Marine Structures 39 (2014) 315–334

Contents lists available at ScienceDirect

Marine Structures

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

Study on crack propagation simulation of surface crack in welded joint structure

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ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form 1 August 2014
Accepted 27 August 2014
Available online 18 October 2014

Keywords:
Finite element method
Extended finite element method
Welded joints
Surface crack
Crack propagation analysis

ABSTRACT

Recently developed computational techniques are applied to the simulation of the crack propagation of a surface crack in a welded joint. The results are compared with those obtained by the conventional techniques. Three approaches are adopted: three-dimensional finite element analysis using quadratic tetrahedral finite elements; the two-dimensional extended finite element method using the *Mk* factor; and the use of three-dimensional *Mk* factor formulae. In the numerical examples, stress intensity factors, *Mk* factors, crack paths and fatigue cycles are evaluated for a surface crack in a T-shaped welded joint. The accuracy and effectiveness of the approaches are discussed.

1. Introduction

Welded joints are often adopted in ships and ocean structures. Evaluation of fatigue strength of the welded joints is important in assessing the structural integrity of welded structures. The detailed description for mechanics of materials, fatigue and fracture are given in Refs. [1–5]. Methods of evaluation include fracture mechanics analysis and crack propagation simulation. So far, several analytical/numerical approaches have been proposed and new computational techniques have been

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http://dx.doi.org/10.1016/j.marstruc.2014.08.001
0951-8339/

developed. Additionally, simulations for complex shape geometry are easily handled by advances in computer power.

Fracture mechanics analysis and crack propagation simulations are conducted to evaluate the fatigue crack growth life of welded joints. To carry out such simulations, the stress intensity factor (SIF) of cracks embedded at the weld toe should be evaluated accurately. However, there are difficulties in obtaining the SIF of cracks because the welded joints have complex geometry, and they have a crack front singularity and high stress concentration near the weld. Weld toe magnification factor (*Mk* factor) can be used to evaluate the SIF of a surface crack located at the weld toe. The *Mk* factor was originally proposed by Maddox [6] to quantify the change in stress intensity due to the presence of welded attachments. The SIF of a surface crack located at the weld toe can be predicted from formulae for the *Mk* factor and reference SIF solutions of a surface crack on a rectangular plate; *i.e.*, the so-called Raju-Newman solution [7]. In addition, simplified prediction of the crack propagation can be carried out by adopting the Paris law [8]. The *Mk* factor is evaluated using two-dimensional (2D) or three-dimensional (3D) welded joint models. In this paper, the *Mk* factors in 2D and 3D cases are denoted $Mk_{(2D)}$ and $Mk_{(3D)}$, respectively. Simplified formulae for the *Mk* factor have been proposed for several types of welded joints and have been included in standard specifications: *e.g.*, BS7910 [9] and WES2805 [10]. The use of the *Mk* factor is a simple and effective approach, and the *Mk* factor is used by service engineers in evaluating the structural integrity of welded structures.

In recent years, new computational techniques have been proposed to reduce the modeling tasks in crack analyses. Finite Element Analysis (FEA) is widely used in the fracture mechanics problems and the applications for ships and ocean structures were carried out [11–16]. FEA using triangular or tetrahedral finite elements (FEs) is one such technique. The FE modeling of complicated geometry including cracks is made possible by software that automatically generates meshes. Techniques to compute the SIF have been proposed and employed in the simulation of crack propagation using triangular or tetrahedral elements [17–20]. Meshfree approaches, such as the element-free Galerkin method [21,22], eXtended finite element method (X-FEM) [23,24] and free mesh method [25,26] can reduce the modeling tasks for structures with complex shape. As one such approach, the X-FEM is suitable for solving crack problems and analyzing crack propagation; the new basis functions are introduced to the original displacement function of the finite element method (FEM) to represent the displacement discontinuity of the crack surface and the near crack tip asymptotic solutions. The crack propagation is effectively analyzed because relocations of the enrichment functions are performed without remeshing procedures. As another approach, the boundary element method [27–29] reduces the modeling tasks since only the surface meshing of cracked bodies is needed in the discretization.

In this study, propagation of a surface crack in a T-shaped welded joint is simulated using the new approaches of computational fracture mechanics. Although actual fatigue failure in welded joints starts multiple surface cracks and forms a very shallow surface crack along the stress concentration region, single semi-elliptical crack is assumed to validate the fracture mechanics analysis and crack propagation simulation. The results are compared with those obtained with conventional techniques. Three approaches are employed: (i) 3D FEA using quadratic tetrahedral FEs, (ii) the 2D X-FEM using the $Mk_{(2D)}$, and (iii) the use of $Mk_{(3D)}$ formulae. In (i) 3D FEA using quadratic tetrahedral FEs, automatic mesh generation software [30] is adopted to model surface cracks in welded joints. The surface crack is defined by the 3D model directly and the FE model is automatically generated using the tetrahedral FEs. The virtual crack closure-integral method (VCCM) [31] is adopted to evaluate the SIFs. The remeshing is incrementally performed as the crack extends. For the (ii) 2D X-FEM using the $Mk_{(2D)}$, a method proposed by the authors [32] is adopted. The method is based on the wavelet FEM [33–35] and the X-FEM. The discretization is based on fixed grids (the so-called voxel approach) [36], and the approach is suitable for modeling complex shape geometries such as welded joints. Hereafter, the method is referred to as the WX-FEM. Although the analysis is 2D, simplified propagation of a surface crack in a welded joint can be simulated using the $Mk_{(2D)}$ and Raju-Newman solution. Furthermore, 3D crack propagation simulations are carried out using the $Mk_{(3D)}$ formulae and Raju-Newman solution in the (iii) $Mk_{(3D)}$ formulae approach. The Paris law is adopted for the crack growth law. The SIFs, *Mk* factors, crack paths and fatigue cycles obtained with the three approaches are compared, and the accuracy and effectiveness of the proposed approaches are discussed.