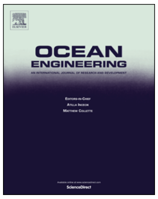
Ocean Engineering 113 (2016) 246–254

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Prediction of fatigue crack growth in a ship detail under wave-induced loading

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ARTICLE INFO

Article history:
Received 15 March 2014
Accepted 30 October 2015
Available online 20 January 2016

Keywords:
Stress intensity factor
Fatigue crack propagation
Unique curve model
Design wave approach
Hatch corner

ABSTRACT

Fatigue life prediction based on fracture mechanics has become the focus of research on the strength of ship structures; however, it is difficult to summarize a general formula for calculating stress intensity factors (SIF) for cracks in ship details, and the application of fatigue crack propagation (FCP) theory is limited to simple structures and simple loads in some way. To address this problem, in the present study, the SIF of a crack in a ship detail was calculated by combining a PATRAN finite element model for the whole ship with the advantages of ANSYS for SIF calculation, incorporating a macrocode written to achieve the transformation. The method was validated by comparison with existing empirical formulas. Also a method of generating the ship fatigue loading spectrum is demonstrated based on the design wave approach. Finally, an example is given of combining the unique curve model of FCP with the proposed SIF calculation method and the fatigue loading spectrum generation method, to predict the fatigue life of a welded hatch corner joint in a vessel with large hatch openings. This serves as a reference for fatigue assessment of other complex ship details.

1. Introduction

Since a ship is frequently subjected to complex loads during its service life, fluctuating stresses always exist in structural members. These may cause fatigue failure of local as well as global structures, with catastrophic consequences. Therefore, fatigue strength assessment is an important criterion in structural ship design. Among the approaches to assessing fatigue strength, fracture mechanics-based fatigue evaluation has the capability to take initial crack size, load sequence, residual stress, etc. into consideration (Cui, 2003; Fricke, 2003; Sumi and Inoue, 2011). Much effort has been spent over the past several decades to develop a fatigue crack propagation theory and put it into practice (Doerk and Rörup, 2009; Doshi and Vhanmane, 2013; Fricke et al., 2002; Okawa and Sumi, 2008; Sumi, 2013).

Despite the many studies of fracture mechanics-based fatigue life prediction over the years (Cui et al., 2011; Huang et al., 2008; Paris et al., 1961), some problems remain when applied to the practice of marine structures. An important issue is the calculation of stress intensity factors (SIFs) when complex loads are applied to intricate engineering joints. Stress intensity factor (SIF) is a fundamental parameter of fracture mechanics, and many attempts have been made to calculate it accurately. Newman and Raju (1981) calculated the SIFs of semi-elliptical surface cracks of different sizes in plates. Empirical formulas developed by 3-D finite element analysis were shown to be consistent with experimental observation. Rhee et al. (1991) developed empirical formulas for the SIFs of surface cracks in the weld toe of T-shaped tubular joints subjected to brace tension and in-plane and out-of-plane bending loads, for a wide range of joint dimensions in existing jackets. Bowness and Lee (2000) used several empirical formulas to predict weld toe magnification factors for semi-elliptical cracks in T-butt joints. Some relevant fatigue design rules such as BS7910 (British Standards Institution, 2005) etc. also recommend empirical formulas for determining SIFs in the weld toe of different kinds of joints.

However, at least two problems arise when using any of these empirical formulas in practical engineering situations: (1) All the empirical formulas were derived from finite element simulations or laboratory experiments, the models for which were simple and were subjected to elementary tensile or bending stresses, and the stress distribution in all cases was assumed to be uniform and acting in a direction normal to the cross-section. However, such circumstances are almost unachievable in actual ocean engineering structures, and the formulas would obviously be different for realistic stress distributions and directions. (2) The stresses

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http://dx.doi.org/10.1016/j.oceaneng.2015.10.056
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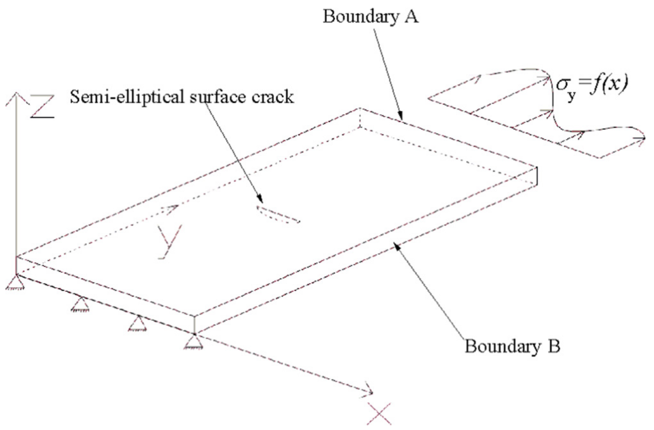

Fig. 1. A flat plate with crack in ship structures.

defined in empirical formulas are generally nominal (far-field) stresses, but it is difficult to define the nominal stress in real structures. For example, in Fig. 1 the stress on boundary A of the plate is not uniformly distributed—so which node stress represents the nominal stress? How far along *y* axis can reasonably be said to be "far-field"? Obviously, the node that is chosen on the boundary parallel to the crack and its distance from the crack both contribute significantly to the SIF. In addition, authoritative empirical formulas proposed are all, by far, about relatively uncomplicated structures and cannot be applied to general marine structures such as hatch corners in vessels with large hatch openings, aggregate junctions in the bilge, tubular joints with stiffeners on platform decks and so on, all of which are particularly vulnerable to fatigue failure. Some joints are so intricate that it is unlikely that it would be possible to propose a unified, reasonable empirical formula.

To sum up, the current simplified methods permit only a rough evaluation, and limit the broad application of a fracture mechanics-based fatigue strength assessment. In order to apply advanced fatigue crack propagation (FCP) theory to fatigue life prediction in general, a universal and accurate method of calculating SIFs of cracks in complex stress fields is required.

The present study mainly investigates the FCP method of fatigue life prediction in complex ship structures subjected to wave-induced stresses. To make use of the pre-modeled whole-ship finite element model in PATRAN (commercial FEM software widely used in ocean engineering) and take the advantages of ANSYS for SIF calculation, a macroprogram was written as part of this study to achieve the transformation from PATRAN to ANSYS. The SIFs for differently-sized cracks in the detail of a hatch corner subjected to wave-induced loading were then calculated. The fatigue loading spectrum for the hatch corner of a ship was generated using the design wave approach, and its fatigue life was predicted based on the unique curve model, which will be detailed later in this paper, of fatigue crack propagation.

2. SIF calculations for structures subjected to complex load

2.1. Coupled degrees of freedom and node transformation

During structural analysis, marine structures are widely modeled by the commercial FEM software PATRAN; the elements used are mainly 2-D shell and 1-D beam. Therefore, in order to calculate the SIFs of 3-D surface cracks, it is necessary to create solid models and the connections which link the shell elements and solid elements.

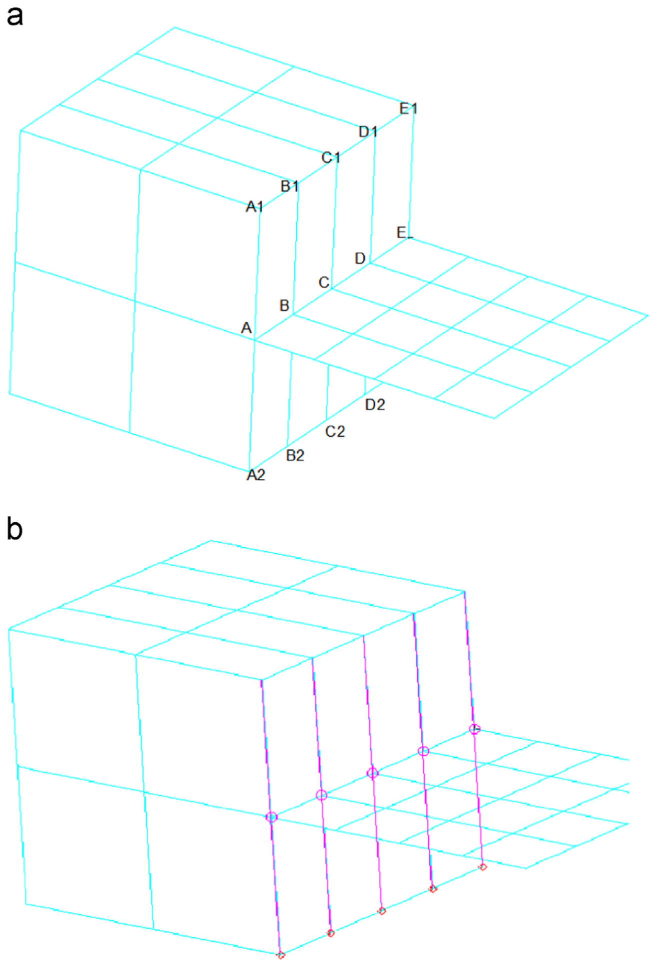

Fig. 2. MPC for connection of shell and solid connection ((a) before connection; (b) after connection).

The shell elements and solid elements are linked by multi-point constraints (MPCs). In PATRAN, either of the MPC types RSCCON Surf-Vol or Rigid meets the requirement; the former was selected in the present work. The nodes on the shell elements were selected as the dependent nodes, and the corresponding nodes on the solid elements were selected as independent. In Fig. 2(a), nodes A–E are dependent, while nodes A_1–E_1 and A_2–E_2 are independent. Fig. 2(b) shows the PATRAN model after the MPCs were created.

When the SIF of the crack is calculated, the result is inaccurate if the FEM mesh at the tip of the crack is too coarse. The ANSYS software provides a specialized singular element and KSCON command for SIF calculations, and is recognized as an accurate method of calculating SIFs. Conversely, PATRAN does not possess this capability, and relatively little research using PATRAN to calculate 3-D crack SIFs has been carried out. It was therefore necessary to derive a suitable method of combining the capabilities of PATRAN and ANSYS.

In practice, the coordinates of PATRAN and ANSYS do not always coincide, and transformation and rotation are needed. In the present study, the macro patran2ansys.mac was written to achieve the following functions: (1) reading the PATRAN node coordinates and displacement data; (2) reading the ANSYS node coordinates; (3) the transformation and rotation of the coordinates; (4) displacement interpolation; (5) to add the loading at each node to the ANSYS boundary. To be clear, the stiffness of solid model in ANSYS differs due to surface crack growth. Since the influence is small, this paper does not take it into consideration.