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Behaviors of a cracked lapped joint under mixed mode loading

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ABSTRACT

Fatigue failure of steel connections is a common failure mechanism, especially for structures which sustain heavy cyclic loads like steel bridges. In this paper, lapped bolted joints were modeled numerically to study the effect of a crack on the ultimate response of the joint. The site of crack initiation was located under different mixed mode loading in single and multiple bolts joints. The effects of axial to transverse loading ratio or load mixity (LM = F_x/F_y), friction coefficient (μ), and bolt diameter were analyzed. For a single bolt pin-joint, by increasing LM, the crack initiation site angle (γ) increased up to a certain value at which it became constant (γ_f) independent of LM. This value γ_f depended only on the coefficient of friction and the bolt hole diameter. Stress intensity factor and crack path of a propagated crack emanating from the predicted crack initiation site were analyzed in the lapped joints under either mode I or mixed mode loading. It was found that, for multiple-bolt joints, loaded with mixed mode loading, the crack path remained approximately horizontal like that for mode I loading. For pin joints, the crack path remained at the direction of the crack initiation. The numerical model developed was validated using existing experimental results for the initial stiffness of the bolted joint and using theoretical prediction of the stress intensity factor. A parametric study for different bolt diameters and numbers was developed to study the behavior of these connections under double and single side cracks. It was found that the crack advancement in a specific bolt hole may cause crack to initiate in other bolt holes, due to the increase of the stress concentration factor (SCF), K_t.

1. Introduction

Joint design is dependent upon the nature of materials to be joined as well as the method of joining. Cold-formed structural members may be joined with bolted connections that are designed with the aid of applicable national design standards. Rogers and Hancock [1] found that the AISI specification cannot be used to accurately predict failure modes of thin cold-formed sheet-steel bolted connections that are loaded in shear. Hoang et al. [2] studied experimentally single lapped joints under tension and shear, and the results showed that the failure began at both sides and extended up to the full width. Moreira et al. [3] studied numerically the fatigue crack initiation in a single lap joint. A three-dimensional stress analysis using the finite element method was carried out in order to analyze the load transfer as a function of crack geometry and length, and to determine the stress intensity factors (SIFs) for one or two cracks emanating from the edge of the hole located at the critical cross section. It was concluded that, mode I SIF (K_I) is dominant, and mode II and III SIFs (K_{II} and K_{III}) have values which are one order of magnitude smaller. It was also found that the first and the last rivets support the majority of the load. On the other hand, Kiamanesh et al. [4] showed that the circular bolt pattern improves the connection strength, and enhances the

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energy dissipation of the extended end-plate connections. This phenomenon is due to a better distribution of the bolt-forces in the connection which reduces the early yielding of the bolts. It was shown by Kiamanesh et al. [4] that in connections with large bolt diameter and plate thickness, all the four bolts carry approximately the same load when circular bolt pattern was used. Ju et al. [5–7] examined the position of maximum K_{I} of a crack emanated from a pin joint at a specific initial crack length under uniaxial loading. It was observed that the pure opening mode for cracked bolted-joint structures is not always at a 0° angle, but occurs between 0° and 22.5°. The first hole sustains the largest pin load and K_{I}, which are reduced slightly with crack advance [7]. Ju et al. [5] concluded that the linear elastic fracture mechanics can still be applied to the bolted joint problem for the major part of the loading, even though this problem reveals highly nonlinear structural behavior. Heo and Yang [8] studied SIF in a crack emanated with an angles from a bolted joint with a single bolt under mode I loading. It was found that there exists a critical angle under the most critical situation; corresponding to a pure mode I. Mohammed and Kennedy [9] concluded that lap-joint misalignment causes a considerable reduction in the fatigue resistance of the joint.

Sallam et al. [10–12] studied the behavior of a short fatigue crack emanating from bolted/riveted joints. Both the stress distribution in each bolt and the maximum stress concentration factor, i.e. site of crack initiation, in the bolted/riveted holes were determined. It was found that the highest value of the stress in the first bolt/rivet depends on the number of bolts and the type of arrangement. They also found that the clamping force with rough surfaces has a significant effect on decreasing K_{I} in cracked lapped joints [10]. This decrease is due to the decrease in the bearing load in addition to the resistance of the contact surface of bolt head or washer to open the surfaces of the crack beneath it. Rao et al. [13] found that the bolt axial force varies linearly with the torque applied up to 65 N m, and the bolt axial force predicted from their experimental studies is closer to the force suggested by the standards. Chakherlou et al. [14–16] studied the effect of clamping force and friction coefficient on stress concentration factor (SCF), SIF, and fatigue life of bolted joints. They found that, the fatigue damage process and crack initiation location is different for various tightening torques and cyclic load ranges.

Limited research studies exist on evaluating the stationary crack emanating from bolted joint under a mixed mode of loading [6,8,18]. Toribio et al. [17] stated that the longitudinal section of the fatigued specimen, without reaching total fracture, after revealing its microstructure, shows that the crack path presents frequent deflections and branches. This deflection implies the existence of a strong local mixed mode of crack propagation. To the best of the authors' knowledge, our research is the first of its kind to predict the site of crack initiation of a crack emanating from the bolted joint and subsequently its path under different load ratios. Therefore, the main objective of the present work is to study the effect of load mixity ($LM = F_x/F_y$) on the initiation site and path of a crack emanating from a bolted joint in addition to the variation of modes I and II SIFs through crack propagation under mixed modes of loading.

2. Numerical modeling

Two dimensional (2D) models created by ANSYS 10 [19] were used to evaluate bolted connections and crack propagation characteristics around the hole. The element, material, contact, and crack models used in this paper are described in the next sections [11,12].

2.1. Element type and material properties

Higher order PLANE82 element [19] was used to model the connection parts. This element is a 2D element, which contains 8 nodes with 2 translation degree of freedoms at each node. Two options were used to describe the element thickness, plane stress option in which the thickness is considered equal to unit length and plane stress with thickness option in which the thickness can be specified [19]. Additional advantages are found in PLANE82, such as the mid-side node and the support of quadrilateral and triangular meshes. These two advantages are helpful in the modeling of crack tip and calculation of fracture mechanics parameters.

El-Sisi [20] studied the effect of mesh size and found that the suitable element size around the crack should be less that 0.2 mm. In this study the minimum element size was 0.05 mm, and furthermore using PLANE82 gives flexibility in meshing since it is a higher order 8 or 6 node element [19]. The material was assumed elastic with a modulus of elasticity of 200 GPa and a Poisson ratio of 0.3.

2.2. Contact properties

ANSYS [19] provides a library of several element types to include surface-to-surface contact and frictional sliding. To simulate the 2D contact between bolt and hole, CONTA172 and TARG16 elements were used. The normal penalty stiffness of 10 [10–12,19] was used, which is the most important parameter for the contact characteristics of the connection, and Coulomb friction models at which the friction coefficient (μ) with different values was used [11].

2.3. Modeling of crack

A 2D singular element is employed for modeling of the crack since the displacements near the crack tip vary as a function of $\sqrt{r_c}$, where r_c is the distance from the crack tip. To resolve the singularity in strain, the crack faces should be coincident,