predict crack growth under variable amplitude loading. To overcome the problem, Huang and Moan (2007) proposed a crack growth model which can condense data under different R-ratios to the curve corresponding to $R = 0$. Knowing that not only the stress intensity range but also the actual stress intensity levels influence the crack growth, it is of major importance to evaluate crack growth behaviour in residual stress fields introduced by e.g. fabrication procedures such as welding and/or residual stresses introduced by overloads. LaRue and Daniewicz (2007) used an elasto-plastic finite element based approach to evaluate crack growth starting from the edge of a hole in a specimen. The specimen was exposed to an overload introducing compressive residual stress at the edge of the hole. Crack growth predictions from simple analytical superposition methods were compared to experimental results and the results calculated by a finite element based approach. It was concluded that crack growth predictions in the presence of residual stress using simple elastic superposition are relatively accurate.

Jo *et al* (2007) considered the effect of redistribution of residual stresses introduced by an overload as a crack propagates in the residual stress field. The shakedown of crack growth was related to the plastic zone in front of the crack tip applying an effective stress intensity factor. The plastic zone and the redistribution of residual stress were analysed using an elasto-plastic finite element analysis. Experimental crack growth data for a compact tension (CT) specimen was related to crack growth predictions based on effective stress intensity ranges showing good agreement. Richard *et al* (2008) compared in numerical analyses several fatigue crack growth models with respect to their capacity to predict crack velocity (crack growth rate) and crack configuration (crack path) considering the influence of residual stresses and mixed-mode loading conditions. The models were applied on three-dimensional structures such as machine components. Mann (2007) compared various equations to account for the mean stress dependence of crack propagation data. The equations were fitted to three aluminium alloys and their applicability to those materials is discussed. Two equations were applied for the description of near threshold data for an aluminium alloy. A new equation that accounts for the mean stress dependence of crack propagation data was proposed and its excellent applicability was demonstrated.

Okawa *et al* (2006) present a methodology developed for the analysis of multiple fatigue cracks propagating in a three-dimensional stiffened panel structure. The fatigue crack life can be predicted numerically by taking into account the interaction of multiple cracks, load shedding during crack propagation and welding residual stresses. The methodology is illustrated by studying the fatigue propagation in longitudinal stiffeners of a ship structure comparing the numerical results with experiments. It is shown that crack propagation may change considerably depending on the loading conditions, structural details and residual stress distributions. It is proposed to apply the methodology for realization of rational fatigue crack management if it is possible to estimate the fatigue crack propagation behaviour during the ship lifecycle. Zhang and Moan (2005) studied the remaining life after through-thickness crack at typical joints in the deck and bottom structures of FPSOs. Both analytical and finite element simulations were carried out. The finite element simulations considered the effect of residual stresses and the J-integral approach was used to determine the stress intensity factor at the crack tip during different stages of crack growth. A Paris-type crack growth relationship was used to predict crack growth. The effect of welding residual stresses on fatigue behaviour was considered by the adoption of an effective stress intensity factor concept. The conclusion is that stable crack propagation can be conservatively predicted by using relatively simple approaches.

Cui *et al* (2007) presented a two-parameter model for fatigue crack propagation analysis of marine structures. The fundamental assumptions made in the model are: (1) the true material behaviour is represented by the long crack growth properties, (2) fatigue damage must be described by two driving force parameters $\Delta K$ and $K_{max}$ instead of one, and (3) the deviations from the long crack growth behaviour arise from the internal stresses present ahead of the crack tip which contribute to $K_{max}$. These internal stresses are responsible for the accelerated growth in short crack, underload region and decelerated growth during overloads. The influence of plasticity induced crack closure is incorporated in the model but with some restrictions related to residual stresses due to the overload plastic zone which is an important factor contributing to retardation of crack growth.

#### *4.1.2 S-N based Approach*

Mann *et al* (2006) studied the fatigue life of a welded T-joint made of beams with rectangular hollow section. The fatigue life was predicted using a crack propagation analysis and compared with experimental results from joints with different residual stress levels. The residual stresses were incorporated in the numerical analyses at the weld toe using Walker's equation. The experimentally and analytically found S-N curves showed good agreement and the effect of the residual stress was successfully included in the analyses. Lotsberg and Landet (2005a) carried out full scale fatigue testing of typical details representing the connections between the longitudinals and the web frames of FSPOs. The loading on the test specimens simulated the non-linear water pressure on the hull in the waterline. The effect of the mean stress was found to be significant. In the process of formulating a method for fatigue assessment of welded joints in FSPOs, Zhang and Moan (2006) presented a review of the JBP and JTP approaches. They formulated a new procedure for fatigue assessment explicitly taking into account the effect of mean stress including possible redistribution of residual stresses due to shakedown. The advantage of the approach is that stress ranges at different R-ratios can be condensed to the equivalent stress range at R-ratio equal to 0 applying the design hot-spot curve FAT90. The proposed approach was compared to results based on the JBP and JTP rules showing a relatively small scatter.

Piles driven into the seabed by hydraulic hammers are often applied in the offshore industry for fixation of platforms or as casings for conductors. The driving generates stress waves which travel trough the piles. The corresponding cyclic stress ranges are dominated by the compressive stresses which can be close to the yield stress of the piles. The design against fatigue for the driving scenario is however normally based on fatigue data related to external tensile loading. Lotsberg *et al* (2008) therefore decided to investigate possible positive effect of the loading being mainly in compressive or if shakedown of residual stresses arising from manufacturing can be observed. Their investigation included a large number of small scale tests and determination of residual stresses in a driven full scale pile which has been decommissioned after 30 year of service. The main finding was that significant shakedown of residual stresses due to pile driving was not observed in the full scale investigation. It was therefore recommended not to include positive effects of the stress ranges dominated by compressive stress unless residual stresses have been removed by e.g. Post Weld Heat Treatment (PWHT).

To summarize the above, possible integration of the mean stress effect in the design phase is now generally accepted. It should however be noted that when applying the beneficial effect of compressive stresses in the design phase, all relevant contribution to the total stress level shall be accounted for and possible shakedown effect should be evaluated before applied in design.

### *4.2 Effect of Load Sequences*

An often applied practice has been to decouple the load history into a number of stress ranges and corresponding number of load cycles in order to calculate the total damage by summing the damage from each scenario neglecting the actual load sequence. However, it is generally known that in some cases an overload can create a shakedown of the fatigue growth, which mainly is due to redistribution of residual stresses at the crack tip. The effect of such a shakedown has been reported by numerous experiments; see e.g. Kim and Lotsberg (2005), Zhang and Moan (2006) and Jo *et al* (2007).

Many models have been developed for the analysis of fatigue lives of structures exposed to variable amplitude loading. However, no universal models have yet been generally agreed on. Xiaoping *et al* (2008) proposed a concept for the modelling of crack growth based on a Paris equation with equivalent stress intensity factor and modified Wheeler model taking into account the effect of overloads and underloads. The model makes it necessary to obtain material data for R=0 only (see also Huang and Moan (2007)) which reduces the required experimental work. The model is benchmarked using experimental fatigue crack growth data for aluminium and steel alloys including load cycle with overload following underloads and vice versa showing good agreement. Li *et al* (2007) developed the idea of considering the effect of variable amplitude cyclic loading with shakedown of residual stresses in a fatigue procedure. Some typical welded connections in ship-shaped structures were investigated with three-dimensional finite element analyses. The effect of residual stress relaxation, initial residual stress and the applied load after variable amplitude cyclic loading was revealed. A formula for predicting the residual stress at hot spot was quantitatively proposed. An improved fatigue procedure was introduced which was validated against fatigue experimental results obtained for welded joints.

Choung and Yoon (2008) outlined the theory for a fully stochastic model for fatigue analysis of a Floating-Production-Storage-Offloading (FPSO) tanker. The approach has been condensed into a program, which can be used for the fatigue analysis of a FPSO at the design stage. Stochastic evaluation of floating structures is dealt with in detail in chapter 7.

### *4.3 Thickness and Size Effect*

The thickness and size effect is related to the decrease in fatigue strength of welded structures as the wall thickness of the member increases. A common approach for reduction of fatigue strength of welded structures is to multiply the stress range by a factor $k_s = (t_{ref}/t)^k$ where $t$ is the relevant plate thickness, $t_{ref}$ is a reference thickness and $k$ is an empirical constant. The formula shall only be applied when the thickness of the member exceeds the reference sheet thickness, $t_{ref}$. A general overview over the available technical literature and approaches proposed by codes for the description of the thickness effect is given by Mashiri and Zhao (2005) including $t_{ref}$ and $k$ for a large number of design codes. Mashiri *et al* (2007) studied the fatigue behaviour with regard to the size effect of welded thin-walled tubular joints. This study also includes a summary of the existing research on the size effect in the perspective of newly defined terminologies. It identifies the gaps in knowledge in the design of tubular joints using the hot spot stress method, i.e. thin-walled tubular joints with a wall thickness less than 4 mm and thick-walled joints with a wall thickness larger than 50 mm. Their study concluded that there is a life reducing thickness effect for joining of tubulars with thicknesses less than 4 mm (not predicted by common approaches). See also Dong and Hong (2008) for fatigue analysis of welded tubular joints considering the thickness correction in the calculation of the structural stress. The influence of sheet thickness on fatigue strength in thin-walled (sheet thickness less than 5 mm) and welded structures have also been studied numerically and experimentally by among others Fourlaris *et al* (2006), Gustafsson (2006), Mashiri *et al* (2001), Ringsberg *et al* (2008) and Sonsino *et al* (2007).

As part of the search for new types of foundations for offshore wind turbines, Puthli *et al* (2006 a) carried out a literature review with focus on effect of wall thickness and steel grades on the fatigue strength. A comparison of proposed reduction in fatigue strength by five different design codes was presented by the authors. Experimental work based on specimens with wall thickness in the range of 8 mm to 30 mm were analysed in order to confirm the effect of wall thickness and steel grades on the fatigue strength. However, their conclusion was that neither a negative effect of the steel grade nor the wall thickness was observed. Poutiainen and Marquis (2006) present a fatigue assessment method applicable on welded plate-type structures. It was found that the conventional structural stress approach is not sensitive to plate thickness. It was therefore recommended to use an empirical thickness correction factor. The method was verified using both fracture mechanics calculations and experimental results from cruciform joints with varying weld sizes, base plate thicknesses and attachment sizes.

Recently, the Common Structural Rules (CSR) for tankers and bulk carriers developed by the International Association of Classification Societies (IACS) entered into force, in which a thickness effect is taken into account in the fatigue strength assessments. The thickness effect in the CSR adopts $k = 0.25$, regardless of the types of the welded joints. The thickness effects in the CSR and the IIW standard were summarised in Table 3; note that the exponent $k$ is referred to as m in the table, Nakamura and Yamamoto (2007). Their study was carried out motivated by the fact that it is not clear whether the thickness effect influences welded joints of large-scale components such as the longitudinal stiffeners, since the thickness effect is in general derived from only small-scale fatigue tests and various analyses. The thickness effect on the welded joints between the longitudinal stiffeners and the web stiffeners was examined from the viewpoint of the stress concentration at the weld toe. The thickness effect on a boxing welded joint was examined using results of fatigue test data and conducted finite element analyses. The results of the test and the analyses confirmed that the thickness effect on the welded joints between the longitudinal stiffeners and the web stiffeners is not dependent upon the faceplate thickness.

Table 3

Thickness effect in the CSR and IIW standard; Nakamura And Yamamoto (2007)

| design standards and rules | exponent m | reference thickness t0 | types of welded joints |
|---|---|---|---|
| IIW | 0.3 | 25mm *gross | cruciform joint, T joint, plate with an attachment (as weld) |
| | 0.2 | | cruciform joint, T joint, plate with an attachment (ground) butt joint |
| | 0.1 | | butt joint removed reinforcement, base metal, etc. |
| CSR | 0.25 | 22mm *net | all joints including the longitudinal stiffners |

To summarize the above, relatively simple methods exist to incorporate the thickness effect at design stage. The guidelines cover the normal range of plate thickness applied in the offshore and ship industry. However, for thin members (~4-5 mm and below) the approach applied in most guidelines has been demonstrated to be un-conservative. For very thick plates the commonly applied approach results in relatively large reduction of the fatigue strength as no upper limit is included. Finally, engineering judgement will have to be applied in the design of certain details, e.g. when determining the thickness effect of longitudinal attachments under cyclic loading.

### *4.4 Effect of Corrosive Environment and Temperature*

Structures exposed to corrosive environments such as seawater will normally experience higher rates of fatigue growth and thereby a low overall fatigue life compared to structures in non-corrosive environments. For offshore and ship structures, a common way of reducing the corrosive effect in structures in seawater is to apply coating and/or cathodic protection in the form of aluminium or zink anodes. In fatigue codes different S-N curves and crack growth curves are given depending on the environment in question.

Baxter *et al* (2007) present an overview article describing the effect of seawater for free corrosion and cathodic protected structures, load frequency and sweet and sour service of risers. The main finding for structures in seawater is that cathodic protection increases the fatigue lives. The effect is largest at low stress ranges. The crack growth rates increase sharply for structures exposed to a load frequency smaller than 0.1 Hz and high stress intensity ranges. The article also includes findings on sweet and sour services, where crack growth for sour service was up to 50 times higher than for air. McMaster *et al* (2008) present a study undertaken to measure the fatigue “knockdown” factor of sour/brine environments compared to that of laboratory air. Stress-life samples were removed from segments of pipe with an outside diameter of 9.625” welds in API steel grade X65 (WT 1.26”) containing fully inspected, production-quality circumferential welds. The environment examined in the tests included laboratory air conditions as well as deoxygenated brine supplemented by a gas mix of $H_2S$ and $CO_2$. It was found that the measured fatigue life decreased in the curved pipe segments in the range of 3-12 times when tested under sour brine environmental conditions compared to lab air. Hence, the importance of performing environmentally relevant fatigue testing when considering material selection for offshore applications that may contain sour environment was illustrated. See also Buitrago *et al* (2008) and Pargeter *et al* (2008) for influence of testing frequency on fatigue crack growth in various corrosive environments and Fourozan *et al* (2008) for simulation of stress corrosion crack growth in pipelines under the influence of residual stresses.

Benedictus *et al* (2004) studied the fatigue crack initiation behaviour of a welded aluminium alloy in seawater environment. This alloy is often used in high speed ferries, subjected to dynamic loads, because of its excellent corrosion resistance and its favourable mechanical properties. The influence of corrosive environment together with a welded condition was studied with respect to fatigue performance and results presented as fatigue limits and S-N curves. Morgenstern *et al* (2005) studied the influence of variable amplitude loadings, incorporating load sequence effect and mean load fluctuations on fatigue performance of aluminium welded joints in a corrosive environment of salt spray. See also Jin *et al* (2006), Pan *et al* (2006), Somervuori *et al* (2006), Tan *et al* (2006), Taravel-Condat and Desamais (2006) and Chilistovsky *et al* (2007) for investigations on seawater’s corrosive influence on the fatigue crack initiation and fracture behaviour of aluminium and steel materials.

Robinson and Czyryca (2006) present high-cycle and low-cycle fatigue crack growth tests carried out in air and in artificial seawater. The results show that the titanium alloy tested was unaffected by seawater environment in comparison with the tests carried out in air. Fatigue crack growth tests on titanium alloy weld metal were conducted in air and artificial seawater with and without cathodic potential. The results indicated a minor effect of seawater in increasing crack growth rate of the weld metal. However, the application of a cathodic potential of 0.987 V versus Ag/AgCl reference electrode showed crack growth rates similar to crack growth rate in air. Kim and Paik (2007) studied the corrosion fatigue crack propagation characteristics of a TMCP steel in synthetic seawater to imitate the conditions in seawater ballast tank structures under corrosive environment. The tests were carried out with and without the application of cathodic protection. The fatigue loading test speed was 0.17 Hz corresponding to a typical sea wave period and the stress ratio was R=0.1. It was found that the fatigue crack propagation rate of the TMCP steel in synthetic seawater condition was faster than that in air condition by almost a factor of two. It was observed that the fatigue crack propagation rate of TMCP steel in seawater condition with cathodic protection was in between air condition and seawater condition without cathodic protection, see Figure 7.

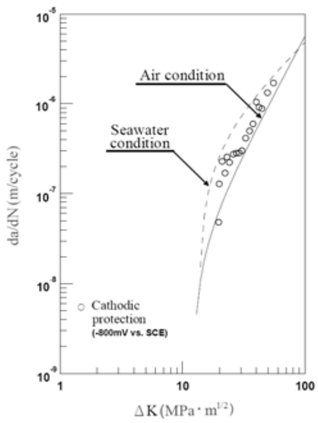


Figure 7: Corrosion fatigue characteristics of TMCP steel; see Kim and Paik (2007)

Lardier *et al* (2008) studied crack growth in chain links of mooring lines considering the influence of corrosive environment. Crack growth was modelled using the two-dimensional Paris-Erdogan equation. The corrosion was treated by considering the diameter reduction and the fatigue crack growth rate, using three zones of corrosion, namely the splash, catenary and bottom zones. This is done by using the material parameters applicable in sea water and by considering the increased crack growth rate induced by the rise of stress range due to the corrosion wastage. A sensitivity study was carried out on the initial crack size, the crack aspect ratio and the material correlation between links, when applying the fracture mechanics approach.

The ductility and fracture toughness is lower at low temperatures in comparison with ambient temperature, and ductility and fracture toughness is increased at higher temperatures, Suresh (1998). Ship and offshore structures that operate in Arctic regions must have steel grades suitable for very low temperatures. In addition, composite materials are nowadays commonly used in ship building industry and these materials have often a very limited temperature range of operation in contrast to steel or aluminium materials, Ericksonkirk and Ericksonkirk (2006) and Sumpter and Kent (2006) present experimental results from the influence of temperature on fracture toughness of steel materials at low temperatures -50 to -180º C. Park *et al* (2007) present a study on the temperature effect on the fatigue properties of laminated composite structures in the temperature range -15 to 45 º C.

It is observed that corrosive environments significantly affect the fatigue endurance of different material (with exception of titanium). The effect of a corrosive environment shall therefore always be included in the design phase by proper material selection (including possible cladding of local surfaces) and by protection against corrosion.

### *4.5 Design*

In the phase of designing structural components which during the lifetime are exposed to dynamic loading, significant cost savings can be gained by including effects of fabrication and details with fatigue robustness. The performance of a structure is largely determined by the initial design.

Fricke *et al*. (2008b) discuss critical ship weld connections between primary ship structural components that are subjected to fatigue and recommendded design improvements in order to increase fatigue strength. The details investigated were; bracket toes, knuckled transitions and corner connections of I-beams. The design of these connections is highly important in order to reduce the local stress concentration and hence minimize fatigue damage. They concluded that bracket designs with soft transitions to the main steel have the best fatigue performance. For knuckled flanges or plating good support of the knuckle is of major importance for the fatigue strength. Finally it was concluded that full penetration welds reduces the risk of early fatigue crack from non-welded root faces and that the hot-spot stress approach is an appropriate tool for fatigue strength evaluation. Maddox (2008b) carried out a critical review of current design methods for fillet joint welds in order to investigate weld size optimization and the fatigue performance. The review covers fillet and partial penetration welds in cruciform, T or lap joints under transverse loading. The fatigue performance was revived in comparison to the joint fit-up and alignment, weld quality, the influence of residual stress, applied mean stress and plate thickness correction.

Reduction of wall thicknesses using high strength steels is desirable for structures where weight is an issue. Applying high strength steel in a dynamic loaded structure often results in the fatigue strength being the governing factor for design. Local design of details with high fatigue strength therefore becomes very important. Puthli *et al.*

(2006b) experimentally investigated the fatigue resistance of longitudinal attachments for details made of high strength steels S690, S960 and S1100. Influence of geometry of the attachments and welding details where included in the investigation. It was found that local geometry has a significant impact on the fatigue life of a component and that quality of the weld also is of major importance. Details with "inward–running" were found to be especially efficient.

One of the major focus areas within the ship industry is to maintain a high productivity. In order to improve the productivity by a fast fabrication process, Polezhayeva *et al* (2007) have investigated possible designs of one of many joints being the knuckle line in the web frames in a VLCC. Several layouts were investigated by numerical methods and by large scale fatigue testing. A layout with a large radius between the horizontal and the inclined part of the web frame was found to provide the best fatigue characteristics.

### *4.6 Fabrication*

Fabrication of a welded structure can significantly affect the fatigue life. As an example misalignment of butt/girth welds raise stress concentrations. The stress concentration is proportional to the fabrication tolerances due to allowable misalignment, see e.g. Quintin (2007). Thus, reducing the allowable misalignment by good workmanship will increase the fatigue life of a structure. Further information and details regarding fabrication can be found in the Committee V.3 – Materials and Fabrication Technology report.

Gilmour *et al* (2005) studied the effect of fabrication tolerances on the fatigue performance of welded ship structures. The study aimed to improve knowledge of actual shipbuilding tolerances, and comparison of these to standard assumptions. Shipyard measurements show that modern automated panel lines can achieve better quality than commonly assumed in the guidelines. Measurement of block and large assembly connections indicate that mean fabrication tolerances are similar to default values assumed in fatigue design guidelines. However, the variation in tolerances is larger than implied by standard fatigue analysis. Chakarov *et al* (2008) investigated the structural impact of fabrication tolerances focussing on a longitudinal stiffened welded structure of a containership. The work was based on finite element modelling of thickness change misalignments, angular imperfections and rotation of transverse welds. Parametric equations were set up based on the results of the finite element models allowing for investigation of interaction between the different contributions to stress increases imposed by misalignments during fabrication.

In the offshore industry, pipelines with relatively high internal pressure are often used for the transport of oil and gas. The pipelines are constructed from joints with an approximate length of 12.2 m. Lotsberg and Holth (2007b) presented analytical expressions for stress concentration factors for the circumferential butt welds of the pipeline joints taking into account fabrication tolerances of the single sided welds and difference in wall thickness of joining pipes. Large pipes (OD from 20” and above) made from rolled plates and joined by a longitudinal weld can contain some degree of ovalisation due to fabrication and SCFs imposed by the ovalisation were presented. Good agreement between analytical expressions and finite element results were obtained.

### *4.7 Fatigue Improvement Methods and Material Selection*

The use of post weld improvement methods to enhance the fatigue resistance of welded joints are applied either during design in order to increase the life of a component or under operation for life extension. In previous ISSC reports, post weld improvements techniques have extensively been addressed. However due to the importance of this topic, the committee has decided to present the recent publications, in addition Committee V.3 addresses the same issue.

In general, fatigue life improvement techniques rely on extending the initiation phase by reducing the severity of the weld toe details and/or introducing compressive residual fields. Improvement techniques can also reduce the crack propagation speed, which increases the total fatigue life of the structure. An overview of the most important methods and their surface influences is presented in Figure 8.

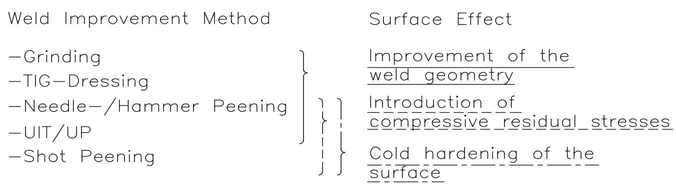


Figure 8: Surface effects of weld improvement methods, based on Ummenhofer *et al* (2006)

Extensive research work was carried out in the 90’s and IIW published several papers and guidelines, one mayor document was the IIW recommendations on Post Weld Improvement of steel and aluminium structures which was issued in a revised guideline in 2008, Haagensen *et al* (2008). Several of the Codes today have recommendations for the different methods available (see Table 4), like DNV RP-C203, IIW XIII-2151r1-07 / XV-1254r1-07 (revision of XIII-1539-96 / XV-845-96), Hobbacher (2008), and ISO 19902, in addition to ship rules and regulation, see chapter 6. Based on the different methods, the enhancement is in the range of a factor 2 up to maximum 4. The maximum fatigue improvement is based on hammer peening, however due to uncertainties regarding quality assurance of the process, this method may not be recommendable for general use at the design stage. If several methods are applied, only the benefit from the one giving the highest factor of improvement can be accounted for.

Table 4
Overview, improvement factors by selected guidelines

| Rules | Weld to burr grinding | Hammer peening | TIG dressing |
|---|---|---|---|
| ISO 19902 | 2 | 4 | - |
| DNV RP-C203[1] | 3.5 (SMYS>350 MPa) | 4 (SMYS>350 MPa) | 3.5 (SMYS>350 MPa) |
| IIW<br>XIII-2151r1-07 / XV-1254r1-07 | Increase in nominal stress of 1.3 max FAT 112 class after improvement<br>For m=3=> 2.2<br>For m=5=> 3.7 | Increase in nominal stress of 1.6 (SMYS>355 MPa)<br>Max FAT 125 class after improvement<br>For m=3=> 4.1<br>For m=5=> 10.5 | Increase in nominal stress of 1.3 max FAT 112 class after improvement<br>For m=3=> 2.2<br>For m=5=> 3.7 |
| BV Rules for the Classification of Offshore Units (2007) | No improvement factors provided | Hammer peening not in principal accepted, | No improvement factors provided |
| BV Rules for the Classification of Offshore Units (2007) and Classification of Steel ships (2007) | 2.2 (SMYS<355 MPa)<br>3.4 ( 390 >SMYS>355 MPa) | No improvement factors provided | No improvement factors provided |

1) The maximum S-N class that can be claimed by weld improvement is C2-C depending on NDE and quality assurance for execution see Table A-5 in Appendix A in DNV RP-C203.

For fillet welds, the weld roots may be the critical point and it is important to notice that e.g. toe grinding does not avoid failure from the weld root, which often can be the case for improved fillet welds. Maddox (2007) investigated the additional benefit from toe grinding by use of full penetration rather than filled welds. Based on limited fatigue data the recommendation was still to use the recommended IIW factor of 1.3 on increased stress even though the fatigue test showed better results than for partly penetrated welds. However, the paper tentatively recommended that the factor 1.3 for fillet welds should only be applied for nominal stress ranges less than 60% of yield. Ryu *et al* (2007) tested the effect of weld toe grinding for five types of welded specimens including three types of small welded specimens and two types of scaled models of structural details typically applied in the ship industry. The improvement of the fatigue life by toe grinding was found to be larger for the small welded specimens than for more complicated welded structural details. Since weld toe grinding primarily extents the crack initiation phase which dominates the fatigue for small welded specimens with a minimum of structural redundancy, i.e. the crack is initiated to a certain level after which it propagates rapidly. In details with structural redundancy (as structural details in real ship structures), the crack propagation phase also contributes to the fatigue life of the structure. The fatigue life extension for the models with structural redundancy was in the order of 2 corresponding to the levels indicated by ISO and IIW in Table 4.

Ye and Moan (2007) tested 31 non-load carrying cruciform welded joints made from aluminium. Approximately half of these joints were post-treated by burr grinding and the rest left in as-welded condition. The fatigue lives were increased by approximately a factor of 2 corresponding well to the IIW and ISO recommendations.

In order to save weight, higher grade strength steel is more and more frequently used in design, however the fatigue life is not increased, i.e. the same S-N fatigue curve is applied. Lieurade *et al* (2007) investigated the effect of weld quality and post weld improvement techniques on the fatigue resistance of extra high strength steels. Cruciform and symmetrical butt welded joints were improved by either burr grinding or TIG dressing and were fatigue tested. The TIG dressed specimens obtained the best fatigue lives. Wästberg and Salama (2007) presented fatigue test data for full scale girth welded tubulars (OD 24", T 0.812"). The tests were carried out as as-welded, TIG dressed and ground flush weldments. The obtained results are compared against the S-N curves D, C1 and C design curves provided in DNV RP-C203. The as-welded specimens were above the D-design curve but below the D-mean curve. For some of the grinded specimens, the initiation sites were near surface flaw and therefore the grinding had minor improvement of the fatigue life. Therefore, the TIG dressed specimens for some cases showed better fatigue performance than the grinded ones, which normally is contrary. Baptista *et al* (2008) investigated the effect of weld toe grinding experimentally for two types of stainless steel: Duplex S31803 and Austenitic 304L. Weld toe grinding is based on removing material from the weld toe increasing the weld toe radii and consequently reducing the geometrical severity of the detail. They found that weld toe grinding introduces compressive stress in the vicinity of the weld and that the fatigue lives were significantly improved (60% in terms of stress range for cycles near $10^7$). The toe grinding technique was found to be especially superior for lower stress ranges and increases the high cycle fatigue life.

It should be noted than when applying fatigue improvement methods in the design phase such as weld toe grinding, possible effect of corrosion shall be included. In addition, quality control is crucial when taking improvement methods into account during design and operation, in order to ensure good quality work.

## 5. DEVELOPMENTS IN MATERIALS AND NEW STRUCTURES

### *5.1 Material for Cold Climate Condition*

Oil and gas exploration and production is moving into arctic areas. This means additional challenges for design, construction and operation of offshore installations and ships. In addition, very low temperatures are required for storage and transport of LNG. These low temperatures influence the fatigue and fracture properties of the material. Horn *et al* (2007) reviewed the challenges regarding material related issues with main focus on steel and the lack of experience and guidelines to safely explore and develop oil and gas in the artic regions. They showed that the situation regarding material selection and qualification for the arctic condition is characterized by limited recommendations in current design rules and limited field experience from installations in cold climate regions, and further work is needed. Suzuki *et al* (2005) developed "JFE

EWEL," a new technology for improving HAZ toughness in high heat input welding. By applying JFE EWEL to the steel used in shipbuilding, such as YS390 N/mm2 (class heavy section unknown expression) plate for container ships and low-temperature service steel plate for LPG carriers. Excellent properties in both base plates and welded joints for high heat input welding were achieved.

### *5.1.1 Brittle Fracture*

Materials need acceptable toughness properties at the installation and operating temperatures expected in the cold climate site in question. In brittle fracture, no apparent plastic deformation takes place before fracture.The Japan Welding Engineering Society published the standard WES2808-2003 (Method of assessing brittle fracture in steel weldments subjected to large cyclic and dynamic strain) whose main objects are architectural steel frame structures subjected to cyclic and dynamic large straining due to seismic loading. WES2808 employs a CTOD design curve relating tensile strain, fracture toughness and defect size, and gives limit values for these parameters. One of the characteristics of the method is a consideration of the deterioration of the fracture toughness of steel resulting from large cyclic and dynamic straining. WES 2808 is characterized by two unique ideas. One is a reference temperature concept for fracture toughness evaluation in the seismic condition. The fracture toughness under cyclic and dynamic conditions is replaced by the static toughness without pre-strain at a reference temperature of $T - \Delta T_{PD}$ , where T and $\Delta T_{PD}$ are the service temperature and the temperature shift of the fracture toughness. The other idea is a correction of CTOD fracture toughness for constraint loss in structural components in large scale yielding. The CTOD toughness correction is carried out with the equivalent CTOD ratio $\beta$ and procedure for determining $\beta$ is standardized in the succeeding IST (International Standardization of Fracture Toughness Evaluation Procedure for Fracture Assessment of Steel Structure) project in Japan, Minami *et al* (2006). The WES2808 procedure may also be applicable to the evaluation of tensile strain limit against brittle fracture initiation from girth weld flaws in gas pipelines that are subjected to large cyclic deformation, Kubo *et al* (2007). In their study, a fracture assessment method which considers biaxial loading conditions was developed, and the applicability of the WES2808 CTOD design curve in fracture assessment of pipeline under biaxial loading condition was examined. They found that the effective plastic strain can be used as a parameter that characterizes the deterioration of fracture toughness of pipe material by large cyclic deformation under biaxial loading conditions. They developed a method of estimating the strength increase and deterioration of fracture toughness of steels with tensile strength of 780 MPa. In Figure 9 it is shown that the dynamic strength estimated agrees well with the experimental values. They also demonstrated that the CTOD design curve adopted in WES2808 gives non-conservative estimation when a surface flaw exists on the inner surface of a pipeline under biaxial loading conditions.

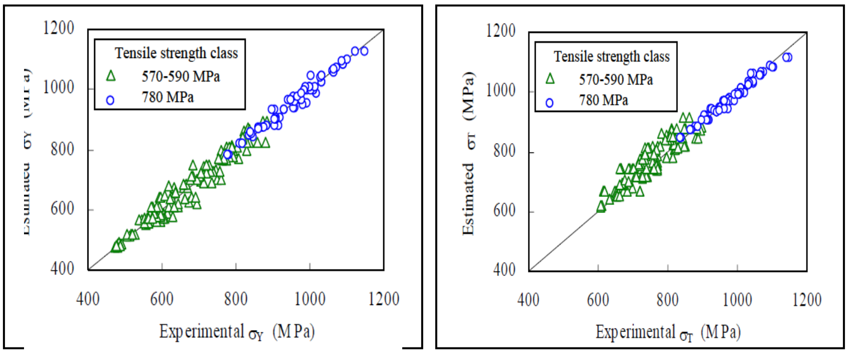


Figure 9: Comparison of estimated and experimental dynamic strength of pre-strained steel, Kuzbo *et al* (2007)

For integrity assessments of pipelines with high internal pressure, Minami *et al* (2007) analyzed the stress fields for through-thickness crack and semi-elliptical surface cracks subjected to biaxial tension by 3-dimensional FEM. The biaxial load effect on the CTOD correction for constraint loss in large scale yielding conditions was examined. The IST method is applied to the fracture assessment of welded joints of high strength line-pipe steel (API 5L X80). In their analyses, CTCP (center through-thickness crack panel) and CSCP (center surface crack panel) were analyzed under various biaxial load ratios and the yield-to-tensile ratio YR. The effect of biaxial loading on the stress fields was qualified in terms of the equivalent CTOD ratio β, see Figure 10.

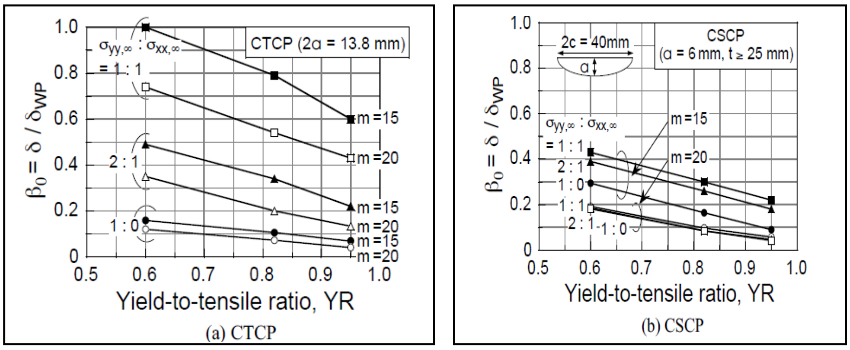


Figure 10: Effect of biaxial loading on the equivalent CTOD ratio β for CTCP and CSCP

### 5.2 *New Steel with Improved Crack Growth Properties (FCA, FMDP Steels)*

It is often assumed that the fatigue crack growth properties of structural steels fall in a common scatterband like in BS 7910. However studies have shown that improvement of the microstructure of the steel can leads to an increased life for the component in question. Katsumoto *et al* (2005) and Konda *et al* (2007) showed that the fatigue crack growth rates of fracture crack arrester (FCA) steel were reduced compared to the conventional steel in side longitudinal structural model and side wide gusset welded joints, see Figure 11. They also showed that the stress concentration at the weld toe of a FCA steel specimen is smaller than that of a conventional steel specimen. The steel has already been applied to some ships and vessels. The developed steel plate has been approved as FCA in grades AH36, DH36, EH36 and AH40, DH40, EH40 by Nippon Kaiji Kyokai, Lloyd's Resister, Det Norske Veritas and American Bureau of Shipping.

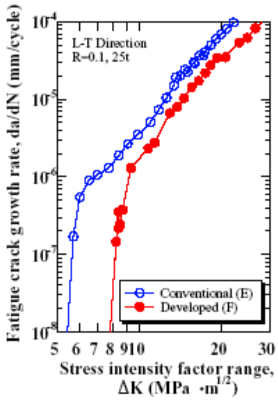


Figure 11: Fracture crack growth test results in atmospheric environment, Katsumoto *et al* (2005)

Sakano *et al* (2005) investigated the fatigue life extension effect of FCA steel through fatigue tests using welded girder specimens made of FCA steel and a conventional high strength steel (JIS SM570Q), with welded joints between cross beam bottom flanges and main girder web. They showed that the fatigue strength of web gusset joint of FCA steel specimens is about 1.3 times higher than that of conventional steel specimens. Youn *et al* (2007) carried out fatigue tests for FCA and conventional steel weldments. They found that the fatigue strength of FCS steel weldment is in the upper region of the fatigue strength data band of conventional steel weldments, and the fatigue crack propagation rate in HAZ of FCA steel weld is smaller than that of the base metal of conventional steel.

Osawa *et al* (2006a) investigated the relation between fatigue crack propagation resistance and cyclic softening characteristics in steel numerically using Crystalline-Elastic-Plastic F.E. (CPFE) analysis in order to clarify the microscopic mechanisms of the fatigue strength improvement of FCA steel. They found that the microscopic crack opening level increases and CTOD decreases when the cyclic softening occurs. In later work Osawa *et al* (2007b) investigated the relation between the fatigue crack propagation behaviour and the microscopic characteristics of Ferrite / Martensite Dual Phase (FMDP) steel using CPFE analysis. They reported that the relation between the crack growth rate and the morphology of FMDP steel predicted by the simulation agrees approximately with experimental results. Nakashima *et al* (2005) examined the relation between fatigue crack growth rate and fatigue life of welded joint in steel with dispersed secondary phase. Fatigue crack growth tests of base metals and fatigue tests of gusset welded joint were carried out. They found that the fatigue life increases by 10% when the growth rate decreases by half, and the fatigue life doubles when the growth rate decreases by a factor of 10.

It is recommended that more details need to be introduced in the ECA procedures for fatigue crack growth with the advent of steels with improved crack growth properties.

### *5.3 Extra High Strength Steels and Stainless Steel*

There is an aim from the oil industry to use higher grade steels in order to save weight and reduce e.g. transportation and field welding cost in order to develop new fields in more remote locations. API X70 and X80 grades linepipe have become popular and even X100-X120 grades have been developed. One of the main challenges when higher steel strength is chosen for construction, is the low toughness values obtained in the HAZ and a lot of efforts have been made to improve the HAZ properties in order to avoid brittle fracture or running fracture. Ishikawa *et al* (2006) investigated the relationship between microstructural characteristics, HAZ toughness and the fracture behaviour. They concluded that preventing martensite-austenite MA formation in HAZ was the key issue for improving HAZ toughness. Nagai *et al* (2004) developed the YS500N/mm$^2$ high strength offshore structural steel with good CTOD properties by reducing MA and they obtained high strength (YS500N/mm$^2$) and good properties at welded joints (CTOD at -10 deg C.).

For conventional steels, grain coursing in the HAZ can be prevented by promoting ferrite formations with help from dispersed particles such as TiO and TiN. Kaneko *et al* (2008) developed high strength steel plates with YP460MPa, up to 60mm in thickness by the application of extreme strong cooling TMCP and PROME system. The steel had low carbon equivalent and small amounts of Ti to ensure HAZ toughness for high heat-input welding. The developed steel plate has the potential to contribute to higher efficiency in giant container ship fabrication. Nagahara and Fukami (2004) developed TS530N/mm$^2$ grade steel plate applicable for tanks for multi-purpose gas carriers. This developed steel plate has excellent toughness in base metal and HAZ according to improvement technology in HAZ toughness, such as HTUFF and Ti oxide technology. However, for higher strength steel one way to improve the toughness is to reduce the Si and Ni contents.

Arai *et al* (2007) presented a metallurgical design of seamless pipe with high strength reaching X80-X100 grade (minimum yield strength 552 - 689 MPa) manufactured by steel containing very low carbon and with a microstructure of uniform bainite. They showed that the developed microstructure is very effective in obtaining good toughness for tempered steel and sufficiently low hardness and good toughness in HAZ. Glover *et al* (2006) presented the results from the installed 36” 3,6 km X-100 test line on the Godin Lake loop in Canada. The welding was carried out by mechanized gas metal arc welding (GMAW), CvN testing at -5°C results in the range of an average of 118 J for the weld and 236 J for the pipe body. From the work carried out, it was concluded that X100 technology was a viable approach for pipeline construction. The construction of the 1.6 km long segment of X120 Godin Lake trial was performed under harsh winter conditions, with temperatures down to as low as -40°C during the construction, Biery *et al* (2006). The girth welds were welded with PGMAW (Puls Gas Arc manual Welding) and the tie-in welds with semi automatic STT/PGMAW. The properties obtained were comparable to those derived during qualification and development and it was concluded that X120 is ready for field application. Fonzo *et al* (2006) investigated the crack arrester design for X-120 gas pipelines. However more investigation is still needed in order to achieve good toughness properties, reduce local brittle zones and preventing running fracture before available pipelines in X-100 and higher strength will be commercially feasibly and economically.

Inoue *et al* (2006) carried out large-scale welded joint and base metal crack arrest tests to investigate the long crack arrestability of heavy-thick (over 65mm) shipbuilding steel plates. The results suggest that EH-grade cannot ensure arrestability even in base plate in case of heavy thick shipbuilding steel, and these risks shall be evaluated carefully to avoid fatal brittle fracture.

Ishikawa *et al* (2007) examined the validity of fracture toughness Kc estimation technique based on the results of V-notched Charpy (CVN) impact tests for high strength shipbuilding steel plate with heavy-thickness (over 50mm). They found that Kc strongly depends on the matching of hardness in the welded joints, and the actual Kc values become much smaller than the expected Kc calculated from the results of CVN tests when the hardness of weld metal is much higher than that of base metal, see Figure 12. Considering this mismatching effect, shipbuilding steel with a yield strength of 460MPa with improved fracture toughness was developed.

Hatano *et al* (2003) investigated the improvement of HAZ toughness under large heat input in thick 590 MPa class steel plate (SA440) with a new concept; Low Carbon Fine Bainite. It was found that Low Carbon Fine Bainite can be obtained by reducing carbon and by increasing alloy elements which do not form carbides. Kojima *et al* (2004) developed the innovative technology for HAZ microstructure refinement, HTUFF, in order to produce high HAZ toughness steel plates with tensile strength of 490MPa or 590MPa class. It has been discovered that very small oxides and/or sulfides can be dispersed in steel by the appropriate addition of Mg and/or Ca. Utilizing these fine particles, the strong pinning technology to retard γ grain growth in a HAZ has been commercially established. Liu *et al* (2006) showed that welds that contained only 0.6 ml H2/100 g weld metal can be produced combining yttrium and fluorides into one single flux-cored consumable. This weld metal exhibited excellent ductility, elongation and impact toughness, and the consumable designed using the proposed concepts can produce high strength steel welds that meet stringent mechanical performance requirements. Puthli *et al* (2006) examined the fatigue strength of longitudinal attachments welded to plates and tubes made of high strength steels, S460, S690, S960 and S1100. They showed that high strength steels do not exhibit any disadvantage in fatigue resistance compared to mild steels.

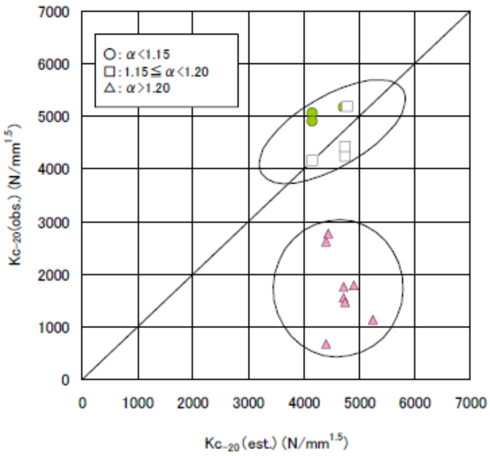


Figure 3: Relationships between Estimated Kc values and measured Kc values, Puthli *et al* (2006)

## *5.4 Other Materials*

### *5.4.1 Titanium*

Titanium is still looked at as an exotic material. The material offers benefit compared to other materials and can provide an elegant solution in order to solve corrosion problems and save weight. Grade 23 and/or 29 titanium alloy are often used in the fabrication of offshore riser components such as tapered stress joints (TSJs) for top-tensioned risers and as hang-off for dynamic catenary risers. Failure of critical titanium offshore components has drawn attention to delayed cracking in Ti-6Al-4V. When tensile loads are applied for a sustained period, higher strength metals and alloys can experience reduction in mechanical properties, named delayed cracking, or sustained load cracking (SLC), which can occur at low to moderate temperature (approximately: -50 to 200ºC), depending on the titanium alloy and condition. Leonard *et al* (2008), investigated SLC resistance in GTA butt-welded joints between base material grade 23 and filler material grade 29. The aim was to derive SLC data for the weld and HAZ, for a full production scale pipe weld for tapered stress joints qualification. Kostrivas *et al* (2005), assessed the threshold stress intensity factor for sustained load cracking, KISLC, in Ti-6Al-4V parent metals and MIG and keyhole plasma weldments in the as-welded and postweld heat treated conditions. Material and weldments from selected forgings, plate and pipe, including standard (ASTM Grade 5) and extra-low interstitial (ELI), (ASTM Grade 23 and 29) materials were examined with examples of typical mill-annealed and beta-annealed batches being included. Step-loading and single-load testing techniques of through-thickness SENB specimens, notched in the appropriate zones were used in order to establish KISLC. They found that the parent material with a beta-annealed (fully-transformed) microstructure and low aluminum and oxygen contents had the greatest KISLC value; 67.1MPa√m. Based on the obtained results, the authors did not recommend to purchasing material in a general ‘mill annealed’ condition without specifying acceptable microstructures.

Steel Catenary risers (SCR) are widely used since the first one was installed in the Golf of Mexico in 1994. Since then, more than 100 deep water SCR's have been installed worldwide mainly in the Golf of Mexico, Brazil and West Africa. The deepest installed SCR has been 8000 ft water depth, Song *et al* (2006). The most widely used design codes for SCRs are the API RP 2RD and DNV OS F201. Fatigue life is normally based on a S-N approach and fracture mechanics is only used for engineering critical assessments in order to establish allowable welding defects. Different methods to increase fatigue performance of steel catenary risers in the touch down zone was investigated by Aggarwal *et al* (2007). Four different methods were looked at; thick weight coating, steel risers sections with upsets ends, high strength steel riser sections with integral connectors and a titanium segment. For sour service environment Grade 29 titanium was selected and the fatigue life from the case study analysed (OD=10,75", semi-submersible vessel, water depth 4000 ft and Golf of Mexico conditions) showed an improvement in fatigue performance of 400 for the sour service case compared to conventional X65 steel riser. This increase in fatigue performance was much higher than the other solutions proposed which was in the range of a factor of 3 to 42 depending on the case applied. Mohr and Lawmon (2006) examined the fatigue resistance of titanium 6Al-4V alloy and its welds. In the fatigue design recommendations derived by them, the slope exponent of the design lines was changed to 3.5 to better fit fatigue crack growth rate and fatigue S-N test results.

### *5.4.2 Aluminium*

A critical factor while drilling at deep depths (extended reach wells) is the weight of the drill string used in the high inclination angle section of the well. Lourenco *et al* (2006) investigated the fatigue mechanisms of aluminium drill pipes designed and manufactured in compliance with ISO15546. They showed that good correlation between full-scale and small-scale high-cycle fatigue tests are observed when the actual 3D stress distribution estimated by numerical analyses is taken into account in full-scale tests. Eight aluminium (Al-Zn-Mg alloy) and drill-pipes (LAIDP 103x9) multi-axial full scale tests were run with combined axial and bending loads, in addition to small scale fatigue tests at a stress ratio of R=-1, (1953 T1; Al-Zn-Mg), Lourenço *et al* (2008), see Figure 13. In addition, a finite element model of the drill pipe was analyzed in order to simulate the correlation between full and small scale fatigue tests. The full scale test results were similar for the two different alloys, and below the small scale test results, which do not include any stress concentration factors. Based on the numerical analyses the sealing surface showed high values of both equivalent alternate, $\sigma_{eqa}$ and mean $\sigma_{eqm}$ stress for the connection, and they recommended that one way to improve the design was to shift the sealing surface from the region where test/operation loads are high. Thus, peaks of $\sigma_{eqa}$ and $\sigma_{eqm}$ would occur at different points, diminishing the corrected stress and improving the fatigue life.

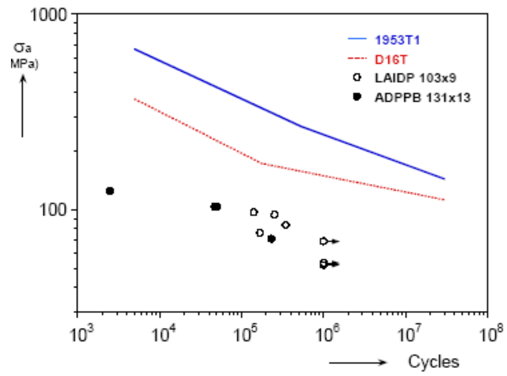


Figure 13: S-N curves based on small scale tests and full-scale results

### *5.4.3 Nickel*

9% nickel steel is often used in cryogenic applications, such as e.g. LNG storage tanks. A study was carried out by Gioielli and Zettlemoyer (2008) in order to confirm that fatigue behavior at cryogenic temperature was at least as good as that at room temperature. A total of 12 cruciform specimens were fatigue tested at -165°C. Prior work had shown that that 9% nickel weldments could be safely analyzed by the usual S-N curves for carbon steel weldments when at room temperature, Gioielli and Zettlemoyer (2007). Comparison of the results showed that the cryogenic condition improved the life noticeably, see Figure 14. This finding was not unexpected based on literature evidence showing reduction in crack growth rate at lower temperatures for this particular material.

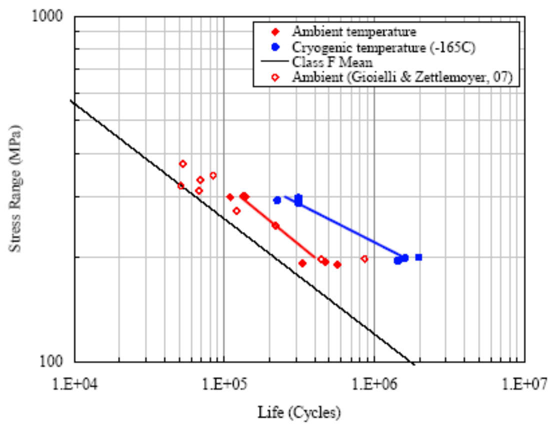


Figure 14: Fatigue test data of nine percent nickel steel at ambient temperature and cryogenic temperature (Gioielli and Zettlemoyer 2008)

The use of 36%Ni Fe (Invar) alloys for subsea LNG loading lines has been investigated lately, since the alloy is a low-expansion alloy; approximately 10 times lower than for steel, Wright (2007). The alloy has been used for cryogenic applications such as LNG tank lining and small scale piping. If stainless steel as used today, can be changed by 36% Ni, a straight sub-sea pipeline can be used and eliminate the use of expansion loops which reduces costs and environmental disturbance among others. An extensive test program was run by Newburry *et al* (2007) in order to investigate the mechanical properties of five commercially available filler metals. The tests were carried out at +20°C and -196 °C, and the objective was to identify a filler metal that overmatched the base material at both temperatures. However, the test results were not fully satisfying and require further work in order to increase tensile and toughness properties of the welds.

#### *5.4.4 Corrosion Resistant Alloys (CRA) Material*

Clad has successfully been used as corrosion protection in reduce the effect of H2S. For pipelines, two different methods are available; metallurgically cladded pipes and lined pipe. The first cladded pipeline installed with the reeling method, is the Norne 15" insulated clad steel pipeline in the Norwegian Sea. The maximum reeling strain was nearly 2%. The line pipe is longitudinally welded SAWL joints, with 21mm backing steel (X60) and 3mm metallurgic alloy bonded 316L CRA internally. AUT on cladded pipelines are very challenging in order to find reliable ways of detecting and sizing defects in welds with a combination of Austenitic and Ferritic structures, Haabrekke *et al* (2007). A follow up of this project, was to investigate the fatigue performance of nickel alloy filler girth welds in order to study the benefit of using clad sections in highly fatigued areas of risers subjected to sour service. A full scale fatigue test program was carried out, where 24 girth welds were tested and 11 results reported, Kristiffersen *et al* (2008). In addition to the as welded tests, hammer peening of the OD was also carried out and results compared to the D air mean curve from DNV-RP-C203, see Figure 15. Specimens that have been improved by hammer peening shows very high fatigue performance.

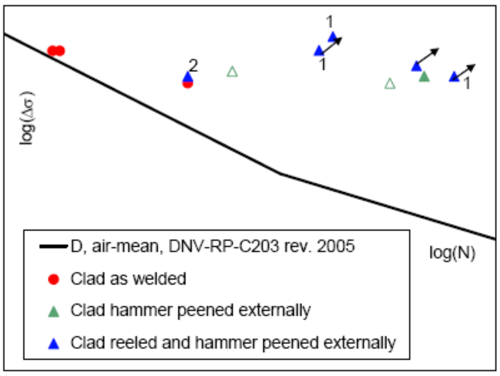


Figure 15: Nominal stress vs fatigue life for the different test parameters (Open symbols represents failure in pipe body.) 1) One specimen run-out tested at different stress levels. 2) specimen treated with partly fractured hammerhead, Kristiffersen *et al* (2008).

### *5.4.5 Duplex*

Larsen *et al* (2006) carried out full scale and strip fatigue test specimens and showed that S-N curves for welded SAF2507 super duplex stainless steel are superior to the mean S-N fatigue performance of welded carbon steel. The degree of improvement is approximately two fatigue classes and is primarily due to microstructural aspects associated with the processing of duplex stainless steel and the resulting transformation of BCC crystal structure to FCC. Olden *et al* (2007) carried out numerical simulation of hydrogen induced stress cracking in fine grained 25% Cr duplex stainless steel using hydrogen influenced cohesive zone elements. Boundary conditions of mechanical stresses and environmental loads on a pipeline in subsea conditions were applied. It was shown that a linear traction separation law fits well with the experimental results for stress levels of 0.85-0.9 times the yield stress.

### *5.4.6 Composite*

Yu and Wu (2006) presented a methodology for analyzing progressive damage accumulation on multiple spatial scales in composite materials. The classical homogenization theory is extended to account for damage effects on distinct spatial scales through the introduction of an asymptotic expansion of damage parameter. The numerical examples demonstrate the capabilities of the presented methods for the simulation of damage growth due to thermo-mechanical loading. Tilbrook *et al* (2007) carried out fatigue crack propagation test in homogeneous and graded alumina-epoxy composite specimens. In homogeneous composite specimens under monotonic load crack-extension toughening was observed.

Sabelkin *et al* (2006) carried out a combined experimental-analytical investigation to characterize the fatigue crack growth behaviour in a stiffened thin 2024-T3 aluminium panel repaired with one-sided adhesively bonded composite patch. They found that the bonded composite patch repair as well as stiffener decrease the stress intensity factor and crack growth rate. The increase in fatigue life of the cracked structure depends upon the relative values of stiffness of the cracked panel, spacing between the stiffener, and composite patch.

## *5.5 New materials*

A 5 year exposure test has been conducted on new materials and materials used for new environmental applications for marine structures in tropical climates. The focus was on new light weight materials anticipated to reduce the running and maintenance costs of structures exposed to harsh marine environments. A total of 21 different materials have been corrosion tested for three different environments, in the sea of Okinotori-shima and Miyako-jima and in a test laboratory in Tokyo with 60% humidity, Tomosawa *et al* (2006). The corrosion resistance and the tensile strength have been measured during the exposure period of 5 years, see Table 5 below for results obtained.

Table 5
Material test matrix

| Category | Okinotori-shima (Tropical climate) | Laboratory (thermal-hydrostatic room) | Miyako-shima (Subtropical climate) |
|---|---|---|---|
| I -no signs of corrosion or deterioration | Non Ferrous metal; Titanium Alloy, All composite materials, Coated Steel (with Zinc silicate, Epoxy glass flake paint ++ | | |
| II -marginal corrosion with no strength changes over time | Nickel- Based alloy (C-22) | Nickel- Base alloy (825) | Stainless Steel |
| III - light corrosion, such as macroscopically recognizable pitting corrosion but with no strength loss over time | | Copper Alloy Plated Steel, Plated Wire Rope | Aluminum Alloy |
| IV -corrosion with strength losses of less than 50% over time. | | Nickel Steel (for low temp.) Polyester Fiber Rope Aramid Fiber Rope | Coated Steel w. Epoxy marine paint |
| V -corrosion with strength losses of 50% or more over time | Normal Steel | | |

The study has been carried out under no loading. It must be noted that a combination of corrosion and fatigue under repeated loading can substantially reduce the durability of structural members. Therefore, a phase III of this test program was launched in 2006, Tomosawa *et al* (2008) in order to investigate the durability of aluminum alloy 5083, stainless steel SUS329J4L, 3 9% Ni steel ASTM A553 Type1, structural steel SM490A and CFRP (carbon fiber reinforced plastic material). This phase of the program is planed to last for 5 years where the specimens will be axially loaded during the test period at the test locations Okinotori-shima and Miyako-shima.

Different types of material are used for different applications depending on the structure and environment in question. It is believed that in the future, the material geochronology will further develop and new "fit for purpose" materials will be launched.

### *5.6 Laser Welded and Composite Structures*

During the past few decades, the shipbuilding industry has shown increasing interest in laser welding to reduce welding distortion and to improve dimensional accuracy. Hybrid welding, i.e. laser combined with gas-shielded metal arc welding, is expected to become especially widespread. Hybrid welding offers special advantages, such as low welding distortions, high productivity and easy automation welding. Additionally, this new welding method opens opportunities for design of light weight structures.

However, the welding process of laser-based welding differs from that of arc welding. Laser welding causes localised heat input with narrow weld and heat-affected zones, leading to smaller weld dimensions than those of the arc weld, see Figure 16. Remes and Varsta (2007) studied fatigue strength of laser-hybrid welded joints using notch stress approach. Fatigue notch factor for laser and hybrid welded joint was about 40 % smaller than that of submerged arc welded joint affecting also fatigue strength of the joint. Similar results are also reported by Caccese *et al* (2006) for filled welded joint. At present, the fatigue test results for the Hybrid welded joint were limited to small-scale specimens under constant amplitude loading. Therefore, on the basis of the existing fatigue test results, it is still difficult to state the proper S-N curve for design, at present laser and hybrid welded joint is classified as good as conventional arc welded joints.

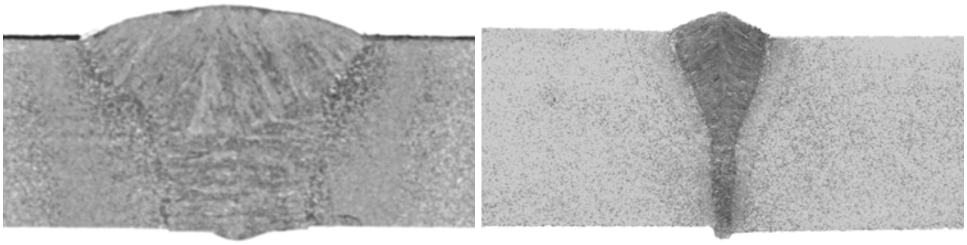

Figure 16: Difference between geometry of submerged arc (left) and laser hybrid (right) welded joint (Remes and Varsta, 2007).

Sandwich structures are in general made of two face-sheets and a core, which is formed as an assembly of complex geometrical and material properties. Moreover, the connection between face-sheets and the core presents specific properties by itself, being connected by different processes like welding, bonding or other. Fatigue properties are a subject of growing interest. Harte *et al* (2001) tested sandwich beams made from aluminum alloy foam core and half-hard aluminum face sheets under four point bending load. Results showed that theoretical predictions and associated fatigue strength are in general in agreement with observations. Romanoff *et al* (2003) made investigations on fatigue tested web-core steel sandwich panels loaded from one stiffener and between two stiffeners. A regression analysis based design equation was derived. Boronski *et al* (2004) fatigue tested laser welds between the web plates and the faceplates of web-core sandwich panels. They showed that the local bending of the weld due to specific joint geometry is an important issue when fatigue of these panels is considered. Kozak (2006) suggested, that strength properties of sandwich panels considerably differ from those of ship single-shell structures because of anisotropy of stiffness resulting from their geometrical features as well as specific properties of laser welds. The different properties make possible application of the algorithms for the assessment of fatigue life prepared for single-shell structures, directly to sandwich structures, doubtful.

Experimental research was carried out on laser joints made of 18G2A steel, Boronski (2006). The aim of the study was to investigate the material cyclic properties distribution in a laser-welded joint. They found that the cyclic loadings alter the material in relation to static loading and plastic softening was observed during the first loading cycles in the plastic regime. Caccese *et al* (2006) investigated the weld geometric profile effect on fatigue life of laser-welded joints. Systematic FE analyses, carried out on different weld profiles characterized by varying shape parameters, are used to calculate stress concentration factors based on the hot-spot stress approach and on Dong's mesh insensitive approach. FE analyses have also been performed to evaluate the sensitiveness of hot-spot stress to the mesh technique. Other than the main aim of the study, which was to demonstrate that with hybrid-laser welding a much better geometry control can be achieved and hence the fatigue life will be substantially improved, very interesting outcomes have been gained on suitability and limitation of the hot-spot stress method.

Sandwich structures with thin plates, complex geometries and stake welds with contact effect causes special challenges for fatigue assessment. Due to these factors the traditionally used fatigue assessment methods, such as nominal, hot spot and notch stress approaches, are not applicable. Thus, further research on this field is required to obtain robust method for fatigue design of steel sandwich structures and their joints to embedding structures.

# 6. FATIGUE DESIGN METHODS FOR SHIP AND OFFSHORE STRUCTURES

This section concentrates mainly on fatigue design procedures for ship structures which have been published for the first time or updated since 2006. This includes the IACS CSR rules: Common Structural Rules for Bulk Carriers and Oil Tankers and rules or recommendations provided by the different classification societies. A section including the resent updated and the most common Offshore codes addressing fatigue are presented. In addition a section discussing alternative fatigue design management methods are provided.

## *6.1 Fatigue Design Codes for Ship Structures*

The common fatigue approach for the IACS CSR rules, Common Structural Rules for Bulk Carriers and Oil Tankers are all based on S-N curve approach under the assumption of linear cumulative damage (Miner's rule). Several methodologies for long term stress response assessment exist. A summary of the details of the different procedures used for fatigue design is given in Table 6. The procedures are composed of three main parts: Load History Assessment, Stress Evaluation and Fatigue Strength Assessment.

### *6.1.1 Overview of Fatigue Analysis Methodologies used for Stress Response Assessment*

Several methodologies exist to determine long term stress ranges: simplified rule based analysis, spectral fatigue analysis methodology and design wave approach.

Simplified Rule based analysis assumes a two parameters Weibull distribution for the long term stress distribution. The Weibull distribution is defined by a Weibull shape parameter and a reference stress at an appropriate probability level. Stresses are based on rule loads (given in terms of analytical formulas) and they may be calculated by more or less refined structural analysis (analytical approach or Finite Element Method).

Spectral Fatigue Analysis Methodology allows to determine the long-term stress range from the wave environment (assumed or actually) encountered by the ship. This approach assumes linear load effects and linear stress response and is performed in the frequency domain. Two variants of fatigue spectral methodologies exist:

- Full spectral methodology: all linear loads effects (including phasing between them) are automatically included in the analysis via an integrated hydrodynamic/structural program.
- Load component spectral methodology is proposed by DNV CN 30.7 (2008) and DNV-RP-C206 (2007), LR, FDA Level3, (2004). This approach is a variant of the full spectral analysis, in which the description of loads applied on the structure is simplified. All load effects which are contributing to the total stress can be isolated and the total stress transfer function is obtained by a linear summation of the load transfer function (calculated by means of a hydrodynamic analysis) multiplied by the corresponding stress response per unit load (calculated individually from FE model for each unitary load). This method is simple to use but attention has to be paid not to duplicate the stress effects in the analysis. In reality, duplication can occur where effects are difficult to separate from one another.

Design Wave approach is a simplification of the frequency domain analysis. In this approach, each load is defined by an equivalent wave corresponding to a certain probability of exceedance which gives the maximum load response (see report from Committee I.2 (Loads) for further details). In practice, several wave frequencies and heading combinations should be analysed for each response studied. Design Wave Method is generally used to determine rule loads and the Standard Wave data (IACS Rec 34) for North Atlantic Zones is generally the base in most of the classification society rules. Fatigue design codes procedures for FPSOs are based on quasi-static wave loads and on cargo (still water loading) variations because the number of cycles due to the loading/unloading process of the tanks may be high for special details.

### *6.1.2 Common Structural Rules for Oil Tankers and Bulk Carriers*

Both IACS Common structural rules (CSR) for Oil Tankers and Bulk Carriers Hull structure published in January 2006 have been effective for new-buildings since 1st of April 2006. They consider Double hull oil tankers longer than 150 m and Single skin and double skin bulk carriers of with length in the range from 90 m to 350 m and with further requirements concerning geometrical characteristics (L/B, B/D and Cb). The fatigue assessment concept, characterizing both CSR rules is: North Atlantic Wave Environment as basis for fatigue loads (fatigue loads are based on $10^{-4}$ probability level of exceedance), net thickness approach is used, design life is taken as 25 years and allowable miner sum is taken equal to unity with use of design S-N curves (mean minus two standard deviations).

The maintenance of the CSR Rules leads to several amendments including Corrigenda and Rules Changes. A new consolidated Edition incorporating the amendments was published 1st July 2008. IACS has also put in place a long-term plan to further increase the harmonisation between the Tanker and Bulk Carrier rules. The action plan for 2008 in order to harmonize structural rules doesn't include the Fatigue Rules for which the harmonisation is postponed until 2009.

*6.1.2.1 Common Structural Rules for Bulk Carriers*

Fatigue assessment performed according to CSR Bulk Carriers (2008) is based on a simplified rule methodology. A list of critical details to be checked is given, however no guidance for detailed design is provided. Assessment of fatigue strength requires the following three steps: Calculation of stress range, selection of design S-N curve and finally calculation of cumulative damage. A summary of the fatigue procedure is given in Table 6. The notch stress is calculated by multiplying the hot spot stress by a fatigue notch factor ($K_f$) which corresponds to the "stress concentration due to the weld shape". For primary supporting members, hot spot stress is obtained from a fine mesh t x t shell elements FEM model with no modelling of the weld and using standard derivation method (surface stress extrapolation over 0.5t/1.5t from the structural intersection of plates). For ordinary stiffeners and hatch corners, a simplified analytical procedure is used.

The design S-N curve used with the reference notch stress is the original B curve from BS 5400(1980) but modified for stresses below the fatigue limit (i.e. $N \geq 10^7$) by means of Haibach's correction. The value of the inverse slope in the second part of the curve for $N \geq 10^7$ cycles is equal to 2m-1, ref. Haibach (1970). In case of welded detail in seawater and free corrosion, the S-N curve in air is to be used with no slope change at $10^7$ cycles, in combination with a reduction factor of 2 on the obtained fatigue life. The corrosion protection is assumed partially effective during the design life. Fatigue life of base material is enhanced according to the enhancement in material's yield stress. No additional safety margin is applied to the calculated fatigue life in addition to the safety level included in the S-N curves (based on mean minus two standard deviations curves corresponding to a probability of survival of 97.7%), e.g. if the miner sum is less than 1 the fatigue life is acceptable. Please note that for offshore structures, additional fatigue safety factors are required by the rules.

Mean stress, residual stress, plate thickness, corrosive environment and material effects are taken into account by means of factor correction of the notch stress range. Mean stress is considered as the loading conditions in the CSR BC in conjunction with the introduction of the initial weld residual stress and its shake down. When the maximum stress (residual stress + structural mean stress + stress amplitude) or the minimum stress (residual stress + structural mean stress – stress amplitude) exceeds the yield stress in tension or compression, shake down is considered. The amount of shake down is assumed to be the amount of excess, Yamamoto and Matsuoka (2002). Recently, weld residual stress was modified for primary members, RCN3 (Sept 2008) to correct calculated fatigue lives which were far from damage experience of the primary members in empty and loaded holds. The new value of initial weld residual stress for primary members is taken equal to zero. But, this correction is unsatisfactory and perhaps too simple to explain satisfactorily based on experience and does not always improve unrealistic fatigue life of primary member connections of empty and loaded holds.

#### *6.1.2.2 Common Structural Rules for Oil Tankers*

Fatigue assessment performed according to CSR Bulk Carriers (2008) is based on the simplified rule methodology. The list of critical details to be checked is limited to; longitudinal end stiffener connections and scallops in block joints on the strength deck within the cargo tank region and hopper knuckle between inner bottom and hopper plate for at least one transverse frame close to amidships. Guidance for these details is provided and the same fatigue assessments as for the bulk carrier (see chapter 6.1.2.1) is adopted. However, instead of using the hot spot approach, nominal stress approach is used as reference stress for fatigue evaluation of longitudinal stiffener end connections. Some special effects are taken into account such as the warping effect due to unsymmetrical stiffener, the increase of bending caused by relative deformation between supports, etc.

However, the hot spot stress approach is used for the hopper knuckle connection. Stresses are determined by FEM based on txt shell elements mesh model without modelling the weld. Hot spot stress is defined as upper surface stress at specified location 0.5 t from the actual weld toe location Classification of typical longitudinal end connections is proposed with their respective design S-N curves (F, F2). The effect of mean stress is considered by assuming a stress range equal to the tensile part and 60% of the compressive component, is similar to that used in BS5400 (1980) for fatigue analysis of the base material. Lotsberg (2006a) proposes other formula for correction factor than the one used in CSR oil tankers and CSR Bulk Carriers based on comparison analysis with fatigue test data. The effect of corrosive environment is taken into account by the same approach as for CSR Bulk Carriers. Fatigue damage is calculated in the same way as in CSR Bulk Carriers except that Weibull shape parameter is adjusted for side shell, longitudinal bulkheads and bottom structures.

### *6.1.3 Additional Rules and Recommendations for Trading Ships*

Fatigue design codes procedures for trading ships are mainly based on quasi-static wave loads. Other types of loading including e.g. temperature, cargo variations and dynamic wave loads due to natural vibration or impact loads (such as slamming, whipping or sloshing) which may induce fatigue damage are usually not relevant for design of trading ships except in special cases. Summary of the fatigue procedures used in trading ship's rules and guidelines are given in Table 6. Three common methods are available;

- Simplified rule based analysis (ch. 6.1.1) is typically used in all rules, guidance or guidelines for fatigue assessment of longitudinal stiffeners, shell plating, hopper knuckles and stiffener-frame connection (lugs). This approach may be applied to standard structural cases, standard wave environment (namely standard North Atlantic Zone) and standard operational route.
- Spectral fatigue analysis methodology (ch. 6.1.1) is recommended to be carried out for non-conventional ships or ships with restricted navigation or typical trade pattern. The full spectral analysis is used for all types of structural details of (theoretically) any ship, typically hopper knuckles, chamfer knuckles, stringer toes and heel, webframe brackets, at bottom girder-bulkhead connection, etc.
- The Load component spectral methodology is typically used for longitudinal stiffeners and shell plating by DNV CN 30.7 (2008), DNV-RP-C206 (2007), LR, FDA Level3, (2004).

The stress calculations are typically based on the hot spot stress approach except in BV rules and CSR BC which use notch stresses.

For longitudinal stiffeners, an analytical method based on elastic beam theory is used for nominal stress calculation and geometrical stress concentration factors are used to determine hot spot stress. For other welded details, FE analysis with fine mesh txt shell element model with no modelling of the weld is generally used by classification societies to determine hot spot stress. In most classification societies fatigue rules, hot spot stress evaluation may be obtained by two methods: (1) by extrapolation of surface stresses to the weld toe (i.e. structural intersection point when the weld is not modelled); or (2) by considering the surface stress at 0.5 t from the weld toe (i.e. structural intersection point when weld is not modelled). When using the first definition, the most commonly extrapolation technique used is the linear extrapolation of surface stresses over reference points at 0.5t and 1.5 t (t= plate thickness) away from the structural intersection point. When linear stress extrapolation is used, the derived hot spot stress is usually linked to the original design D curve, BS5400 (1980) or FAT 90 curve which are similar to the S-N curves provided by NK guidance (2008), KR guidance (2008)) for D curve and DNV CN 30.7 (2008) for FAT90. When hot spot is obtained it is recommended to link the stress to FAT80 curve DNV CN 30.7 (2008). An exception to that is the LR approach which links the hot spot derived at 0.5 t from the structural intersection to its own reference hot spot design S-N curve (provided from research study) which is close to UK DEn D curve or FAT90 curve. Some rules or guidelines like NK guidance (2008) recommend to use modified D curve instead of original D curve (i.e. residual stress including in the original D curve is removed) in order to consider initial residual stress and shake down separately in their procedure. For non-welded details, B and C design S-N curves are used in most rules and guidelines. S-N curves for aluminium welded joints are proposed in addition to S-N curves for steel welded joints in the GL Rules (2008).

Fatigue assessment is generally carried out on the basis of damage ratio (Miner's rule) using long term stress distribution and appropriate design S-N curves (Mean minus two standard deviations S-N curves) and taking the design life equal to 20 years. No safety factors are used, except for BV rules (2007). Generally, allowable miner sum is equal to unity (see table 6) except for BV Rules (2007) and NK Guidance (2008) procedures. Even if recent research studies indicate that a miner sum equal to unity may be unconservative, generally both fatigue procedures (based on simplified or spectral analyses) consider an allowable miner's sum equal to unity because other conservatisms are present in the analysis methodology and balance potential non-conservatism in the miner sum.

Factors influencing fatigue strength such as thickness effect, mean stress, residual stress, corrosion, material effect are taken into account differently in fatigue design procedures. Thickness effect is usually taken into account by means of a correction factor $k_s$ ($k_s = (t_{ref}/t)^q$ ) which is to multiply by the stress range. The formula shall only be applied when the thickness of the member (t) exceeds the reference thickness, $t_{ref}$; (q) is a thickness exponent (q) which is dependent on joint category in ref. Hobbacher (2007). See Table 6 and section 4.4 for further details.

Effect of mean stress (due to external loading) is accounted for in several rules and guidelines for fatigue assessment of both welded and base material by a reduction factor on the stress range. The reduction factor is taken independent of the residual stress level in some procedures like DNV CN 30.7 (2008) whereas in some rules and recommendations GL (2008) and Hobbacher (2007), the reduction factor depends on the level of residual stress (which is partly included in fatigue strength classes). Effect of mean stress, initial residual stress and its shake down are considered in NK (2008) and CSR BC (2008) and are based on the same methodology proposed by Yamamoto, N., Matsuoka, K. (2002).

Corrosion is accounted for, in most of rules and guidelines, by use of net scantling and use of S-N curves in air with no slope change at $10^7$ cycles and with reduction on fatigue life with a factor of 2 in case of welded detail in seawater and free corrosion. For base material, DNV-RP-C203, (2008) presents the corresponding S-N curve for free corrosive environment with an inverse slope equal to 3. In some cases, the corrosion protection is assumed partially effective while others propose a more accurate modelling of with time variant simulation of thickness. Material effect (Yield stress effect) on fatigue strength of non welded material is taken into account in LR Guidance (2004) and GL Rules (2008).

Workmanship practices affect the fatigue strength through the weld quality and misalignments. In most of the procedures, these aspects are covered by a general statement of good workmanship and by referring to respective quality standards (IACS Rec No. 47, DIN EB ISO 5817, JSQS, etc). In almost all rules and guidelines, no explicit factors are given for the effect of misalignment on fatigue strength. In those approaches, it is assumed that S-N curves take into account, implicitly, the stress concentration due to the permissible axial and angular misalignment given in the quality standards. Additional misalignment outside construction tolerance is taken into account by explicit analytical factors like in BV Rules (2007), DNV CN 30.7 (2008) or by FE analysis to calculate stress concentration factor due to misalignment as in LR Guidance (2004).

Post Weld Treatment such as grinding is mentioned by BV Rules (2007) and GL rules (2008). DNV CN 30.7 (2008) proposes several post weld treatment such as grinding, TIG dressing and hammer peening. The benefit of weld improvement may only be claimed for welded joints that are adequately protected from corrosion and where the root is not considered to be a critical initiation point for fatigue cracks. LR Guidance (2004) recommends that improvement methods should not be used as design tool and only should be considered where remedial measures are required. See ch. 4.6 for further details concerning comparison between different methods of post weld treatment proposed in several codes.

#### *6.1.4 Additional Rules and Recommendations for FPSOs*

During the last three years, DNV and BV published or updated rule documents for fatigue design of offshore ships structures (DNV-RP-C206 published in October 2006 and amended in April 2007) and (BV rules for FPSOs updated in March 2007, the original edition issued in 2006). Background and content of DNV-RP-C206 is presented by Lotsberg *et al* (2006b). Specific fatigue methodologies were developed for classification of offshore ships permanent installation on a specific field. As a consequence, of no dry-docking during the intended service life, the objective of offshore ships design is to achieve a reliable long term operation of the structures avoiding repair during the intended service life.

For offshore ships, the full spectral analysis is recommended in order to be able to calculate actual wave loads and stresses directly from the site-specific meteorological ocean data relative to the location where the ship will be installed (DNV-RP-C206 (2007)) and (BV rules for FPSOs (2007)). As specified in ch. 6.1.1, spectral analysis doesn’t take into account non-linear effects that affect stress ranges which may contribute significantly to fatigue damage. An example of such effect is the intermittent wetting for the side shell longitudinal stiffeners close to the waterline and the resulting effect on the pressure loads. Some rules propose to take into account this phenomenon by making a correction on the linear pressure model like BV rules for FPSOs (2007).

The effect of a corrosive environment on the fatigue life of offshore ships is taken into account through appropriate S-N curves. S-N curves for different environment are presented in DNV-RP-C203, (2008); air environment (two slopes), seawater environment with cathodic protection (two slopes curves) and seawater environment free corrosion (one slope curves). Moreover, corrosion is accounted for by means of thickness parameter for fatigue calculations. For new built offshore structures, gross thickness is used (i.e. without deducting the corrosion additions) because a corrosion protection system is normally required. For conversions of old tankers to production and storage units, fatigue calculations are based on actual scantling documented by thickness measurements.

Some details may be subjected to severe stress cycles during loading and unloading i.e. welded bulkheads connections for tanks that experience a full load reversal according to loading steps. A simplified method is proposed in (DNV-RP-C206 (2007)) and (BV rules for FPSOs (2007)) to calculate the damage due to loading/unloading cycles and wave cycles. Alternatively, fatigue damage may be obtained by making a time domain simulation of the combined stress process and applying the Rainflow counting method. This method gives a better estimation of fatigue damage if t performed rigorously with a sufficient number of time simulations representative of the wave scatter diagram (DNV-RP-C206 (2007).

As the objective of offshore ships design is to achieve a reliable long term operation of structures that are permanently installed on a field, DNV-RP-C206 (2007) and BV rules for FPSOs (2007) provides design fatigue factor (DFF) on the calculated lifetime of structural details of offshore ships. The factor DFF is a safety factor on the calculated fatigue life and is linked to the accumulated probability of fatigue failure during the design fatigue life. Both of them require a minimum DFF of 2, or higher, taking into account the consequences of failure and the degree of accessibility for in-service inspection and repair of structural details of offshore ships. Knowing that allowable miner sum is taken equal to unity divided by DFF, the allowable miner sum is less than 0.5.

Table 6
Summary of fatigue design procedures for trading ships

| Rules and Guidelines | Fatigue Analysis Methodology | Loads: Loads Calculation | Loads: Long Term Distrib.: Law (Shape, Prob) | Loads: Long Term Distrib.: Wave Scatter Diagram | Stresses: Stress Approach | Stresses: Stress Calculation | Fatigue Strength: S-N Curves (Welded Joint) | Fatigue Strength: Thick Effect (9) | Fatigue Strength: Mean Stress | Fatigue Strength: Residual stress And Shake down | Post Weld Treatment | Allowable Miner Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BV Rules (2007) | Simplified Analysis | Rule Approach | Weibull (1) (xsi,pb=$10^{-5}$) | | Notch Stress | Analytical | B curve [1] modified by BV | tref=22 mm; q=0.25 [4] | No | (10) | Grinding | $1/g_{R}$ (23) |
| | Full Spectral Analysis (NI 539) | Hydrodynamic Analysis | Rayleigh (short term sea state) | (12) | Notch Stress | FEM | | | | | | $1/g_{R}$ (23) |
| CSR BC (2008) | Simplified Analysis | Rule Approach | Weib (xsi=1, pb=$10^{-4}$) | | Notch Stress | Analytical or FEM | B curve [1] modified with [2] | tref=22 mm; q=0.25 [4] | Yes | Yes [6] | Grinding (RCN 3, Sep 2008) | 1.0 |
| CSR OT (2008) | Simplified Analysis | Rule Approach | Weibull (2) (xsi, pb=$10^{-4}$) | | Nominal/Hot Spot stress | Analytical or FEM | D curve [1] for Hot Spot Stress | tref=22 mm q=0.25 [4] | Yes [1] | No | (22) | 1.0 |
| DNV Classification Note (2008) | Simplified Analysis | Rule Approach (21) | Weibull (2) (xsi, pb=$10^{-4}$) | | Hot Spot Stress | Analytical or FEM | FAT90 [3] | tref=25 mm q=0.25 | Yes (11) | No | Grinding TIG dressing Hammer Peening [7] | 1.0 |
| | Full Spectral Analysis & Load Component Spectral Analysis | Hydrodynamic Analysis | Rayleigh (Short term sea state) | (12) | Hot Spot Stress | FEM | | | | | | 1.0 |
| GL Rules (2008) | Simplified Analysis (6) | Rule Approach | Standard Stress Range Spectrum | | Nominal Stress/ Hot Spot Stress | Analytical or FEM | FAT classes [3] | tref=25 mm several q based on [3] | Yes based on [3] | Yes Partly included in FAT classes | Grinding [3] & GL Research | 1.0 |
| | Full Spectral Method (7) | Hydrodynamic Analysis | Actual Stress Range spectrum | (13) | | | | | | | | 1.0 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KR Guidance (2008) | Simplified Analysis | Rule Approach | Weibull (3) (xsi, pb=$10^{-4}$) | | Hot Spot Stress | Analytical and FEM | D curve[1] (5) | No | Yes [1] | No | No | 1.0 |
| | Full Spectral Analysis | Hydrodynamic Analysis | Rayleigh (Short term sea state) | (14) | Hot Spot Stress | FEM | | | | | | 1.0 |
| LR Guidance (2004) | Load Component Spectral Analysis | Hydrodynamic Analysis | Rayleigh (short term sea state) | (15) | Hot Spot Stress | FEM | Lloyds Register's S-N curves | tref=22 mm [4] and several q | No | No | Yes | 1.0 (24) |
| NK Guidance (2008) (17) | Simplified Analysis | Rule Approach | Weibull (4) (xsi=1, pb=$10^{-4}$) | | Hot Spot Stress | Analytical | D curve [5] modified by NK (5) | No | Yes | Yes | No | 0.6 (25) |
| NK Guidelines [8],[9],[10] (18) | Simplified Analysis/ Design Wave Method/ Spectral Analysis (19) | Rule Approach/ Hydrodynamic Analysis | (20) | | Hot Spot Stress | FEM | D curve [5] modified by NK (5) | No | Yes | Yes | No | 1.0 (26) |

(1) and (2) : xsi (Weibull's shape parameter) is function of ship's length and position in the ship/ (3): xsi is function of ship length/ (4): xsi is equal to unity for the standard North Atlantic Zone
(5) Original design D S-N curve from BS(5400(1980), U.K, DoE(1990), U.K, HSE (1995) are the same.
(6) For standard applications, simplified rule based analysis is performed. Fatigue strength assessment is carried out on the basis of a permissible peak stress range for standard stress range spectra.
(7) For special applications with consideration of specific operational areas, full spectral method can be applied in order to determine actual stress range spectrum. In this case, fatigue strength assessment is carried out on the basis of a cumulative damage ratio.
(9) Thickness effect is taken into account by means of a correction (factor) on the stress range which is function of reference thickness (tref) and a thickness exponent (q).
(10) Residual stresses due to welding are taken into account with no shake down. They are taken equal to yield stress.
(11) Mean stress is accounted for by a reduction factor on the stress range when the dynamic stress cycle is partly or entirely in compression whereas no reduction is applied when entire dynamic cycle is in tension.
(12) North Atlantic scatter diagram (IACS Rec 34), World Wide Scatter diagram or Actual Trade Route Wave data given by the ship's owner may be used.
(13) In normal cases, North Atlantic scatter diagram (IACS Rec 34) or Typical trade route pattern on request
(14) According to ship's typical trading routes or ship's owner spec, the related wave data is applied.
(15) The Global Wave Statistics data (BMT) has been used to provide the annual wave scatter diagrams for each sea areas. Typical trade pattern function of ship's type is used.
(17) NK Guidance (2008) is applied for fatigue study of longitudinal stiffeners in any types of ships except tankers and bulk carriers.
(18) NK Guidelines [8],[9],[10] are applied for the fatigue study of primary supporting members in each type of ships.
(19) For standard applications, simplified analysis is performed using design analytical loads. For special applications, design loads are determined using "direct load analysis" based on design wave method or spectral method.
(20) Design wave loads and standard long term stress distribution parameters are established from Standard Wave data (Rec 34) for North Atlantic zones. Correction factors are applied on standard long term stress distribution parameters when typical trade routes other than North Atlantic route are used for fatigue calculation.
(21) The rule loads are based on North Atlantic zones. If the vessel is trading in a less harsh environment equal to a world wide trade, a reduction factor of 0.8 may be applied on the stress range.
(22) No Grinding at design stage except for the Hopper Knuckle Connection
(23) Partial safety factor covering uncertainties regarding Miner's sum (gR) is taken equal to 1.02 except for details at ends of ordinary stiffeners for which gR is taken equal to 1.10.
(24) Allowable Miner's sum is taken equal to 1.0 except for specified critical locations in way of the cargo containment barrier, e.g. inner bottom, hopper sloping plate, inner longitudinal bulkhead, etc for which allowable Miner's sum is taken equal to 0.8.
(25) Allowable Miner's sum is taken equal to 0.6 for longitudinal stiffeners in any types of ships except tankers and bulk carriers.
(26) Allowable Miner's sum is taken equal to 1.0 in all cases for primary supporting members in bulk carriers, oil tankers (for which IACS CSR is not applicable) and container ships except in case where the initiated crack in the member may affect directly the watertight integrity of the compartment.

[1] (BS5400 (1980)) /[2] Haibach(1970)/ [3] Hobbacher (2007), Doc XIII-2151-07/XV-1254-07/ [4] (U.K, DoE (1990))/[5] (U.K, HSE (1995))
[6] (Yamamoto, N., Matsuoka, K. (2002)), [7] Haagensen (2006), Doc XIII-1815-00/ [8] NK Guidelines for Tankers Structures (2001)/
[9]NK Guidelines for Bulk Carriers Structures (2002)/ [10] NK Guidelines for Container Carrier Structures (2003)

## *6.2 Fatigue Design Codes for Offshore Structures*

### *6.2.1 Rules for Offshore Structures, Recent Updated Codes and Amendments*

An updated version of the DNV recommended practice Fatigue Design of Offshore Steel Structures, DNV-RP-C203 was issued in April 2008, Lotsberg (2005b). The Recommended Practice (RP) presents recommendations in relation to fatigue analyses based on fatigue tests and fracture mechanics. The guideline is valid for steel materials in air with yield strength less than 960 MPa. For steel materials in seawater with cathodic protection or steel with free corrosion the Recommended Practice is valid up to 550 MPa. The main changes from the previous version dated 2005 are: The eccentricity, $\delta 0$, in equations for stress concentration factors for butt welds in pipeline is removed, the section on grouted joints is extended to include joints with the annulus between tubular members filled with grout and the stress concentration factors at circumferential butt welds in tubulars subjected to axial load are included for thickness transitions on inside and for welds made from outside only.

Two recently updated Bureau Veritas Guidance provide guidelines and recommendations for fatigue design are: Bureau Veritas Guidance Note NI 493 DTM R01E, "Classification of mooring systems for permanent offshore units", July 2008. It is the first update of the original edition issued in 2003 and Bureau Veritas Rules for the Classification of Offshore Units (2007), “Fatigue Check of Structural Details, Section 7, §7 in Part D, Chapter 1(Production, Storage and Offloading surface units), NR 445.D1 DT R02 E, March 2007, which is the first update of original edition issued in 2006.

A new update of the European standard for the design of Fixed Steel Offshore Structures “EN ISO 19902” was issued in January 2008, EN ISO 19902 (2008). The standard covers design for the Fatigue Limit State (FLS) for the whole lifetime of the structure including fabrication, sea transport, installation, in-place situation and removal. The general method for determination of fatigue lives is based on an S-N approach with cumulative damage determined by the Palmgren-Miner rule. It is recommended that fracture mechanical approaches are not applied for general design but only for special purposes and for estimation of remaining lifetimes of structures. Weld improving techniques are in general not to be applied in the design phase as long as sufficient fatigue strength of the structure can be reached by other means, i.e. change of geometry or construction details.

## *6.3 Arctic design codes*

Oil and gas exploration and production is moving into arctic areas. This means additional challenges for design, construction and operation of offshore installations and ships. The new ISO 19906 was issued in an updated draft version November 2008, and it specifies requirements and provides guidance for the design, construction, transportation, installation, and decommissioning of offshore structures, related to the activities of the petroleum and natural gas industries, in arctic and cold regions environments. However the rules do not contain specific requirements for the operation, maintenance, service life inspection or repair of arctic offshore structures. For most of the structural members the code refers to ISO 19902 Fixed steel offshore structures, ISO 19903 Fixed concrete offshore structures and ISO 19904-1 Floating offshore structures. Thee are no specific rules and guidelines on how fatigue limit states (FLS) shall be analysed, the requirement is that FLS shall be satisfied for all parts of a structure, and that fatigue shall be given particular attention at cold temperatures. For material requirements reference is given to ISO 19902.

## *6.4 Alternative Fatigue Design Management Methods*

### *6.4.1 Fitness-for-Service Methods, Monitoring of Crack Growth*

The FFS process aims at evaluating whether or not equipment, although being in a downgraded condition, is still safe enough to continue its service in specified conditions for a certain period of time.

The FFS procedure has been included in an European Community project FITNET. Koçak (2005a) gives an overview of the objectives and technical content of the developed procedure and the validation by the European FFS Network FITNET. It embraces advances in flaw assessment procedures such as SINTAP, industrial codes such as R5, R6, API579, as well as national and international standards such as BS7910, ASME Sec. XI, A16, and WES2805. It must be noticed that a new standard designated as API579/ASME FFS-1 2006, based on the first edition of API579 includes new parts covering FFS assessment procedures, Osage and Prager (2006). Before performing a FFS analysis for flaws detected in in-service components, an investigation should be carried out to establish the most likely cause of cracking. Then a selection of the analysis module should be made: One is the Fracture Module and the other is the Fatigue Module. In the Fracture Module 6 Assessment Options are provided which enable advantage to be taken from increasing data quality and which reflect the variation in availability of input data, user knowledge, experience, and assessment purpose. Several papers by Webster (2005), Cicero and Ainsworth (2005), Koçak *et al* (2005c) and Luçon *et al* (2005) cover specific features of FITNET Fracture Module. Validation of the FITNET Fracture Module has been performed through the results of over 300 full-scale and large-scale tests, including wide plate, pressure and bend tests on welded and plain materials, Hadley and Moore (2006). In the Fatigue Module, five Fatigue Damage Assessment Routes are used to foresee basic application scenarios, Koçak *et al* (2005b). A final draft of the FITNET procedure, MK8, is published by Koçak *et al* (2008a, 2008b).

Bureau Veritas guidelines for performing FFS (2005) give some extended cases where FFS assessments are required. At the same time, a new philosophy appears, that is a reverse process in order to extend the life. It shows that the main problem is to have a balance between the gain expected from the additional services associated with the life extension of the item, versus among other things which implies costs in terms of fees due to the study itself and possible complementary investigations. It is to be underlined that, considering damaged equipment, risk based inspection (RBI) can also be performed together with FFS. Another concept of FFS is Engineering Critically Assessment (ECA) method. The procedure is based on Fracture Mechanics that may determine the flaw acceptance and inspection criteria in fatigue and fracture design of risers and flowlines, Luk and Wang (2007). A number of design codes provide guidance for this procedure, where the most common one is BS-7910:2005.

#### *6.4.2 Methods to Calculate Damage due to combined Low Frequency and High Frequency load*

Several methods are proposed to calculate the damage of structural components subjected to combined effect of high frequency loads and low frequency loads. In the Simple Damage Summation Method, high frequency damage and low frequency damage are calculated independently and then simply added. Simple summation method is non-conservative in all cases and this method shall not be used according to DNV-RP-C206, NF EN ISO/FDIS 19901-7 and Huang and Moan (2006). Since the combined fatigue damage is not equal to the sum of high frequency damage and low frequency damage because of the non linear relation of fatigue damage and stress.

In the *Combined Spectrum Method*, the two stress response spectra (related to low frequency and high frequency) are calculated separately and are added together in order to obtain the combined spectrum. The characteristics of the combined spectrum in terms of standard deviation and up crossing rate are then determined and the damage is calculated using the combined spectrum characteristics. This method is also used to determine the damage of structures submitted to wave conditions described as a combination of swell and wind seas like in areas of West Africa. Combined spectrum method is used for the offshore specific interfaces such as Fluid Transfer Line, Oil Offloading Line (OOL), risers and mooring lines that are governed by non linear dynamics as well as wave hull-interactions. The method was used to determine the damage due to swell and wind seas of the Agbami FPSO located in the west-offshore of Nigeria using a bi-modal spectrum, Hwang *et al* (2007) and to assess fatigue of side shell details of an FPSO located in the south-eastern part of the Norwegian Sea which is an area exposed to wind sea and swell propagating in different directions, Andersen *et al* (2008) (seee ch. 7.1). The impact of wave and swell directionality on fatigue damage result could be significant in critical structural locations, Kim *et al* (2007). Combined Spectrum method provides a conservative estimate of the damage with respect to Rainflow counting when responses spectra are independent. Nevertheless, in the case of dependent stress response (case of ships submitted to combination of quasi static wave response and springing response), this method is un-conservative.

*The combined spectrum method* with dual narrow-banded correction factor corresponds to a modification of the combined spectrum method presented above by multiplying the fatigue damage with a (dual narrow banded) correction factor (DNV-RP-C206 and NF

EN ISO/FDIS 19901-7). This last method can greatly decrease the conservatism of the combined spectrum method with respect to rainflow counting method and is applicable when frequencies of the two spectra are very distinct i.e. frequency ratio is greater than 4 according to DNV-RP-C206. The improvement tends to be lost when the low-frequency load is strongly dominant. This method is particularly applicable to mooring systems or risers which are subjected to low frequencies stresses induced by vessel slow drift motion combined to wave frequency stresses.

*Simplified Analytical Method* for calculation of combined fatigue damage requires a damage accumulation law together with a cycle counting method (e.g Rainflow counting). Analytical prediction formulas are proposed by several authors in order to estimate fatigue damage in case of combined low and high frequency loads.

- Combination of two narrow-banded Gaussian high and low frequency processes with well-separated spectra. Jiao G., Moan T. (1990) derived a reduced factor by which the narrow band approximation of the combined fatigue damage is taken into account. By using Naess's method to predict the fatigue damage of narrow banded processes, Gao and Moan (2006) extended this method to the combination of non-gaussian narrow band low and wave frequencies mooring line tensions of a semi-submersible.

- Combination of a wide band process, where the combined fatigue damage may be evaluated from analytical formulae proposed by several authors; Wirsching and Light (1980), Dirlik (1985), Benasciutti and Tovo (2005) in order to estimate the expected Rainflow damage.

- Combination of low and high frequency loads (Gaussian and non Gaussian) for which the combined fatigue damage is determined from explicit practical formula, Huang and Moan (2006) which is based on the information about individual low frequency and high frequency responses such as individual fatigue damage, mean up crossing frequencies and kurtosis. The numerical simulations show that the predicted damage due to Gaussian wide band loads obtained by the derived formula is very simple to use and close to the rain-flow damage prediction; the ratio of the new formula damage result versus Rainflow damage is included between 0,8 to 1,2. The above formula is derived by considering actual loads as random processes and not constant amplitude stresses as in the derivation of the DNV's formula, Lotsberg (2005 b). Indeed, Lotsberg (2005b) considered the combination of two equivalent-damage constant amplitude stress histories, and following the rainflow counting, derived a simple explicit formula which is taken as DNV's rule formula in DNV-RP-C206 (2007). A similar approach is proposed by BV Rules for FPSOs (2007) for evaluating the combined fatigue damage due to high cycle load and low frequency load. However, according to the results of numerical examples studied in the paper by Huang and Moan (2006), DNV's formula may overestimate the combined damage by a factor of 30% up to more than 100%.

# 7. PRACTICAL EXAMPLES AND A BENCHMARK STUDY

Obviously, fatigue evaluation becomes a general requirement for ocean structures such as ships and offshore structures. As more economic and reliable design is required, many comparative studies have been performed to justify upgrading of current fatigue design S-N curves, to provide a better basis for design, or to propose improved methods. In this section, typical practical examples and benchmark studies are summarised, in addition to a benchmark study carried out by the Committee.

## *7.1 Practical Examples and Dissemination of Results*

Important fatigue research results have been continuously reflected in the design codes or design. For ocean structures, probabilistic approach based on the design S-N curves has become well-established and required procedures. Park *et al* (2008) presented fatigue analysis procedure and results for a drillship based on probabilistic method, DNV-RP-C203 (2005). Her operating sites are Gulf of Mexico and North Sea in summer season. Fatigue loads from waves were directly calculated from hydrodynamic analysis. Hot spot stress RAOs were made based on component based method and DNV D curve was applied for fatigue damage calculation of weld toes. Hot spot stress was taken as the surface stress of 4-node shell elements read out for point 0.5t away from the interaction line and multiplied by 1.12. Principal stress within an angle +/- 60 degrees normal to the weld was used. Since bending component of resultant stress is less influencing compared to membrane component, it was reduced to 60%. If part of the stress cycles is in compression at base metal, i.e., non-welded areas, mean stress influence was considered by reducing the stress range. Thickness effect was also considered for the weld toes where plate thickness is more than 25 mm. Fatigue evaluation was performed for hull and hull-topside interface structures. If the result did not satisfy the required fatigue life of 25 years, local structural improvement or toe grinding was applied according to DNV-RP-C203 (2005).

Hwang *et al* (2007) presented the fatigue results for an FPSO based on probabilistic method. As per the design requirement, the hull of the FPSO was designed to meet ABS's (2002) SFA (Spectral Fatigue Analysis) notation and the seagoing condition. The seagoing condition was a mandatory condition required by Client, assuming a navigating vessel at North Atlantic. The FPSO operates at offshore Nigeria with spread moored and experiences three wave components, primary swell, secondary swell and wind wave. Fatigue evaluation was performed for hull details and hull-topside interface details. The evaluation was based on hot spot stress and full ship FE model. Thickness effect was considered for the weld toes for thickness more than 22 mm. The combined damages from the three wave components were calculated from the spectral combination method. The result shows that the FPSO experienced at least 7 times higher fatigue damage during the seagoing, compared to the on-site operating condition.

For ships in operation and FPSOs operating in a harsh environment, several cracks have been reported for structural details sensitive to roll motion and dynamic pressure.

The traditional approach assumes all wave energy to be collinear. The relative direction between the FPSO and waves is normally taken as 0, +/-15, and +/-30 degrees, with a corresponding symmetrical probability for each direction. Andersen *et al* (2008) proposed a simple methodology to calculate fatigue damage in non-collinear wind generated sea and swell for a weather vaning FPSO in the Norwegian Sea. The fatigue damage of selected side shell longitudinal stiffeners at midship were presented. The combined damages from two wave components; swell and wind wave, were calculated from the spectral combination method. The relative contributions from sea and swell to the total damage were identified as well as the sea-states and headings that contributed most to the total damage. The fatigue damage was based on the component-based spectral fatigue calculation and notch stress calculated from nominal stress and factors recommended by DNV CN30.7 (2007).

Healy (2007) performed a spectral fatigue analysis using both the surface extrapolation and Battelle structural stress methodologies (BSSM) for a side shell connection detail typical of a representative FPSO or tanker vessel. This marks the first time the Battelle method has been adapted to spectral fatigue. Fatigue damage at the toe along a number of weld lines was computed for a variety of surface extrapolation strategies and Battelle method options. When compared with the fatigue damage produced by the BSSM, the fatigue damage at the examined weld end details tends to be over-predicted by surface extrapolation methods. This is particularly true when extrapolating from <0.5t, 1.5t>. The best agreement at the weld end details comes from the surface stresses extracted at 0.5t. At the corner of the overlap weld, where the in-plane shear is not significant, there is good agreement between the fatigue damage produced by the BSSM and that produced by extrapolation from <0.4t, t> and extraction at 0.5t. In comparison, the fatigue damage produced by extrapolation from <0.5t, 1.5t> is under-predicted. In this particular study, the extrapolation from <0.5t, 1.5t> over-emphasizes the importance of the weld ends in relation to hot spots along the weld line.

For fatigue life prediction of ship structural details, structural hot-spot stress or the effective notch stress should be applied in the assessment. Although these approaches are able to consider the local geometry more rationally, they have the disadvantage that different guidelines for modelling and procedures for stress evaluation exist, see chapter 2 and 6 for further information. In order to quantify the modelling uncertainties and to identify the sources of scatter of stress results, a round robin was carried out for typical ship structural details within the Network of Excellence MARSTRUCT, Fricke *et al* (2007a). Several partners took part in the round robin, utilizing their own expertise and software. In total three details were selected for the round robin, two of which being suited for the computation of structural hot-spot stresses and one for the computation of notch stresses.

The first study concerns the hot spot stress assessment of a thickness step between plates, which creates an increased structural stress due to secondary bending, see Figure 17. A butt joint with a thickness step from 20 to 30 mm is arranged at half length and the tapering of the thicker plate is 1:3. Two different models are considered, Model 1, where the 30 mm plate extends over the whole deck width, and Model 2, where the 30 mm thick plate extends over 880 mm at the side of the deck. Different modelling schemes were applied; shell or solid element, mesh sizes corresponding to thickness ‘t’ or 0.4t or less. Also different methods to model the thickness step were applied. Hot spot stresses were calculated from linear or quadratic extrapolation. The resulting mean SCF is 1.595 and 1.608 for Model 1 and Model 2, respectively, and these are slightly lower than the SCF from the Hobbacher formulae, 1.75, due to the presence of the longitudinal stiffeners. The maximum deviation from the mean value is less than 5.0 %. As no clear relationship between the kind of modelling and evaluation and the results can be recognized, modelling with shell elements is sufficient for the analysis of the stress rising effect of a thickness step in comparable structures.

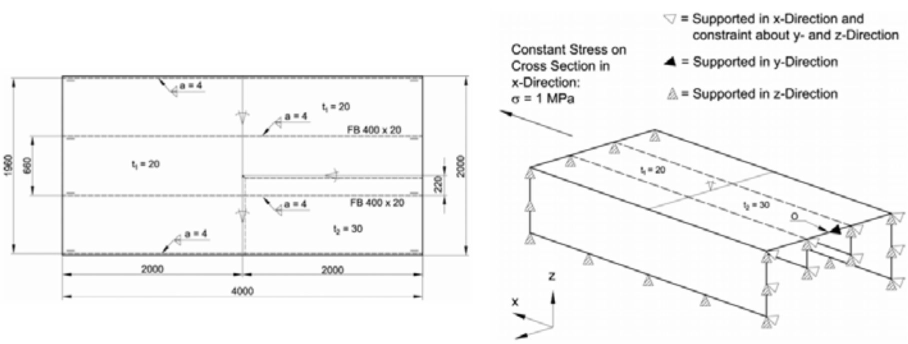


Figure 17: Geometry, boundary conditions and loads of deck strip with a thickness step (Fricke *et al* 2007a)

The second study concerns the hot spot stress assessment of a T-shaped longitudinal through a bulkhead with four hot-spots at different locations, see Figure 18 along with a typical finite element model and hot spot locations. Two types of transitions through bulkheads are realized. At the left transition, the T-bar penetrates through the slotted bulkhead, whereas a cut-out is arranged at the right side, which is closed by an overlapping patch. All plate connections are continuously fillet-welded with a nominal throat thickness of 5 mm. The results are normalized with respect to the nominal stress obtained in the mid-span of the beam onto the flange (lower side), for comparison purposes. The resulting SCFs are given in Table 7 along with element type, weld modelling and stress extrapolation method. This complex details show somewhat higher scatter compared to the first study particularly if shell elements and simplified weld modelling are used. From the fatigue tests, target SCF values were derived based on the difference between the hotspot fatigue class FAT 100 and the nominal fatigue class obtained from tests. This yields smaller SCFs between 1.24 for hot-spots 2 and 3 and 1.44 for hot spots 1 and 4. Compared to these numbers, the computed values are conservative.

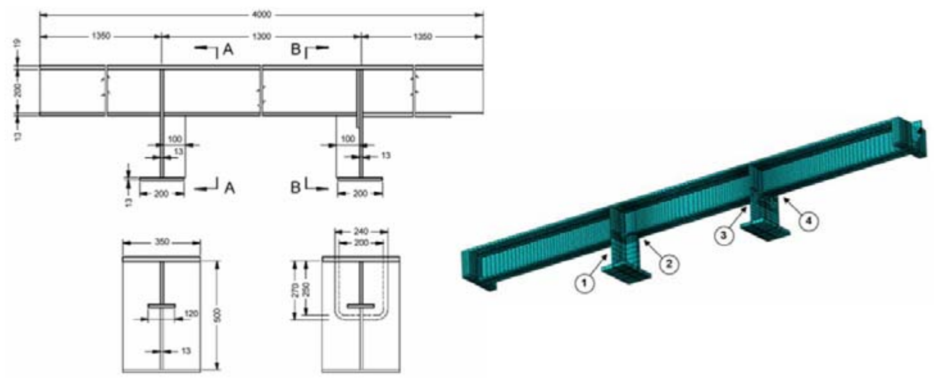

Figure 18: Structural details of the longitudinal / bulkhead penetration and typical finite element (Fricke *et al*, 2007a)

Table 7
Modelling details and analysis results for longitudinal / bulkhead penetration (Fricke *et al*, 2007)

| Parti-cipant | Soft-ware | Elem.type, weld mod., stress extrap. | SCF 1 | SCF 2 | SCF 3 | SCF 4 |
|---|---|---|---|---|---|---|
| A | Ideas/ Permas | solid, weld not modelled | - | 1.93 | 1.83 | - |
| B | Ansys | solid, weld modelled | 1.62 | 1.67 | 1.61 | 1.61 |
| C | Patran Nastran | Shell Quad4, with shape function | 1.76 | 1.50 | 1.48 | 1.67 |
| C | Patran Nastran | Shell Quad8, with shape function | 1.66 | 1.37 | 1.36 | 1.53 |
| D | Ansys | p-meth., no weld, global convergence | 1.81 | 1.60 | 1.54 | 1.79 |
| E | Abaqus | Shell, weld not modelled | 1.67 | 1.69 | - | - |
| E | Abaqus | Solid, weld 1+4, IIW 0.4t / 1.0t | 1.61 | 1.68 | - | - |
| E | Abaqus | Solid, weld 1+4, linearis. over t | 1.74 | 1.63 | - | - |
| F | Nisa | 8 nodes shell IIW 0.5t / 1.5t | 1.90 | 1.43 | 1.37 | 1.89 |
| Mean value | | | 1.72 | 1.61 | 1.53 | 1.70 |
| Coefficient of variation | | | 5.8% | 10.3% | 11.4% | 8.4% |

The third study is for a fillet-welded end joint of a rectangular hollow section where the root of the one-sided weld is prone to fatigue and may be assessed with the effective notch stress method (see section 2.2.3). The weld root was idealized by a circle with fictitious radius of 1 mm. Although different modelling techniques were used, the scatter of the results is fairly small if the element size at the weld root is less than 0.25 mm.

For ships and floating offshore structures, fillet welding or partial penetration welding is applied to a large extent to join structural components. This leads to non-fused root faces, which can behave like initial cracks. In several cases the situation is even worse, when welding can be performed from one side only, resulting in a highly-stressed weld root. In these cases, the nominal stress approach has shortcomings as locally increased stresses and local throat bending are not considered. The notch stress and crack propagation approaches are generally well-suited for fatigue assessment in these cases. Fricke (2006) presented practical approaches for such problems which were based on a structural stress or a local nominal stress in the weld. Their application was demonstrated by several examples shown in Figure 19 taken from ship and offshore structures. Two different approaches were described together with application examples, where fatigue tests are available. The first one concern loaded attachment ends, where increased stresses are present. By calculating a local nominal stress, averaged in a clearly defined effective weld area, the 3D situation becomes similar to the 2D situation of a cruciform joint so that the fatigue classes defined in different codes and guidelines for weld root failure can be applied. The attachment end with a soft toe, showed a corresponding fatigue class of just above FAT 40. The second approach concerns fillet and partial penetration welds which are subjected to local throat bending. It was proposed to compute the linearised stress in the leg plane in extension of the non-welded root faces. This structural weld stress was analysed for a tubular joint, a doubler plate and a cruciform joint. The fatigue tests of these details suggest a fatigue class FAT 80 based on structural weld stresses including the bending portion. The method has strong merit because the computation of the structural weld stresses is possible with rather coarse finite element mesh, which is also usual for the computation of the structural hot-spot stresses at weld toes.

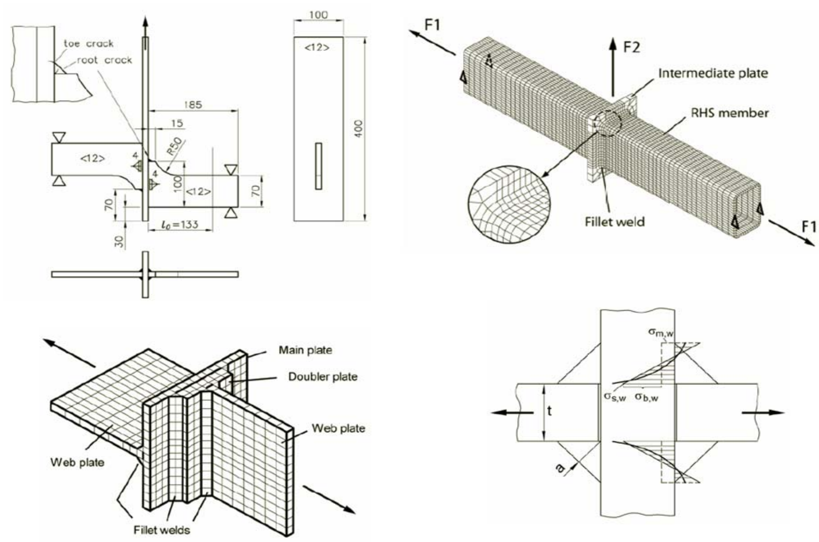


Figure 19: Examples of numerical and experimental study for weld root fatigue assessment (Fricke, 2006)

For fatigue design it is necessary to provide guidelines on how to calculate fatigue damage at weld toes based on S-N data when the principal stress direction is different from that of the normal direction to the weld toe. Some different fatigue criteria for these stress conditions were available from IIW (2007) and Eurocode (2005). Lotsberg (2008) compared these criteria against some relevant fatigue test data presented in the literature and proposed a new method. Only proportional loading conditions were considered. (By proportional loading is understood that the principal stress direction is kept constant during a load cycle). The IIW's quadratic interaction equation and the proposed method showed good agreement with test data while the Eurocode's damage summation equation was not that good. The Eurocode showed a rather small interaction effect between normal stress and parallel stress when the angle between principal stress and welding line is 45 degrees. The proposed method is considered to be efficient for calculation of fatigue damage when used together with the hot spot stress concept (or structural stress concept) with stresses read out from finite element analysis.

Heo *et al* (2007) performed a great deal of experimental validation work in order to verify the combination method proposed by the DNV and the well-known linear combination of calculated damages due to low and high cycle loading. A number of fatigue tests using cruciform welded joints under various loading cases were carried out. In order to evaluate a mean stress effect on high cycle loading, various loading cases were also applied to fatigue tests. All the fatigue test data with various loading cases were compared with the results from low cycle and high cycle fatigue tests, respectively. Fatigue damages due to combined fatigue tests were calculated and compared based on pseudo hot spot stress and nominal stress. Based on fatigue tests and damage calculation results using various methods, see Figure 20 , the most accurate damage calculation was obtained from the case of the linear combination method with peak-to-peak range based on pseudo hot spot stress considering mean stress effect.

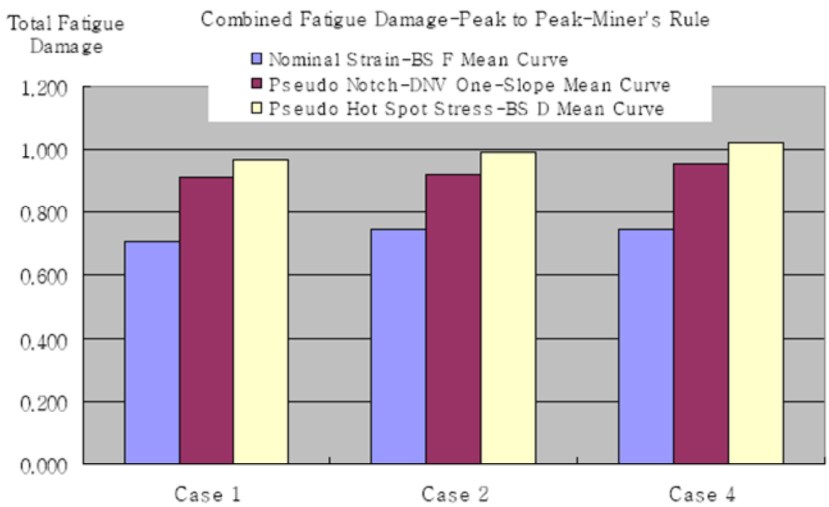

Figure 20 : Comparison of total fatigue damage calculation methods (Heo *et al*, 2007)

Pipes with high quality one-sided girth welds are increasingly used for steel catenary risers or subsea pipelines (see ch. 5.4). However, the widely used fatigue design classification, UK Class F2, for such welds made without backing is not well founded, but probably over-conservative for high quality pipeline welds. In an attempt to justify upgrading current fatigue design classifications and providing a better basis for design, fatigue tests and evaluation works have been performed. Maddox *et al* (2006) performed full scale fatigue tests on a range of girth-welded pipes produced by pipeline welding contractors. They presented fatigue results and an evaluation in terms of the factors that influence the fatigue performance of girth welds, including welding process, welding position, backing system, joint alignment, weld quality, specimen type and fatigue loading conditions. The key features to obtain the highest fatigue performance are the achievement of good joint alignment and full penetration welds with root beads that are flat and blend smoothly with the pipe surfaces. A 'hi-lo' on the inside of the pipe seems to have a dominant effect on the achievement of such welds and therefore it should be minimized by careful joint alignment and appropriate choice of tolerances on pipe ovality and wall thickness. The authors showed that depending on this control, the current design curve, UK Class F2, can be upgraded to UK Class C for 1G position, and at worst Class F for 5G position. Haagensen *et al* (2007) also performed full scale fatigue tests for 6" pipes full with high quality girth. Artificial welding defects were introduced, in the form of lack of penetration defects of approximately 2 x 50mm which were placed at the bore, and hi-lo's which were varied up to 2mm at the inside and outside. The scatter in the fatigue test data was reduced when comparisons were based on local stress at the point of fracture initiation. The results supported the use of the E design curve, despite large defects that were deliberately introduced in the pipe specimens. When analysed on the basis of local stress at the inside surface where cracks initatiated the data showed little scatter, with a standard deviation of s = 0.141. The Exxon data, Buitrago *et al* (2003) also provided in this paper for high quality riser welds in 6" pipes with WT of 15.9 and 18.3 mm also supported the E design curve when the ID surface stresses were used while D design curve when the OD surface stresses were used in the regression analysis.

## *7.2 Benchmark Studies*

### *7.2.1 Comparative Study on Estimation Techniques for Structural Hot Spot Stress of Web Stiffened Cruciform Connections*

Recently, new shell-based HSS determination techniques have been proposed by Lotsberg *et al* (2007), Osawa *et al* (2007) and IACS CSR-B (2005). The validity and applicability of these new techniques are examined in this benchmark study.

#### *7.2.1.1 Target Hot Spot Stress*

The target HSS is calculated using fine shell-solid coupling FE model. Solid and shell meshes are connected by the PSCM method Osawa *et al* (2007b). In the solid part of the model, welds are modelled with 6 or 8 layers of solid elements are arranged over the thickness in the solid part of the coupling model. HSS is determined by an extrapolation of calculated surface stresses to the weld toe from t/2 and 3t/2, where t is the thickness of the main plate.

#### *7.2.1.2 Derivation of HSS from Shell FE Results*

Shell FE analyses are carried out using t x t or (t/3) x (t/3) shell FE models. The surface stress on the intersection between the main plate and the web plate is calculated. HSS is derived by the four following methods.

(1) SR202B method (0.5t-1.5t linear extrapolation)

The stresses are read out from a shell FE model at read out points shifted away from the intersection line by 0.5t and 1.5t where t is the plate thickness. HSS is derived by a linear extrapolation over these points away from the intersection.

(2) Lotsberg's method (Lotsberg *et al*, 2007)

The stresses are read out from a shell FE model at read out point shifted away from the intersection line by the following value

$$\chi_{shift} = \frac{t_1}{2} + \chi_{wt} \tag{1}$$

where, $t_1$ is the plate thickness of plate at hot spot area, and xwt is the additional fillet weld leg length. HSS is derived as

$$\text{HSS} = \sigma_s\left(x_{shift}\right) \times \beta \tag{2}$$

where, σs is the surface stress at the point shifted away from the intersection line by x, and the correction factor β is given by

$$\beta = \gamma + \alpha_1 \frac{x_{wt}}{t_1} + \alpha_2 \left(\frac{x_{wt}}{t_1}\right)^2 \tag{3}$$

Coefficients $\gamma, \alpha_1, \alpha_2$ depend on the bevel angle between the main and attachment plates, θ, and they are given as follows:

For θ=135º connections, $\gamma = 1.07,\ \alpha_1 = 0.15,\ \alpha_2 = 0.22$.
For θ=120º connections, $\gamma = 1{,}09,\ \alpha_1 = 0.16,\ \alpha_2 = 0.36$.
For θ=90º connections, $\gamma = 1.20,\ \alpha_1 = 0.04,\ \alpha_2 = 0.30$.

(3) Osawa's method, Osawa *et al* (2007b)

The stresses are read out from a shell FE model at read out points shifted away from the intersection line by the following values

$$x_{0.5t} = \frac{t_h}{2} + \Delta \ , \quad x_{1.5t} = \frac{3t_h}{2} + \Delta \tag{4}$$

where, $t_h$ is the plate thickness of the main plate at hot spot area. Offset $\Delta$ is given by

$$\Delta = \frac{t_v}{2}\text{cosec}\ \phi - \frac{t_h}{2}\cot\phi \tag{5}$$

where, $t_v$ is the plate thickness of the attached plate, and $\phi$ is the angle between the main and attached plates (the supplementary angle of the bevel angle $\theta$, see Figure 21). HSS is derived as

$$\sigma_{hot\,spot} = 1.5\sigma_s\left(x_{0.5t}\right) - 0.5\sigma_s\left(x_{1.5t}\right) \tag{6}$$

where, $\sigma_s(x)$ is the surface stress at the point shifted away from the intersection line by x.

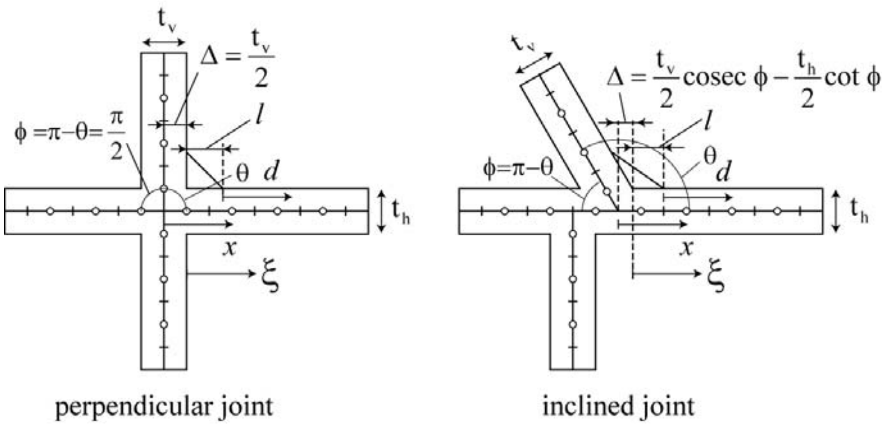


Figure 21: Distance of the read-out-points (ROPs) from the hot spot used in Osawa's method.

(4) CSR-B method (IACS CSR-B, 2005)

In the fatigue assessment in the latest revision of CSR-B, HSS derived by SR202B method is modified by the correction factor $\lambda$ defined by

$$\lambda = \begin{cases} 0.8 & \phi \le 75° \\ 0.8 - \dfrac{0.2}{15} & \phi > 75° \end{cases} \tag{7}$$

where, ϕ is the angle between the main and attached plates defined in Figure 21.

### *7.2.2 HHI Hopper Corner Model (135deg.)*

A joint industry project (JIP) FPSO Fatigue Capacity, JIP FPSO Fatigue Capacity (2000) carried out a comparative study on the hopper corner model shown in Figure 22. The critical weld is located at the transition from the beam consisting of 10 mm thick flange and web plates to the sloped hopper plate. The structure is subjected to a vertical point force F producing bending and shear in the beam. With F=220N, a nominal unit bending stress at the hot spot region σ=1MPa is created under the assumption of full effective breadth.

The JIP members (GL, AMT, NUS, HHI, LR, BV, BLU, GL, ABS) employed various types of models. In their analyses, the following element types were considered in the investigation, using special short names as mentioned below:

- 1Solid20w and 2Solid20w: 20-noded isoparametric solid element, used either with one or two element layers over the plate thickness modelled. The welds are included disregarding the root gap.
- 4Solid8w: 8-noded solid element, used with 4 layers over the plate thickness modelled. The welds are included disregarding the root gap.
- XSolidpw: Higher-order solid elements (geometric p-elements) with refined mesh in the critical area. The welds are included disregarding the root gap.
- Shell8: 8-noded shell element without weld representation. In case of offsets, a plate connection between the mid-planes of the plates is arranged.
- Shell4: 4-noded shell element without weld representation. In case of offsets, a plate connection between the mid-planes of the plates is arranged.

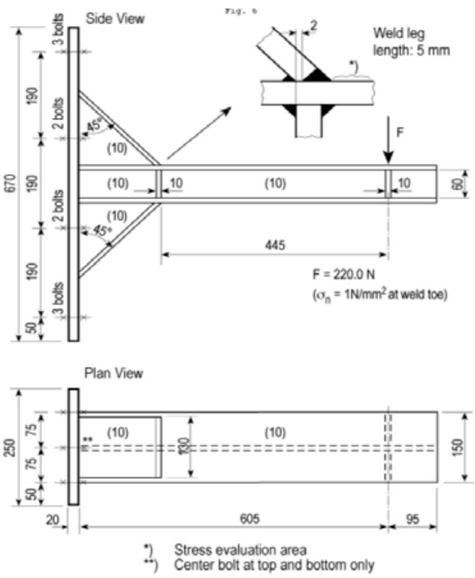


Figure 22: HHI Hopper corner model (135deg.).

Calculation results are identified by the short name and the name of the organization, for example 4Solid8w_HHI. The details of stress evaluation are listed in the table below. Osaka University also carried out a stress analysis of the same hopper corner model using 4-noded shell element without weld representation, Osawa *et al* (2007a). They used Msc. NASTRAN in their analysis. This result is identified as Shell4_OU.

For reference reasons, the target HSS was also calculated using PSCM-based shell-solid coupling model by Osaka University, Osawa *et al* (2007a). 8-noded solid element with 8 layers over the plate thickness is used in the solid part. The welds are included disregarding the root gap. This result is identified as 8Solid8w_OU. Surface stresses at the extrapolation points are derived by linear interpolation of surface stresses at the center points of solid elements. The surface stresses to the weld toe from t/2 and 3t/2, $\sigma_{0.5t,solid}$ and $\sigma_{1.5t,solid}$ are 1.650 MPa and 1.202 MPa. The target HSS is 1.875 MPa.

Table 8
Details of Stress Evaluation in the analyses of JIP FPSO Fatigue Capacity

| Short name | | Element size longitudinal x transverse x thickn. dir. | Stress Evaluation Technique | | | | Program |
|---|---|---|---|---|---|---|---|
| | | | location of ROPs | | extrap. to ROPs | averaging | |
| | | | longit. | transv. | | | |
| 1Solid20w | GL | t x t x t | el. Center[1)] | surf. cent. | linear | within el. | ANSYS |
| | AMT | 0.7t x t x t | int. points | surf. edge | linear | no | SESAM |
| 2Solid20w | UM | t x t x t/2 | int. points | surf. edge | in program | no | SESAM |
| | AMT | t/2 x t/2 x t/2 | int. points | surf. edge | linear | no | SESAM |
| | NUS | t/4 x t/2 x t/2 | int. points | surf. cent. | no | no | ABAQUS |
| 4Solid8w | HHI | t/4 x t/4 x t/4 | el. center | surf. cent. | dummy shell | no | ABAQUS |
| | ABS | t/2 x t/2 x t/8 | el. center | surf. cent. | linear | within el. | NASTRAN |
| XSolidpw | LR | Automatic | user-def. | user-def. | in program | no | MECHANICA |
| Shell8 | BV | t x t | at nodes | surf. edge | in program | betw. el. | NSO |
| | AMT | t x 1.2t | int. points | surf. edge | linear | no | SESAM |
| | UM | t x t | int. points | surf. edge | in program | no | SESAM |
| Shell4 | BV | t x t | at nodes | surf. edge | in program | betw. el. | NSO |
| | HHI | t x t | el. center | surf. edge | dummy rods | no | NASTRAN |
| | LR | t x t | el. center | surf. cent. | in program | no | LR STRAND |

1) Hot spot stress determined at 0,5 t line parallel to the centre line,

Figure 23 shows a comparison of solid surface stresses calculated by various models. Measured stresses are also plotted in this figure. It is shown that all JIP-FPSO's solid results except XSolidpw_LR agree very well with 8Solid8w_OU, and they show fairly good agreement with the measured stress.

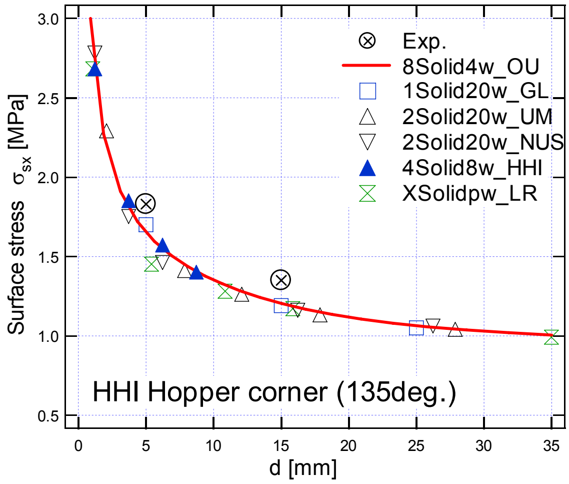


Figure 23: HHI Hopper corner (135deg.) model: comparison of solid surface stresses.

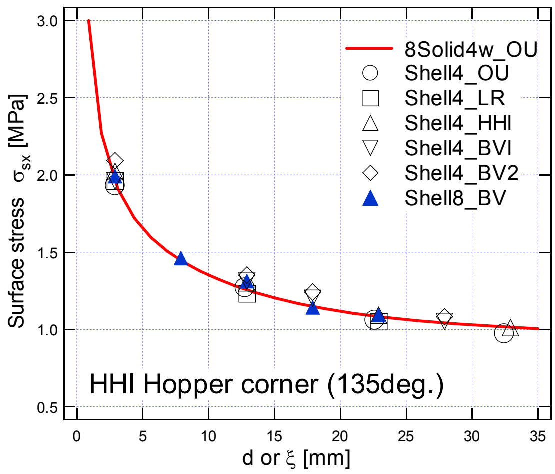


Figure 24 : HHI hopper corner (135deg.) model: comparison of shell and solid surface stresses.

Osawa *et al* (2007b) claimed that the shell surface stress at the read out point shifted away from the intersection line by d + Δ approximately agrees with the solid surface stress at the point shifted away from the weld toe by d, when the offset Δ is given by Eqn. 5. For this model, $\phi$=45deg., $t_h$=$t_v$=10mm and Δ=2.071mm. Figure 24 shows the relation between shell surface stresses and the reference solid stress (8Solid8w_OU).

The horizontal axis is the distance from the weld toe, d, for solid stress, and $\xi = d - \Delta$ for shell stresses. It is shown that the shell stresses show fairly good agreement with the reference solid stress.

Table 9
Hot spot stresses of HHI hopper corner (135deg.) model derived from various shell FE models (Unit: MPa)

| Calc. ID | SR202B | | Lotsberg's method ($\beta$=1.07) | | | Osawa's method ($\Delta$=2.071) | | | | CSR-B ($\lambda$=0.8) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | HSS | HSS /target | $\sigma s$ ($x_{shift}$) | HSS | HSS /target | $\sigma_s$ (x0.5t) | $\sigma_s$ (x1.5t) | HSS | HSS /target | HSS | HSS /target |
| Shell4_OU | 2.37 | 126% | 1.93 | 2.07 | 110% | 1.66 | 1.02 | 1.97 | 105% | 1.89 | 101% |
| Shell4_LR | 2.33 | 124% | 1.96 | 2.10 | 112% | 1.81 | 1.19 | 2.12 | 113% | 1.86 | 99% |
| Shell4_HHI | 2.38 | 127% | 2.02 | 2.16 | 115% | 1.87 | 1.26 | 2.18 | 116% | 1.90 | 102% |
| Shell4_BV1 | 2.29 | 122% | 1.96 | 2.10 | 112% | 1.82 | 1.26 | 2.10 | 112% | 1.83 | 97% |
| Shell4_BV2 | 2.46 | 131% | 2.09 | 2.24 | 119% | 1.94 | 1.30 | 2.25 | 120% | 1.97 | 105% |
| Shell8_BV | 2.33 | 124% | 1.99 | 2.13 | 114% | 1.77 | 1.24 | 2.04 | 109% | 1.86 | 99% |
| min | 2.29 | 122% | | 2.07 | 110% | | | 1.97 | 105% | 1.83 | 97% |
| max | 2.46 | 131% | | 2.24 | 119% | | | 2.25 | 120% | 1.97 | 105% |
| mean | 2.36 | 126% | | 2.13 | 114% | | | 2.11 | 113% | 1.89 | 101% |
| stdev | 0.060 | | | 0.061 | | | | 0.099 | | 0.048 | |
| CV | 0.026 | | | 0.029 | | | | 0.047 | | 0.026 | |

$t_1$ and $x_{wt}$ are 10 mm and 0 mm, and $x_{shift}$ of Eqn. 1 becomes 5 mm. The bevel angle is 135 deg., and the correction factor $\beta$ of Eqn. 2 is 1.07. The surface stress at the ROP for Lotsberg's method, $\sigma_s(x_{shift})$, and HSS calculated by Eqn. 2 for various shell models are shown in Table 9.

The surface stresses at the ROPs for Osawa's method, $\sigma_s(x_{0.5t})$ and $\sigma_s$ $(x_{1.5t})$, and HSS calculated by Eqn. 6 are shown in Table 9. This table also shows HSSs derived by SR202B and CSR-B methods. Table 99 shows the followings:

- The mean value of HSS derived by the method SR202B is 126% of target HSS. The ratio of derived HSS to the target HSS is between 122% and 131%, i.e., ±4%.
- The mean values of HSSs derived by Lotsberg's and Osawa's methods are almost identical, and they are 113 ~ 114% of the target HSS. The ratio of the derived to the target of Osawa's method is between 105% and 120%, i.e. ±7%, while that of Lotsberg's method is between 110% and 119%, i.e. ±4%.
- The mean value of HSS derived by CSR-B method is almost the same as the target HSS. The ratio of the derived to the target of CSR-B method is between 97% and 105%, i.e. ±4%.

### *7.2.3 MHI Right Angle Joint Model*

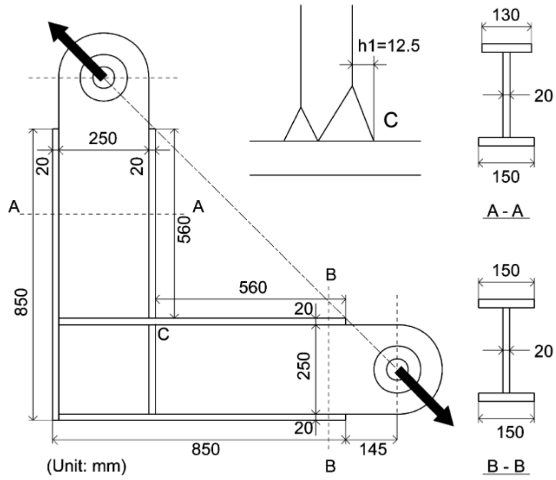


Figure 25: MHI right angle joint model.

Sugimura *et al* (2001) examined the local stress in the vicinity of the weld of the perpendicular corner joint model where the point loads are applied on both ends of the web plates as shown in Figure 25. The hot spot is located at the intersection of the upper horizontal flange and the inner vertical flange. The flank angle of the weld bead is about 45 deg., and the leg length is 12.5mm. The thickness of all plates, t, is 20mm. The surface stresses of the upper horizontal flange were measured by strain gages.

Osaka University carried out a stress analysis using 4-noded shell element without weld representation, Osawa *et al* (2007a). They used Msc.NASTRAN and Msc.MARC in their analysis. These results are identified as Shell4_MARC1 (MARC, t x t shell), Shell4_MARC3 (MARC, t/3 x t/3 shell), Shell4_NAST1 (NASTRAN, t x t shell), and Shell4_NAST3 (NASTRAN, t/3 x t/3 shell).

The target HSS was calculated using PSCM-based solid- shell coupling model by Osaka University Osawa *et al* (2007b). 8-noded solid element with 8 layers over the plate thickness is used in the solid part. The welds are included disregarding the root gap. This result is identified as 8Solid8w, and it is used as the reference stress. Surface stresses are evaluated by linear extrapolation of the solid element stresses. Surface stresses at the extrapolation points are derived by linear interpolation of surface stresses at the centre points of solid elements. The surface stresses to the weld toe from t/2 and 3t/2, $\sigma_{0.5t,solid}$ and $\sigma_{1.5t,solid}$ are 10.36 MPa and 6.04 MPa. The target HSS is 12.52 MPa.

For this model, $\phi$=90deg., $t_h$=$t_v$=20mm and $\Delta$=10mm. Figure 26 shows the relation between shell surface stresses and the reference solid stress (8Solid8w). Measured stresses are also plotted in this figure. The horizontal axis is the distance from the weld toe, d, for measured and solid stresses, and $\xi = d - \Delta$ for shell stresses. It is shown that the reference solid stress shows good agreement with the measured stress in the region where d is larger than 5mm. It is also shown that shell stresses show fairly good agreement with the reference solid stress excluding the shell element nearest the intersection. Shell stress of the nearest element depends on the FE code and the element type and it has a tendency to underestimate the surface stress.

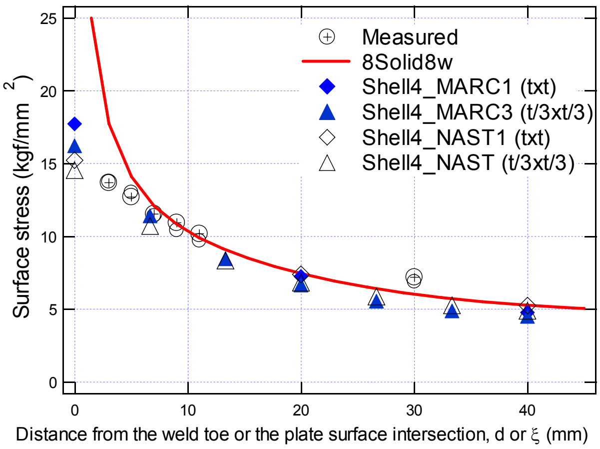


Figure 26: MHI right angle joint model: comparison of shell and solid surface stresses.

Table 10
Hot spot stresses of MHI right angle joint model derived from various shell FE models (Unit: MPa)

| | SR202B | | Lotsberg's method (β=1.342) | | | Osawa's method (Δ=10) | | | | CSR-B (λ=0.6) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Calc. ID | HSS | HSS /target | σs ($x_{shift}$) | HSS | HSS /target | $\sigma_s$ (x0.5t) | $\sigma_s$ (x1.5t) | HSS | HSS /target | HSS | HSS /target |
| Shell4_MARC1 | 22.95 | 183.2% | 11.16 | 14.98 | 119.6% | 12.47 | 6.00 | 15.71 | 125.4% | 13.77 | 109.9% |
| Shell4_MARC3 | 20.99 | 167.6% | 8.82 | 11.84 | 94.5% | 9.92 | 5.20 | 12.28 | 98.1% | 12.59 | 100.5% |
| Shell4_NAST1 | 19.14 | 152.8% | 10.31 | 13.84 | 110.5% | 11.29 | 6.30 | 13.79 | 110.1% | 11.48 | 91.7% |
| Shell4_NAST3 | 18.40 | 146.9% | 8.62 | 11.57 | 92.3% | 9.51 | 5.55 | 11.49 | 91.7% | 11.04 | 88.1% |
| min | 18.40 | 146.9% | | 11.57 | 92.3% | | | 11.49 | 91.7% | 11.04 | 88.1% |
| max | 22.95 | 183.2% | | 14.98 | 119.6% | | | 15.71 | 125.4% | 13.77 | 109.9% |
| mean | 20.37 | 162.6% | | 13.06 | 104.3% | | | 13.32 | 106.3% | 12.22 | 97.6% |
| stdev | 2.03 | | | 1.64 | | | | 1.86 | | 1.22 | |
| CV | 0.100 | | | 0.125 | | | | 0.140 | | 0.100 | |

$t_1$ and $x_{wt}$ are 20 mm and 12.5 mm, and $x_{shift}$ of Eqn. 1 becomes 22.5 mm. θ is 90 deg., and the correction factor β of Eqn. 2 is 1.342. The surface stress at the ROP for Lotsberg's method, $\sigma_{shift}(x_{shift})$, and HSS calculated by Eqn. 2 for various shell models are shown in Table 10. The surface stresses at the ROPs for Osawa's method,

$\sigma_{surface}(x_{0.5t})$ and $\sigma_{surface}(x_{1.5t})$, and HSS calculated by Eqn. 6 are also shown in Table 10

This table also shows HSSs derived by SR202B and CSR-B methods. Table 10 shows the followings:

- The mean value of HSS derived by SR202B method is 162% of the target HSS. The ratio of derived HSS to the target HSS is between 147% and 183%, i.e. ±11%.
- The mean values of HSSs derived by Lotsberg's and Osawa's methods are almost identical. They are 104 ~ 106% of the target HSS. The target ratio of the Osawa's method is between 92% and 125%, i.e. ±16%, while that of Lotsberg's method is between 92% and 120%, i.e. ±13%.
- The mean value of HSS derived by CSR-B method is 98% of the target HSS. The ratio of the derived to the target of CSR-B method is between 88% and 110%, i.e. ±11%.

### *7.2.4 VLCC Bilge Knuckle Model*

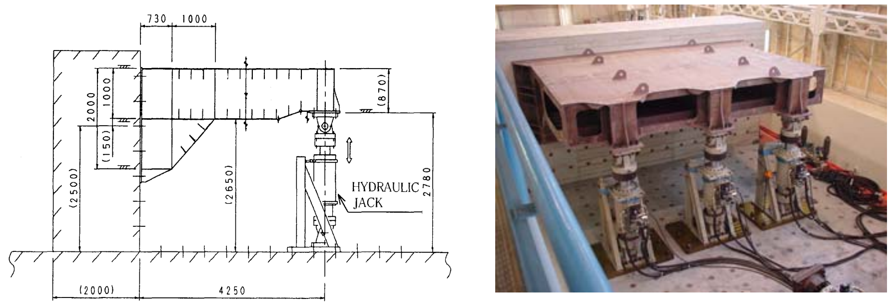


Figure 27: VLCC bilge knuckle model.

Ship Research Panel 245, ref. (Panel SR245, 2001) examined the local stress in the vicinity of the welded joint of a VLCC bilge knuckle model shown in Figure 27 (SR245, 2001). A three-floor space in the longitudinal direction was modelled and the model was fixed to a rigid wall at the double hull side. The loads are applied by three synchronised hydraulic jacks on the centreline of the double bottom as shown in Figure 27. The thickness of the inner bottom plate, t, is 10mm. The hot spot is at the intersection of the inner bottom plate, the inclined inner hull plate and the floor and the side girder. The flank angle of the weld bead is about 45 degree and the bead is flush with the hopper plate. The plates intersect at an angle of 45 deg.

SR245 carried out a stress analysis using 4-noded t x t shell element without weld representation (Panel SR245, 2001). They used Msc.NASTRAN in their analysis. These results are identified as Shell4_NAST. The target HSS was calculated using PSCM-based shell-solid coupling model by Osaka University Osawa *et al* (2007). 8-noded solid element with 8 layers over the plate thickness is used in the solid part. The welds are included disregarding the root gap. This result is identified as 8Solid8w and it is used as the reference stress. Surface stresses are evaluated by linear extrapolation of the solid element stresses. Surface stresses at extrapolation points are derived by linear interpolation of surface stresses at the centre points of solid elements. The surface stresses to the weld toe from t/2 and 3t/2, $\sigma_{0.5t,solid}$ and $\sigma_{1.5t,solid}$ are 391.5 MPa and 219.7 MPa. The target HSS is 477.4 MPa.

For this model, $\phi$=45deg., $t_h$=$t_v$=10mm and $\Delta$=2.071mm. Figure 28 shows the relation between shell surface stresses and the reference solid stress (8Solid8w). Measured stresses are also plotted in this figure. The horizontal axis is the distance from the weld toe, d, for measured and solid stresses, and $\xi$ = d - $\Delta$ for shell stresses.

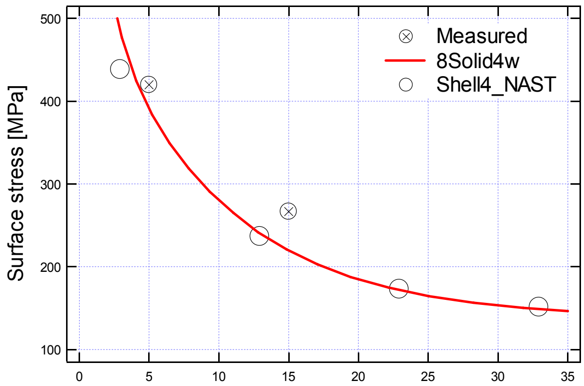


Figure 28: VLCC bilge knuckle model: comparison of shell and solid surface stresses.

$t_1$ and $x_{wt}$ are 10 mm and 0, and $x_{shift}$ of Eq. (1) becomes 5 mm. $\theta$ is 135 deg., and the correction factor $\beta$ of Eq. (2) is 1.07. The surface stress at the ROP for Lotsberg's method, $\sigma_{shift}(x_{shift})$, and HSS calculated by Eq. (2) for SHELL4_NAST models are shown in Table 11. The surface stresses at the ROPs for Osawa's method, $\sigma_{surface}(x_{0.5t})$ and $\sigma_{surface}(x_{1.5t})$ and HSS calculated by Eq. (6) are shown in this table. This table also shows HSSs derived by SR202B and CSR-B methods.

Table 11
Hot spot stresses of VLCC bilge knuckle model derived from various shell FE models (Unit: MPa).

| Calc. ID | SR202B | | Lotsberg's method ($\beta$=1.07) | | | Osawa's method ($\Delta$=0.2071) | | | | CSR-B ($\lambda$=0.8) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | HSS | HSS /target | $\sigma_s$ ($x_{shift}$) | HSS | HSS /target | $\sigma_s$ (x0.5t) | $\sigma_s$ (x1.5t) | HSS | HSS /target | HSS | HSS /target |
| Shell4_NAST | 539.05 | 109.3% | 438.26 | 468.93 | 95.1% | 396.51 | 223.48 | 483.02 | 97.9% | 431.24 | 87.4% |

Table 11 shows the followings:

- HSS derived by SR202B method is 113% of the target HSS.
- HSSs derived by Lotsberg's and Osawa's methods are almost identical, and they are 98 ~ 101% of the target HSS.
- HSS derived by CSR-B method is 90% of the target HSS.

#### *7.2.5 Summary*

Under the conditions chosen, the following may be stated:

- Conventional 0.5t-1.5t linear extrapolation technique (SR202B) tends to overestimate the target HSS. The ratio of the derived and target stresses is between 109% and 183% with a mean value ratio of 138%.
- Lotsberg's and Osawa's methods give almost identical HSS. They predicted smaller stress than SR202B. The ratio of the derived and target stresses is between 92% and 119% for Lotsberg's method and between 92% and 125% for Osawa's method. The mean value ratio is 109% for both methods.
- CSR-B method tends to derive a slightly lower HSS than Lotsberg's and Osawa's methods. The ratio of the derived and target stresses is between 87% and 110% and the mean value of the ratio is 98%.

## 8. OPERATING EXPERIENCE AND LIFE EXTENSION OF SHIPS AND OFFSHORE STRUCTURES

Fatigue design is an important consideration in design of ships and offshore units in order to mittigate risk of fatigue damage. Inspection, maintenance and repair strategies provide the means to ensure operations during the life of the vessel and offshore structures. An important aspect in fatigue prediction is the determination of a representative long-term environment. Hoogeland *et al* (2003) present a comparison between estimated loading conditions during design and actual loading conditions. One has to consider the joint occurrences of wind, waves, current and swell. Bamford *et al* (2007) proposed the use of listed environmental data in which wind, waves, current and swell data are specified per sea-state for the evaluation of fatigue life of FPSO hulls, for details see ch. 6.1.4. Storhaug (2007) found that vibration fatigue can have a significant contribution to the total fatigue damage. The results show that in high sea-states the damage contribution of vibration fatigue becomes less relative to the wave frequent contribution. Therefore, vibration fatigue in vessels with zero speed, such as FPSOs, will be small, however the effect shouls be investigated further.

Recently, life extension assessment has been recognised by the offshore industry and a lot of research has been conducted during the resent years. However, there are still several questions that have to be fulfilled, like e.g. if an offshore unit is operated for e.g. 20 years is inspected and no fatigue cracks found, does that mean that the structure can sustain another 20 years period in service, should a degradation factor be applied to the life or should fatigue re-analysis show at least 40 years design life not including safety factors.

### *8.1 Operating Experience*

Newport *et al* (2004) discuss the discovery, investigation and repairs of local cracking in the tank structure of the Kuito FPSO, a converted tanker that is deployed offshore Angola. Prior to being converted to FPSO, the vessel served as a trading tanker, at the TAPS trade route and worldwide trading service. Significant amount of cracks were found in ballast tanks in poorly designed bracket and connection details. Detailed analysis showed that primary cause of cracking was the induced fatigue damage during tanker service at the TAPS trading route and therefore needs to be accounted for in a fatigue re-assessment. Hoppe *et al* (2004) present a case study of a Petrobras FPSO, cracks were found at the toe of sniped longitudinal bulkhead stiffeners inside cargo tanks. A fatigue assessment was performed to identify the cause of the cracks by standard fatigue software. Johansen *et al* (2006) discuss aspects regarding life cycle management. Considerable amounts of data are generated during the operational life of an unit and data management etc. are demanding issues. This also makes it challanging forecast the technical condition and plan effective inspection and maintenance activities.

### *8.2 Life Time Extension*

A significant number of offshore units at the UK Shelve, Norwegian Shelve and in the Gulf of Mexico have been at the field for a significant part of their intended design life or longer. Many of these units are expected to operate for several years, Stacey *et al* (2008), May *et al* (2008) and Ersdal *et al* (2008) and accurate assessment methods to determine the structural integrity of a unit become crusial. When extending a unit beyond the intended design life, the structural integrity needs to be re-evaluated. Inspection, maintenance and repair strategies provide the means to ensure untroubled operations during the life of the vessel, Van der Cammen (2008). Structural integrity can reduce over time for instance by wear and tear due to normal operations, corrosion, or fatigue, Stacey *et al* (2008). The fatigue life of a unit needs to conform with applicable design codes. A major concern is that fatigue may not have specifically been addressed during design for some older platforms, Muragishi (2006).

Manzocchi *et al* (2008) discuss the findings of a Joint Industry Project (JIP) wich developed and implemented a methodology for system reliability updating based on the results of in-service inspections. The reason for chosing a reliability-based assessment is because it is more rational and can more accurately assess the structural integrity of a unit than is possible with a deterministic methods. Monitoring has the potential to play a role in the structural integrity management of a unit, since a more accurate status of the structural integrity of the unit can be obtained. Design codes and standards only refer briefly to the use of structural monitoring.

To date, offshore experience in the field of structural integrity monitoring is limited, May *et al* (2008). A review of relevant monitoring techniques for offshore applications is given by May *et al* (2008). An often used monitoring system is leak detection, however the system can only detect crack-through failures and should therefore not be used for non-redundant members. Another much used non-destructive testing method is accoustic emission (AE). The system can reliably detect crack initiation and crack growth. The system is able to detect fatigue cracks in an early stage. Accoustic emmision can play a role in maintaining the structural integrity of the unit in terms of fatigue. Another failure detection method for a jacket is natural frequency response monitoring. These frequencies are measured with accelerometers fitted to the subsea and topsides structure. Changes in vibration modes can be detected by analysing the acceleration spectra and consequently damage can be detected. The method is investigated in the On-Line Monitoring (OLM) JIP, where the method is tested on a number of jackets and is found not capable of detecting small defects. The monitoring techniques described above can only detect the state of the structure in terms of found defects, but not how much load the structure has seen during its life. Hence, if no cracks are detected, it is not possible to determine how much load the structure needs to receive before fatigue cracks start to occur.

Kaminski (2007) discusses the contents of the Joint Industry Project Monitas in which a fatigue monitoring system for FPSOs is investigated. The intention of the system is to measure vessel responses to obtain an updated load history that can be compared with the load distribution that was applied during the design stage. This data is valuable for offshore IMR planning, but also for life time extension scopes. Van der Cammen (2008), investigated the number of sensors necessary to reconstruct the load history on structural members in the hull of a FPSO. It was found that with a limited number of sensors and the use of neural network techniques, it is possible to reconstruct the load history.

Muragishi (2006) describes the application of a fatigue damage sensor, similar sensor is also described by Zhang *et al* (2007). The sensor consists of two foils, one of which is precracked and the propagation of the crack is accurately known in relation to a given S-N curve. By monitoring the crack length, the amount of fatigue damage of the structure can be determined. One of the advantages of such a system is that one can predict the actual damage of the structure.

Several of the offshore units operating today are approaching their design life or even passed the target life. However, due to more reserves and new technology, the operaters want to extrend the operation. It is therfore of higly importance, that operating experince is well included in life extension assesments. The same is also applicable for the life ectension og vessels.

## 9. CONCLUSION

The committee has reviewed recent works concerning the topics fatigue and fracture identified by the committee mandate. This report describes the results of a literature survey of more than 280 references, a comparison study of different ship rules and a benchmark study carried out by the committee. Fatigue failure is an extremely complex physical process which is governed by a great number of parameters related to, for example, local geometry and material properties of the structural region surrounding the crack growth path. Different S-N and fracture mechanics approaches have been evaluated. It will appear evident that, even if the accuracy of the various approaches proposed is not the same (i.e., they do not guarantee the same fatigue damage estimation), "the best approach" is just the most suitable one for each single case.

The review includes various state of the art of life prediction methods, and an overview of these approaches and methods are addressed in Section 2. The most common and traditional approach where details are provided in the codes, is based on nominal stresses and classifications of joint by the geometry, where each class have S-N curves experimentally evaluated. The structural stress approach, defines the stresses at the weld toe location taking all geometrical influences into consideration except for the local weld geometry. The research community encourages pursuing the development of stress concentration factor determination methods for structural components.

Fracture mechanics approaches have been evaluated and most of the developments in the theoretical aspects are attempted to enhance the practicality and refinement of existing models and methods. The committee would also like to see more research within probabilistic fracture mechanics as discussed in Section 3. It is also recommended that more details need to be introduced in the ECA procedures for fatigue crack growth with the advent of steels with improved crack growth properties. Strain based fracture mechanics is a quite new field of research where several methods are proposed by different authors, however it is of great importance that a common applicability for a strain approach is standardised into a practical design procedure. Most of the design rules only considers the first principal stress component only, however the stress state in real structures at fatigue critical locations is typically multiaxial in nature as discussed in Section 3. The committee believes that a better understanding of these stresses and their fatigue influence is of great importance and should be investigated further.

The performance of a structure is largely determined by the initial design. In Section 4, factors that influence the fatigue life of structures are discussed such as mean and residual stresses, thickness effect and corrosive environments. Some methods which have been developed for improving the fatigue performance are also evaluated. Good quality design and fabrication of a welded structure can significantly affect the fatigue life, and more effort and attempt should be put into understanding the challenge of good design and standardisation of quality assurance during fabrication.

Today, it is anticipated that about 25% of the unknown oil and gas resources are located in the Arctic areas. In order to exploit these resources, ships and offshore structures have to be made of materials which have properties that can sustain the loading conditions in this environment. In addition, materials have to have properties which over time sustain high pressure, high temperature and sour service cost-effectively in order to explore oil and gas in deep waters. Section 5 focuses on new developments and applications of non-traditional materials seen in the offshore and shipping industry. Emphasis has been put on new steel with improved crack growth properties, titanium which is still looked at as an exotic material, aluminium, nickel steel, duplex, corrosion resistance alloys and composite materials. The committee is of the opinion that significant efforts towards better understanding of some of these materials are crucial in order to obtain a safe and cost effective design, since limited field experience is available today for some of these materials. During the past few decades, the shipbuilding industry has shown increasing interest in laser welding to reduce welding distortion and to improve dimensional accuracy. This new welding method opens opportunities for design of light weight structures. Sandwich structures with thin plates cause special challenges for fatigue assessment due to complex geometries and stake welds with contact effect. Due to these factors the traditionally used fatigue assessment methods, are not applicable and thus, further research in this field is required to obtain robust method for fatigue design of steel sandwich structures and their joints to embedding structures.

In Section 6, fatigue design methods for ship and offshore structures are discussed. For ships, rule-based-methods for fatigue evaluation are proposed by classification societies, and a comparison of the different fatigue methodologies provided by BV, DNV, GL, KR, LR and NK are summarised in Table 6. The IACS Common structural rules (CSR) for Oil Tankers and Bulk Carriers Hull structure, published in January 2006, have been effective for new-builds since the 1st of April 2006 and it has been evaluated extensively. The recent updated offshore codes addressing fatigue issues have been reviewed. The committee encourage pursuing the development towards improved harmonisation of today's codes, especially for the classification design codes would be welcomed.

Alternative fatigue design management methods, like fitness-for service and engineering critical assessment methods are essential for safe service evaluation, and it is expected that these more tailor made and detailed methods will be further used also during the design stage. However, fatigue life predicted by these methods are often over-conservative, since they ware originally developed for the pressure vessels and the nuclear power industry and do not include the crack initiation. Therefore a harmonization of obtained life based on fracture mechanics and S-N approaches are welcome, especially in order to define a common safety level approach between the two methods.

The understanding of fatigue is mainly based on observations from experiments or structural failure and the interpretation of these events. Section 7 reviews and discusses some significant work in this area. In addition, a benchmark study is presented, performed by the committee, in order to validate hot-spot stresses assessed from different models. The details discussed are: HHI hopper corner model (135 deg.), the MHI right angle joint model and the VLCC bilge knuckle model.

Inspection, maintenance and repair strategies provide the means to ensure safe operations during the life of vessels and offshore structures; these topics are discusssed briefly in Section 8. The past few years have shown a rising interest in different monitoring techniques, since several offshore units are beyond their intended service life. The re-assessment of the fatigue loading they received is important and fatigue hotspots spots need to be re-evaluated, in order to ensure a safe operation. The societies today's are working in order to peruse guidelines and recommendations, however there are still several uncertain questions that have to be fulfilled, like to judge if an old unit has operated within design conditions specified. The fast development of monitoring technology opens new possibilities for continuous recording and new platforms today can be monitored in order to ensure that the unit operates within design conditions specified. However, monitoring of platforms will create tremendous information and one main challenge would be how to analyse the data and draw meaningful conclusions.

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