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Boundary element analysis of fatigue behavior for CFRP-strengthened steel plates with center inclined cracks

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ABSTRACT

This paper presents a numerical study on the stress intensity factor (SIF) and fatigue behavior of carbon fiber-reinforced polymer (CFRP) strengthened steel plates with center inclined cracks under uniaxial tensile fatigue loading. Effects of prestress level in CFRP and initial crack inclination angle were investigated. Results indicated that the CFRP laminates could reduce the mode I SIF and effective SIF range, thereby enhancing the fatigue life of the steel plates. The strengthening was more efficient by using the prestressing technique. It was found that fatigue life was approximate for specimens with an identical crack projection length on the plane perpendicular to the load. This indicated that the effect of the initial crack inclination angle on the fatigue crack propagation life of the steel plate was limited when subjected to a unidirectional load. The findings of this study can be adopted as a reference for the repair of existing metallic structures with inclined cracks.

1. Introduction

Fiber-reinforced polymer (FRP) materials have advantages of high strength-to-weight ratio, good resistance to corrosion and ease of installation, and therefore are recognized as an innovative approach in retrofitting of aged infrastructures [1–3]. Steel structures are susceptible to fatigue damage when subjected to long-term cyclic loading. Since fatigue fracture is a brittle failure without macroscopic plastic deformation, effective techniques should be taken to prevent it from happening. Compared with the traditional mechanical fastening or riveting, adhesively bonded composite patch repair not only avoids new defects introduced by welding or drilling, but also exhibits more outstanding strengthening effects. Aljabar et al. [4,5], Ye et al. [6] and Colombi et al. [7] performed fatigue experiments on carbon FRP (CFRP) repaired steel plates and discovered that the fatigue life was generally improved by 1–2 times. Chen et al. [8] conducted both numerical and experimental studies on the fatigue behavior of non-load-carrying cruciform welded joints reinforced by CFRP sheets, and it was demonstrated that the overlays had considerable effects on retrofitting. Aakkula et al. [9] proposed a series of fatigue experiments on boron fiber-reinforced polymer (BFRP) and CFRP-repaired aluminum plates, and the results indicated that CFRP and BFRP patching enhanced the fatigue life up to 6 times. In terms of steel members, Yu and Wu [10] carried out fatigue tests on cracked steel beams with various strengthening techniques. They concluded that CFRP laminates were superior to high-strength steel plates and SAFSTRIP® plates as repair materials. Jiao

et al. [11] also conducted four-point bending fatigue tests on CFRP strengthened cracked beams. The fatigue life was prolonged by 7 and 3 times for specimens retrofitted with one layer of CFRP plate and 4 layers of CFRP woven sheets, respectively.

It is therefore concluded that the application of fiber-reinforced polymer (FRP) materials has a promising future in the rehabilitation of civil structures [12]. However, it has been found that it is difficult to take advantage of FRP materials' high tensile strength when they are directly bonded to repaired members. Therefore, many researchers adopt prestressed FRP to achieve better strengthening effects. Emdad et al. [13] conducted fatigue tests on prestressed CFRP-repaired center-notched steel plates. The results indicated that the fatigue life was enhanced as much as 35.24 times compared to that of the control specimens. The increasing enhancement was more notable with a higher prestress level. Experimental results obtained by Ye et al. [6] showed that the fatigue life was improved by 3.7 times when the prestress level was increased from 600 MPa to 1200 MPa. With the increasing computational power, numerical analysis on the fatigue crack propagation was employed. Yu et al. [14] and Liu et al. [15] conducted extensive numerical simulations on the mode I fatigue crack propagation of CFRP strengthened steel plates, and good consistency was observed with the experimental results.

Most of the previous research was focused on the mode I fatigue crack. Whereas, in engineering practice, the initial cracks are usually loaded in mixed-mode conditions due to randomly located initial defects [16]. Though fatigue behavior of aluminum panels with inclined

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crack have been investigated [17–19], a limited investigation has been reported on steel plates. Aljabar et al [1] conducted fatigue tests on CFRP-strengthened steel plates with inclined initial cracks and developed a mixed-mode modification factor for fatigue life prediction. Different damage degrees were also considered in a series of tests [5]. Further theoretical and numerical analysis is necessary to explore the mixed-mode fatigue problems.

In this paper, the mixed-mode I and II fatigue crack propagation of steel plates with prestressed and non-prestressed bonded CFRP was simulated by using the boundary element method (BEM). Both the stress intensity factor (SIF) and fatigue crack propagation life were calculated with fracture mechanics. The effects of prestress level in CFRP and crack inclination angle on fatigue performance were studied.

2. Numerical simulation of crack propagation

The BEM has been successfully employed to simulate the mode I fatigue behavior of cracked metallic structures patched with CFRP materials [14,15,20–22]. With regard to mixed-mode fatigue problems, crack trajectories have to be taken into consideration besides the range of SIFs during the crack propagation analysis.

2.1. Boundary element method (BEM)

The Boundary element method (BEM) is a general numerical computational technique which solves boundary integral equations. It can be applied in many areas of engineering and science such as fracture mechanics [23]. The BEM endeavors to utilize the given boundary conditions to fit boundary values into the integral equations, instead of fitting values throughout the space defined by a partial differential equations. Thereafter, the integral equation can then be used again to numerically calculate the solution directly at any desired point in the interior of the solution domain during the post-processing stage. Crack growth can be simulated with the technique of dual boundary element method (DBEM) [24,25]. The method integrates two independent boundary integral equations: the displacement equation applied at the collocation point on one of the crack surfaces and the traction equation applied to the other surface [26].

In comparison with the finite element method (FEM), BEM has been proven to be time-saving since only boundary discretization is required. This can significantly reduce both the number of elements and degrees of freedom [27]. When applied to simulate a crack growth process, the remeshing work is dramatically reduced compared to FEM. The boundary element analysis system (BEASY) software has the capacity to perform numerical analysis based on BEM.

Extended finite element method (XFEM) is another approach for solving crack growth problems. The method has advantages such as there is no need to alter the mesh generation with the appearance of a new crack front and to define crack tip elements with singularities in finite element models. The XFEM model has been adopted to simulate the crack growth of an aluminum pipe which showed a good consistency with tests [28].

2.2. Stress intensity factors (SIFs)

Calculation of SIF at the crack tip is critical to fatigue crack propagation rate [29]. It is determined by the J -integral method, as expressed by Eq. (1) [30].

$$J = \int_{\Gamma} \left(\omega dy - T_i \frac{\partial u_i}{\partial x} ds \right) \quad (1)$$

where ω is the strain energy density; T_i is the component of the traction vector; u_i is the displacement vector component and ds is the length increment along the contour Γ . The relationship between J -integral and SIFs is shown by Eq. (2) [30] as

$$J = \frac{K_I^2 + K_{II}^2}{E'} \quad (2)$$

where E' is the elasticity modulus (E for plane stress conditions and $E' = E/(1-\nu^2)$ for plane strain conditions). The integral J can be decomposed into the symmetric and antisymmetric components of displacement and stress fields. Finally, the following relationships hold:

$$J^I = \frac{K_I^2}{E'}, \quad J^{II} = \frac{K_{II}^2}{E'} \quad (3)$$

2.3. Crack growth criterions

The description of fatigue crack propagation under mixed-mode conditions is of prime importance in fracture mechanics. The main concern is in which direction will the crack propagate. The authors have performed a preliminary on fatigue crack propagation prediction by using two popular crack growth criteria [31], i.e., the maximum circumferential stress criterion (MCSC) [32] and the minimum strain energy density criterion (MSEDC) [33]. The criteria were introduced in the frame of the standard BEM, where the field variables are evaluated in the vicinity of the tips [26]. The results obtained based on MCSC and MSEDC were approximate to each other and MSEDC criterion was adopted in this study.

2.4. Crack propagation law

The classical Paris Erdogan Law [34] was adopted to establish the relationship between the crack growth rate and SIF range, as shown in Eq. (4).

$$\frac{da}{dN} = C (\Delta K_{\text{eff}})^m \quad (4)$$

where N is the number of applied fatigue cycles; a is the crack length; da/dN is the crack growth per cycle; ΔK_{eff} is the effective SIF range; while C and m are material constants.

For fatigue crack propagation under mixed-mode I and II cyclic loading, an effective SIF range can be calculated with Eq. (5) proposed by Tanaka [33].

$$\Delta K_{\text{eff}} = \sqrt[4]{(\Delta K_I)^4 + 8(\Delta K_{II})^4} \quad (5)$$

3. Numerical modeling

In this study, CFRP-strengthened steel plates with two inclined cracks were analyzed under fatigue tensile loading. All specimens were central notched with different crack inclination angles to study the mixed-mode fatigue fracture. A total of 22 models were analyzed to investigate the repairing effect on fatigue performance.

3.1. Geometry configurations and material properties

Fig. 1 shows a typical specimen configuration and details of the initial crack. The rectangular steel plate had a length of 200 mm (L), a width of 90 mm (W) and a thickness of 10 mm (t). Two inclined slots were cut from a central hole with a radius of 2.5 mm. Different inclination angles (0° , 15° , 30° , 45° and 60°) with respect to the vertical axis were adopted while the vertical projection of the crack lengths a_{xp} was kept constant as 4.5 mm ($a_{xp} / W = 0.05$). The mixed-mode cracks were presumed to occur when the specimens were subjected to a remote tensile fatigue loading. The composite patch had a nominal thickness of 1.45 mm. They were prestressed and patched on both sides of the steel plates as illustrated in Fig. 1. The dimensions of the patch were 300 mm $\times$ 25 mm. The thickness of the adhesive was assumed as 1.0 mm.

Table 1 presents a summary of the modeling matrix and simulation

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