Crack extension analysis and fatigue life assessment of single lug and yoke joints containing initial defects

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Abstract

To investigate the impact of initial cracks on the fatigue performance of single lug and yoke joints, fatigue testing was performed for defective welding joint models. The crack extension behaviors were investigated based on the theories of fracture mechanics using ANSYS-FRANC3D interactive technology, and the effects of the initial crack location, morphology pattern, and surface angle on fatigue performance were determined. The results showed a fatigue failure mode in which the crack extended along the welding line for single lug and yoke joints. The fatigue life was shorter when the initial crack was in the corner of the single lug plate. Moreover, the crack growth rates during the early stage of crack extension varied significantly with different initial crack morphology patterns. However, the crack growth rates during the later stages were similar to one another. The remaining fatigue life increased with the shape ratio for the same crack depth. Finally, the crack growth rate was the fastest, and the remaining fatigue life was the shortest when the initial crack surface angle was inclined toward the stress concentration area.

1. Introduction

Steel bridges are the main equipment used for emergency traffic security and play an important role in rescue activities and disaster relief. A steel bridge is comprised of a series of steel structures connected by joints. Therefore, the quality of joints directly affects the safety and service life of steel bridges. Common types of joints, such as single lug and yoke joints, are characterized by the advantages of simple structures as well as quick assembly and disassembly, and are thus widely used in various temporary installations. In terms of the bridge equipment, single lug and yoke joints were connected to each bar. Additionally, they are the key force carrying and transmission structural members, and have thus become important elements of structural design and manufacturing. However, with the extension of the service life of bridges, single lug and yoke joints often develop defects, such as cracks [1]. To ensure the overall safety of bridges, the study of the fatigue performance of single lug and yoke joints is important for the safety assessment of the bridge.

The presence of cracks is likely to result in stress concentrations, and the long-term repeated loading of single lug and yoke joints may lead to crack propagation or even sudden fracture failure, resulting in structural damage and tragedies such as personnel falling into water. In terms of time, fatigue fractures often occur within the normal use cycle with no obvious signs when one or more cracks propagate until the occurrence of a sudden fracture. As for spatial distribution, cracks tend to appear at the welding point, which is due to internal defects are easily forming during welding. When followed by crack propagation, this results in fatigue fracture. Therefore, it is important to study the crack growth pattern of single lug and yoke joints to properly understand and prevent structural damage.
Fatigue failure of metallic materials usually consists of three stages: crack initiation, crack propagation, and failure fracture. Of these, the first two stages account for most of the fatigue life. In welded structures, however, the weld often contains defects such as cracks, and the crack propagation stage accounts for most of the fatigue life [2]. Therefore, only the crack propagation stage is generally considered in the fatigue life assessment of welded structures.

Single lug and yoke joints are typical fit-up welded structures with complex structures that involve many welding processes and inevitably defects. There are several methods for assessing the fatigue life of welded structures [3]. In addition to the most direct experimental methods, S-N curve-based nominal stress and fracture mechanics-based fatigue crack propagation methods are often used. However, the S-N curve-based nominal stress method has one major inherent flaw: it cannot describe crack propagation and thus cannot be used to accurately determine the fatigue life of structural members containing initial flaws [4]. Fracture mechanics theory combines the crack propagation rate and stress intensity factor at the crack tip, thus making it a valid method for assessing fatigue life.

Numerous scholars have conducted multiple studies on the fatigue crack propagation characteristics of welded joints based on the fracture mechanics theory. Schiaretti [5] explored the accuracy of the stress intensity factor of welded joints obtained using various theoretical calculation methods. Xu [6] established a model to predict the rate of fatigue crack propagation by corrosion in welded joints of steel structures in a marine environment and analyzed crack growth. However, some scholars have discovered that when the configuration is complex, obtaining an analytical solution for many of the theoretical formulae is difficult, and finite element analysis might provide good solutions to this problem. Kuts [7] and Delkhosh [8] established a crack growth calculation model based on the finite element method and Paris’ law, and investigated the impact of various welding parameters on the fatigue intensity. Some scholars have investigated the crack extension mechanism in depth from a microscopic perspective to reveal the damage development pattern of welded joints [9, 10]. However, it has been difficult to perform microscopic analyses to provide intuitive conclusions regarding fatigue performance. Thus, an increasing number of studies have focused on the analysis of influencing factors, including the impact of initial defect geometry, crack location, and yield strength distribution, on the growth path and fatigue performance [11–15]. Furthermore, targeted fatigue life assessment models have been developed for welded joints. In summary, the studies currently available have mainly focused on crack-propagation mechanisms and the analysis of influencing factors. However, their models are generally simplified, with most considering only 2D propagation scenarios. Only a few in-depth studies have investigated the other aspects of the fatigue performance of 3D crack propagation.

In this study, single lug and yoke joints of the lower chord member of a steel bridge prone to fatigue fracture were selected to establish a 3D finite element model. The initial welding defects at a single lug were considered, and a numerical solution of the crack growth and stress intensity factor at the crack tip was obtained based on M-integral and the maximum circumferential stress criterion in fracture mechanics. Moreover, the accuracy of the prediction of the fatigue crack growth path and service life of a structural member obtained using ANSYS-FRANC3D interaction technology [16] was demonstrated through experiments. Finally, the effects of the initial crack location, initial crack morphology, and inclination angle of the initial crack surface on fatigue performance were investigated through a simulation. The results of this study provide rationale for the application of bridge equipment.

2. Crack propagation theories and model construction

2.1. Characterization of initial defects

Single lug and yoke joints are structural members welded from multiple parts and are prone to welding defects of various types, including pores, undercut, lack of penetration, and burn-through. For fatigue life assessment, various types of welding defects on the surface may be equated to cracks according to the guidelines recommended by the International Institute of Welding [17]. Common surface cracks can be simplified, as shown in figure 1, where the crack length is 2c and the crack depth is a.

2.2. Crack propagation theory based on fracture mechanics

In fracture mechanics, the stress intensity factor is an important parameter for describing the stress field at the crack tip, and plays a decisive role in determining the intensity of the stress field [18]. The numerical solution of the stress intensity factor is also of paramount importance in the study of the joints containing cracks. In 1980, Rice [19] proposed the M-integral, a crack path-independent method for calculating the global energy release rate based on the J-integral, which can be used to calculate the stress intensity factor for the three fracture modes. The M-integral is expressed as follows:
where $C$ is the integral loop at the crack tip, $W$ is the strain energy density, $n_i$ is the unit outer normal vector of curve $C$, $T_i$ is the surface force acting inside the curve, $u_k, x_i$ is the reference displacement, and $x_i$ is the reference coordinate.

For composite crack propagation, the equivalent stress intensity factor was used to characterize the stress field at the crack tip, and the maximum circumferential stress theory was adopted to calculate the crack extension angle using the following expression [20]:

$$K_{eq} = \sqrt{K_f^2 + (T_{II} K_{II})^2 + (T_{III} K_{III})^2}$$  \hspace{1cm} (2)

$$\theta = 2 \arctan \left( \frac{1 - \sqrt{1 + 8(K_{II} / K_f)^2}}{4(K_{II} / K_f)} \right)$$  \hspace{1cm} (3)

where $K_{eq}$ is the equivalent stress intensity factor; $\gamma_{II}$ and $\gamma_{III}$ are the weight factors; and $K_{II}, K_{III}$ and $K_{III}$ are the stress intensity factors for the three crack modes, respectively.

Next, the NASGRO growth model was used to calculate the crack growth rate. NASGRO is an improved version of the FORMAN model, in which the magnitude of the stress intensity factor is used as the main driver for crack growth, and the effects of the stress ratio, growth threshold, and fracture toughness are considered. Therefore, the NASGRO model is more comprehensive than the Paris model, and is expressed as follows [21]:

$$\frac{da}{dN} = C \left( \frac{1 - f}{1 - R} \right) \Delta K \left( \frac{1 - \Delta K_{th}}{1 - \Delta K_{th}} \right)^p \left( \frac{1 - \Delta K_{max}}{K_c} \right)^q$$  \hspace{1cm} (4)

where $f$ is the function for crack opening; $R$ is the stress ratio; $\Delta K$ is the amplitude of the stress intensity factor; $C$, $n$, $p$, and $q$ are material-based parameters; $\Delta K_{th}$ is the threshold of the stress intensity factor amplitude; $\Delta K_{max}$ is the maximum stress intensity factor; and $K_c$ is the fracture toughness of the material.

### 2.3. Key factors and processes for 3D crack growth analysis

The key to analyzing the fatigue crack performance of a member is the selection of an appropriate crack growth model. Some scholars have simplified the 3D crack propagation criterion to a 2D crack propagation criterion [22], that is, a crack is considered to grow along a surface. In fact, cracks exist in the member in 3D, and simplifying 3D cracks to 2D cracks decreases the accuracy of the solution, and many necessary intrinsic laws may be ignored [23]. In the 2D theory, the crack tip is a point on the surface where the stress intensity factor determines the crack propagation pattern, and there is no difficulty in defining the crack front. However, when the crack front is a spatial curve, the stress intensity factors of all points in the crack front must be calculated to predict crack propagation prior to determining the fatigue life.

The actual load distribution in a structural member is often asymmetric with varied crack orientations, thus making the stress on the crack extremely complex, rather than just a single type I crack. Moreover, the stress intensity factors of complex single lug and yoke joint structures cannot be accurately calculated using the stress intensity factor formula provided in the Stress Intensity Factors Handbook [18]. Therefore, a numerical simulation approach was selected.

FRANC3D uses $M$-integral as the computational theory to provide accurate stress intensity factor values for type I, II, and III cracks to solve complex crack propagation problems [24]. The stress intensity factor was calculated based on the $M$-integral by implanting singular elements at the crack tip using the displacement extrapolation method at the 1/4 node [25] and the self-adaptive mesh technique.

It is insufficient to study only the stress intensity factor at the crack tip during the crack propagation. Crack generation does not signify immediate fracture; rather, the crack propagation phase begins, causing further growth until fracture failure. In this study, the maximum circumferential stress criterion was used as the fracture criterion to determine the crack-propagation direction. When the shear stress was zero, the crack grew in the direction of maximum circumferential stress. When the circumferential stress in this direction reached a critical value, the crack destabilized and propagated.
In our numerical simulation of the crack propagation, a quasi-static method based on the finite element method was used. The core of this method was to adopt the idea of discretization to discretize the crack propagation into multiple points and calculate the local kink angle and extension, along with the smoothed fitted front by iterative calculation to simulate crack propagation. The cycles were counted until fracture to obtain the fatigue life of crack propagation, as shown in figure 2.

FRANC3D is based on the finite element method to calculate the fracture mechanics parameters and 3D crack propagation. The flow of the analysis is illustrated in figure 3.

3. Fatigue testing and validation of the crack propagation simulation method

Fatigue testing is an indispensable method for studying the fatigue performance of single lug and yoke joints. The objectives of fatigue testing are to study the fatigue crack propagation process, obtain the life curve, and verify the accuracy of the model and calculation method by comparing their results with the simulations.
3.1. Experimental procedures
The lug plates were connected to the disk by welding. The single and double lug plates were connected via a single pin to create single lug and yoke joints with the geometrical sizes shown in figure 4. The material 30CrMnSiA was used, the properties of which are listed in table 1.

This single lug and yoke joint model was applied to a long-span steel bridge model. Boundary conditions were generated based on the calculation results for the static loads. When considering only the self-weight of the entire bridge, the single lug and yoke joints were subjected to a tension force of 180 kN. Under extreme working conditions, a vertical load of 100 t was applied at the midspan. The maximum axial tension of the single and double lug and yoke joints was 780 kN under the joint actions of an impact coefficient of 1.2, lateral wind load of gale force of 8, lateral force of the vehicle, deflection, and self-weight. The boundary conditions are shown in figure 5(a).

The experiment was set up based on the boundary conditions, as shown in figure 5(b). The two ends of the single lug and yoke joints were connected to the MTS (Mechanical Testing & Simulation) test machine through transition members, and the entire experimental setup was vertically loaded with a cyclic load of 180–780 kN. Fatigue testing was performed on the single lug and yoke joints at a stress ratio of 0.23 and a frequency of 2 Hz.

3.2. Analysis of experimental results
The welding focus areas were monitored in real time. Regular noise from the single lug and yoke joint was observed during the test at approximately 5,800 rounds of fatigue testing. At round number 9,500, a small crack

Table 1. 30CrMnSiA material properties.

| Material type | E/MPa | σu/MPa | σs/MPa | Poisson’s ratio |
|---------------|-------|--------|--------|----------------|
| 30CrMnSiA     | 203   | 886    | 1,177  | 0.3            |

Figure 4. Schematic of the structural details.

Figure 5. Setup of single lug and yoke joints: (a) Boundary conditions (b) Test setup.
was found at the chamfer of the joint between the single lug plate and disk, as shown in figures 6(a) and (b). As the number of fatigue load times increased, the crack propagated along the joint between the single lug and disk, where the propagation was faster along the edges without chamfers. The propagation process is illustrated in figure 6(c). Finally, at 11,969 loading rounds, the connection end of a single lug fractured suddenly and separated from the disk. Figure 6 shows the entire process of crack generation, propagation, and damage.

Generally, defects were present at the welded site between the lug plate and disk, and the cracks tended to originate and propagate from there. The cracks tended to incline in the direction of the joint between the lug plate and disk owing to the high stress concentration and low crack resistance at the joint. Thereafter, the crack continued to propagate on a plane along the welding line between the lug plate and disk, without any significant inclination. When the crack had propagated to a certain extent, the strength of the remaining section of the member was insufficient to support the load stress, thus leading to rapid destabilization and propagation of the crack, which then resulted in a transient fracture [26]. Figures 6(e) and (f) show that the member fractured from the crack propagation at the welding line, with the fracture remaining almost perpendicular to the loading direction with a slight inclination toward the inner side of the disk. Additionally, a clear boundary was observed between the instantaneous fracture and crack propagation zones, with the instantaneous fracture zone having a rougher surface than that of the crack propagation zone.

### 3.3. Validation of the crack propagation simulation method

Fatigue crack propagation analysis is an important method for studying and analyzing the entire life cycle and fatigue patterns. The damage to the single lug and yoke joints caused by fatigue loading is similar to the fracture of other metallic materials, with the fracture bearing obvious morphological characteristics that retain traces of the fracture process. Through simulations, the entire crack propagation process can be accurately inferred.

According to the test results, the crack observed at 9,500 cycles was assumed to be the initial status of the defective member, which fractured after 2,469 fatigue loading cycles. In this study, the shape of the initial crack was approximated as a semi-ellipse on the surface with an inclination angle that was consistent with the observations. This process was modeled and simulated using ANSYS and FRANC3D interactive techniques. To ensure the accuracy of the solution, 20-node isoparametric degenerative singular elements were used for the crack front, and the crack tip nodes were replaced by 1/4 nodes to solve the stress singularity issue. The element assignment of the crack and nearby area was complex; thus, the self-adaptive mesh assignment technique was used. A comparison of the crack propagation paths, and morphological changes is presented in figure 7.
During crack extension, the shape of the crack front was a series of circular arcs. The overall section of the test member was parallel to the surface of the disk, with significant differences between the crack extension and instantaneous fracture areas. However, it was difficult to precisely reproduce the test results during the simulation because of the uncertainty in the angle between the initial crack surface and the surface of the lug plate.

The overall crack propagation life values observed at the focal locations during the tests were compared with the crack extension life curves calculated using FRANC3D, as shown in figure 8. The path length represents the sum of the extension distances between the midpoints of the crack front and the initial crack at each extension step. The comparison revealed that both paths were essentially the same during the early expansion. However, the error was more evident during the later stages of the extension, which was caused by instabilities in the test. In contrast, the numerical simulation followed the ideal test process; thus, the crack extension life curve was smoother and more accurate. The number of remaining fatigue lives, as indicated by the results of the software simulation, was 2,377, with an error of −3.73% compared with the experiment. Thus, the ANSYS-FRANC3D
interactive technology simulated the crack extension and predicted the remaining fatigue life reasonably well, thereby meeting the accuracy requirements for general engineering applications.

4. Analysis of the factors influencing the crack parameters

Based on the test results, the location where fatigue fractures were most likely to occur was determined to be the welded area between the root of the lug plate and disk. In this study, for structural modelling and simulation, the crack was assumed to be near the welding joint without a chamfer. Next, the effects of the initial crack location, morphology, and inclination angle on the fatigue performance were investigated through a simulation.

4.1. Initial crack location

Defects that appear during the welding process have different effects depending on their location. Therefore, it is important to study the initial defect impact on the remaining fatigue life. The crack models were established at different locations, as shown in figure 9. The vertical crack distance from the disk at each location was 2 mm and the horizontal spacing was 15 mm. The initial crack was assumed as $a = 1$ mm and $c = 2$ mm, and the shape ratio was $a/c = 0.5$ [27]. The cracked surface was perpendicular to the surface of the lug plate.

Figure 10 shows the relationship between the number of load cycles and crack extension length at five different locations. Figure 11 shows a graph of the remaining fatigue life as a function of the location, where L indicates the distance between each crack and crack location 1 (the crack near the edge of the chamfer). Crack location 1 has the largest extension rate and shortest remaining fatigue life. The remaining fatigue life increased...
linearly with $L$. Because the initial crack location exerts a large impact on the remaining fatigue life, additional attention should be paid to cracks at the edges during use.

4.2. Initial crack morphology
Crack position 5 was selected, with the crack surface perpendicular to the surface of the lug plate. Eight crack patterns were introduced, and the crack depth of $a = 1$ mm was kept constant. The shape ratios $a/c$ were chosen as 0.2, 0.4, 0.6, 0.8, 1.0, 1.3, 1.6, and 2.0, respectively. The crack patterns are shown in figure 12.

The crack extension process for each of the above-mentioned crack shapes was simulated to obtain the relationship between the number of load cycles and crack extension length, as shown in figure 13. The relationship between the remaining fatigue life and the initial crack length $c$ was obtained. The results are shown in figure 14.

The relationship between the number of load cycles and the fatigue crack extension length can be used to qualitatively analyze the impact of the initial crack shape on the fatigue performance. As shown in figure 13, as the initial crack length $c$ increased, the more obvious the initial defect of the crack, the life of the joint became shorter. Significant differences were observed in the crack extension rate during the early stages. At a given crack depth, the larger the initial crack length, the greater the extension rate. However, minimal difference was observed in the extension rate during the later stages, which was because of the shape ratio tending to reach a stable value as the crack extended [28, 29]. When the crack shape ratio $a/c > 1$, the single lug and yoke joints were more sensitive to the change in crack length, and the remaining fatigue life rapidly decreased with increasing crack length. The overall exponential decay is observed as follows:

$$N = 61666.27(2c)^{-0.518}$$

where $N$ is the remaining fatigue life.

The stress intensity factor at the initial crack front was obtained to investigate the change in the crack tip. The results are shown in figure 15. The crack front length was normalized such that its horizontal coordinates were between 0 and 1, thus characterizing the crack front from one end to another. It can be observed that the stress intensity factor of the crack tip is strongly influenced by the shape ratio. When the crack was flat ($a/c < 1$), the stress intensity factor was greatest in the middle of the crack front, whereas when the crack sharpened gradually
4.3. Initial crack angle inclination

Owing to the uncertainty in the initial angle crack inclination, it was necessary to model numerous different angles to simulate crack extension. The initial weld defect was assumed to be located at the upper edge of the welding line without a chamfer. The direction of the crack perpendicular to the surface of the plate was set as $0^\circ$. A crack inclined in the direction of the pinhole was assumed to be positive, and a crack inclined in the direction of the disk was assumed to be negative, as shown in figure 16.

Crack growth was calculated for cracks with surface inclination angles of $-60^\circ$, $-40^\circ$, $-20^\circ$, $0^\circ$, $20^\circ$, $40^\circ$, and $60^\circ$, as shown in figure 17. The crack front continued to extend forward upon cyclic loading of the member with increasing extension rates. When the initial crack surface angle was less than $0^\circ$, a minimal difference was observed in the remaining fatigue life of the members. However, when the angle was greater than $0^\circ$, the remaining fatigue life increased rapidly with the increase in the angle. Correspondingly, a similar pattern was observed in the initial stress intensity factor of the crack, where the stress intensity factor at the crack tip increased with crack length.
decreased rapidly when the angle was greater than 0° and decreased relatively slowly when the angle was less than 0°. For details, see figure 18.

Because of the consistent crack morphology, all the maximum values of the stress intensity factor at the crack front were observed at the bottom of the crack, whereas all the minimum values were observed near the surface edges. However, the analysis showed that the stress intensity factor was greatest at a crack surface angle of $\theta = 0^\circ$. Moreover, the stress intensity factors of the crack tips on the two sides were asymmetrical and generally larger for $\theta < 0^\circ$. The crack expansion process was further analyzed, as shown in figure 19.

From the crack growth path shown in figure 19, it can be seen that for cracks with the same morphology and different initial angles, all paths tend to be inclined at $-20^\circ$ and $0^\circ$. This result is consistent with the experimental results. Crack growth was adjusted in the first several steps. The crack surface transitioned to curves, and as the cracks deepened, they extended along a near-flat surface.

5. Discussions

The crack extension behaviors were investigated based on the theories of fracture mechanics using ANSYS-FRANC3D interactive technology, and the effects of the initial crack parameters on fatigue performance were determined. The results of this study provide rationale for the application of bridge equipment. However, the main results were obtained under certain assumptions. Limited to the experimental conditions, there is currently no experimental verification of the relevant conclusions. The established model was only limited to the welding defects of the joint, and the specific performance is as follows:
Figure 17. Change in the number of load cycles with crack extension length.

Figure 18. Change in the stress intensity factor at the crack tip with different crack surface angles.

Figure 19. Schematic of the crack extension.
1. Initial crack location. The initial position assumed was near the weld on the long side of the single lug plate, and the fatigue life was shorter when the initial crack was in the corner of the single lug plate. The initial defect position of welding is random. In fact, the initial defect location for welding is random.

2. Initial crack morphology. The shape ratio tending to reach a stable value as the crack extended. It is meaningful for the preliminary study of crack propagation. However, when the crack propagates to the later stage, the semi-elliptical crack transforms into an angular crack. The crack model changed and failed.

3. Initial crack angle inclination. The propagation angle of the crack front is a complex issue. In principle, the front edge will be deflected in the direction of greater stress during the crack propagation process. However, the appearance of cracks will change the original stress-strain field, and for complex components, it needs to be analyzed according to the actual stress situation.

6. Conclusions

In this study, the fatigue performance of single lug and yoke joints containing cracks was investigated based on the theories of fracture mechanics and simulations using ANSYS FRANC3D. The following conclusions were drawn.

1. The results of the 3D crack extension simulation using FRANC3D are in strong agreement with the experimental results. The change patterns of the stress intensity factor at the crack tip were analyzed.

2. The crack growth rate changed from low to high at different initial crack locations. The initial cracks in areas with higher stress had a greater impact on the fatigue performance of the joint. The number of remaining fatigue lives increased linearly as the initial crack location moved from the edge of the lug plate to below the pinhole.

3. The crack extension rate during the early stage varied significantly with the different initial crack morphologies. However, the extension rates during the later stages were similar. The stress intensity factor in the middle of the crack front was largest at a shape ratio of \( a/c < 1 \). When \( a/c > 1 \), the points with the maximum stress intensity factor were located at the ends of the crack surface. Overall, at a given crack depth, a greater initial crack length may be associated with a higher crack growth rate and exponential decay of the remaining fatigue life.

4. At different initial crack surface angles, the crack front tended to align with the direction of the higher stress during crack growth, thus changing the crack surface into curves. An angle more inclined toward the region with a greater stress concentration corresponded to a faster crack growth rate and shorter remaining fatigue life.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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