SCHRIFTENREIHE SCHIFFBAU

LESEPROBE
Application of advanced notch stress approaches to assess fatigue strength of ship structural details: literature review

ABSTRACT:

This report summarizes the literature review carried out at the beginning of the research programme in compliance with Task 1 of the research project proposed to and funded by the A. Von Humboldt Stiftung. Conclusions of the present report address the future steps to be undertaken in the research.

DISTRIBUTION:

Alexander Von Humboldt Stiftung, Hamburg University of Technology, Università di Genova.

NOTES:

Rev. 0 (December 2010, including Prof. Fricke’s comments)
Rev. 1 (January 2011, including papers sent by Prof. Lazzarin and Dr. Meneghetti)
Rev. 2 (February 2011, including papers available in the library of the University of Genova)
Application of advanced notch stress approaches to assess fatigue strength of ship structural details

Summary:

1 Introduction ................................................................................................................................................. 3
2 Theoretical background of N-SIF approaches ........................................................................................... 4
2.1 Stress field at crack tips and fracture mechanics .............................................................................. 4
2.2 Stress field in way of notch corners ................................................................................................... 7
3 N-SIF based fatigue assessment approaches ......................................................................................... 15
3.1 N-SIF as fatigue strength criterion: early applications ................................................................. 15
3.2 Interpretation of N-SIF approach in fatigue strength assessment ................................................... 19
3.2.1 Stress field singularities in way of notches and cracks: two sides of the same medal ............ 19
3.2.2 Extensions and recent developments of N-SIF interpretations .............................................. 24
3.3 Application of N-SIF approach in fatigue assessment ..................................................................... 28
3.4 Strain energy and strain energy density approaches ...................................................................... 30
3.4.1 Background and earlier papers .................................................................................................... 30
3.4.2 Key contributions of the Padua group ......................................................................................... 32
3.4.3 Estimates of volume for SED averaging ...................................................................................... 34
3.4.4 SED applications in case of plasticity, blunt notches and torsion loading .................................... 39
3.4.5 Comparisons between SED and 1mm-radius notch stress approach .......................................... 41
3.4.6 Assessment of three dimensional welded details ....................................................................... 43
3.4.7 Multiaxiality of stresses ................................................................................................................ 43
3.5 The cyclic plastic zone (CPZ) approach ........................................................................................... 45
3.6 The Peak Stress Method (PSM) ...................................................................................................... 46
4 Independent applications of N-SIF based approaches ................................................................. 49
5 Conclusions and future tasks ................................................................................................................... 49
References ...................................................................................................................................................... 51
1 Introduction

This report summarizes the literature review carried out at the beginning of the research programme in compliance with Task 1 of the proposed research project.

Fatigue assessments of welded joints by local approaches have been applied since many years, though not always successfully. As a matter of facts, the fatigue limit state was mainly approached empirically by prescribing suitable geometries of structural details based on successful design shapes and by paying appropriate attention to welding procedures and fabrication technologies. This is even more true in the shipping field. There was the fundamental assumption that the quality of workmanship was in accordance with construction standards that are acceptable to and verified by attending surveyors.

Traditional approaches for fatigue assessment are based on simplified structural analyses and fatigue tests of standard structural details. The well known nominal stress approach is still widely applied and provides consistent results in several practical cases; local stress approaches were introduced later, mainly based on finite element (FE) models of relatively large parts of the structure refined according to well established regulations. Local approaches should be able to avoid long lasting testing of specific structural details; however, results are not always conservative and sometime are largely over-conservative, depending on loading and geometry of the captioned structural detail and applied approach.

Indeed, the trend towards local approaches to assess fatigue strength of structural details is still in progress and methodologies for fatigue strength assessment of welded structures are advancing faster and faster while new ones are continuing to appear in the literature.

Many local approaches have been developed in the last 20-30 years in addition to the nominal stress approach which is based on the stress in a component resolved using general theories and disregarding all local stress raising effects of the welded joint. Fatigue strength assessment approaches are categorized in the well known sketch of the book by Radaj, Sonsino and Fricke, [143], on the basis of the parameter believed to govern the fatigue strength behaviour (see Fig. 1):

- Structural stress approach, based on the structural (or geometric) stress at the hot spot that includes all stress raising effects of a structural detail excluding all stress concentrations due to the local weld seam profile itself,
- Notch stress approach, based on the effective notch stress, i.e. the total stress in the notch, obtained assuming linear-elastic material behaviour, generally replacing in the calculations the actual weld seam profile by an effective one to account for the scatter of weld shape irregularities as well as for the plastic material behaviour in way of the notch root,
- Notch strain approach, based on the notch strain instead of notch stress and considering the elasto-plastic behaviour of the material occurring in the notch, thus overcoming at the root the problem of the unrealistically high stress values obtained by the notch stress approach but not removing the need of rather complex calculations to obtain the stress and strain at notch root,
- Crack propagation approach, evaluating the crack growth up to failure according to the fracture mechanics model, i.e. the fatigue strength is related to the stress intensity factor range by the well known Paris-Erdogan law, provided that an initial crack is assumed existing in the welded detail and propagating at each applied loading cycle in a stable way.

Actually, fatigue phenomena in welded structures are by far more complex than the existing descriptions and rather controlled by what occurs in the area surrounding the weld notch, therefore involving a lot of other geometrical and material parameters not included in the current approaches. Indeed, every approach has its own features and applicability limits while a unified approach seems rather far from current practice.
The book by Radaj, Sonsino and Fricke, [143], updated by a recent paper, [144], present several alternatives of the above mentioned local approaches proposed in open literature and by standards and regulations, applied more or less successfully in many relevant engineering fields. A few of them have not yet systematically been investigated by naval architects and marine engineers for potential application in shipbuilding.

Among the others, the most promising fatigue assessment approaches seem the ones based on the concept of notch stress, particularly those accounting for the singularity of the stress field at the notch without fictitious description of it, if any. Such approaches can be regarded as in between the notch stress or notch strain based approaches and the rather more complex crack propagation approaches (Fig. 1).

The starting basis of the literature review is therefore Ch. 7 of ref. [143], which reports the fundamentals of the most recently proposed notch stress intensity factor (N-SIF) based approaches. This chapter was supported by Prof. Paolo Lazzarin, one of the scientist of the research group in the University of Padua mostly developing such methods since some years, along with Prof. Bruno Atzori. In more recent years, another approach evolved from the N-SIF one, based on the strain energy density (SED) in a volume. Later on, another method based on the N-SIF concept was proposed, allowing relatively straightforward fatigue assessments of welded joints if well calibrated in advance (Peak Stress Method, PSM).

Above mentioned approaches seem to overcome the difficulties introduced by other local fatigue assessment approaches, also including several different effects not considered by other methods. However, N-SIF based approaches are not yet recognised as a procedure for fatigue life assessment in the various industrial fields nor they were agreed to be included in any regulation or standard.

2 Theoretical background of N-SIF approaches

2.1 Stress field at crack tips and fracture mechanics

A notch can be defined as an angular or V-shaped cut, indentation, or slit in an object, surface, or edge; specifically, several different notches exist in welded structural details of ships. The notch of fillet welds or butt welds is the critical region with regard to fatigue crack initiation and propagation.

A notch is defined as a sharp notch if the notch radius can be assumed (practically) null, alternatively as a blunt notch if a finite notch radius can be estimated. In case of sharp notches, high stresses occur and their
description under elastic material hypothesis may not suffice or elastically determined stresses should be considered as a fictitious parameter for strength assessments.

Indeed, by studying the relevant literature, it clearly appears that the theoretical principles of the above mentioned N-SIF based fatigue assessment approaches originate in the second half of the last century, around 1950, when analytical formulations for the stress fields in way of crack tips and notch corners were derived considering stress singularities at sharp notches.

Publications describing the analytical formulations of the stress field in way of notches are ref.s [69], [47], [168], [169], followed in more recent years by ref.s [33], [164]. A recent Ph.D. thesis, [173], reviewed the relevant literature, summarized notch stress expressions for tensile and shear loading (mode I and mode II) and extensively dealt with formulations for torsion loading (mode III).

In turn, such works were based on the fracture mechanics theory, dealing with a special case of sharp notch, i.e. a crack. In fact, a crack may be regarded as a notch having null opening angle and null radius at tip. A very brief introduction to fundamentals of fracture mechanics is given in the following.

In 1924, the British physicist A.A. Griffith developed an approach to put fracture prediction on an analytic basis, [87], [88]. Griffith developed an analytic approach to predict the conditions under which the flaws would propagate unstably in brittle materials, namely he dealt with glass materials. He considered the well known example of the infinite plate containing a crack subjected to a remote stress.

From the theory of elasticity comes out the concept that the strain energy contained in an elastic body per unit volume is simply the area under the stress-strain curve; there is a reduction (that is, a release) of energy in an elastic body containing a flaw or a crack because of the inability of the unloaded crack surfaces to support a load. Assuming that the volume of material whose energy is released is an area of a circular region around the crack, then the total released energy due to the crack is the energy per unit volume times the volume. It comes out that, assuming a crack size \( a \) and linear elastic material behaviour: 
\[
U = \sigma \varepsilon \pi a^2 = \sigma^2 \pi a^2 / E = \text{(force x deformation) x crack area}
\]

Therefore the energy release rate \( G \) when crack propagates is:
\[
dU/d(2a) = (\sigma^2 \pi a) / E = 2 \gamma_s = G_{IC}
\]

i.e. the energy released for crack propagation \( 2 \gamma_s \) or \( G_{IC} \), according to 1st principle of thermodynamics, is estimated based on the acting stress and assuming the linear elastic material behavior.

By carrying out a sophisticated mathematical analysis and by testing glass specimens, Griffith was hence able to determine the conditions under which the energy of the system would be reduced should the crack extend in a brittle material. Such conditions favour continued crack extension since systems tend naturally to minimize their energy.

However most structural components are fabricated from metals which do undergo plastic deformation, i.e. they are not brittle but rather ductile materials. The effects of plastic deformation were accounted for by Irwin, [78], and by Orowan, [138], by simply noting that the effective surface fracture energy (which includes the work of plastic deformation around the fracture surface) can be substituted by the true surface energy in the Griffith’s equation. In practice, this effective surface energy was simply an adjustable parameter used to force agreement with observed fracture loads and crack lengths:
\[
G_{IC} = 2\gamma_s + 2\gamma_p
\]

Although the mentioned methods are limited to the geometry of the infinite plate, they allow understanding fracture mechanics fundamentals. It is now clear that fracture depends on stress as well as on a geometrical parameter, namely the size of the crack.