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Numerical Simulation of Fatigue Crack Propagation in Steel Bridge with Welded Stiffeners Subjected to Out-of-plane Loadings

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***Abstract*—The main purpose of this paper is to simulate the fatigue crack growth in welded steel bridge subjected to out-of-plane loadings. FRANC3D and ABAQUS are jointly used to calculate the stress intensity factors and predict the fatigue crack growth life. The results shows that the mode I SIFs of crack front of this case increase significantly as the loading increases and they also increase when the crack has bigger initial size. Among the factors which affect the fatigue crack life, the loadings are the most effective one while the size of the initial crack has little influence on the fatigue crack growth life.**

Keywords—fatigue crack propagation; steel bridges; welded stiffeners; stress intensity fator; FRANC3D

I. Introduction

Fatigue cracking can be considered as one of the most important factors which influence the structural durability and safety of welded steel bridges [1]. A member's local stress can be greatly changed by the existence of cracks [2]. Most fatigue cracks initially appeared at welded joints of steel bridges where stress concentration occurs due to details at end restraints and flange terminations, residual stresses, weld or initial defects and out-of-plane loadings [3]. Figure 1 shows the mechanism of formation of fatigue cracking under out-of-plane loadings [4]. As shown in the figure, the structure comprises three main parts: beams, stiffeners and diaphragms. The stiffeners connect the diaphragms with the beams and the diaphragms provide resistance to the transverse loadings. Under cyclic out-of-plane loadings which can be considered as a vertical displacement of the adjacent beam (δ), fatigue crack normally initiates at the end of weld toe at stiffeners and I-beams.

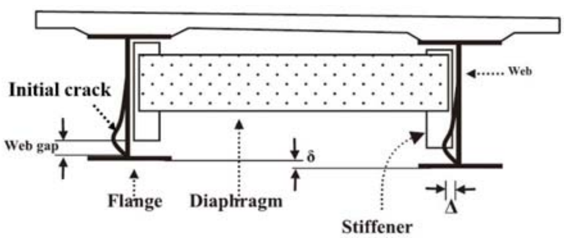

FIGURE I. FATIGUE CRACKING IN WELD AT STIFFENERS AND I-BEAMS UNDER OUT-OF-PLANE LOADINGS

There were previous research works on the numerical simulation of fatigue crack propagation for some specific problems in steel bridges [4-7]. The focus of this study is simulating fatigue crack propagation in the weld which connects the web and stiffeners under out-of-plane loading. This kind of fatigue crack is also a typical one in steel I-beams bridges with welded stiffeners [8]. Different parameters will be compared in the following simulation including the magnitude of loadings, initial crack's size and location.

II. Fundamental Theories and Numerical Implementation

A. Stress Field and Displacement Field Near Crack Tips

Cracks can be classified as Mode I: opening mode, Mode II: sliding mode, and Mode III: tearing mode [2]. Irwin [9] analyzed the stress and strain fields near the crack tip and proposed simple and practical formulas for all three cracking modes. Irwin [9] uses stress intensity factor (SIF) to represent the strength of local stress distribution near the crack tip. SIF can be written as follows,

$$K_n = Y\sigma\sqrt{\pi a} \qquad (1)$$

where σ is the nominal stress which can be calculated by assuming there is no crack exists, a represents the crack length or depth and Y is the shape coefficient which depends on crack size and location.

B. Fatigue Crack Growth Rate Model

Fatigue crack growth rate can be defined as da/dN which dN represents the increment of cycles of alternating stress and da represents the increment of corresponding crack length. With da/dN and crack length, the number of cycles in which the crack extends to a certain length can be calculated as follows:

$$N_f = \int_{a_0}^{a_c} \frac{dN}{da} da \qquad (2)$$

where a_0 is the initial crack length and a_c is the certain crack length after propagation.

In this study, the widely used Paris law [10] is applied to determine fatigue crack growth rate which can be written as follows,

$$\frac{da}{dN} = C\left(\Delta K\right)^m \quad (3)$$

where ΔK is the SIFs' range, C and m are material empirical constants.

C. Procedure of Fatigue Crack Growth Simulation

In this study, FRANC3D V7.1 combined with ABAQUS were used to simulate the fatigue crack propagation. FRANC3D has been applied in many research works and proved to be effective and accurate [7, 11-12]. The first step is to employ ABAQUS to create the 3D finite element model including geometries, material parameters and boundary conditions [13]. ABAQUS is used to be the static analysis solver for FRANC3D. While FRANC3D is responsible for remeshing, insertion of initial crack(s), calculation of SIF(s), crack growth settings and fatigue life predictions.

III. Modeling and Finite Element Analysis

For modeling, a structure similar to an existing highway steel bridge girder (I-96/M-52) in Webberville, Michigan, was chosen [14].

A. Geometry, Boundary Conditions and Loadings

Figure 2 shows the detailed geometry of the model. The structure was simply supported in its top flanges. The top flanges of the three beams were restrained with respect to translation in the z direction and rotation along x axis. Vertical displacements were applied as loadings to the cut edges of the lower flanges of the two exterior beams [15]. The imposed displacements were 3mm, 5mm and 7 mm vertical displacement, respectively.

B. Material and Other Modeling Parameters

The material used for the beams, diaphragms and stiffeners, was steel with density ρ=7850 kg/m^3, Young's modulus E= 210 Gpa and Poisson's ratio υ= 0.3.

Hexagonal solid element type C3D8R was used in this work and the meshing global size is 20mm.

IV. Numerical Analysis by FRANC3D

After completing the full 3D finite element model in ABAQUS, the model can be imported into FRANC3D and continue with fracture analysis.

A. Subdivision and Insertion of Initial Crack

In order to improve computational efficiency, the weld and nearby area was cut out as a submodel in FRANC3D.

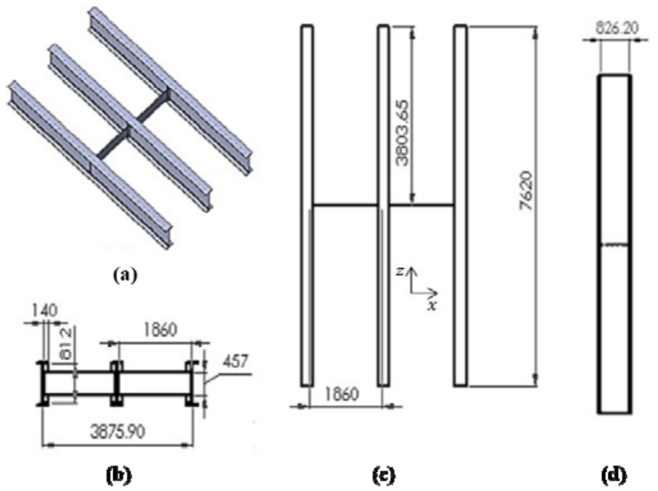

FIGURE II. DETAILED GEOMETRY OF THE MODEL [16]

The initial crack was inserted in the weld toe of stiffeners and I-beams. According to previous studies, the fatigue cracks generally maintain a semi-elliptic shape during the propagation [16]. The length of initial crack in welding defects is about 0.5~2mm. Figure 3 displays different location and size of initial crack chose in this study. a_0=1mm, 1.5mm, 2mm, c_0=1mm, 1.5mm, 2mm, respectively.

B. Analysis of Initial Crack's Stress Intensity Factors

FRANC3D calculated SIFs by using opening and sliding displacements of cracks. In cases like this study, mode I SIFs are much greater than mode II and mode III [7]. Therefore, mode I SIFs under different circumstances will be compared in the following parts.

1) Effect of loadings: SIFs subjected to out-of-plane loadings of 3mm, 5mm and 7mm were calculated, respectively. The initial crack size was a_0=1.5mm, c_0=1mm. Figure 7 displays the mode I SIFs distribution curve of crack's front. In the X-axis, the normalized distance is used to represent the location of the leading front of crack. It refers to the ratio of the arc length from the certain point to the starting point (A) on the elliptic crack leading edge to the whole arc length.

As shown in figure 4, the mode I SIFs increase significantly as the loading increases. The SIFs' distribution curves are basically axisymmetric about the midpoint and decrease at first and then increase along the crack front.

2) Effect of crack size: Different cracks' SIFs subjected to out-of-plane loadings of 5mm were calculated. As shown in figure 5, SIFs at the crack front increase gradually as the initial crack radius increases. The SIFs' distribution curves are still basically axisymmetric about the midpoint and decrease at first and then increase. However, the minimum SIF along the crack front increses as a_0/ c_0 decreses which makes the bottom of the curve a bit higher.

3) Effect of crack location: Different cracks' SIFs subjected to out-of-plane loadings of 5mm were calculated. As shown in figure 6, the left and right cracks' maximum SIFs are bigger than the center crack's and their distribution curve is not strictly axisymmetric as the center crack. This is caused by the difference of stress distribution in these areas.

C. Fatigue Life Prediction

FRANC3D calculated the fatigue life using Pairs law. C and m are material constants taken as 2.4×10^{-12} and 3.3, respectively [17]. All the fatigue life analysis in this study calculated 100 steps with median extension of 0.25mm each step and stress ratio of 0.1.

1) Effect of loadings: Fatigue life of crack subjected to out-of-plane loadings of 3mm, 5mm and 7mm were calculated, respectively. As shown in figure 7, The fatigue life of crack is very sensitive to the change of loadings. The number cycles decreases sharply as loadings increase and fatigue life shortens greatly.

2) Effect of crack size: As shown in figure 8, a crack's fatigue crack growth rate will be quicker at first if the initial crack owns a bigger size. After several steps of crack propagation, the crack growth rates of different cracks trun to be almost the same due to their smiliar shape or size.

3) Effect of crack location: As shown in figure 9, Fatigue life of crack at different locations differ at first due to their different SIFs. After several steps of crack propagation, these curves trun to be close as well.

V. CONCLUSIONS

Mode I SIFs of crack front increase significantly as the loading increases. They also increase when the crack has a bigger initial size.

After several steps of crack propagation, the final crack shape of the initial crack with different shapes will approach gradually. Among the factors which affect the fatigue crack life, the loadings are the most effective one. As the loading increases, the fatigue crack growth life decreases significantly while the size of the initial crack has little influence on the fatigue crack growth life.

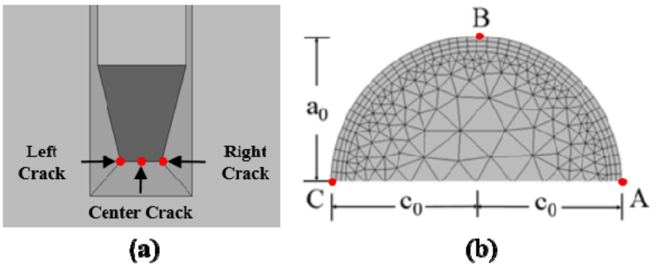

FIGURE III. CRACK LOCATION AND SIZE

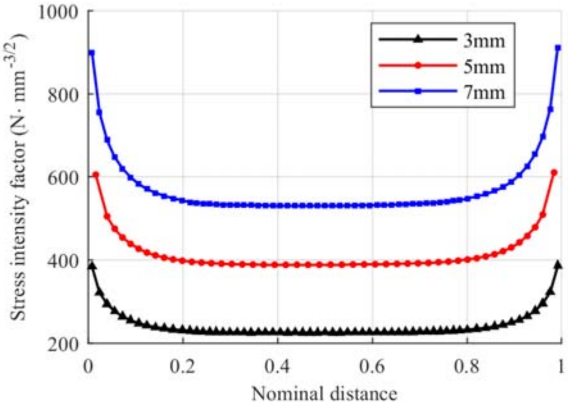

FIGURE IV. EFFECT OF LOADING ON MODE I SIFS

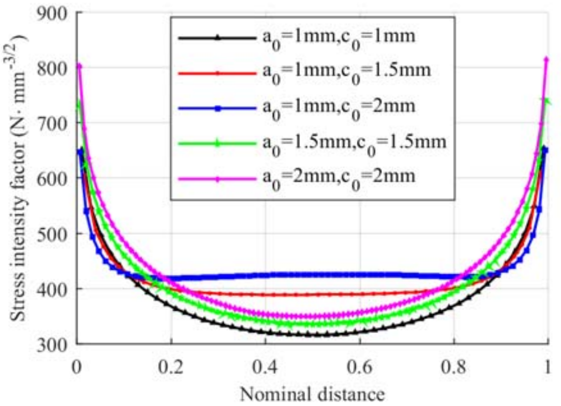

FIGURE V. EFFECT OF CRACK SIZE ON MODE I SIFS

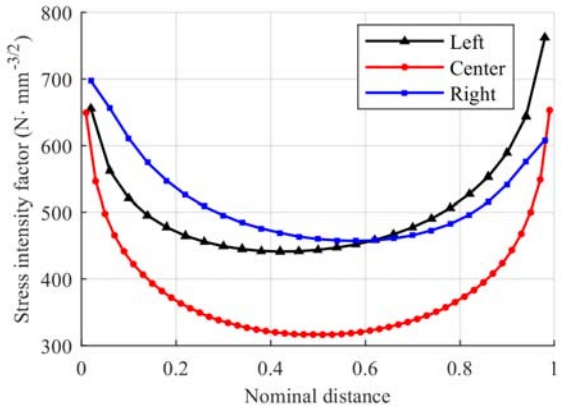

FIGURE VI. EFFECT OF CRACK LOCATION ON MODE I SIFS

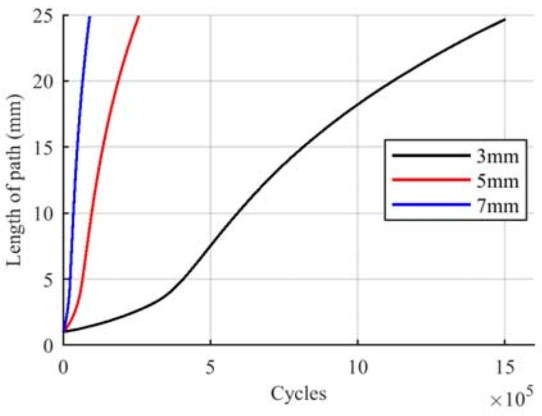

FIGURE VII. EFFECT OF LOADING ON FATIGUE LIFE

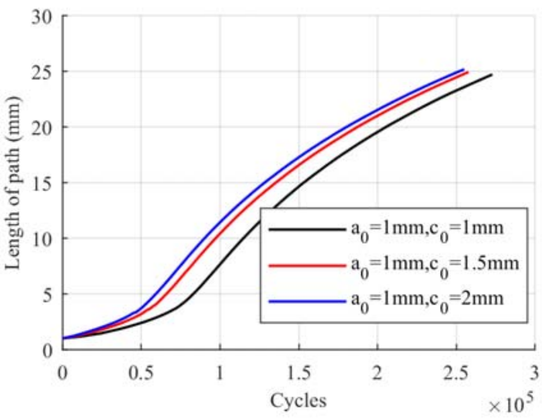

FIGURE VIII. EFFECT OF CRACK SIZE ON FATIGUE LIFE

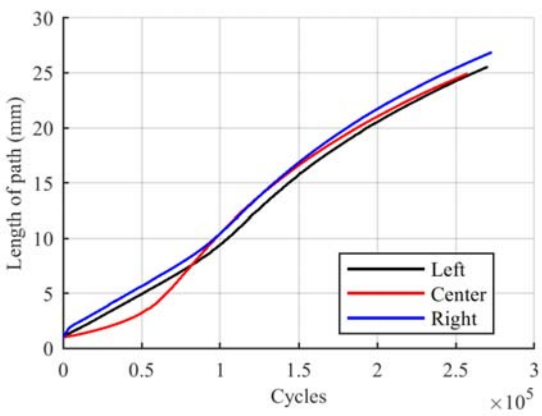

FIGURE IX. EFFECT OF CRACK LOCATION ON FATIGUE LIFE

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