Proceedings of the 20th International Ship and Offshore Structures Congress (ISSC 2018) Volume III – M.L. Kaminski and P. Rigo (Eds.)

doi:10.3233/PMST200007

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 the ship and offshore structures. Due attention shall be paid to the suitability and uncertainty of physical models and testing. Consideration is to be given to practical application, statistical description and fracture control methods in design, fabrication and service.

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1. DISCUSSION

1.1 Official Discussion by Wolfgang Fricke

It is a great honour for me to discuss the report of ISSC Committee III.2 “Fatigue and Fracture”. I joined ISSC 30 years ago already in 1988, as a member of the Committee on Materials and Fabrication Technologies – by the way together with Mirek Kaminski, Chairman of the current Congress. Later I was Chairman of the Committee “Fatigue and Fracture” in the years 1994 - 2000, and afterwards, I joined the Standing Committee for 15 years, chairing the Congress in 2012. Insofar I can say that I belong to the ISSC-family, being happy to finally contribute with the official discussion.

My professional career regarding fatigue and fracture was mainly influenced by my employment by the classification society Germanischer Lloyd from 1986 until 2000, where I was responsible among others for the revision of the fatigue rules and assessment procedures for ships and offshore structures. Afterwards, I became full professor for ship structural design and analysis at the Hamburg University of Technology (TUHH), teaching and supervising students in naval architecture and planning and performing theoretical and experimental research projects until 2014, mainly regarding fatigue. I was a member in several committees and working groups, in addition to ISSC also in IIW (International Institute of Welding), where I chaired a working group in Commission XIII “Fatigue Behaviour of Welded Components and Structures” for 14 years. My special research fields match those of ISSC Committee III.2 so that I think to be well prepared for the discussion.

The present Committee did a great job in elaborating an extensive and very informative report on the developments during the past three years. It consists mainly of a literature review but also includes several benchmark studies on the fatigue assessment of a pre-deformed thin plate panel and a fatigue load estimation and strength assessment of a structural detail in a bulk carrier, based on simplified procedures, spectral analyses and also reliability analysis. The reference lists contain almost 500 publications, much more than the previous reports. Although the field of fatigue is generally characterised by a huge number of publications, an “inflation” can be observed when looking at papers of the same authors with similar titles and contents. It is a difficult task of the Committee to filter the literature, i.e. concentrating the review and description of those publications containing the main findings and summarising whole projects.

Filtering also includes the selection of those papers being relevant for ship and offshore structures. Some references seem to be less relevant, e.g. those concerning very special materials or for instance fatigue at very high temperatures typical for power plants. If the latter would have been intended to be adequately covered, special types of loading and material behaviour like a creep, including all the different models and analyses should have been discussed. The Committee report contains at the end some statistics about the publication dates, the technical fields covered and the publishers. There are no statistics about the authors, which would have shown how often the Committee Chairman is cited, only topped by the Chairman of the last ISSC Congress. This helps to improve the citation index but might bear a conflict for the Committee members responsible for certain sections.

The mandate of the Committee is well covered by the report, although the main emphasis is placed on fatigue, while the field of fracture seems to be only touched. Its importance for ship and offshore structures has been shown by Prof. Sumi as Official Discusser of the last report. Furthermore, it would have been nice to report more about service experience regarding fatigue and fracture, although it is admitted that relevant publications are rare. Sometimes, investigations about repair point at fatigue damages. Such information has been collected in the past by the Tanker Structure Cooperative Forum in order to improve the situation for this ship type. Similar efforts can also be found for other types of steel structures, such as bridges [1].

The following discussion will be oriented at the chapters in the Committee report. All details of the extensive contents cannot be discussed. Attention is paid, and comments are given particularly to the subjects which, from own perspective and experience, seem to be the most relevant. Also some references from the period covered by the report will be added.

1.1.1 Fatigue and Fracture Loading

This chapter starts with the Metocean description resulting in wave scatter diagrams which are widely used for deriving loads for ships and offshore structures. It is mentioned that "it is generally admitted that the worst navigating condition corresponds to the North Atlantic environment." Is this true? I remember the discussion about many fatigue damages, e.g. in tankers operating in the TAPS (Trans-Alaska Pipeline Service) trade [2], indicating an unusually hostile wave climate in the North Pacific. The view of the Committee about this would be appreciated. **Reply (1)**

On the other hand, the fatigue loads are downgraded in some rules from the North Atlantic environment to worldwide service using a factor of 0.8. What does this mean for the structural reliability and safety if ships operate in such hostile environments like the Northern Atlantic or Pacific? **Reply (2)**

Several operational influence factors exist, as generally discussed in the report. These are known for decades, but there seems to be no progress regarding their consideration in the design. Does the Committee share this observation? **Reply (3)**

Chapter 1.1.2 also discusses the effect of springing and slamming-induced whipping on fatigue. The previous Official Discusser stated that "some investigations confirmed the validity of the rainflow method, others not". The former Committee recommended that this Committee addresses that important issue.

As I have not seen this, I like to mention fatigue tests [3] (also referenced as "Kahl, A., Fricke, W., Paetzold, H. and von Selle, H., 2015, Whipping Investigations Based on Large-Scale Measurements and Experimental Fatigue Testing, *International Journal of Offshore and Polar Engineering*, 25, (4), pp. 247-254." in the Committee report), where a 30-minute stress history measured on a large container ship was repeatedly applied to a cruciform joint specimen. The stress history contained many whipping cycles induced by bow-flare slamming. Rainflow counting was performed in order to obtain the stress spectrum for the original stress history and a filtered one, omitting the whipping cycles and resulting only in wave-induced cycles.

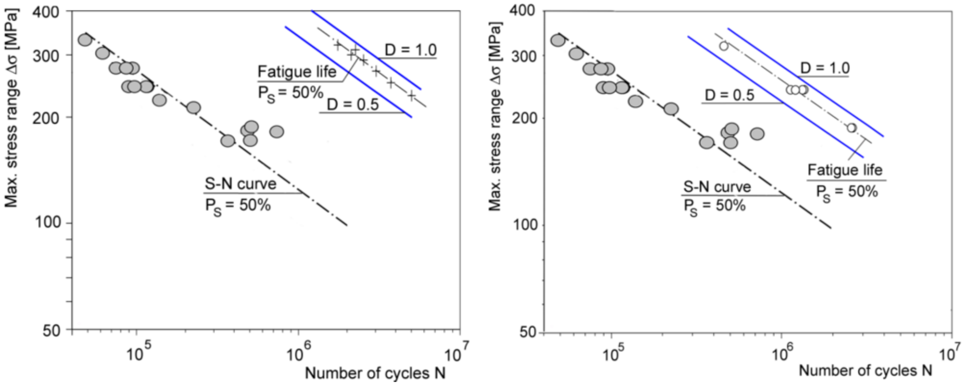

Figure 1: Fatigue lives from constant and variable amplitude tests with original (left) and low-pass filtered (right) stress history [3]

Fig. 1 shows the test results for the original and the filtered stress history and life prediction based on mean S-N curve. In both cases, the life prediction is unconservative if the Palmgren-Miner damage ratio D = 1.0 is used, and it is conservative if D = 0.5 is assumed. The latter is in agreement with the IIW recommendations [4]. However, the main issue here is that no principal difference can be seen between the results so that the rainflow method and Palmgren-Miner rule seem to be well suited also for typical stress histories containing vibrations such as whipping. Does the Committee have opposite information? **Reply (4)**

A small remark concerns Chapter 1.1.5 about temperatures, which are said to have "a limited effect on fatigue and are therefore disregarded except for gas carriers". It should be noted that very high stresses are caused by heated heavy fuel oil as well as special cargo (e.g. asphalt). **Reply (5)**

Chapter 1.1.7 contains opposing statements about the relevance of loading/unloading in the last paragraph. I can only support the last sentence, i.e. "for all types of cargo ships, loading and unloading caused fatigue damage cannot be ignored". **Reply (6)**

The last sub-section concerns fracture loading, pointing at temperature and strain rate as the main influencing parameters on the loading side. It is noted that "observed fractures almost never occur for marine structures in as-built condition, …but as the result of an abnormal extensive fatigue crack propagation". Is this statement based on references? **Reply (7)**

1.1.2 Material Properties and Testing

This chapter starts with the monotonic and cyclic material behaviour, particularly the latter being of great significance for the application of local strain approaches. The sub-chapter on cyclic material behaviour deals with a topical aspect regarding the effect of High-Frequency Mechanical Impact (HFMI) treatment on the material behaviour of the surface layer of treated welds, where some progress in understanding the mechanical effects including residual stresses and fatigue strength has been achieved. **Reply (8)**

Also fracture properties are discussed. Can the Committee explain, what is a "non-linear elastic J-integral"? **Reply (9)**

Regarding fatigue properties, the short crack behaviour, as well as the threshold value for crack propagation, are missing, which follow different mechanical rules compared to the Paris law. Some progress was seen during the last years, e.g. in the IBESS project cited in the report under "Madia, M., Zerbst, U., Beier, H. T. and Schork, B., 2017, The IBESS model - Elements, realisation and validation, *Engineering Fracture Mechanics*, Article in press". Some further comments by the Committee on these factors would be welcome. **Reply (10)**

Reference "Maljaars, J., Pijpers, R. and Slot, H., 2015, Load sequence effects in fatigue crack growth of thick-walled welded C-Mn steel members, *International Journal of Fatigue*, 79, pp. 10-24" discussed in Chapter 2.1.6 shows quite interesting findings for variable amplitude loading. However, it should be mentioned that 'wave' loading – as compared there with random loading – is not representing a load history in ocean waves, but changes the load sequence from random to steadily increasing and afterwards decreasing amplitudes, so that the load history looks like a wave.

The chapter 2.1.9 on "Similarity", which could also have been called "Full-scale Fatigue Testing", summarises different investigations on large structures, partly in direct comparison with small-scale specimens. One investigation, which might be added, concerns the effect of residual stresses on the fatigue strength of large-scale welded assembly joints [5]. Test models having two different scales were investigated, showing significant differences in local residual stresses. Also the fatigue strength based on structural hot-spot stresses differs, although being conservative in both cases.

The relatively long chapter 2.2 "Polymer composites testing" deals exclusively with wind turbine blades, a certain important subject influencing the relevant industrial sector. The subsequent chapter 2.3 "Testing methods and measurement techniques" covers mainly high-frequency fatigue testing as well as modern measurement techniques like Digital Image

Correlation (DIC), giving much more insight into the structural and material behaviour by scanning the whole surface instead pointwise as being the case with strain gauges. The cited references show very interesting and partly surprising results because the local behaviour can be much affected by slight variations in plate thickness, distortion or material properties. Even the local cyclic stress-strain behaviour of the inhomogeneous material in the way of welds during low-cycle fatigue tests can be identified using measured strain fields in combination with finite element models, as shown in [6]. This can be used for fatigue assessment based on the local strain approach and particularly for the identification of fatigue critical points, is not necessarily the weld toes. **Reply (11)**

1.1.3 Fatigue Damage Accumulation Approaches

This rather long chapter gives at first an interesting overview of the complex phenomenon of fatigue and describes the governing parameters and current approaches. These include the structural hot-spot stress approach. Recent developments concern the application to thin-plate structures, considering the nonlinear stress increase due to straightening effects. It should be noted here that cyclic loading usually occurs from zero or mean load into tensile and into compressive direction. The latter is coupled with an increase of pre-deformations, i.e. no straightening so that a linear calculation might yield a good estimate for the stress range. Furthermore, the correct determination of the structural stresses creates a big problem in practice because the actual stresses at the hot spot can only be calculated with a 3D model containing the field of pre-deformations. Analytical formulae based on 2D beam models are not helpful here, but 3D finite element analyses, as will be further discussed below. **Reply (12)**

Chapter 3.3.2 describes well the notch stress approach. One missing reference [7] investigates an old observation regarding the effect of symmetric and non-symmetric transverse attachments on local stresses and resulting fatigue strength. The notch effect at the weld toe is decreased in case of bending compared to axial loading. However, the opposite occurs in case of symmetric welds, i.e. an additional attachment on the opposite plate surface. The paper shows the stress concentration factors and fatigue strength obtained for these cases. **Reply (13)**

Some problems regarding the notch stress approach should be highlighted here. The first concerns so-called mild notches, being discussed at the end of the sub-chapter. An additional reference [8] shows the application of the relevant provisions in the IIW recommendations on the fatigue assessment of a pressure vessel, having a fatigue life of about 10,000 cycles. The problem of mild notches might also be the reason for obtaining FAT-values below 225 for steel from fatigue tests. **Reply (14)**

Another problem is very high, localised stress peaks at certain hot spots, e.g. weld ends as well as fillet welds around stiffener ends (Fig. 2). The latter was investigated in [9], where fatigue cracks did not appear at the most highly stressed corner of the stiffener, but along the weld toe on the stiffener surface. The statistical size effect, based on the critical volume or weld length [10], could explain the results. **Reply (15)**

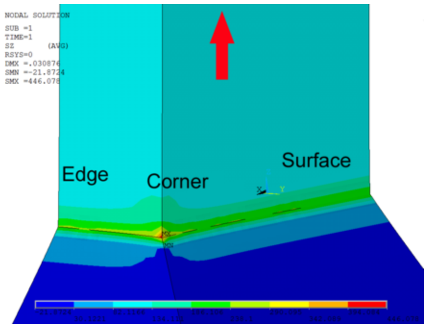

Figure 2: Local stress peak at the corner of a fillet weld around a stiffener end

The effective notch strain concept is discussed in Chapter 3.2.3. It might be added that the approach by Saiprasertkit et al. [11], using the common notch radius of 1 mm and an S-N curve based on effective strain, has further been successfully applied particularly to the low-cycle fatigue regime [12, 13]. As an alternative, it is tried to use directly the measured weld toe shape in finite element models, whereby the local stress gradient is taken into account to consider micro-support effects of the material [14]. **Reply (16)**

The subsequent sub-chapters describe developments regarding the relatively new strain energy density (SED) and Peak Stress approaches, both based on the notch stress intensity factor N-SIF. The re-analysis of data (ref. “Fischer, C., Fricke, W. and Rizzo, C. M., 2016, Review of the fatigue strength of welded joints based on the notch stress intensity factor and SED approaches, *International Journal of Fatigue*, 84, pp. 59-66” in the report) considering the effect of welding-induced misalignment, which is usually to be taken into account on the load (stress) side in local approaches in order to assess different structural applications equally, has led to a uniform control volume radius of 0.32 mm for weld toe and root (compared to 0.28 mm derived before for weld toes and 0.36 mm for weld roots). Comparable fatigue strengths have been derived for the notch stress, and the SED approaches. Promising is the Peak Stress approach, which can be applied using not only a special ANSYS finite element but also several others from different finite element programs, as verified in [15]. **Reply (17)**

Regarding the total stress, obtained from a linear superposition of all stress components (Sub-chapter 3.2.8), the question arises, how the relaxation of residual stresses after the first loading cycle(s) is taken into account? **Reply (18)** The sub-chapter 3.4.4 “Environment” even supposes residual stresses as high as the yield stress during corrosion attack, which seems to be a too conservative assumption. Normally it is assumed that only the sum of welding-induced residual stresses and load-induced stresses may reach the yield stress. **Reply (19)**

Chapter 3.2.9 describes developments regarding stress parameters at the crack tip as well as crack propagation models and crack propagation simulations. This is a very interesting and important sub-chapter. However, the Official Discusser wonders, why this is included in Chapter 3 on “Fatigue Damage Accumulation Approaches” and not in the subsequent Chapter 4 “Crack Growth Approaches”? **Reply (20)**

Chapter 3.4 gives an interesting view on the “complete strength criteria”, including extensively stress multiaxiality (without explaining 6D in this connection), for which numerous studies have been performed and models developed. It is stated that non-proportional loading is more damaging than proportional loading, although previous studies [16] had shown that this holds true only for ductile (like steel) and not for semi-ductile (like aluminium) and brittle materials. Is this still state-of-the-art, including variable amplitude loading? **Reply (21)**

Regarding mean and residual stresses, the relaxation of the latter is stated to depend on the amount of far-field stresses. Isn’t it much more complex, as especially the amount of the local residual stress as well as the notch effect of the detail play a major role? The effects can be well studied at structural details with high stress concentration, e.g. ends of longitudinal attachments [17, 18]. **Reply (22)**

Chapter 3.5 "Total Life Criteria" concerns a very important aspect, i.e. the consideration of both the crack initiation as well as crack growth within the fatigue damage assessment approach. Unfortunately, the text is difficult to understand, partly because terms like "2-stage, 2-parameter model" are not explained. Maybe, some introductory explanations would have been helpful. This also applies to "Multi-Stress Criteria" (Chapter 3.6), where some promising approaches regarding composite materials are described. **Reply (23)**

1.1.4 Crack Growth Approaches

This chapter starts with considerations about defects and initial cracks, justifying the application of fracture mechanics for engineering assessment. It should be mentioned that also non-fused root faces occurring in the design of fillet-welded joints can be well assessed with crack growth approaches.

However, also for weld toes, crack growth approaches are not only applied to fitness-for-service assessment after having found a crack or defect but also to the design assessment regarding the total fatigue life. Here, the assumption of a suitable initial crack or defect size is important, as has already been discussed in Chapter 3. This question was further investigated in the IBESS-project, focusing on the short crack behaviour (ref. "Madia, M., Zerbst, U., Beier, H. T. and Schork, B., 2017, The IBESS model - Elements, realisation and validation, *Engineering Fracture Mechanics*, Article in press" in the report). Here, the crack arrest size is taken based on the cyclic R-curve, if no larger defect size exists. The statistical model also includes the growth of multiple cracks along the weld toe, based on observations showing that the number of cracks occurring along the crack front depends on the level of cyclic loading [19 - 21], see Fig. 3. **Reply (24)**

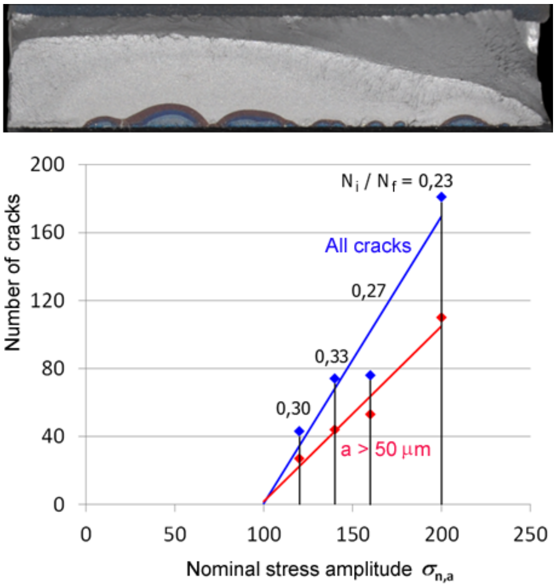

Figure 3: Number of cracks along the 50 mm weld toe of butt welds [20], visualised by heat-tinting and illustrated on top by an example of observed crack fronts

The subsequent chapters show various models mainly based on Paris' power law as well as a great number of applications to different materials and structures. Several effects are considered by extended and modified models such as load sequence effects and crack closure. The main emphasis is placed on the so-called long crack behaviour, while even simulations of the crack propagation in the crystalline structure are performed with a focus on short crack growth. **Reply (25)**

The final part of the chapter deals with statistics about crack growth assessment, being important for planning of inspections, monitoring and repair action. Service life can be extended in case of fatigue cracks by the stop-hole method or by composite patch repair, the latter having recently been in the focus of extensive investigations, which are discussed once again in Chapter 5.4. **Reply (26)**

1.1.5 Fabrication, Degradation, Improvements and Repair

Regarding fabrication, imperfections are mentioned, where it is distinguished between misalignment and distortion, and welding-induced defects. It should be mentioned here, that rules and regulations distinguish between imperfections and defects, the first being tolerable, while the latter requires actions like repair or proofs of fitness-for-purpose. **Reply (27)** Maybe "quality aspects" would better describe the subchapter, as also weld toe radii are included which are neither imperfections nor defects. **Reply (28)**

The considerations about the effect of welding-induced distortions on the stresses at butt joints in stiffened plate panels in Chapter 5.1.1 as well as in the Annex seem to indicate that the mechanics are not well understood. It has to be noted that pre-deformations of the plate, if axially loaded, cause a complex stress distribution, which is illustrated in Fig. 4 and characterised by:

1. Membrane stresses, which are normally decreased within the plate field and increased at the stiffeners. This stress redistribution, which results in an 'effective width' for the stiffeners, can be observed already in linear analyses, if the deformed structure is modelled (i.e. it is a first order effect, occurring in thick as well as thin plates). The effect is strongly influenced by the shape of the deformation, including curvature in both directions. In the benchmark study, the effective width is not very pronounced (Fig. 4a) due to the actual shape of pre-deformations, but the stress reduction within the plate field is visible. Other examples show much more membrane stress redistribution [23].
2. Secondary bending stresses due to the offset of the pre-deformed plate under axial loading. Also this effect can already be observed in linear analyses.
3. Both membrane and secondary bending stresses are altered by nonlinear (second-order) effects, e.g. due to straightening under tensile or magnified deformations under compressive loading. The effects are more pronounced under high axial loads and/or in thin-plated structures.

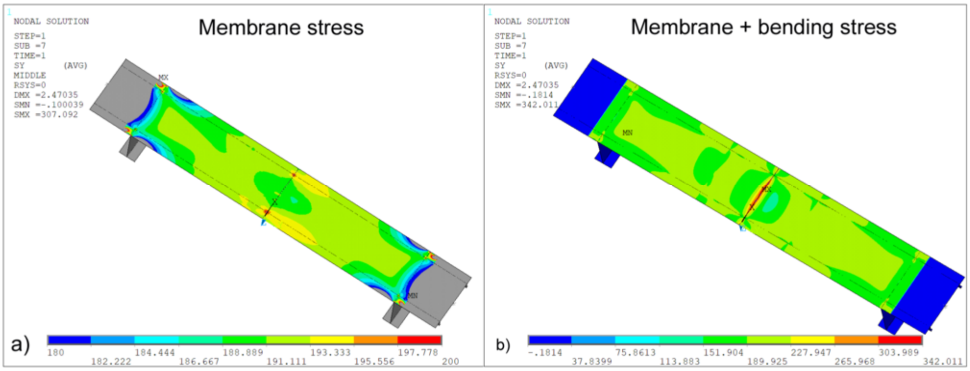

Figure 4: Calculated distribution of membrane (a) and membrane and bending stresses (b) in the benchmark study of a distorted panel subjected to an axial force of 620 kN [22]

The simplified formulae are shown, e.g. in recommendations, and the Annex consider linear as well as nonlinear effects mentioned above (the latter by the tanh term). However, they are derived by 2D (beam) models. Therefore, they are well-suited for small-scale test specimens, as long as the curvature of the plate strips is negligible. However, their application to plate panels as shown in the 1st and 3rd benchmark study in the Annex is highly questionable, because 3D-effects like the redistribution of membrane stresses as described under 1. above are not considered. This is also the main reason for the differences in the related results shown in the first chapter of the Annex. At present, only the finite element method seems to be suitable for analysing plate panels, although participant #4 used an interesting method [24] which avoids the extensive field measurement of distortions by using only a few measurement points. **Reply (29)**

Welding-induced distortions, as well as residual stresses, can be computed by so-called thermo-mechanical welding simulation considering the local heat input as well as the nonlinear mechanical response. The description of current research misses the consideration and effects of phase transformation showing significant influence on the results even for common structural steel [25]. Regarding weld quality, the weld toe radius is certainly an important parameter, although the calculated stresses or strains are frequently not directly used for fatigue strength assessment, but modified to account for the micro-structural support effect of the material. Nevertheless, a harmonised procedure for the evaluation of the radius from a measured point cloud is still needed. The view of the Committee on this would be appreciated. **Reply (30)**

The initial crack size described in the next subchapter in the context of the Equivalent Initial Flaw Size (EIFS) concept has already been discussed under 1.1.4 above.

A large number of references discussed in Chapter 5.3 on "Strength Improvement" shows the significance of this subject and the attempts to optimise structures and utilise high-strength steels. One important question concerns the stability of compressive residual stresses, induced by peening, during variable amplitude loading. Even after high compressive stress peaks, benefits regarding fatigue are there. Based on these references, can the Committee give recommendations with respect to the benefits in fatigue strength under spectrum loading in comparison to constant amplitude loading? Furthermore, are applications of the low transformation temperature filler material to ship or offshore structures known? **Reply (31)**

1.1.6 Fatigue Reliability

This chapter starts with an extensive discussion about the random variables or 'statistical descriptors', which can be associated with fatigue loading, fatigue damage accumulation and crack growth. The latter is also used to classify limit state functions. The limit state for fatigue damage accumulation is usually described by the damage ratio according to the Palmgren-Miner rule. This simple rule is commonly associated with model uncertainty, being quite large, because very large and small damage ratios have been observed in the past when comparing test results with calculations – see also the 3rd benchmark study in the Annex.

During the past decades, the laboratory of TUHH has performed some variable amplitude test series with random loads. In these as well as in other tests the Official Discusser observed frequently a very low scatter in the life curves (Gassner lines). Fig. 1 gives a typical example, where the scatter of the S-N results for constant amplitude is comparably large. This means that the scatter in the S-N curve would have to be reduced and not increased when applying the Palmgren-Miner rule for variable amplitude loading. It is admitted that the observations were made for welded specimens, while it is well-known that variable amplitude tests of plain specimens show larger scatter. Have Committee members made a similar experience? **Reply (32)**

Of course, the question remains if there is a reason for this. Maybe Fig. 3 gives an answer, showing that several cracks initiate under high load cycles so that a straight crack front will be formed after crack coalescence. Under variable amplitude loading, the same seems to occur due to the relatively high load cycles contained in the spectrum. Under constant amplitude loading at lower load level, single semi-elliptical cracks appear instead frequently showing more variation in crack initiation and crack propagation life.

The limit state for fatigue crack growth is unstable fracture (the report occasionally mentions ‘brittle failure’). It seems that the critical stress intensity factor K_{Ic} is still used, which is not a suitable parameter for the failure occurring with extensive plastic zones in the material. The view of the Committee on this is appreciated with particular focus on reliability analyses. **Reply (33)**

1.1.7 Fatigue Design and Verification based on Rules, Standards, Codes and Guidelines

The Common Structural Rules (CSR) for bulk carriers and oil tankers are briefly described. It is interesting to note, that weld root fatigue is not addressed, but covered by the standard design of structural details. A few remarks would be welcome on how does this work? **Reply (34)**

One critical point is, however, the allowable damage ratio according to the Palmgren-Miner rule, which seems to be still D = 1.0. Many fatigue tests have shown that this is unconservative, as also validated by the results in Fig. 1. A limit of D = 0.5 has been suggested [4, 16]. **Reply (35)**

The quite interesting description of the fatigue rules of four different classification societies shows that these seem to be largely influenced by the CSR, which is a good development in view of rule harmonisation. The comparison of simplified fatigue approaches applied to a bulk carrier in Chapter 7.6 confirms this by rather similar total damages calculated. Some differences in the approaches can be identified when comparing the detailed tables of intermediate results, for instance, the factor of 1.2 for hull girder vibration applied only by DNV GL, which is more than compensated by the reduction factor of 0.8 for world-wide service. Are there further comments by the Committee on this? **Reply (36)**

Larger differences occur in the 2nd benchmark study in the Annex, where a fatigue assessment of the butt joint in a bulk carrier is performed using the spectral method. Particularly the hydrodynamic analysis and some assumptions in the rules, e.g. regarding mean stress correction are responsible for this. Further harmonisation of the procedures seems to be necessary. **Reply (37)**

Also Chapter 7.7 on the fatigue provisions in the revised International Gas Carrier Code is very interesting, because this code is characterised by extensive rules regarding fatigue, having been a pioneer with respect to the introduction of fatigue requirements for ships. However, the remark in the paragraph on Part C concerning design S-N curves based on 97.6% survival probability, which “introduces clear design S-N curves for initial crack calculation” is not understood. Such design curves are generally used in fatigue assessment representing the results of fatigue tests up to specimen fracture, coupled with an additional safety factor (mean minus two standard deviations). Microcracks can be initiated even before the design S-N curve is attained. **Reply (38)**

1.1.8 Conclusions and Recommendations

The last chapter summarises the report by giving an overview about the main contents of each chapter. As already mentioned in the beginning, the focus is on fatigue, whereas unstable fracture is hardly covered. The next Committee should place more emphasis on the latter.

Not many recommendations for future work are given. It would be nice to hear the views on this by the Committee members, who have worked for three years on the topics and have a good overview about what has been reached and what is missing.

In summary, I like to state again that the Committee has done an excellent job in fulfilling the mandate and delivering an extensive report about the reviewed references, which is extremely valuable for our community in their daily work. The Chairman is congratulated for having successfully led the activities of the Committee and delivered the rather extensive report in time. Three benchmark studies described in the Annex were performed with much effort by the Committee members. These give a good insight into the state-of-the-art regarding fatigue assessment of ship and offshore structures.

1.2 Floor and Written Discussions

1.2.1 Alexander Babanin

This is my opinion with regards to the comment from the Official Discusser regarding the worst navigating conditions in the world. The highest waves on the planet are in the North Atlantic, and it is, therefore, the worst sea condition. **Reply (39)**

1.2.2 Suqin (Sue) Wang

I have one question and one recommendation. Question is for the corroded specimen shown in the benchmark study, is it uniform corrosion? in your review, it is reported as pitting corrosion. The recommendation is that it is nice to see a review of different rules and standards, but I see that only a few class societies have been selected. Recommend to also include guidelines and rules from all major class societies like ABS etc. **Reply (40)**

1.2.3 Askoendu Samanta

I have a suggestion to the Committee and question for the Official Discusser. My suggestion is as we know that CSR (Common Structural Rules) mainly address fatigue at weld toe location, but there have been some questions from IMO to address root fatigue. There are no procedures available in the CSR on how to address the root fatigue. I suggest Committee to address this issue of root fatigue in the Class Rules and guidelines. My question to the Official Discusser, Prof. Fricke is related to the effective notch stress approach for weld root fatigue. There are some limitations in the procedures as this includes 3D or solid modelling which might not be possible to be incorporated in the class guidelines as it is not possible to do such modelling for all the connections at the shipyards. How can guidelines incorporate the use of effective notch stress approach and peak stress approach which requires volume models and which one will be preferable? **Reply (41)**

1.2.4 Agnes Marie Horn

Normally for fatigue design, we use the S-N curve, which is based on constant amplitude loading while in reality, we have variable amplitude loading. There has been some research done with VA loading, and if we look at the results, we see that in some cases fatigue testing under VA loading is very conservative compared with miner's damage, while in some other cases are non- conservative. What is the opinion of the Committee on this? Are we conservative or non-conservative while using the dual-slope S-N curve in design? Moreover, what is the opinion concerning the inclusion of environmental effects? **Reply (42)**

1.2.5 Robert Sielski

Question 1. The issue of mean stress on fatigue crack growth can be considered as much as phenomenal as analytical. Depending on whether the mean stress is tension or compression, the fatigue crack growth rate can vary by a factor of ten. This could be an issue for example, following damage and flooding, the still water bending moment can change from sagging to hogging. A fail-safe crack growth analysis of an existing crack that was based on mean compressive stress could change to tensile mean stress, and a previously evaluated crack that was judged to be safe could cause catastrophic failure. Can the Committee comment on how they believe such situations should be considered? **Reply (43)**

Question 2. The Committee has not dealt much with fracture, all though other committees have mentioned the effect of cold temperature on material toughness. However, I do not believe that any rational, fracture mechanics based means of specifying required material toughness have ever been developed. Indeed, I wonder if we had progressed much beyond 1946 when standards for the Charpy toughness were first developed. What is Committee response? **Reply (44)**

1.2.6 Koji Gotoh

This committee report gives a comprehensive review of the status and development trends in the fatigue and fracture in the ship and offshore structures. I would like to express respect for the active contribution of the Committee chairman and members. I will give questions and comments on this report as follows.

Question 1. Importance of consideration of the cyclic material behaviour was addressed in subsection 2.1.2. I agree with this indication. However, we sometimes face difficulty in identifying the stress-strain curves under cyclic loading. Although the cyclic stress-strain curves under small plastic strain range were reported, few databases of the stress-strain curve under large plastic strain range can be used. Not only the fatigue phenomenon in the vicinity of a crack tip but also the plastic deformation caused by HFMI treatment occurs where large cyclic plastic strain occurs. I am expecting that the database of stress-strain curves applied to hull materials under cyclic loading with large strain range. **Reply (45)**

Question 2. The advantage of the ultrasonic fatigue test was addressed in section 2.3. In such an ultrasonic fatigue testing, local temperature rises inside the specimen increases so significantly that appropriate temperature control systems must be required. In addition, the loading frequency is quite higher than the in-service condition of ships and offshore structures. Therefore, various discussions have been continued on the validity of fatigue test results by the ultrasonic fatigue testing machines. I am going to introduce one solution to the problem mentioned above. A multiplex rotating bending fatigue machine was developed in [26] can perform the fatigue test on multiple specimens under different load magnitude simultaneously at an appropriate loading frequency, which applicable maximum frequency is 5,000 rpm, with small local temperature increase inside the specimen which does not affect the material properties. **Reply (46)**

2. REPLY BY COMMITTEE

2.1 Response to the Official Discusser

The Committee is extremely grateful to Prof Wolfgang Fricke for the excellent and in-depth discussion and is pleased with his comments, in particular "*…the Committee has done an excellent job in fulfilling the mandate and delivering an extensive report about the reviewed references, which is extremely valuable for our community in their daily work*".

In the following sections, a detailed reply to his comments is presented.

2.1.1 Fatigue and fracture loading

Reply (1): It is generally admitted that using the North Atlantic environment would lead to conservative fatigue estimate for common ship trading operations. However, no publication has been found during the last three years to confirm that point. Initially, the North Atlantic environment was a safe assumption for representing the wave environment of the trading routes before the 70's mainly between the US, Europe and the Middle East. Nowadays, the question of the adequacy of the North Atlantic environment to describe the global shipping operations solely is particularly relevant given the recent development of trading routes in Pacific area (Australia, China and Japan) and also the future development of the Arctic Northern Sea route due to the Climate Change. The Climate Change might also require a continuous update of the design wave environments, and should be the concern of the Technical Committees I-1 and I-2.

Finally, the ships operating in the TAPS (Trans-Alaska Pipeline Service) environment are mostly encountering beam seas that might primarily expose the side shell members, while the IACS Recommendation 34's North Atlantic environment assumes the equal probability of wave headings for fatigue damage assessment. Therefore, it might be interesting to compare the fatigue damage obtained for the two environments.

Reply (2): Fatigue wave loads for ships might be downgraded by employing milder wave environments than the North Atlantic when the actual trading route is well-defined, and the utilisation of a milder environment such as the Worldwide environment is justified, and it is explicitly mentioned in its Class Notation. Therefore, the fatigue wave loads downgrading would be accepted under the condition that the milder loads would ensure a level of safety equivalent to that implicitly taken by the rules for the North Atlantic environment.

Reply (3): The operational factors are taken into consideration for the design of offshore structures for which the climatology and operational profile are well known a priori. For ships, the detailed operation pattern is not known in advance. Therefore, assumptions are made on the conservative side to describe the long-term operations of the vessel on a ship-type world fleet perspective, (e.g. long-term average speed, the fraction of time in each common loading condition). The only case known by the Committee of operational factors well considered in the design of a ship is for the case of FPSO conversions from Tankers. For FPSO conversions, Classes (BV NI593) require to combine the fatigue damage of the predicted operations as an FPSO to the fatigue damage of the previous operations as a Tanker that implies the precise representation of the past trading routes and loading conditions history.

Reply (4): For the time series that have been investigated [3], rainflow counting and the Palmgren-Miner hypothesis are suitable to estimate the fatigue damage for stress histories with and without (whipping) vibrations indeed. The Committee did not come across research results with opposite conclusions. However, according to the latest edition of CSR-H (2018), fatigue limit state of structural details is to be assessed from long-term distribution loads based on loads at 10-2 probability level, including the whipping-springing effects. See Pt. 1 Ch.3 Sec. 5 2.4 and relevant Technical Background.

Reply (5): The Committee agrees on the comment of the Official Discusser that thermal loads are prone to induce a significant level of fatigue damage on some cargo ships such as asphalt carriers. Unfortunately, as far as the Committee knows it, the question did not raise to now in the Classification Societies rules as very few of those ships reach the length where a fatigue assessment is required. In practice, only a few asphalt carriers have been checked against fatigue failure accordingly to a procedure defined on a case by case basis. The Committee believes that thermal loads should be addressed in the design rules.

Reply (6): The Committee agrees with the Official Discusser statement and proposes the following precision for the sake of clarity:

Loading/unloading caused low cycle fatigue damage is generally negligible for deep-sea ships which the trading pattern can generally be characterised by long trips between harbours and thus the low frequency of loading/unloading variations. However, their effect on the mean stress and thus on the wave-induced fatigue cannot be ignored.

Reply (7): The Committee is not aware of fracture in as-built condition except for accidental cases (e.g. LNG liquid leak on deck plating). It is always challenging to provide references to phenomena with the infrequent occurrence. However, the Committee agrees that even if the fracture in the as-built condition is very seldom, special care is to be taken on fracture loads and particularly for very thick parts in high tensile steels such as YP36, YP40 and YP47.

2.1.2 Material Properties and Testing

Reply (8): The Committee agrees with the Official Discusser on the importance of local strain approaches.
Reply (9): The J-integral represents a way to calculate the strain energy release rate, and for isotropic, perfectly brittle, linear elastic materials, the J-integral can be directly related to the fracture toughness
Reply (10): The Committee did not see, in the reviewed period, much progress concerning the short crack behaviour and the threshold value for crack propagation, however, several references have been mentioned in the report.
Reply (11): The Committee agrees with the Official Discusser on these important observations.

2.1.3 Fatigue Damage Accumulation Approaches

Reply (12): Concerning the hot spot structural stress calculation for thin-plate structures, the pre-deformation induced contribution is essential indeed. Concerning practice, establishing a representative pre-deformation pattern for design is a challenge as well and related to production aspects (which can be different from one yard to another).

Reply (13): Reference [7] is missing, indeed.

Reply (14): The problem related to mild notches is recognised, explaining why a reference from the same first author addressing the same content has been referred to at the end of the effective notch stress paragraph 3.2.2. Reference [8] should have been mentioned there as well.

Reply (15): High localised stress peaks at certain hot spots are significant indeed. However, it is considered that the involved physics are not related to a particular fatigue assessment concept (i.e. effective notch stress or hot spot structural stress). The most highly stressed location in the perfect, intact geometry does not match the most highly stressed location of the as-welded specimen/structure if that geometry is different. The compressive residual stress argument, typically also not taken into account, could also be responsible for a different failure location. Statistical size effects may be a concept that can be used to explain the different failure location as well, but concerning the reference, a few remarks have to be made since it profoundly affects the results and conclusions:

- The reference (volume or weld seam length) can be chosen indeed, but should also be incorporated in the used design curve, i.e. the IIW FAT225 useful notch stress design curve in the mentioned references.
- The involved exponent 0.12 in the reference is based on experimental data and seems to come from laser beam welded automotive components and not from the MAG welded joints in a different range of plate thicknesses.
- The selected weld seam length that contains the stress peak seems arbitrary.

Summarising the previous points: representative fatigue resistance information should be used to establish the reference length and fitting exponent, justifying the selected/equivalent weld seam length that contains the stress peak.

Statistical size effects correlate with the fatigue strength and the volume or weld seam length. The physics of the statistical volume or weld seam length effects are that the larger the volume or, the longer the weld seam, the shorter the lifetime because the probability of a more extreme (welding induced) defect increases. This principle seems not to hold for the considered problem. It seems that the weld seam length is confused with the effective stress peak length (in line with the effective stress in a through-thickness direction).

Reply (16): Reference [11] is from 2012, and it is a valuable addition indeed.

Reply (17): The Committee agrees with the Official Discusser and his explanations pointing out the conclusions of "Fischer, C., Fricke, W. and Rizzo, C. M., 2016, Fatigue tests of notched specimens made from butt joints at steel, *Fatigue & Fracture of Engineering Materials & Structures*, 39, (12), pp. 1526-1541".

Reply (18): The total stress criterion does not take relaxation of the residual stress into account. Relaxation is considered to be essential for the first few cycles. This number of cycles is considered to be small in comparison to the fatigue lifetime. The through-thickness welding-induced residual stress distribution is assumed to consist of equilibrium and self-equilibrating part. Relaxation is deemed to affect the equilibrium equivalent part predominantly. After relaxation it is considered to be zero, meaning only the self-equilibrating part is left. This part – considered to be crack length-dependent over a lifetime – is taken into account and it is considered to be tensile at the notch location.

Reply (19): It seems that the sentence "The corrosion rate in the heat-affected zone, at the weld toe location, is typically higher in comparison to the base material values because of the welding-induced residual stress close to yielding and …" is not entirely clear. The sentence tries to say that in the heat-affected zone at the weld toe location the residual stress is high and that, as a consequence, the corrosion (crack growth) rate is higher in comparison to base material corrosion crack growth rates (without residual stress at yield magnitude).

Reply (20): The crack growth relation, as well as the involved cracked geometry parameters like the crack tip stress intensity, are also an input for more recently developed equivalent stress criteria like the Battelle structural stress and Total stress. These criteria are used for fatigue design (traditionally Chapter 3), whereas traditionally the crack growth relations and the corresponding parameters were maintenance (traditionally Chapter 4) related. The boundaries are fading.

This explains why up to some extent, crack growth relations and the corresponding criteria as far as (numerical) modelling is concerned is included in Chapter 3. However, it may introduce some overlap, indeed.

Reply (21): The term 6D is referring to the six stress/strain components. The statement that non-proportional loading & response is more damaging than proportional loading & response is quite general indeed. The material contribution is not explicitly mentioned here. Models are still under development, and state-of-the-art studies are comparing the results for the different models show that consensus is not reached yet.

Reply (22): The residual stress relaxation is a complex topic, indeed. The residual stress distribution in a through-thickness direction (e.g. Figure 6a and Figure 8a from reference [17]) can be split between an equilibrium equivalent and a self-equilibrating part. Because of relaxation, the equilibrium equivalent part will (partly) diminish; the self-equilibrating part will remain but can be redistributed as well. The residual stress distributions in Figure 6a and 8a from reference [17] shows that it is tensile in the notch affected region. Together with the mechanical loading induced response, a highly stressed notch affected region seems to be ensured.

Reply (23): The fatigue damage process consists of 2 stages: crack initiation and crack growth. Different models have been developed which try to match initiation and growth lifetime contributions by using a dedicated parameter for each stage. It means that the two parameters will be involved: 1 for the initiation and 1 for the growth. These type of models are referred to as 2-stage 2-parameter models. Alternatively, a 2-stage 1-parameter model can be adopted as well. For instance, an equivalent stress (1 parameter) describing the two stages: both initiation (i.e. micro-crack growth) and (macro-)crack growth, by involving a loading & response level-dependent elastoplasticity coefficient in the crack growth relation. It allows for a change from monotonically increasing to the non-monotonic crack growth behaviour.

2.1.4 Crack Growth Approaches

Reply (24): The Committee agrees with the view to mention the application of crack growth approaches to the design of fillet-welded joints. The references and the research achievements for the design assessment regarding the total fatigue life based on fracture mechanics approaches especially the assumption of a suitable initial crack or defect size need more attention, avoiding duplication with the content of Chapter 3.

Reply (25): The Committee agrees on the comment that increasing study on the crack propagation in the crystalline structure can be found. Much research in the field of basic mechanics can be referred to. However, these research achievements have not been widely applied in the field of ship and offshore structures in recent years. Therefore, there are not many publications in this report related to the grain-scale fracture mechanics theory.

Reply (26): The Committee emphasises the role of the fracture mechanics-based approaches in the analysis of crack repair methods, but the discussion on specified crack repair methods are more suitable in Chapter 5.

2.1.5 Fabrication, Degradation, Improvements and Repair

Reply (27): The Official Discusser's definitions as far as imperfections and defects are concerned are noted and shared. However, the Committee used a different categorisation in the light of the organisation of the report content. It was deemed worthy to distinguish between fabrication and in-service scenarios as long as remedial actions can be slightly different. Moreover, most available literature concerns fabrication induced imperfections while consideration of other effects during service is somewhat lacking, and it has been underlined in the report.

Reply (28): The Committee agreed that weld toe radius is a matter of fabrication quality rather than an imperfection itself, but the shipbuilding industry requirements are more and more stringent. Also, the quality aspects in fabrication are more and more viewed as imperfections, impacting on the structural performance. As a matter of facts, recent rule requirements also consider improvement methods and the weld toe radius is a parameter to be optimised.

Reply (29): The Official Discusser described very clearly and in full detail what is actually included in the references cited in the report and also he added a few ones.

The Committee wholeheartedly agree with Discusser's explanations and would like to point out that, in the Committee opinion, FEA can be successfully used for a better understanding of the 3D local structural behaviour as well as to calibrate simplified analytical formulae.

Reply (30): The Committee agrees that the weld toe radius is not the only indicator of a well-performing weld process but also a potential input parameter of the fatigue assessment procedure, as previously pointed out. This is the only parameter accounted for in everyday design practice by structural designers, besides specialised firms involved in fatigue improvement methods. Thermomechanical analyses have been established by different studies but in the Committee's opinion they are still too cumbersome for current ship structural design, and they should be limited to special cases. Moreover, the quality of shipbuilding productions in shipyards is very different and depending on a vast number of affecting issues, not accounted for in such analyses, whose results can be biased concerning reality.

It could be very beneficial if a harmonised procedure for the evaluation of the radius is defined in standards and guidelines. The effective notch stress approach to the fatigue assessment relies on the well-known Radaj's assumption, which is a conventional approach. Collection (and sharing) of weld toe geometries may substantially improve the understanding of the fatigue phenomena and support the evolution of local approaches to the fatigue assessment.

Reply (31): Fatigue improvement methods have been only recently included in the Classification Societies Rules. This is somehow a symptom that they are more and more accepted and considered. Although several references have been cited in the report about such methods, the Committee recommends that further independent research is carried out in this field. The Discusser points out a few questions worthy of further investigations and requiring new ad-hoc testing campaigns.

2.1.6 Fatigue Reliability

Reply (32): Committee agrees with the Official Discusser that considerable scatter is being observed in the determination of S-N curve. In reality, structural stress responses are random under variable amplitude loading. The paper (first published in the 24th International Ocean and Polar Engineering Conference, 15-20 June, Busan, Korea, 2014) pointed out by the Official Discusser discusses the contribution of high-frequency stresses due to whipping to the total fatigue damage of structural details of a container ship. Committee already pointed out that the Ultrasonic fatigue testing under multiaxial and variable amplitude loading conditions has recently also received increasing research attention.

Reply (33): Committee wholeheartedly agrees with the Official Discusser comment that the report discusses the limit state for the fatigue crack growth based on the SIF concept. To deal with the large plastic zones in the material, critical J-integral concept or CTOD - crack tip opening displacement concepts are to be used to estimate the fatigue life. Also, the equivalent SIF can be determined using J-integral. To the knowledge of the Committee, the limit states purely based on the J-integral concept or CTOD is not yet established and demonstrated in the reliability analysis. However, the limit states based on the fatigue life (computed using the J-integral concept or CTOD) are not new.

2.1.7 Fatigue Design and Verification based on Rules, Standards, Codes and Guidelines

Reply (34): The detail design standard provides welding requirements at critical structural details. Among others, full or partial penetration welds to prevent fatigue cracks initiating from the weld root and propagating through the weld throat or into the plate section under the weld (see Figure 5).

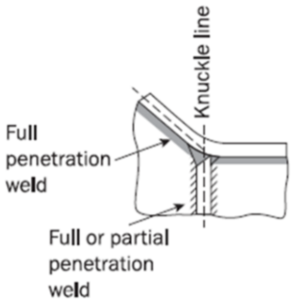

Figure 5: Hopper knuckle, radiused type for double hull oil tanker

Reply (35): Class rules for fatigue approaches have been developed over a long time and are verified by the damage statistics of the operating fleet. A reduction of the allowable damage ratio to D = 0.5 is technically feasible but would be not applied without further adjustments of the fatigue approach, because the overall level of fatigue strength, which is based on the experience with the operating fleet, is considered most relevant. With D = 0.5, mainly the load side would be adjusted due to the uncertainties which still exist here, in particular, concerning weather routing and other operational effects as well as an appropriate consideration of hull girder vibrations, i.e. whipping and springing. In short, it can be concluded that rule requirements have been calibrated considering partial safety factors in different phases of the assessment. The D=1.0 limit is not necessarily unconservative if appropriate input feeds the damage evaluation procedure.

Reply (36): Typical trades are sufficiently represented by a worldwide load spectrum which includes 34% operation in a harsh wave environment. When the owner intends to operate his/her ship for a longer time in a harsh environment, the North Atlantic spectrum is to be applied for the fatigue strength assessment with DNV GL Rules.

Reply (37): As written in conclusion, the Committee agrees with this statement.

Reply (38) S-N curves are used to evaluate the fatigue life of structural details until the crack initiates. In the sentence 'initial crack' means an initial detectable crack (at a macro-mechanical level) and not micro-cracks being orders of magnitude less than the plate thickness. Such an approach is indeed difficult to achieve considering the large thickness of the walls of a cargo containment, and therefore other methods as leakage detection/inspection are used to detect the initiation of the crack

2.2 Reply to Written and Floor Discussion

2.2.1 Alexander Babanin

Reply (39): The Committee agrees with the comments of Prof. Babanin.

However, it is not only about the significant wave height or wave period but also about the heading and how the ship operator is operating in these conditions. About 30 years ago because of computational limitations, a conservative assumption had been adopted for design. However, now we can go for a more detailed study – for a description of the routing, scatter diagram, the kind of spectrum we need to use for specific quotation etc. Nowadays, we have very effective tools that could provide a better statistical description of the possible routes. With advancements in wave modelling and simulation, we are now in a good position to better describe the loading and response on the structure and its effect on the fatigue damage description. We need to look for routing and find a better description of the ocean environment which would affect the description of loading and ultimately the estimated fatigue

2.2.2 Suqin (Sue) Wang

Reply (40): With regards to the recommendation, we did not have any representative with affiliation to the ABS. For the current study, we have utilised experts from the Committee representing class societies since they have the better knowhow of the rules and can take responsibility thereof. The Committee noticed that a few years ago, there was a good representation of different class societies. However, this time, it was our limitation.

With regards to the question, corrosion degradation starts with isolated pits and grows later more or less uniformly but still developing the sharp corners as the sights for a crack imitation and propagation. Several experimental and numerical analyses studied the impact of corrosion degradation of ageing marine structures demonstrated a significant decrease of the structural capacity, flexural rigidity [27, 28]. However, the corrosion degradation not only affects the structure geometry but also for the elastic limit and modulus of elasticity [29, 30] and how to translate the experimental results to real structures has been demonstrated in [31].

Figure 6: Plastic hinges and plate tearing, severely corroded box girder [32].

The effect of corrosion degradation of corroded specimens subjected to fatigue load was analysed in [33], where a reduction of the fatigue strength from FAT 100 to 65 MPa was identified.

The experimental tensile tests conducted in [34] indicated that the net-section reduction due to corrosion degradation in the HAZ decreases the ductility compared to the corroded base metal specimens in the same conditions. Increasing the corrosion degradation severity, the fractal dimension decreased, and the fatigue fracture arises due to the interaction between multiple site corrosion pits not due to a single pit for Q235 steel as reported in [35, 36].

Small-scale corroded specimens have been tested under tensile load in [37] indicating a severe influence of corrosion degradation on the mechanical properties of mild steel including, Young's modulus, yield stress, tensile strength, resilience, fracture toughness and total uniform elongation. Intensive tensile tests of cleaned and non-cleaned corroded mild steel specimens were carried out [38] demonstrating a reduction of the modulus of elasticity as the degree of degradation increases as a function of the cleaning method as sandpaper cleaning, non-maintained corroded and sandblasting.

A profound analysis has been performed in [39] recently. The major conclusion was that the reasons for the decrease in fatigue strength in the corrosive environment are considered to be the initiation of a fatigue crack from the bottom of the corrosion pits and the accelerated crack propagation due to the dissolution of the crack plane, which was already confirmed also in [33]. It is recognised that the corrosion fatigue phenomena in the long fatigue life region has a significant effect on the fatigue strength and still need more studies.

2.2.3 Asokendu Samanta

Reply (41): Let me point out that the Committee is just reviewing the already existing approaches and not developing any new ones. However, the Committee can confirm that weld root fatigue is only implicitly covered in the Rules and, being the topic not sufficiently established, the Rule developers did not include any specific procedure.

Official Discusser reply – If there is a conflict in modelling shell elements, then you need to go back to the nominal stress approach, which has worked quite well in the past.

2.2.4 Agnes Marie Horn

Reply (42): The fatigue damage estimate, also depends on fatigue damage criteria adopted. The figures presented before by the Official Discusser showed that the fatigue damage is acceptable. However, there are other fatigue criteria’s like Battelle structural stress and total stress, which show that if we use those in combination with VA loading and response, even otherwise unacceptable damage ratio of 1 provides safe results. Regarding the Class Rules, this aspect must be investigated and included in the Class Rules.

2.2.5 Robert Sielski

Reply (43):
The Committee agrees that, besides stress range, the mean stress is an important parameter governing fatigue and fracture phenomena. Considering fatigue assessment, the effect of the mean acting stress is generally well-considered in the Rules and design practices. However, especially for welded structures, residual stresses complicate the problem so much that, in practice, the worst-case scenario (maximum tension stress taken equal to yield stress) is used.
The Committee also agrees that the mean stress effect (or stress ratio effect) must be taken into account in fatigue life evaluation based on crack growth approaches.
However, the effect by mean stress changes from compression to tension is a problem of the assumption on loading sequence. The crack growth is determined by environment, loading, structural characteristics and material properties. Among the four types of influential factors, structural characteristics and material properties can be simulated relatively accurately, and the environmental factors such as temperature and the corrosive condition can be evaluated and incorporated into material properties like fracture toughness and crack growth threshold etc.
Nevertheless, there is still a not precise method to consider the loading sequence effect. Traditional methods to consider it simplifies the problem but neglect the real sequence. Generally, we assume the future loading based on empirical judgements, classifying load cycle types according to their characteristics such as tension or compression. It is difficult to judge after how many cycles the condition will change from compression to tension.
As for the crack growth prediction models, many research results show their confidence to consider the mean stress effect validated by material tests. Furthermore, in recent years, some researchers study the crack growth rate in small-scale time domain, expressed by da/dt, to replace da/dN, which may consider the changes inner one cycle and be promising to consider the effect of stress changes better but it is still on the premise of accurate loading sequence.
Indeed, if the residual life of the structure with an existing crack is evaluated based on the crack growth analysis under the mean compressive stress, that would be unsafe when the condition of tensile mean stress may occur. For such kind of conditions, we recommend to conservatively assumed load spectrum.

Reply (44):
Recently intensive investigations are performed to allow for high utilisation of steel in the Arctic conditions by increasing the level of safety leading to zero-leakage and "maintenance-free design solutions), appropriate test methods and acceptance criteria have been developed. Several examples with this respect can be seen in [41-43].

2.2.6 Koji Gotoh

Reply (45): The Committee agrees of the importance of identifying the stress-strain curves under cyclic loading, and more effort is needed to develop a database of the stress-strain curve under broad plastic strain range. This issue needs to be on focus on the next Committee mandate.
Reply (46): The Committee agrees of the importance of the fatigue test on multiple specimens under different load magnitude simultaneously at an appropriate loading frequency and collecting data in this perspective is a good step ahead.

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