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A consistent crack modelling and analysis of rectangular hollow section joints

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Abstract

This paper proposes a flexible approach to model one or several cracks under the weld toe of a rectangular hollow section (RHS) joint by mapping the two-dimensional crack's curvature onto the three-dimensional crack surface. Based on this model, an automatic mesh technique is developed to generate the entire finite element mesh of the damaged joint. This method can generate the mesh of cracks with any length, position, quantity, shape, and type (surface crack or through-thickness crack). Because of the steep stress gradient at the stress concentration region, the mesh around the crack front is refined using several mesh refinement steps to capture the stress distribution accurately. The generated model is then applied to study the plastic collapse load and crack opening displacement (COD) of some cracked RHS T-joints. Comparison between the numerical results and experimental test data shows that a good agreement is obtained for a typical RHS T-joint specimen subjected to brace end tension load. Thus, it confirms the efficiency and reliability of the proposed modelling approach for any cracked RHS T-joints.

Keywords: Crack opening displacement; Cracked rectangular hollow section joint; Mesh generation; Plastic collapse load; Surface crack; Through-thickness crack

1. Introduction

Cracks do exist, to some extent in all tubular joints, either as a result of manufacturing defects or localized damage in service. In order to assess the integrity of a joint containing defects, detailed analysis of the fracture behaviour and plastic collapse of the joint is absolutely important. For the past decades, finite element (FE) method plays an important role in the analysis of different types of welded cracked and uncracked tubular joints. Burdekin [1] had given a comprehensive review on the usage of finite element method for the study of static strength of cracked tubular members. But most of the previous research works were based only on circular hollow section (CHS) joints. Very few published results can be found in the literature on rectangular hollow section (RHS) joints containing three-dimensional (3-D) surface cracks under the weld toe.

In the previous research works on CHS joints, the surface crack, which was a part through thickness crack, generally was assumed to be semi-elliptical in shape. This crack always initiates from the hot spot region [2] at which the maximum geometric stress occurs. In the case of a rectangular hollow section joint, the highest stress tends to be located at the corner of the brace, either at the brace or chord weld toe under any loading condition. When the crack has initiated, the geometry of the cracked joint will not be symmetric any more, and as a result the crack shape is not symmetric too as it was found in full-scale experimental tests [3]. Hence, the assumption that the crack shape is always in a semi-elliptical form cannot be adopted for RHS joints. Therefore, to obtain accurate stress intensity factors (SIFs) along the crack front or plastic collapse load, a flexible crack modelling technique is needed to simulate the true crack shape.

For modelling a cracked tubular joint accurately and automatically, the choice of the element types is very critical. Shell elements incorporating "line spring" elements were used to model the joints with surface cracks [4,5]. In this approach, an analysis for a joint with a surface crack is not significantly more complicated than an analysis for a joint without a crack. But quite considerable approximations have been made by using linear spring elements, especially in the elastic–plastic case, as this method does not yield accurate results at the two crack tips or locations where the crack depth varies rapidly. Herion et al. [6] had suggested that the 3-D quadratic solid elements

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Nomenclature

d	vertical depth of the crack	n_i	direction cosine of the local coordinate axis with Z-axis direction
d_D	distance between the two close points along the crack front	t_0	thickness of the chord
h_0	height of the chord	t_1	thickness of the brace
h_1	height of the brace	α_{cr}	polar angle of the point at the weld toe
J	J-integral	α_{cr1}	polar angle of crack tip1
L_0	horizontal length of the crack	α_{cr2}	polar angle of crack tip2
l_{cr}	crack length along the weld toe	δ	crack tip opening displacement
l_i	direction cosine of the local coordinate axis with X-axis direction	ε	principle strain
m_i	direction cosine of the local coordinate axis with Y-axis direction	φ	tangent direction angle of the weld toe
		θ	inclined angle of the crack
		σ	principle stress

should be used to model the uncracked tubular joints including the welds. Cao et al. [7] had reported a detailed approach for modelling 3-D surface and through-thickness cracks located at the crown or saddle of a tubular Y-joint, where 3-D quadratic solid elements were used throughout the cracked joint.

Dyer [8] had carried out an extensive study on the effect of mesh density on the ultimate strength and fracture driving forces for tubular joints. He had concluded that a fine mesh, with at least three layers of elements across the chord wall thickness and a similar mesh density in the brace, is required to get reasonable results for such a cracked joint. This is due to large local bending stress at the region around the crack and the stress concentration effect at the weld toe. At regions away from the crack and welds, coarse mesh is normally sufficient. A smooth transition between the fine mesh around the crack and the coarse mesh at the region away from the stress concentration region is required for this purpose.

Although many commercial finite element method (FEM) codes have mesh generation capabilities [9,10], the construction of a properly designed finite element model invariably still requires some human intervention. Crack problems, in particular, require a certain amount of skill on the part of the users. Different methods and programmes were used in the past to generate meshes for tubular joints with cracks by Dyer [8], Kristiansen and Turner [11], Bowness and Lee [12], Qian [13], Klasén and Wästberg [14], Burdekin and Yang [15], and Lie et al. [16]. However, all these methods have focused on CHS joints, adopted a semi-elliptical crack shape assumption, and did not consider joints with multiple cracks. Due to different geometry of cracked RHS joints, a new crack mesh generation technique is proposed in this study. An approach for modelling cracks under the weld toes of cracked RHS joints is presented, and an automatic mesh generation technique is developed to study the fracture and plastic behaviour of these damaged joints. Several cracks can be included in the finite element model, and the elements' aspect ratio can be controlled accordingly. Hence, the approach used in the proposed mesh generation procedure has been found to be efficient and flexible. To check the accuracy and reliability of the finite element model, the numerical results are validated against the actual experimental test data of a typical RHS T-joint specimen subjected to brace end tension load.

2. Definition of crack surface and crack front

The basic geometry and weld dimensions of an RHS joint are defined strictly in accordance to CIDECT [17] and American Welding Society (AWS) [18] specifications, respectively. Before defining the crack front which is under the weld toe, the crack surface must first be determined precisely. From the previous research works of Bowness and Lee [19] for circular tubular joints, the fatigue crack curvature under the weld toe had been found to be slightly curved. In the absence of benchmark solutions for the RHS joints, an inclined crack surface under the weld toe is assumed as shown in Fig. 1. In the local u–v coordinate system, the surface can be defined as shown in Fig. 2. The point W_0 $(X_{W_0}, Y_{W_0}, Z_{W_0})$ is located along the weld toe, and the point D can be determined according to the assumptions that it is located on the crack surface, $|\boldsymbol{W}_0\boldsymbol{D}_0| = d$, where d is the vertical depth of crack, the angle between $\boldsymbol{W}_0\boldsymbol{D}$ and $\boldsymbol{W}_0\boldsymbol{D}_0$ is θ, and the point D is located inside the chord thickness. The coordinates of point D can be expressed as

$$X_D = h_0/2 - d,$$
$$Y_D = Y_{W_0} - L_0 \cos\varphi, \qquad (1)$$
$$Z_D = Z_{W_0} + L_0 \sin\varphi,$$

where h_0 is the chord height, L_0 equals to d tan θ, φ is the tangent direction angle of weld toe, and θ is the inclined crack angle. Hence, if the profile of weld toe is defined in accordance to AWS [18] specifications, the crack surface can be expressed by the vector function as

$$\boldsymbol{r}_D = X_D\boldsymbol{i} + Y_D\boldsymbol{j} + Z_D\boldsymbol{k}. \qquad (2)$$

After the crack surface has been defined, the crack front defined in the u'–v' plane is mapped onto this surface, and the 3-D crack front is obtained as shown in Fig. 3.