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VOLUME 3

COMMITTEE III.2

# FATIGUE AND FRAGTURE

## COMMITTEE MANDATE

Concern for 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.

## CONTRIBUTORS

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# 1 DISCUSSION

## *1.1 Official Discussion by Giorgio Bacicchi*

### *1.1.1 Introduction*

I accepted with pleasure the Standing Committee request to discuss the Committee III.2 report for the following reasons:

- having been active member of three different ISSC Committees (from $11^{th}$ to $13^{th}$) between 1991 to 1997
- considering, on the basis of my personal experience, that the fatigue limit states are the most critical and challenging for a structural designer
- being interested in getting updated information about the latest developments in the subject both from the theoretical and practical point of view.

Having been for about 30 years responsible of the structural department of a major Italian shipbuilding company and being at present responsible of the Basic Design Department in the same company, I have always been convinced that fatigue problems can be greatly reduced in a ship and offshore structure:

- through a proper general design configuration paying attention to the possibility of achieving continuity and tapering of structural elements
- through a careful design of structural details based on proven experience
- by an adequate selection of different steel grades.

Nevertheless I have always been looking with interest at the new developments of new procedures for fatigue assessment paying however more attention towards those methodologies which had been calibrated by experimental work and seemed to be more practical in the application to a new design.

The present Committee did a great job in reviewing more than 200 papers and reporting about the developments of the latest 3 years in the:

- Fatigue Assessment Methods
- Unstable Crack Propagation
- Advances in Materials and Structural Details
- Damage Control and Risk-Based Assessment
- Design Methods for Ships and Offshore Structures.

In addition an interesting and extremely significant case study has been reported in the area of stress multiaxiality.

My discussion will generally follow the sections numbering of the Committee report with more attention and comments to the subjects which, from my own perspective and experience, seem to be the most relevant.

### *1.1.2 Recent Developments in Fatigue Assessment Methods*

Most of the fatigue problems in ships structural details are occurring in my experience in the first years of service life (about $10^4$ cycles): the recommendations given by Lotsberg (2010a) to assess low-cycle fatigue together with the ultimate limit state are shared and should be properly addressed by all Class Societies. In new designs, in order not to increase fabrication costs, ideas of new structural details, not always covered by available codes and tests, have sometimes to be evaluated. In these cases, the time available is normally not compatible with conventional fatigue tests: the thermographic method presented by Crupi *et al.* (2009, 2010) is a very quick approach to determine the fatigue limit and the entire S-N curve and has been successfully used

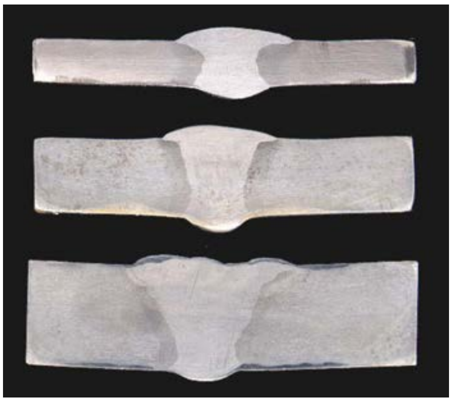

Figure 1: Macrographic cross sections of welds

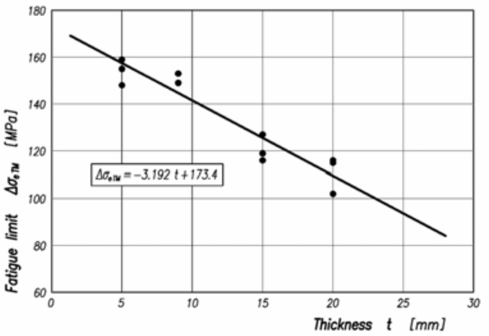

Figure 2: AH 36 steel butt-welded joints: Fatigue limit vs. thickness

also by my company proving that it is consistent with the conventional S-N approach given by IIW code. This method has all the characteristics to be considered as a valid and efficient alternative for quick fatigue tests.

Multiaxial stress states are rather common in ship structures especially in cases where important shear stresses are simultaneous to normal stresses. Although the problem of failure mechanism in mutiaxial fatigue has been continuously investigated and several criteria have been developed also in the recent years, a general applicable criterion is not yet available especially in relation to variable amplitude loading (see also the case study in Section 7). Further research work is therefore needed together with calibration by tests.

With reference to factors influencing fatigue, recent developments have been reviewed considering thickness, corrosive environment and temperature, CA and VA loading, residual stresses and mean stress.

Worth to be mentioned are the experimental results which show an increase of fatigue strength with decreasing thickness down to $3\,mm$. Although in contrast with the conclusions of the previous ISSC Committee III.2 and not yet considered by the present codes and Class Rules, the indicated tendency is also in line with the results observed in tests which have been commissioned by my company. These tests were carried out with the thermographic method on specimen of thickness ranging between 5 and $20\,mm$, applying axial cyclic loads at a frequency of $20\,Hz$ and with a stress ratio $R = 0.5$. The test pieces were AH36 steel butt-welded joints (full penetration), common for ship structures, having thicknesses of 5, 9, 15 and 20 mm (see Figure 1).

The fatigue limits, assumed as the stress ranges at $5\text{x}10^6$cycles, were predicted by test results quickly obtained with the thermographic method and compared to the corresponding limits calculated by the traditional procedure based on S-N curves obtained according to the ASTM E 739-91 Standard. The regression analysis performed on the experimental results showed a clear trend: the fatigue limit was increased by more than 40 % when thickness varied from 20 to $5\,mm$ (see Figure 2).

As for new cruise and RO-PAX vessels the thickness reduction is becoming a design target and recent hybrid welding technologies associated to an increased fabrication accuracy are allowing this trend, further experimental work is advised to confirm the positive effect of lower thickness in the fatigue strength, even if in relationship with fabrication accuracy.

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Developments in the definition of theoretical models for simulating fatigue crack initiation are reported considering both mesoscale (based on crystal plasticity) and continuum based models. Although these research works are aiming to increase the understanding of a crack forming, they seem however to be not yet mature to produce practical consequences.

Several recent papers have been dealing with crack growth assessment methods and models. Generally speaking, Paris law has been considered to give a reasonable estimation of the fatigue propagation life while crack initiation depends on the local notch stress. Some attempts are presented to remove the necessity of computing the stress-intensity factor for complicated geometries. References to experimental data and to practical structural details, which are often reported, are appreciated.

For strain-based designs (with stresses above 0.5% strain) extensive studies are reported together with results of full-scale tests.

### *1.1.3 Unstable Crack Propagation*

The interest towards both brittle and ductile crack propagation is confirmed by the high number of recent developments in this field. This seems at present to be a topical subject due to the growing interest in design of new offshore structures for service in arctic regions and to the use of very thick steel plate for large containerships.

Extensive research has been done:

- in the standardisation of tests concerning crack arrest toughness, confirming CTOD as the most appropriate parameter and recognising the influence of constraint effects on fracture toughness
- in the evaluation of the effects of welding residual stresses in brittle fracture initiation although quantitative results are limited
- in the development of standard test methods for brittle crack toughness $K_{ca}$ of steel plates.

However more interesting and practical are the results of the large scale tests made by Japanese researchers to investigate the behaviour of dynamic crack propagation and arrest for a typical hatch side coaming / strength deck welded connection of a containership, establishing at the end some guidelines to prevent brittle fracture. They concluded that a $K_{ca}$ of $6{,}000\,N/mm^{3/2}$ is required for the structural elements and that a $300\,mm$ shift is recommended between butt welds of the two elements or, as an alternative, an area of unwelded breadth had to be provided. All these research works are confirming that the prevention of brittle fracture initiation and propagation can be achieved both with an improvement of crack arrest toughness of steels and with an improved weld geometry and reduced residual stresses.

### *1.1.4 Advances in Materials and Structural Details*

The use of high strength steel to reduce weight and welding time has become normal practice and consequently the definition of the effects of yield strength on crack growth rate and on fatigue life is gaining increased interest.

Common fatigue design codes are not considering the influence of materials yield strength on fatigue. However steels produced by TMCP and microstructural control, recognised by Class Societies as FCA (fracture crack arrester) steels, have been subjected to several recent tests, confirming that they can guarantee an increased fatigue life compared to conventional strength steels. For sure, the use of this steel can provide a new alternative for fatigue life improvement. Moreover, on the basis of fatigue

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testing, a new design S-N curve has been proposed for FCA steels, concluding that the fatigue life could be increased by a factor of 3 for a typical ship structural detail subject to typical long term stress range. Additional testing is recommended to confirm the above conclusion and to consequently allow Class Societies to recognise the positive effect.

With reference to materials necessary for structures susceptible to brittle fracture (designed for instance for service life in the Arctic regions) limited recommendations are available for materials selection and structural design: therefore, development of new guidelines is recommended.

In the subsection referred to honeycomb structures, information concerning fatigue behaviour is missing and in general no "advance in structural details" (as mentioned in the title) is reported. Future Committees are recommended to collect data and reports on the possible development of new details, designed to improve the fatigue life.

### *1.1.5 Damage Control and Risk-Based Assessment*

This section, discussed for the first time by the Committee III.2 report, is dealing with uncertainties in fatigue assessment from the design phase to the fabrication and to the service life.

In the first subsections new developments are reviewed with regard to the effects of workmanship, of weld quality and of internal defects, of welding procedures, of fatigue improvements methods and of NDE testing associated to the probability of detection of defects.

To produce a final structure consistent with the assumptions done in the design assessment of fatigue life, the welding process requires a high level of control in all the production phases: from the panels construction to the blocks prefabrication, from the blocks assembly into hull sections to the final assembly of sections in the drydock. In the initial phases, automatic welding processes are mainly used and thus the management of spot checks by NDE along the building process is normally sufficient to guarantee a constant weld quality. In prefabrication and fabrication of blocks and sections, visual inspection is required as normal practice together with "in phase" controls by RX (according to Class) and extended UT (normal or phased array) for butt joints and MT controls for fillet joints. The fatigue life of a welded joint is highly dependent on the local stress concentration that arise from the geometrical deviations and weld discontinuities (either embedded or at the surface) introduced during fabrication process. Geometrical imperfections could be misalignments, angular distortions, excessive weld or poor wed shape. Weld discontinuities are weld toe undercuts, cracks, overlaps, porosities, slag inclusions, lack of fusion/incomplete penetrations. Default values are given by rules for fabrication tolerances while the proposed S-N curves are assumed as inclusive of the weld discontinuities relative to the so-called normal workmanship. Although the presence of cracks and lack of fusion is more critical for a weld and these defects are to be corrected when exceeding acceptable values, on the contrary, the presence of embedded discontinuities like porosity and slag inclusion is less dangerous.

Nevertheless, being the present acceptance criteria defined with reference to limiting dimensions of defects of a certain percentage of thickness, in case of welding thin plates ($5 \div 6\,mm$), according to these criteria almost any defect of this kind should be corrected. To assess the effect of the presence of porosity and slag inclusion on the fatigue life of a butt weld, a comprehensive series of fatigue tests has been commissioned by

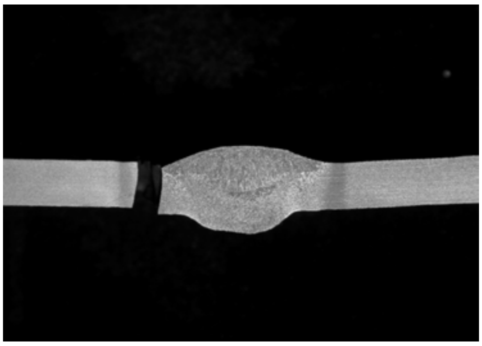

Figure 3: Specimen without defects

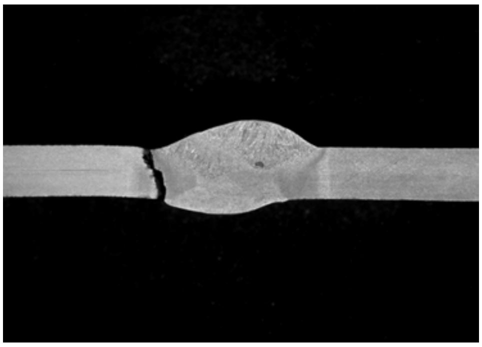

Figure 4: Specimen with slag inclusion

my company. The specimen ($5.5 \div 7\,mm$ thick) were taken from pieces cut from a ship under construction, containing either sound butt welded joints or with weld defects exceeding class limits. The results of the fatigue tests can be summarised as follows:

- for both categories of specimen, with or without defects, the failure mechanism was similar, starting in way of HAZ (see Figures 3 and 4)
- the fatigue tests have been carried out both with the traditional method and with the thermographic method
- elaborating test results according to IIW Fatigue Recommendations, the relevant S-N curves have been calculated (see Figures 5 and 6), deriving a detail category of $69.3\,MPa$ with the traditional method and of $71.5\,MPa$ with the thermographic method, with reference to a theoretical value of $71\,MPa$ (according to GL).

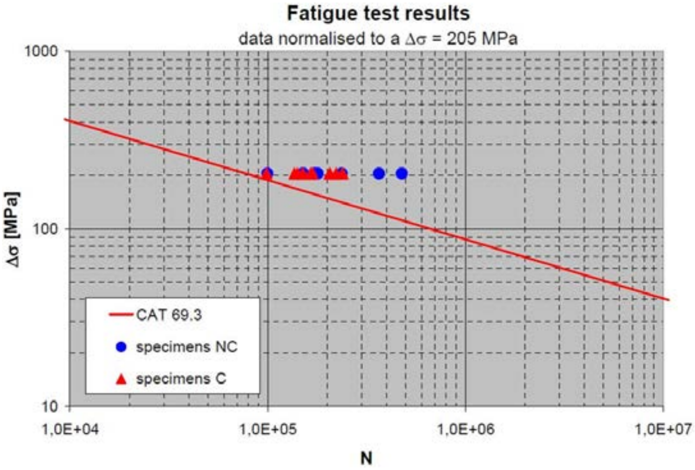

Figure 5: S-N curve from tests by traditional method

The conclusion was that the defects included in the examined welded joints had no influence in fatigue behaviour and strength. Further fatigue tests on specimen including weld defects of limited influence (i.e. porosity and slag inclusion) should be carried out in order to provide more results to support modifications of the present acceptance criteria concerning weld discontinuities.

Another subject to be addressed regarding the Class acceptance criteria of weld quality is that they completely disregard ship redundancy and margins in fatigue life calcu-

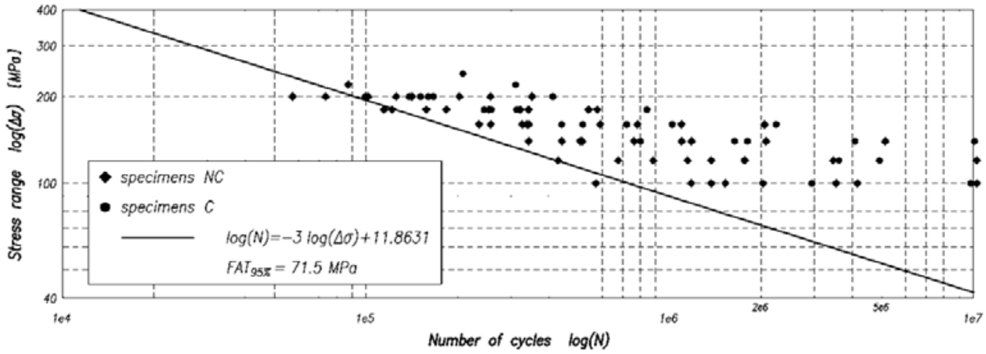

Figure 6: S-N curve from tests by thermographic method

lations. Traditional merchant vessels (tankers, bulkers, containerships) have lower redundancy in the longitudinal strength, if compared to a cruise vessel or a ro-pax vessel and, in the definition of the required number of check points and extension of NDE, reference should be made to the safety margin between the design stress range in a certain location and the corresponding allowable stress range. By these adjustments a constant safety could be guaranteed to structures of different types of vessels, avoiding to require corrections of welds which are not critical either for the limited design stress range or for the type of weld imperfections included.

With reference to the different uncertainties associated with fatigue life prediction, the reported studies concerning reliability and risk assessment, although interesting from a theoretical and scientific point of view, seem in general not to provide practical application except for the FORM/SORM technique based on the S-N approach.

Finally the information given on the problem of ageing ships and offshore structures seem really alarming for the dimension of the problem and its economical implications. The fact that important authorities are involved in defining requirements for Lifetime Extension of aged structures seems not sufficient to guarantee that priority will be given to safety rather than economical aspects. Engineering work should be commissioned to independent companies and the relevant authorities and class societies should support the required repair and improvement measures imposing obligations to owners.

### *1.1.6 Design Methods for Ship and Offshore Structures*

This section is giving a complete overview of the recent developments in fatigue design methods and codes for ships and offshore structures and can be considered as an important and updated reference for designers.

With reference to CRS, the main differences in fatigue assessment between the present rules for Oil Tankers and Bulk Carriers are highlighted in view of the future Harmonized CSR-H which, including the recommendations of the IMO GBS and the experience so far collected in the present rules application, are scheduled for publication in 2014.

Guidelines are reported for fatigue assessment including springing and whipping effects which for some ship types are becoming an important issue.

References are given for fatigue assessment rules and codes dealing with risers systems, pipelines systems, FPSO installations and in general offshore steel structures.

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Due to the increased interest of the industry towards Arctic regions, new guidelines and procedures have been issued by Class Societies to specifically include ice loading and fatigue acceptance criteria for ships (Ship Right FDA ICE of Lloyd's Register of Shipping) and dynamic ice-structure interaction for fixed structures (ISO 19906).

### *1.1.7 Case Study*

The proposed case study is very important in underlying the uncertainties of fatigue assessment procedures in presence of a multiaxial stress field and in calling increased attention of researchers towards a more reliable definition of methods to deal with stress multiaxiality. The idea of this case study and the relevant information have been supplied by my company's designers as one of the most significant example of multiaxial fatigue in a weld seam subject to parallel, normal and shear stresses.

In the superstructure of a cruise vessel the outer longitudinal bulkhead is one of the few longitudinal elements carrying shear forces from the lower hull to the upper decks and is commonly designed with repetitive openings to access from internal cabins to the external balconies. For this reason this bulkhead is normally continuous from a certain intermediate deck to the uppermost continuous deck. However sometimes, as in the proposed case due to production reasons, this bulkhead is interrupted by each deck which is passing through it although with a thickness which is about one half of the bulkhead thickness. Due to hull girder bending, amidships mainly longitudinal stresses are present in the bulkhead elements which are longitudinally continuous , while in the areas around $0{,}25\,L$ and $0{,}75\,L$, in presence of important hull girder shear forces, the vertical elements of the bulkhead develop an "S" deformation producing shear and normal stresses at its upper and lower ends which add to the longitudinal stresses consequent to the hull girder bending moment (see Figure 7). These stresses, which are higher above decks where the lower edge of the opening in way of the radius is closer, are transferred from the upper to the lower vertical element through a weld seam which is full penetration in the critical areas. Stress ranges producing fatigue are consequent to the difference between hogging and sagging wave. Longitudinal stresses are due to the vertical wave bending moment while normal and shear stresses are consequent to wave shear forces. The IACS formulations, which have been followed, establish along the hull girder the envelope of the maximum wave bending moments and shear forces which are not necessarily simultaneous at each frame. In the report there is no evidence of the adjustments which are required on the values of bending moments and shear forces before adding effects which are only partially simultaneous. Moreover in the case study, aiming to compare different approaches in fatigue assessment connected to multiaxial stresses, no misalignment has been considered between upper and lower vertical elements avoiding to increase the stresses by a concentration factor and thus remaining far from practical shipbuilding standards: in reality the structural detail has been built with a maximum misalignment of $2\,mm$ (0,17 x bhd. th.) in the critical areas (see Figure 8).

To calculate the local stresses on which the subsequent fatigue assessment has been carried out:

- an hierarchic modelling from the complete hull girder FE model to the sub-sub model of the cruciform joint has been performed with proper mesh sizes
- 2 hot spots have been selected both on longitudinal bulkhead and on deck, located, as expected, in way of the lower corners of the bulkhead openings
- the hot spot stress approach has been used as the most adequate.

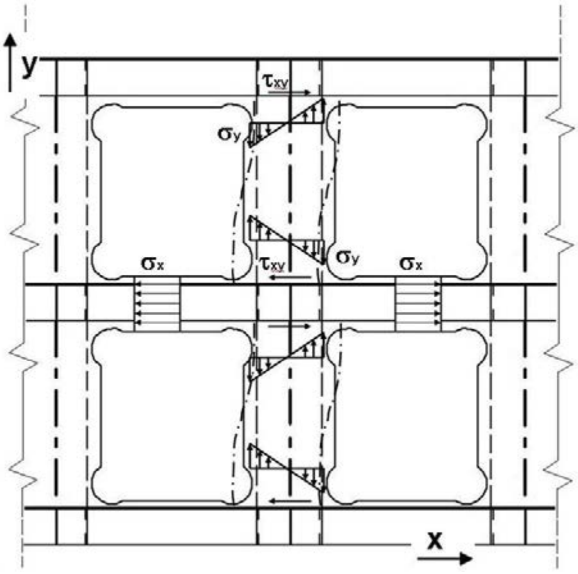

Figure 7: Stresses on the bulkhead

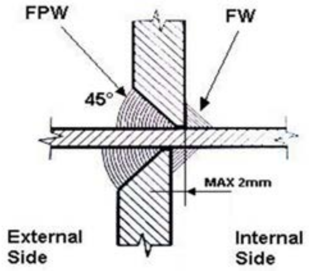

Figure 8: Weld detail

To take into account stress multiaxiality in a load-carrying weld, different formulations propose two ways: either by a reference principal stress or by the single components of the stress tensor ($\sigma$ normal to the weld, $\sigma$ parallel to the weld and shear $\tau$ parallel to the weld).

With regard to cumulative damage calculations and to fatigue life prediction, where long term wave loads are involved, all the methods:

- refer to a design life of 20 years ($10^8$ cycles) limiting to 1 the accumulated fatigue damage
- consider a simplified statistical approach assuming the stress ranges distributed according to a Weibull probability density function
- usually refer to a one-slope S-N curve (as normally designers would do) or to a two- slope S-N curve (as in the case study).

Traditional procedures given by Class Societies guidelines (GL, CSR BC, CSR OT, KR) do not take into account parallel stress to assess fatigue life of a welded joint and in this way the fatigue damages, calculated for the case study, are approaching a zero value. Among the Class Societies only DNV, in the Classification Note 30.7 of 2010, emphasizes the effect of the parallel stress either by a traditional method or better by an enhanced method which considers the maximum principal stresses approach and allows to obtain cumulative damages which seem to be more reasonable. The same DNV Classification Note, although in a previous release, has been used as a reference by the designers who supplied the structural detail for the case study. They assessed the detail on the basis of the addition of the cumulative damages produced by both the parallel and the normal stresses. In addition to DNV, also some IIW guidelines and some research works are indicating how to deal with multiaxial stress fatigue through maximum principal stresses or by summing the effects of shear and of normal stress or by referring to a resultant stress range: the application of these guidelines to the case study entail sometimes cumulative damages even exceeding the allowable limit for the longitudinal bulkhead.

The following conclusions can be derived:

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- in general the contribution of shear stresses is rather insignificant
- in general Class Societies approaches do not consider the effect of parallel stress converging towards a zero risk for both hot spot locations
- only DNV and some additional guidelines consider the effect of stress biaxiality in front of the weld. The calculated cumulative damages is low for deck hot spot, where the maximum principal stress is parallel to the weld toe line, while it is higher for bulkhead hot spot, where the principal stress is acting at about 30° to weld toe line
- the great divergence between the presented results is giving a clear evidence of the fact that fatigue problems in case of multiaxial stresses need further research supported by experimental work. More reliable procedures should be defined hopefully with the agreement of different regulatory bodies and Class Societies and at the same time these procedures should become more practical for designers' application.

Finally and luckily, notwithstanding all the difficulties involved in the fatigue assessment of the case study, the structural detail to which the case study is referred, has been used in a 90,000 $GT$ cruise vessel which has been designed for worldwide navigation and is sailing with positive service experience since the delivery in 2007.

### *1.1.8 Conclusions and Recommendations*

As highlighted along the sections of my discussion, the Committee report has properly covered all the subjects given within the mandate. A large number of interesting references is addressed and can be further studied by the persons who are interested to increase their knowledge in the recent developments on Fatigue and Fracture. Nevertheless, from my experience of designer, too few publications are written including practical application examples of the theoretical developments in the field and only in some cases theoretical works are supported and calibrated by experimental data. Fatigue life predictions are clearly associated to a certain number of uncertainties and any theoretical work contributing to reduce uncertainty, by producing more reliable and practical fatigue design procedures, would increase the confidence of designers in assessing fatigue as a normal design practice and would generally improve the structural safety. I have therefore to encourage researchers and people from different organisations and class societies, interested in fatigue assessment of ships and offshore structures, to think to designers' necessities adding practical examples and experimental calibration to any theoretical work.

With reference to possible recommendations for future Committees on Fatigue and Fracture, I summarise hereafter the comments already anticipated within the different sections of my discussion:

- additional fatigue tests are required to confirm the tendency of increasing fatigue strength with decreasing plate thickness
- additional fatigue tests are required to confirm the fatigue life improvement with the use of steels having Fracture Crack Arresting capabilities
- additional fatigue tests are recommended on weld details including discontinuities like porosities and slag inclusion in order to reassess the acceptance criteria of weld defects particularly for plates of limited thickness
- acceptance criteria of weld defects should be also revised to take into account the margin between design and allowable stress range
- guidelines are recommended for materials selection and structural design of ships and offshore structures designed for operation in very cold environments

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- guidelines are recommended for updated structural details, revised for fatigue life improvement, to support designers
- further research is needed in the field of multiaxial stresses defining the most appropriate approach and calibrating the theories with experiments in order to provide more reliable and practical fatigue assessment procedures.

#### *1.1.9 References*

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### *1.2 Floor and Written Discussions*

#### *1.2.1 Bart Boon*

The normally used design curve for fatigue is based upon the mean fatigue life minus twice the standard deviation. This means that any structural detail (theoretically) has maximum only 2.5% chance of failing during the life of the ship.

Presently the use of composite patches to prolong fatigue life is studied quite a bit.

What is the opinion of the Committee on the potential of such patches? Could they allow a higher risk of fatigue cracking provided that patches will be used when such a crack occurs?

#### *1.2.2 Tetsuya Nakamura*

In this report, peening approaches such as UIT have been mentioned as one of the fatigue improvement methods. I think these techniques are very cost-effective. However, in order to ensure peening is effective during the life of the ship, the compressive residual stress introduced by the peening must be maintained. From this point of view, I would like to make two questions. First, the compressive residual stress may be reduced by variable wave-induced loads. Do you think we have enough experimental data to guarantee the peening effect?

Second, it is about the peening procedure. It is difficult to confirm that compressive residual stress is introduced to the welded joints after performing the peening. What's your opinion with regard to this matter?

#### *1.2.3 Cesare M. Rizzo*

First of all, I would like to congratulate the Committee members for putting on the table some new issues that were not comprehensively dealt with by the previous Committees on Fatigue and Fracture. Significant advancements are reported. It means that the shipping industry is now ready to introduce somehow more complex fatigue assessment methods. Namely, multiaxial fatigue is still an open issue and matter for researchers. However, the report addresses the subject referencing a few multiaxial

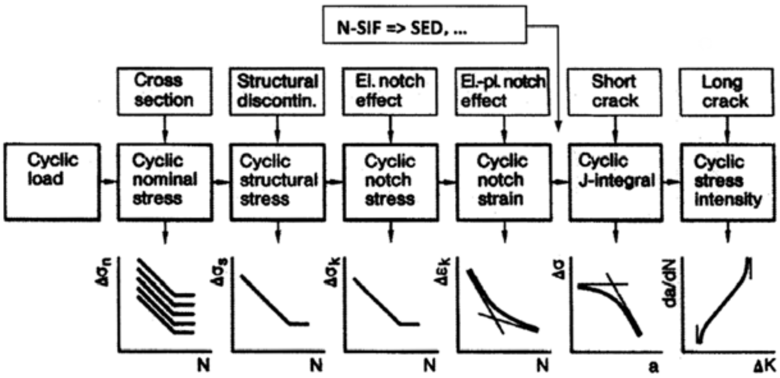

Figure 9: New fatigue assessment approaches added to the well-known figure reported in Radaj *et al.* (2006)

fatigue assessment approaches currently proposed in the literature and by guidelines of international bodies like the International Institute of Welding.

However, I would like to offer a small comment about assessment methods for multiaxial fatigue and the opinion of the Committee about this outlook would be very much appreciated.

Recently, a few novel approaches appeared in the literature and some of them are based on “energy concepts”, i.e. those methods are assuming the deformation energy as the fatigue strength governing parameter. Actually, these new approaches may overcome at the root the multiaxial fatigue problems.

Indeed, it appears from recently developed researches (see ch. 7 of Radaj *et al.* 2006) that such methods represent the link between the stress or strain based approaches (e.g. the notch based approach) and the relatively complex crack propagation method (Fig. 1). In fact, it was demonstrated that the notch stress intensity factor in an open notch (N-SIF) is related to the strain energy density (SED) in a volume of the material, see Lazzarin and Zambardi, 2001).

While several questions are still open for the application of such N-SIF or energy based approaches to geometrically complex ship and offshore structures, it is believed that such methods can fulfil the needs of the shipping industry since their application can be easily automated in numerical analyses but at the same time their background is based on fracture mechanics concept. As a matter of fact, one can remember that the J-integral parameter used in fracture mechanics is basically an energy.

### *1.2.4 Ilson Pasqualino*

Some issues related to fatigue have not been covered by the report. Fatigue under corrosion, under contaminants ($H_2S$, $CO_2$) or in damaged structures.

The review should be extended to composite structures, other materials for naval and offshore application and cladded linepipes.

The report did not mention the development of non-destructive techniques for fatigue damage evaluation like X-ray diffraction method.

### *1.2.5 Weicheng Cui*

I have two brief questions. First, unstable fracture is basically the last stage of crack propagation which is not allowed from fatigue point of view. Why did your committee

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decide to emphasise this stage? Second: from your point of view, what are the physical quantities to decide unstable fracture?

### *1.2.6 Fang Wang*

Unstable fracture is not important for commonly-used materials in normal conditions, but is significant for materials used in cold climates. How to determine the critical condition for unstable fracture is a problem. We always use static fracture toughness to replace fatigue fracture toughness, as the testing of fatigue fracture toughness is quite difficult. However, even the current testing method for static fracture toughness is facing challenge, especially the size criterion related to thickness. Could you give some comments on thickness and crack form effect on fracture toughness as the critical condition of unstable fracture?

Crack growth rate model is important for the fatigue assessment based on fracture mechanics. In the past 20 years there are many improved models proposed but most of them are based on cycle-by-cycle integration. That means the accuracy of calculation results is determined by counting method of cyclic stresses. In my personal opinion, if we would define the model by da/dt in time domain, the problem will be solved. The driving force can be expressed by stress and life integration can be done inside each stress cycle which would solve the problem brought by traditional loading cycle counting method. Could you please give some comments on that?

### *1.2.7 Wolfgang Fricke*

Regarding the case study, it has simply been overlooked that in the weld considered two types of cracks are possible, (a) parallel to the weld line and (b) perpendicular to the weld line. Crack (a) may be assessed with the structural hot-spot approach, but crack (b) requires the assessment with the nominal stress approach with a fatigue class of FAT 90 -100 according to various catalogues of notch conditions. This would lead to much higher damage sums than given in the report. Insofar are the results misleading. A comparable situation exists, by the way, for cruciform joints with non-penetration welds, where also two crack types have to be assessed, one starting from the weld toe and the other from the weld root.

A closed form assessment based on the multiaxial stress state would of course be helpful, but is not unproblematic due to the different fatigue behaviour, calling for simplified assessments mentioned above.

The Official Discusser showed the "thinness effect" by a graph where the fatigue strength of butt joints steadily increases with decreasing plate thickness. This is in contrast to findings in a German joint industry project where specimens with butt welds from block joints were fatigue tested showing a decreased fatigue strength of 4 mm thick specimens compared to 6 and 9 mm thick specimens, see Figure 10. This was even true if the results are based on structural hot-spot stress which already includes secondary bending stresses due to misalignments. I would like to hear the opinion of the Committee about such contradicting results and possible factors affecting them.

### *1.2.8 References*

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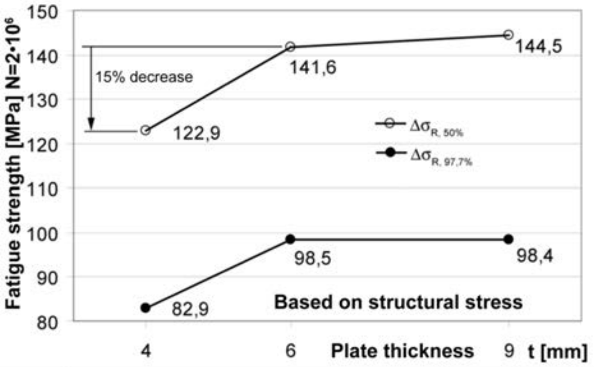

Figure 10: Mean and characteristic fatigue strengths found for block joints with thin plates (Feltz and Fricke, 2011 and 2012)

Feltz, O. and Fricke, W. (2012): Consideration of influence factors between small-scale specimens and large components on the fatigue strength of thin-plated block joints in shipbuilding. Doc. XIII-2418-12, International Institute of Welding

Lazzarin P., Zambardi R. (2001). A finite-volume-energy based approach to predict the static and fatigue behaviour of components with sharp V-shaped notches, Int. J. Fract. 112:275-98.

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## 2 REPLY BY THE COMMITTEE

### *2.1 Reply to Official Discussion*

The Committee would like to thank the official discusser Mr. Giorgio Bacicchi for his effort and kind contribution to the assessment of the Committee Report. The Committee appreciates Mr. Giorgio Bacicchi valuable and inspiring comments which we will try to answer in the following. The discusser also provides valuable supplementary contributions to the contents, including some interesting and important additional references and also suggests some essential future topics for the Committee to study within fatigue and fracture. These recommendations for further work is highly appreciated by the Committee, and will be studied and discussed in the ISSC 2015 report as far as possible based on available publications of these topics and the members' interest.

#### *2.1.1 Recent Developments in Fatigue Assessment Methods (Chapter 2)*

The Committee agrees with Mr. Giorgio Bacicchi comments that it is important to assess low-cycle fatigue together with ultimate limit state and this should be properly addressed by all Class Societies. The committee finds it interesting to note that the thermo graphic method in order to establish fatigue S-N data has been used successfully by Mr. G. Bacicchi‘s company and that the results obtained are in-line with the conventional S-N approach given by IIW code.

The Committee agrees that the developments in the definition of theoretical models for simulating fatigue crack initiation like mesoscale and continuum based models are not yet mature to be applied to practical applications and further research is needed. The Committee agrees that a general applicable criterion is not yet available for multiaxial fatigue especially in relation to variable amplitude loading and should be addressed

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further. Today some valuable guidance can be found in e.g. IIW design code (2009), Hobbacher. The Committee notes the increased fatigue strength obtained for thin plates presented by Mr. G. Bacicchi. However, further research is needed in order to investigate the applicability of the notch stress approach to the plate thickness below 5 mm in order to develop a sound basis for fatigue assessment of thin ship structures, see also comments by Prof. Fricke in section 2.7 and the Committee repay in section 3.2.7.

#### *2.1.2 Unstable Crack Propagation (chapter 3)*

The committee values Mr. Giorgio Bacicchi's interest and the importance of the research within brittle and ductile crack propagation presented in chapter 3 of the report.

#### *2.1.3 Advances in Materials and Structure Details*

The Committee fully recognises the importance of further testing and standardisation of TMPC and FCA steels in order take full benefit of these. It can be noted that some FCA steels have been applied to some ships and vessels. The developed steel plate has been approved as FCA in grades AH36, DH36, EH36 and AH40, DH40, EH40 by Nippon Kaiji Kyokai, Lloyd's Resister, Det Norske Veritas and American Bureau of Shipping.

The committee support the recommendation by Mr. G. Bacicchi that future committees are recommended to collect data and reports on the possible development of new honeycomb structures and their fatigue properties.

#### *2.1.4 Damage Control and Risk-Based Assessment (chapter 5)*

The Committee finds the conclusion from S-N test of thin welded sheets presented by Mr. Bacicchi where weld defects have limited influence (i.e. porosity and slag inclusion) on the fatigue behaviour, interesting and should be further investigated.

Mr. Bacicchi also points that "With reference to the different uncertainties associated with fatigue life prediction, the reported studies concerning reliability and risk assessment, although interesting from a theoretical and scientific point of view, seem in general not to provide practical application except for the FORM/SORM technique based on the S-N approach". The committee has demonstrated an example in chapter 5 to show how the uncertainties related to fatigue damage can be accounted for. There are many examples in the published literature how to use FORM, SORM, Monte Carlo and response surfaces for reliability assessment, which can be time-invariant or time-variant (Feng *et al.*, 2012).

#### *2.1.5 Design Methods for Ship and Offshore Structures (chapter 6)*

The committee agrees with Mr. Bacicchi that it is important to develop new guidelines for selection and qualifications of materials suitable for arctic application to account for low temperature and ice-loading, which is fully supported by this Committee. Initiatives have been taken by the industry lately as can be seen by Horn *et al.* (2012) and Østby *et. al.* (2013), in addition to a recent proposal for a working group within ISO "ISO/TC 67/SC 8 on Arctic materials.

#### *2.1.6 Benchmark Study (Chapter 7)*

Mr. Bacicchi points out that "no misalignment has been considered between upper and lower vertical elements thus remaining far from practical shipbuilding standards". However, the Committee decided to exclude gaps, misalignments and corrosion effects and discontinuities to make comparisons more reliable and forceful.

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Mr. Bacicchi points out that “Traditional procedures given by Class Societies guidelines (GL, CSR BC, CSR OT, and KR) do not take into account parallel stress to assess the fatigue life of a welded joint and in this way the fatigue damages, calculated for the case study are approaching a zero value.” The Committee wants to emphasise that a nominal approach widely accepted exists, which takes into consideration parallel stresses. Such an approach is based on the FAT class 90, applied to normal stresses parallel to weld toe line (see for reference detail No. 323 “Continuous manual longitudinal fillet or butt weld” in IIW design code, Hobbacher, 2009). A fatigue assessment has been carried out in the benchmark study making reference to this approach, obtaining a result aligned with those of the traditional approaches where parallel stress is disregarded.

#### *2.1.7 Reply to conclusion (Chapter 9)*

The Committee is happy to notice that Mr. Bacicchi values the work carried out by the Committee members. The Committee fully supports Mr. Bacicchi that it is important that by adding practical examples and experimental calibration to any theoretical work, will increase the confidence. In addition learning’s from ship and offshore platforms operating today should be traced back to researchers and designers in order to gain knowledge to better ensure the structural integrity in the future. The committee fully agrees with Mr. Bacicchi that preferably the research should end up in practical implementation (to large extend covered by the classification societies). The committee agrees that further research is needed in the field of multiaxial stresses and this is also addressed in our case study in chapter 7. Today some valuable guidance can be found in e.g. IIW design code, Hobbacher (2009). The understanding of fatigue is mainly based on observations from experiments or structural failure and the interpretation of these events. Hence, it is important to add practical examples and experimental calibration to any theoretical work, in order to increase the confidence. In addition learning’s from ship and offshore platforms operating today should be traced back to researchers and designers in order to gain knowledge to better ensure the structural integrity in the future. The Committee has also supported that preferably the research should end up in practical implementation covered by the classification societies and other rule makers.

### *2.2 Reply to Floor and Written Discussions*

#### *2.2.1 Bart Boon*

It is the opinion of the Committee that the composite patch repair should be part of a “crack management” programme. A composite patch will be designed in order to stop/ significantly slow down crack growth. However, there are no inspection methods available today, that the Committee is aware of, which can easily check and verify the bonded strength between the patch and substrate surface. Hence, either the patch is used as a temporary measure to prepare a “permanent” repair or the patch and underlying crack are inspected at regular intervals.

Repairs often need to be carried out at short notice leaving limited time for qualification of the repair design. Hence, the client will need to balance the requirements for quick qualification against the reliability of the repair and hence the risk of having to upgrade or replace the repair in the future. In DNV RP C301 “ Guidens on Design, Fabrication, Operation and Qualification of Bonded Repair of Steel Structures”, repair classes have been designed (ranging from Class 0 repairs which are ad hoc repairs up to the most stringent Class III repairs, which are repairs where sufficient documentation

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is provided to quantify with confidence the reliability of the repair for the intended service life of the structure. Due to the limited service experience that currently exists with bonded repairs, the long term reliability of the repairs cannot be quantified with sufficient confidence. However, the RP provides some recommendations and the reliability of the repairs should in general be taken as $pf = 10 - 3$. In order to limit the risk, manual inspection can be replaced/supplemented by installing some kind of monitoring system based on e.g. optical fibres or strain gauges.

### *2.2.2 Tetsuya Nakamura*

The effectiveness of peening methods has been confirmed in variable amplitude tests. However, overloads may reduce the effect. Reductions in benefits due to overload conditions are described by Haagensen and Maddox (2013). Other recent publications addressing the effect of the variable amplitude loading are provided by Yildirim. and Marquis (2012) and Miki and Tai (2012).

### *2.2.3 Cesare M. Rizzo*

The Committee agrees with Dr. Rizzo's comments and reasoning and supports the statement that "... it is believed that such methods can fulfil the needs of the shipping industry since their application can be easily automated in numerical analyses ...". We recommend the next Committee to continue the work to demonstrate in comparative studies various multiaxial fatigue approaches with the aim to clarify their strengths, weaknesses and potential, respectively, when used in the shipping and offshore industry.

### *2.2.4 Ilson Pasqualino*

Due to member's interests and limited pages allowed, corrosion fatigue, composite structures and cladded linepipes, are topic which have not been mentioned in the report. H2S / corrosive environments were discussed in the 2009 ISSC fatigue and fracture report. The Committee recommends that these topics are addressed further by the next Fatigue and Fracture Committee. Regarding development of non-destructive techniques for fatigue damage evaluation like X-ray diffraction method some information can be found in the group Committee V.3 Materials and Fabrication Technology 2012 report.

### *2.2.5 Weicheng Cui*

Our mandate addresses unstable crack growth and was not covered in the 2009 report. For the recent increasing demand for natural gas, pipelines for natural gas transmission operate at higher pressures for ensuring higher transport efficiency. For realising higher pressure, higher strength pipes are used. Under this situation, risk of unstable shear fracture is increasing. On the other hand in shipbuilding industries, larger scale container ships are being constructed in recent years. In these ships, thicker steel plates are used at strength deck and hatch-side coaming structures. Under this circumstance, risk of cleavage fracture is increasing. One of the main challenges in order to select steel for arctic / low temperature applications is to ensure adequate material toughness in order to prevent brittle fracture to occur during operation. Due to this, the prevention of unstable cleavage fracture has become a big issue and extensive studies have been done for the last few years. Hence, the topic has been thoroughly discussed by the Committee.

The cleavage fracture can happen not only at a final stage of fatigue crack growth; it can also happen directly from defects in welds. Initiation of cleavage fracture takes

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place mostly at welds because it has a higher possibility of defects and higher probability of having a local brittle zone in addition that welds are often more prone to fatigue due to normally high stresses in a wild area. Although prevention of the initiation of cleavage fracture is essential to prevent unstable fracture, it cannot be prevented completely; the double integrity concept should be applied, in which crack arrest capability should be maintained assuming cleavage fracture initiation at the welds.

There are basically two types of unstable fracture, unstable ductile (shear) fracture and unstable cleavage fracture.

There are many factors which affect unstable cleavage fracture:

- material resistance to unstable fracture both at base metal and weld
- applied stress and welding residual stress
- plate thickness
- structural design including welding details.

See reply to Dr. Fang Wang for further discussions of cleavage fracture.

#### *2.2.6 Fang Wang*

As stated above in the reply to Dr. Weicheng Cui, there are many factors influencing unstable cleavage fracture. Because the plane strain condition is maintained in the interior of the thickness and plane stress condition prevails at plate surfaces. This is why cleavage fracture does not take place near a propagating crack; shear lips form near the surfaces. In this sense, thicker plate is more prone to unstable cleavage fracture propagation.

The crack arrest test should be done at an original plate thickness. Also, crack velocity is an important factor. To reproduce the crack velocity which can encounter at actual structural components, sufficient specimen size is necessary. From these viewpoints, a new testing standard has been proposed from Japan.

Regarding Dr. Fang Wang second question, the accuracy of the cycle-counting method, his hypothesis is that if $\Delta K$ is not representative of the true fatigue driving force in an incorrectly counted cycle, the fatigue life based on the cycle counting will not be accurate. Instead, Dr. Fang Wang asks whether it is possible to develop a fatigue crack growth model, which is expressed as $da/dt$ instead of $da/dN$. It is the members' opinion that a fatigue crack growth model based on $da/dt$ will create a lot of confusions among the practising engineers. There are a number of issues to be addressed for such a model:

- the $da/dt$ model will unlikely converge into a uniform model, as the loading frequency varies for each structure and in different periods of the operating life. A simple example is the constant amplitude loading with two different frequencies. The $da/dt$ model will somehow include the frequency into the model; however this requires a cycle counting method.
- time is an important parameter, but it is too general in describing the loading effects that cause fatigue crack propagation; By prescribing $da/dt$ directly, the loading information will be missed (including magnitudes, frequencies, load ratios, etc.) in the model.
- the $da/dt$ model will unlikely be able to describe the overloading effect.

#### *2.2.7 Wolfgang Fricke*

The case study has also looked at the assessment based on that nominal stress approach. In general, according to IIW, fatigue checking may be performed within the nominal stress approach by making reference to the FAT 90 S-N curve for computing fatigue damage of parallel normal stress $\sigma_{||}$ where reference classified detail is No. 323 "Continuous manual longitudinal fillet or butt weld" and to the FAT 100 S-N curve for shear stress $\tau_{||}$, (IIW-1823-07- "Recommendations for Fatigue Design of Welded Joints and Components" by Hobbacher (2009)). This procedure is only recommended for steel and in cases where sufficient experience exists. It is worth pointing out that some classification societies in their rules or guidelines also consider the case of a stress pattern predominantly parallel to weld line and define a proper fatigue checking approach based on the nominal approach. Such procedures give results in accordance to those of the DNV enhanced method and IIW.

With regards to the second question, the Official Discusser showed the "thickness effect" with respect to the plate thickness between $5\,mm$ and $20\,mm$ in Figure 2. In this range, the given results indicate the decrease of the fatigue strength as a function of the plate thickness. However, for the plate thickness between $3\,mm$ and $5\,mm$, the fatigue strength of butt joints may decrease with decreasing plate thickness, Feltz, and Fricke (2012).

The fatigue design of thin and slender structures is challenging due to larger distortions of the plate caused by welding. The recent results by Lillemäeet *et al.* (2012) and Fricke *et al.* (2013) show that the deformations are not only larger but also with different shape. In addition, the geometry of the weld in thin plate joints may be different from the one in thick plates affecting on the fatigue strength of the joints. Thus, further investigation is still needed to obtain a solid conclusion and recommendations for the fatigue design of thin marine structures.

## *2.3 References*

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