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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.

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## CONTENTS

# 1. DISCUSSION

## *1.1 Official Discussion by Yoichi Sumi*

### *1.1.1 Introduction*

It is my pleasure to accept the Standing Committee's request to discuss the report of Committee III.2, whose members chaired by Professor Brennan are congratulated for the well balanced coverage of the topics and also for the good continuation of the context of the committee reports on fatigue and fracture. Personally, I had been serving a technical committee and standing committee member of ISSC for 21 years from 1991 in Wuxi to 2012 in Rostock. During that period I mainly worked for Committee II.1 Quasi Static Response, whose role is supposed to bridge the loads covered by Committee I.2 to strength committees (III.1 and III.2), through the calculation of static load effects by means of numerical computation. Also during that period with the increasing use of HT-steel and the corresponding increase of working stress, the evaluation of stresses at structural details was of immediate interest, so that numerical stress analyses mainly by the finite element method and the fatigue strength research formerly solely based on experiments had met together and began to cooperate with each other. That is my experience in ISSC during 90s and early 2000s.

Having reviewed almost 300 papers, reports and industrial codes regarding the research and the developments of the recent three years, the committee report is organized in the following manner;

- Fatigue life-cycle design philosophies and methodologies
- Factors influencing fatigue/fracture
- Fatigue assessment methods
- Benchmarking study

My discussions will generally follow section by section of the Committee report with some focus on the subjects, which may be of interests from my view point and are not covered by the committee report.

### *1.1.2 Fatigue life-cycle design philosophies and methodologies*

This section is the summary of the definitions of keywords in relation to fatigue and fracture. Regarding the failure definition, some keywords may be added for the identification of the levels of failure such as "incident," "loss of serviceability," and "catastrophic failure," in which consequences of such failures and the corresponding possible counter-measures could be rather different. The Official Discusser appreciates if the Committee is kind enough to reply to this comment.

### *1.1.3 Factors influencing fatigue/fracture*

Factors influencing fatigue and fracture are identified by the Committee as "Resistance", "Material", "Loading", and "Structural Integrity," which compose the subsections for literature review reflecting recent design trends.

– *Resistance*

The Committee considers fatigue strengths of both very thin plates and thick plates. The use of such plates is essentially related to the recent trends of structural design of up-sizing passenger ships and cargo ships, respectively.

Regarding the fatigue strength of thin plates, it is natural that the Committee considers very thin plates whose thickness is down to 3mm used in deck panels of large passenger ships, which are basically in tension under the high hogging moment in still water bending condition. Laser, laser-hybrid and friction stir welding have made it possible to manufacture such panels within certain permissible tolerance for axial and angular misalignment due to welding. Although linear analysis without initial deformation is sufficient for hull-girder strength analyses, geometrical non-linear analyses are needed for the fatigue strength of butt and cruciform joints based on nominal and structural stress approaches as pointed out in the report. Since large deformation stems from the initial distortion induced by welding, permissible limits of initial deformation should be standardized based both on the large deformation finite-element analyses and experiments in the near future. Actually, this is the topic of the benchmark study of the present Committee.

As summarized in the report, a clear thickness effect is observed for butt weld by the simplified formula,

$$f(t) = (t_{\mathrm{ref}} / \mathrm{t})^n,$$

where the exponent of $n = 0.21$ complied well with the results of fatigue tests. For longitudinal stiffener specimens, a small stiffener of the same size does not cause any thickness effect by changing the thickness of the load-carrying plate. Similar results are observed for cruciform joints with attached plates of the same size, while those with attachment of proportional size show clear thickness effect of the exponent $n$=0.27. As indicated by Yamamoto et al. (2014), the stress concentration and the stress gradient at the weld toe could be the governing factors of the thickness effect, so that the detailed stress analysis may help to understand the thickness effects of welded joints. From these considerations, fatigue strength based on the notch stress does not exhibit any thickness effects, while the conventional definition of the hot spot stress may be reconsidered from the view point of the selection of stress evaluation points to determine the hot spot values.

The effect of long welds on fatigue capacity is considered to be important in design of long pipes with seam welds used for transportation and storage of gas and for design of girth welds in ten-dons used for anchoring of tension leg platforms. As explained in the report, a longer weld length implies a larger probability of a less good local geometry, a larger undercut and a possible defect that reduces the fatigue capacity. This length effect may be said to be part of the size effect in addition to the effect of the thicknesses as appropriately indicated in the Committee report.

The rapid enlargement of the size of container ships has led to the application of extremely thick plate in the deck structures such as hatch side coaming, upper deck and other structural members to satisfy the requirement of longitudinal strength. The current classification rules for hull structures have been considered to be valid not only to prevent the brittle crack initiation but also to arrest the brittle crack propagation, regardless of the increase in steel plate thickness. Recent researches, however, have suggested that current classification society rules do not necessarily have the satisfactory background data for the structural integrity of the large container ships constructed by using extremely thick plates (Inoue et al., 2010). Especially, this may lead to some concerns about the fracture toughness of welded joint which is thicker than 50mm, because fracture toughness along the butt welded joint was formerly investigated for plates with moderate thickness by using the so-called Center Notch Specimens. The arrest toughness against brittle crack propagation in base metal had been investigated also for moderate thickness plate, whose thickness is normally less than 50 mm, by the so-called ESSO test with temperature gradient (Kihara et al., 1967). It is our immediate interest to have necessary information about the initiation and arrest toughness of steel plates for ship hull structures in the thickness range of 50-100mm.

Also, the detection of weld-defects during the construction stage of a vessel and fatigue crack detection by periodical in-service inspections are essential to prevent brittle fracture, where fatigue crack propagation from embedded flaws in the weld under realistic seaway loading must be predicted for the proper determination of the acceptable size of the initial defects and the maximum inspection interval based on fracture mechanics approach (Sumi et al., 2013). Regarding the seaway loading, possible difference of the service routes should be identified, so that the collections of data by on-board measurements may help understand the variations of response of individual ships and estimate the effects of slam-induced whipping stresses on the fatigue crack propagation.

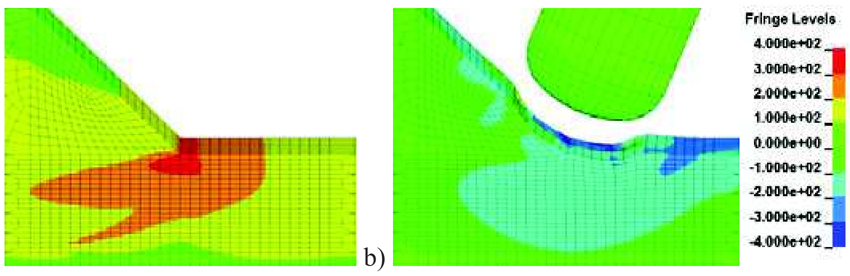
Having observed these technical background information, “UR S33: Unified Requirements for Use of Extremely Thick Steel Plates” was released by International Association of Classification Societies (IACS) in January 2013, and it is applied by IACS Societies to ships contracted for construction on or after January 2014. In UR S33, the measures for extremely thick steel plates used in hatch coaming structure are itemized, among which the introduction of periodic NDT required after delivery is very effective to the keep the structural integrity, while it may have significant impact to ship maintenance cost. Since the timing, the precise extent, and the acceptance criteria of UT are said to be in accordance with individual Society in UR S33, the Official Discusser wonders when is the practical timing of the inspection, where is the possible block-butt joint to be inspected, and etc., i.e.: more concrete inspection procedures for container ships in service. Since the report touches upon this issue in subsection 4.4.1.7, the Committee is kindly requested to give some additional comments on these issues.

– *Materials*

Fatigue improvements were discussed in the Committee Report of ISSC 2012, and also in subsection 3.2.2 of ISSC 2015, entitled “Fatigue and fracture improvements through material changes and surface treatment,” and high frequency mechanical impact (HFMI) technology was separately reviewed in subsection 3.5.1 entitled “Fabrication and repair.” The Official Discusser would like to add some comments on ultrasonic impact treatment (UIT). It is well known that the fatigue strength of steel plates increases in proportion to its static strength. On the other hand, the fatigue strength of the welded joints is little influenced by the static strength level because of the tensile welding residual stress and high stress concentration near the weld toe. Ultrasonic impact treatment (UIT) is a new method for increasing fatigue strength by improving the weld toe geometry, removing defects and introducing beneficial compressive residual stress (Okawa, et. al., 2013). Recently, new IIW guidance on fatigue strength improvement using high frequency mechanical impact (HFMI) methods including UIT has been prepared by Marquis et al. (Marquis et. al., 2013, 2014). In parallel to the development of IIW guideline, ship classification societies have also accepted or investigated the UIT as post-weld treatments in ship and offshore structures (ABS, 2014, Polezhayeva, 2014).

In order to better understand the effects of UIT on fatigue performance of welded joints, its mechanism has been experimentally investigated in several studies. A German research project (Weich, 2013) has presented the experimental data that the compressive residual stress is generated down to a depth of 1.5 to 2 mm with maximum values at approximately 0.4 to 0.5 mm below the surface. After treatment the weld toe radius is averaged by 1.5 to 2 mm with its groove depth of 0.1 to 0.2 mm. The study at the University of Waterloo, Canada (Yekta, et. al., 2013, Ghahremani, et. al., 2014) was carried out to investigate the fatigue performance of structural steel welds subjected to UIT at under-, proper and over-treatment levels, respectively. A close relationship was found between the measured groove depth and local residual stress, indicating the groove depth as an important quality control parameter. Ultrasonic impact treatment consists of ultrasonic waves and mechanical impacts. Very limited studies (Statnikov, 2004, Dutta, et. al., 2013) have demonstrated that the ultrasonic vibration superimposed by UIT on metals has indeed an acoustic softening effect on material properties undergoing deformation.

Normally the experimental methods for residual stress measurements need considerable cost, time and skillful technique. It is practically impossible to obtain full field measurement of residual stress. For this reason, the residual stress induced by UIT has been recently evaluated using finite element analysis. There are mainly two groups of simulation methods for UIT process: quasi-static implicit and dynamic explicit methods. The former is modelled as pressing the pin at the weld toe to one prescribed depth by displacement or load control approaches, rather than peening (Le Quilliec, et. al., 2013). In the latter (Yang, et. al.,2012, 2014), the modelled pin impacts to a symmetry-cell model that is widely used in shot peening simulation, however, the welding residual stress is not taken into account. It is found that the predicted in-depth residual stress and groove depth could not conform well with measurements (Le Quilliec, et. al., 2013), because in the above mentioned simulations the acoustic softening effect has not been introduced, which plays an important role in the mechanism of UIT. Therefore, a novel 3D prediction approach including thermo-mechanical welding simulation, dynamic elastic-plastic FE analysis of UIT-process, and an evaluation of surface fatigue crack growth is needed in this research area, where some simulated results of a fillet welded cruciform joint are illustrated in Figures 1 and 2 (Yuan and Sumi, 2015).



a) b)

Figure 1: Transverse residual stress distributions and plastic deformation at weld toe; (a) as-weld, (b) after UIT.

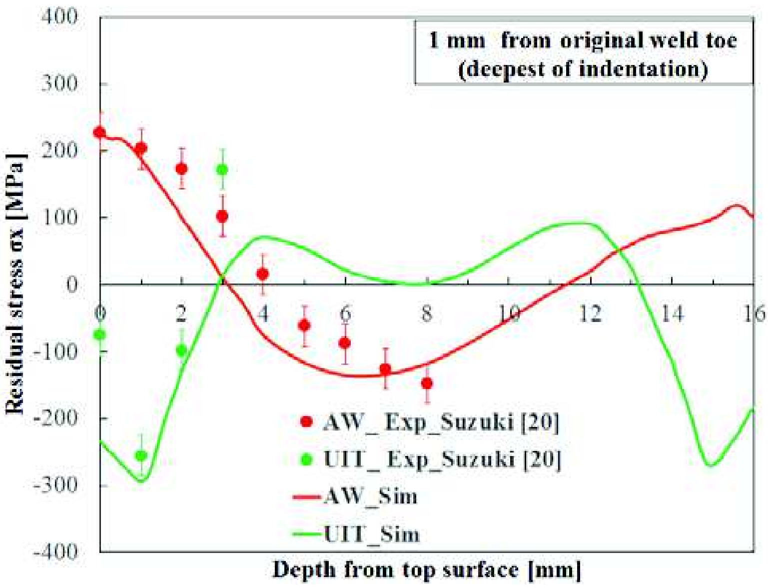



Figure 2: Distribution of transverse residual stress of as-weld and UIT specimens in the depth direction, and comparison with experimental results (Suzuki, et al., 2014).

– *Loading*

In the Committee report, the rainflow method is said to be still the most popular technique in the analysis of random fatigue data. With regard to the stochastic loading, the effects of load sequence, especially the (vibratory) whipping stress superimposed to the quasi-static wave-induced stress are discussed by introducing the results of several references. It seems that some of the results confirm the validity of the rainflow analysis while the others not. The Committee is kindly requested to clarify the range of applicability of the method based on the loading parameters involved in the slam-induced whipping.

The report also extensively reviews the multi-axial fatigue, taking account of the proportional (in-phase) and non-proportional (out-of-phase) load paths. As pointed out in the report, it should be noted that classical yield criteria, such as the von Mises distortion energy criterion, commonly extended to multiaxial fatigue life estimations, may work for in-phase or proportional loading, but they often under-estimate the typically observed shorter lives for out-of-phase or non-proportional loading. The shorter life under non-proportional loading is often attributed to non-proportional hardening. However, materials without this hardening also exhibit shorter life under such a loading. Based on these experiments, it is understood that the fatigue life of the material in the multiaxial stress state depends on the hardness of the material as well as the type of loading (proportional or non-proportional). With regard to the fatigue crack growth under non-proportional mixed mode loading conditions, it has been reported that criteria based solely on the maximum, minimum and mean values of the stress intensity factors, cannot provide accurate predictions of the crack growth rate or of the crack path. The entire load path should be considered so as to predict accurately fatigue crack growth in non-proportional mixed mode conditions. Overall, it seems that due to the challenging nature of the multiaxial fatigue problems, much additional research and development work is still needed for accurate and reliable multiaxial fatigue life estimation.

– *Structural Integrity/Life cycle management*

As discussed in subsection 3.2, high frequency mechanical impact (HFMI) technology has undergone a significant amount of research with the aim of improving the fatigue classes of welded joints in high strength steels. Investigations show the potential of this method to improve the fatigue strength, which would enable weight reduction or longer design lives for marine structures when high strength steels are considered. In order to ensure the improvement of fatigue strength, the long term effects such as corrosion and overloads are to be investigated in the near future.

Non-destructive crack inspection can be done by using UT process. It is reviewed in the report that this test system is not adequate for the in-service screening of fatigue cracks in marine structures. It is also recommended that the conventional methods for detecting cracks and recent techniques for monitoring crack propagation can be combined in order to increase the sensitivity and efficiency of the structural health monitoring (SHM). As I mentioned in subsection 3.1 in the present discussion, IACS

UR S33 may require certain periodic NDT after delivery in order to ensure the structural integrity. The Committee is kindly requested to comment on certain applicable NDT methods for this problem.

### *1.1.4 Fatigue assessment methods*

– *Overview*

Recent development of local approaches developed in the last 20-30 years is reviewed in this section, in which they are categorized as:

- Structural stress approaches, based on the structural (or geometric) stress at the hot spot
- Notch stress approaches, based on the effective notch stress, i.e. the total stress in the notch, obtained assuming linear-elastic material behavior;
- Notch strain approaches, based on the notch strain instead of notch stress and considering the elasto-plastic behavior of the material occurring in the notch;
- Crack propagation approaches, evaluating the crack growth up to failure according to the fracture mechanics model.

– *Fatigue damage models*

The stress based concepts, i.e.; the effective notch stress concept and Battelle structural stress concept, and strain concepts which may take into account of the local plastic strains developed in the vicinity of notches due to stress concentration have been reviewed. Then, a few methods linking fracture mechanics concepts with more traditional stress based approaches i.e.; the Notch Stress Intensity Factor (N-SIF) concept is discussed in the report. Some applications to marine industry have been published, but N-SIF based approaches are not yet recognized as a procedure for fatigue life assessment in the various industrial fields nor were they agreed to be included in any regulation or standard, so that further investigations are required in the future.

In subsection 4.2.2, the determination of S-N curves for the low-frequent wave loading and higher frequent whipping stresses are discussed in relation to the fatigue strength of container ships. The Official Discusser thinks that this subject should have been incorporated into subsection 3.3 Loading, rather than to be treated as the confidence and reliability of S-N curves. Anyway, fatigue experiments under the load sequence based on full-scale measurements of stress histories on container ship, containing typical whipping events, are essential to verify various propositions introduced to this problem.

– *Fracture mechanics models*

As mentioned in subsection 3.1, International Association of Classification Societies (IACS) released a new rule, the so-called “Requirement for Use of Extremely Thick Steel Plates”, whose requirements and recommendations are applied to extremely thick steel plates, i.e. between 50mm and 100mm, concerning brittle fracture toughness and brittle crack arrestabiliy. Obviously, CTOD changes with the grain sizes at different locations near a butt-joint, and the crack arrest toughness depends on the path of a propagating crack. The Official Discusser would like to have some comments from the Committee with regard to the mechanism of brittle crack propagation along butt-weld, i.e.; the conditions which distinguish the propagation along the fusion line and that into the base metal.

Fatigue crack propagation has been considered based on the Paris’ law with some modifications. As can be seen in the report, the effects of load sequence are of interest in recent studies of fatigue strength evaluation, which cannot be analyzed by damage models. Cyclic plasticity ahead of the growing crack tip and the plastic wake on the crack surfaces play important roles in the problems, but they are not properly accounted for by the conventional Paris’ law. In order to predict the effects of load sequence such as variable load ratios, tensile overload followed by retardation, compressive underload followed by acceleration, and random loading, a certain micromechanical model could be introduced at the growing crack tip. The Official Discusser would like to see how the Committee outlooks this issue.

Multiple cracks are initiated at weld toe under relatively high stress range and their individual crack propagations are followed by their coalescence, forming a shallow surface crack. In order to predict this crack propagation process, it is essential to have the information about the initial crack density as a function of the notch stress and stress gradient. In the report, crack path prediction is also reviewed for the first time in the Committee report, which is required by IMO IGC-code for the fatigue strength evaluation of Type-B cargo containment systems.

– *Rules, standards and guidance*

Relevant rules, standards and guidance have been reviewed by the Committee, so that the Official Discusser simply add information of the new IGC-code released in 2014 in relation to fatigue design condition of the Type B independent tank for the cargo containment system. In the revised code, failures are categorized into the following three cases, i.e.

- Failures that can be reliably detected by means of leakage detection,
- Failures that cannot be detected by leakage but that can be reliably detected at the time of in-service inspections,
- Failures in particular locations of the tank, where effective defect or crack development detection cannot be assured.

Based on this categorization, maximum allowable cumulative fatigue damage and the remaining failure development time are defined, differently, which is going to be discussed in the next subsection with respect to their acceptance criteria. In the last category, the predicted failure development time is defined as that from the assumed initial defect until reaching a critical state. Fracture mechanics analyses are to be carried out by considering crack propagation paths, crack growth rate, time to cause leakage from the tank, the size and shape of through thickness cracks, and the time required for detectable cracks to reach a critical state.

– *Acceptance criteria*

The acceptance criteria developed for fatigue and fracture assessment under extreme environmental loading are discussed in the report, where the development was triggered by the unexpected large number of cracks observed in many platforms in the Gulf of Mexico after hurricanes passed. As a result, API RP 2T (2010) recommended a so-called “single event fatigue” analysis, in which components susceptible to low-cycle/high-stress fatigue are to be analyzed to assess fatigue damage during a rare/extreme event. It should be noted that design criteria of this kind may apply to offshore platforms that may serve in a fixed location, while sailing ships, who may possibly avoid these extreme events by weather routing, are to be considered differently.

The acceptance criteria in relation to fatigue cracks detected in service are also discussed in the report, i.e.; the acceptance criteria to determine the minimum allowable size of a crack-stopping hole, whose limiting condition is defined such that no new crack would initiate when the structure is subject to a storm with a return period of one year or longer. A safety factor of 3 was selected in such a way that the predicted crack re-initiation time would be 3 times longer than the time needed for the cracked structure to sail to a repair facility. It is interesting to note that similar safety margins are seen in the revised IGC-code mentioned in the previous subsection, i.e.

- For failures that can be reliably detected by means of leakage detection, the allowable accumulative fatigue damage is to be $C_w \leq 0.5$, and the predicted remaining crack propagation life from the time of detection of leakage to a critical state shall not be less than 15 days,
- For failures that cannot be detected by leakage but that can be reliably detected at the time of in-service inspections, the allowable accumulative fatigue damage is to be $C_w \leq 0.5$, and the predicted remaining crack propagation life from the largest crack size not detectable by in-service inspection methods to a critical state shall not be less than 3 times the inspection interval.

– *Measurement techniques*

As reviewed in the report, digital image correlation (DIC) techniques have become increasingly popular due to their simplicity and effectiveness, where one can find the effective SIFs, including $K_I$, $K_{II}$ and T-stress by using displacements from DIC. This proposed technique is validated by comparing it with the theoretical results of SIF, which show DIC to be a practical and effective tool for full-field deformation and SIF measurement. In experiments, inhomogeneities were observed in the strain field behind the crack tip in both macro- and micro-scales which suggests the necessity for using crystal plasticity models to capture accurate fatigue behavior. These results certainly show the advancements in measurements of fatigue cracks in micro-scales, while it should also be remembered that the on-board macroscopic measurement techniques and the corresponding data analyses in relation to fatigue strength under slam-induced whipping stress are of urgent needs for structural design of large container ships.

### *1.1.5 Benchmarking study*

Higher payload-to-structural weight ratio has increased the need to study lightweight ships especially for the rapidly size-increased passenger ships, where the reduction of hull weight could be accomplished by decreasing the plate thickness of the passenger decks within the superstructure. Based on the discussions made during the previous Congress (ISSC 2012) with regard to the use of thin plates, a question has arose as to whether the very thin plates are favorable from the viewpoint of fatigue strength or not. In order to consider this problem, the Committee defines a benchmarking problem of "dog-bone" specimen of a butt joint having a typical geometrical imperfection observed in such a joint. The problem was analyzed by both linear and geometrically non-linear finite element methods, where the latter may give reduced stress concentration due to the straightening effect of the geometry under relatively high tensile conditions. Since the fatigue strength of thin welded panels are affected by the non-linear geometric effects such as initial deformation, straightening due to high tensile stress, and also the double curvature effects, more comprehensive investigations including experimental validations are necessary to establish a standard analysis methods.

### *1.1.6 Summary and conclusions*

Nowadays, a large number of literatures can be collected from electronic data-bases accessible via internet, so that the selection of information of good quality and the critical review become more and more important. Having read the Committee report, the Official Discusser would like to thank the Committee for the review properly covering all the subjects given in the mandate. In relation to the mandate, it says that "due attention shall be paid to practical application and statistical description of fracture control methods in design, fabrication and service." From the discusser's personal feeling, there are few references reporting practical applications especially to the on-board measurements of ships and defect-detection systems relevant to fatigue analyses in service condition.

In conclusion, I would like to summarize the comments already anticipated in each section in the following;

- permissible limits of initial deformation of thin butt-weld panels should be standardized based both on the large deformation finite-element analyses and experiments,
- with regard to the periodic NDT required after delivery, standardized inspection procedures should be introduced,
- with regard to the stochastic loading, the effects of load sequence, especially the effect of (vibratory) whipping stress superimposed to the quasi-static wave-induced stress should properly be taken into consideration,
- much additional research and development work is needed for accurate and reliable multiaxial fatigue life estimation,
- the mechanism of brittle crack propagation along butt-weld should be clarified, i.e.; the propagation along the fusion line and that into the base metal should properly be distinguished,
- a micromechanical model could be introduced in order to analyze the effects of load sequence such as variable load ratios, tensile overload followed by retardation, compressive underload followed by acceleration, and random loading.

### *1.1.7 References*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## *1.2 Floor and Written Discussions*

### *1.2.1 Shengming Zhang (Lloyds Register)*

The report has presented the study by Walters (2014) on the effects of low temperatures on fatigue. The study showed the fatigue resistance decreases with temperatures decrease. This is diferent from what we got. Lloyds Register has carried out fatigue tests of weld joints at room & low temperatures for ship structures. The results has been published in ref [A] and also used in LR's Shipright FDA ICE (ref [B]). The committee may give comment on this?

Ref [A] R. Bridges, S. Zhang &V. Shaposhnikov (2011) 'Experimental investigation on the effect of low temperatures on the fatigue strength of welded joints'. Ship & Offshore Structures.

Ref [B] Lloyds Register (2011) 'Shipright FDA ICE Fatigue induced by ICE Loading'.

### *1.2.2 Naoki Osawa (Osaka University, Japan)*

The effectiveness of rainflow stress counting for high frequency superimposed loading cases should be carefully examined in order to guarantee the structural integrity of large container ships. In ISOPE2015 [N. Osawa, T. Nakamura, N. Yamamoto, J. Sawamura (2015) Proc. ISOPE2015, paper ISOPE-TPC-1657], we reported that rainflow counting may substantially underestimate the fatigue life of welded joints when the high frequency superimposition occurs intermittently. I hope that this problem is discussed in ISOPE2018 III.2 committee report

### *1.2.3 Per Lindström (Consultant Marine & Welding Engineer)*

May please consider to include/mention the new weld inspection standard ISO 5817:2014 that by the introduction of the weld inspection classes in Annex C, now make it possible for a designer to define critical weld joints' fatigue class (FAT) from the very first beginning on the design drawing.

When it comes to weld joint S/N-curves it is well known that they heritage from a large number of test data obtained from "typical weld joint geometries". Anyhow for the time being are they not reflecting the influence of the used steel plate material's delivery condition (or the base materials' delivery condition). There for example a DH-36 steel plate can be delivered in the following conditions: As Rolled, Normalized Rolled, Normalized, Thermo-Mechanical Process Rolled, Quenched and Tempered. Furthermore, It is known that the actual WPS (Welding Procedure Specification) used will affect the mechanical properties in the HAZ (Heat Affected Zone) and the weld residual stress distribution in the WRAZ (Weld Residual Stress Affected Zone). Do you believe that there is a significant fatigue life time difference between the different delivery conditions when welded by an identical WPS?

### *1.2.4 Wolfgang Fricke (Germany)*

The Committee discusses very well the new fatigue assessment approaches based on the notch stress intensity factor (N-SIF). It is stated that the approach can be regarded as in between the notch stress or notch strain based approaches and the rather more complex crack propagation approaches. However, I see only similarities between the new N-SIF approaches and the notch stress approach. Indeed, there is a strong correlation between the stress in a relatively sharp notch and the notch stress intensity. Insofar I do not fully understand the Committee's statement and like to hear the reasoning for this.

## 2. REPLY BY COMMITTEE

### *2.1 Response to the Official Discussion*

The Committee is extremely grateful to Prof Sumi for a thorough and thoughtful discussion and is pleased with his comments, in particular "…*the well balanced coverage of the topics and also for the good continuation of the context of the committee reports on fatigue and fracture*" We are especially pleased that in this vast subject area Prof Sumi believes that the Committee has properly condicted it review covering all the subjects given in the mandate.

Prof Sumi has provided significant additional insights and references to various aspects of the subject area, addressing these in turn:

> *"Regarding the failure definition, some keywords may be added for the identification of the levels of failure such as "incident," "loss of serviceability," and "catastrophic failure," in which consequences of such failures and the corresponding possible counter-measures could be rather different. The Official Discusser appreciates if the Committee is kind enough to reply to this comment."*

The committee agrees and is grateful for these additional suggested keywords.

With respect to the comments relating to UR S33 namely: Unified Requirements for Use of Extremely Thick Steel Plates and applied by International Association of Classification Societies (IACS) to ships contracted for construction on or after January 2014 with respect to inspection of extremely thick steel plates used in hatch coaming structure after delivery and its timing. We comment that according to GL-rules I-1-5a periodic NDT other than visual inspection may be requested at the discretion of GL and Intended for only in cases where cracks are already detected by visual inspection and consequently further smaller cracks may also exist.

> Prof Sumi comments: *"In the Committee report, the rainflow method is said to be still the most popular technique in the analysis of random fatigue data. With regard to the stochastic loading, the effects of load sequence, especially the (vibratory) whipping stress superimposed to the quasi-static wave-induced stress are discussed by introducing the results of several references. It seems that some of the results confirm the validity of the rainflow analysis while the others not. The Committee is kindly requested to clarify the range of applicability of the method based on the loading parameters involved in the slam-induced whipping."*

The committee has not specifically considered this scenario and agrees that it needs to be reviewed in detail. We recommend that the 2015-2018 committee addresses this important issue.

We have also been asked to respond to the mechanism of brittle crack propagation along a butt-weld, i.e.; the conditions which distinguish the propagation along the fusion line and that into the base metal.

Our response is that the following parameters influence the crack path along butt-welds:

- Residual stress distribution;
- Design issues e.g. Stiffener location and slots etc.;
- Crack resistant material;
- Toughness values (under or overmatching);
- Breath of the heat affected zone (HAZ);
- Weld preparation (inclined or retangular weld angle).

The figures below identify the key regions pertinent to this issue.

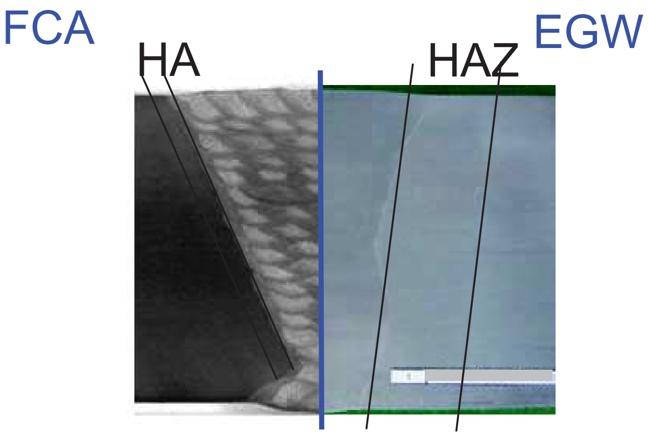


Figure 3: Weld Macros illustrating differing Heat Affected Zones for different welding processes.

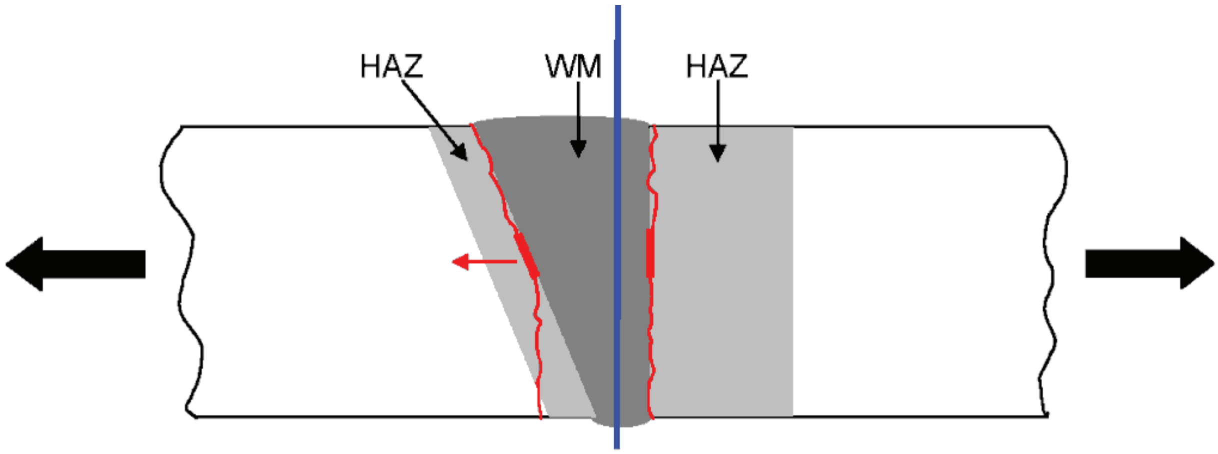


Figure 4: Likely Crack Paths depending on weld preparation detail.

The question of crack propagation mechanism is complex and dependent on a range of parameters as illustrated above.

> Prof Sumi states *"…the effects of load sequence are of interest in recent studies of fatigue strength evaluation, which cannot be analyzed by damage models. Cyclic plasticity ahead of the growing crack tip and the plastic wake on the crack surfaces play important roles in the problems, but they are not properly accounted for by the conventional Paris' law. In order to predict the effects of load sequence such as variable load ratios, tensile overload followed by retardation, compressive underload followed by acceleration, and random loading, a certain micromechanical model could be introduced at the growing crack tip. The Official Discusser would like to see how the Committee outlooks this issue."*

The Committee agrees this can be important in extreme cases and would expect that local methods e.g. N-SIF might hold the key to addressing this in the future.

Prof Sumi expresses that from his personal perspective that the report cites few references reporting practical applications especially to the on-board measurements of ships and defect-detection systems relevant to fatigue analyses in service condition.

The committee agrees this is a vital area however the previous committee report (ISSC III.2 2012-2015) included a significant review of such monitoring systems and the current V.7 (Structural Longevity) Report contains an extensive section dealing with current developments in sensor and monitoring systems and their application to fatigue damage evaluation.

### *2.2 Response to Shengming Zhang*

We thank Dr Zhang for her comment. Our report states that literature discussion on fatigue testing at low temperature is scarce; especially limited data are reported on the fatigue behaviour of weldments.

We emphasise in the report that available studies suggest that *"low temperatures can have both a positive and negative effect on fatigue resistance, depending on the specific load conditions. Evaluations of fatigue take into account both the toughness and strength of the material."* It is therefore entirely consistent that there may be some differences between the behaviour reported by Walters on base material grade S980 and S440 compared to that reported in references [A] and [B] above.

## *2.3 Response to Naoki Osawa*

We are grateful to Prof Osawa for this observation and we too recommend that Rainflow Cycle Counting be revisited during the next committee and considered in the report in particular to its application to large container ships.

## *2.4 Response to Per Lindström*

Dr Lindström helpfully adds reference to the new weld inspection standard ISO 5817:2014, the publication of which was too late for inclusion in the main report. In particular the introduction of the weld inspection classes in Annex C, which Dr Lindström explains now makes it possible for a designer to define critical weld joints' fatigue class (FAT) from outset on the design drawing.

In response to Dr Lindström's question whether we believe that there is a significant effect on fatigue life-time due to the different parent material delivery conditions when welded by an identical WPS, we respond absolutely, but that historically tests incorporated into design standards of safety-critical applications tended to test the worst-case but agree with Dr Lindström's allusion that better definition of delivery state coupled with detailed WPS of both specimens for fatigue testing (and hence resulting design guidance) and within detailed designs is imperative to avoid unconservative fatigue predictions.

## *2.5 Response to Wolfgang Fricke*

The Committee agree with Prof Fricke's comment that the N-SIF (and other associated parameters) is strictly related to the stress at the tip of a sharp notch. It is also agreed that the strain in way of a sharp notch cannot be directly related to N-SIF. Moreover, while the notch stress approach and the N-SIF based approaches assume elastic material, notch strain approach accounts for elasto-plastic effects, especially relevant in low cycle fatigue.

However, it can be stated that engineering efforts and complexity in fatigue assessment increases from left to right in Fig. 26 of the Comittee Report e.g. cyclic stress–strain curve of the material and rather complex nonlinear analyses are required to apply the notch strain approach, possibly distinguishing parent material, heat affected zone and weld metal in case of welded joints.

On the other hand, the notch stress approach is based on a conventional value of stress, obtained by suitably averaging the stress field to account for the micro-structural support effect, while the notch strain approach overcomes the problem switching from stress to strain but in practice still the Neuber's rule (or a similar one) is applied. Hence, the notch strain approach is seen as an advancement from the notch stress approach, even if it cannot be directly related to the N-SIF based approaches.

Substantial analogies between the fracture mechanics and the definition of N-SIF eventually justify the place of N-SIF based approaches inbetween notch stress and strain approaches and the crack propagation approach. Finally, a classification of fatigue assessment approaches has been proposed in Fig. 26 aiming to clarify the presentation of the methods most recently proposed.