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Crack propagation prediction of CFRP retrofitted steel plates with different degrees of damage using BEM

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ABSTRACT

Although carbon fibre reinforced polymer (CFRP) materials have proven effective in strengthening steel structures especially when used to improve fatigue behaviour, further study is required to investigate their effectiveness when applied at different stages of crack propagation in steel elements. This paper presents a numerical study on CFRP retrofitted steel plates with different degrees of damage using the boundary element method (BEM). The numerical results compared well with the experimental data, which demonstrated that the BEM is reliable for crack propagation analysis of CFRP laminate retrofitted steel plates. Finally, a parametric analysis was conducted to investigate the influence of bond length, bond width, CFRP stiffness and adhesive shear modulus on stress intensity factor (SIF) values.

1. Introduction

Bonding repair technique using CFRP materials has been considered as an alternative to traditional methods in structural retrofitting and maintenance [1–4]. In the field of fatigue crack repair of steel structures, the high stiffness of CFRP materials can reduce stress ranges at crack tips and promote a crack bridging effect due to the outstanding fatigue resistance of CFRP materials. The CFRP composite repairing system could completely arrest the crack propagation in some prestressing cases [5,6]. This innovative method avoids drawbacks of traditional repair techniques such as stop holes, steel plate attachment or replacement. Extensive research has been conducted to investigate the improved fatigue behaviour of defective steel elements strengthened by CFRP materials [7,8] and the bond behaviour between composites and steel elements [9]. Detailed principles were discussed for the production of strong, durable adhesive bonds [10]. Concerning the high stress at bond edges observed in this kind of strengthening system, Wang et al. [11] and da Silva et al. [12] attempted edge tapered patches to improve the bond behaviour. However, most previous study on the improvement of fatigue behaviour of bonded elements focused on specimens with small and fixed initial cracks. Very little research has been reported concerning specimens with cracks of different lengths. Considering that the degree of damage varies in different structures within real construction, it is important to know more about the effectiveness of this retrofitting method when applied to different stages of crack propagation in structural elements. Consequently, in order to develop an effective bonded repair methodology, it is important to accurately perform a crack growth study of CFRP retrofitted steel elements with different configurations.

Linear elastic fracture mechanics (LEFM) is usually adopted to describe crack behaviour. The fundamental assumption of LEFM is that the crack behaviour is determined solely by the values of SIF which is a function of applied loads and geometries of cracked structures. The SIF value, thus, plays a fundamental role in LEFM applications [13]. Mitchell et al. [14] first adopted the finite element method (FEM) to analyse the stress and strain fields of a cracked metal sheet strengthened by a composite patch. The predicted strain results compared well with the experimental data. Ratwani [15] performed a similar study on a two dimensional finite element model but paid more attention to SIF values at the crack tip. The analytical SIF values also agreed well with the test results. The influence of out-of-plane bending was also considered. So far, extensive study has been conducted to investigate the stress field around the crack tip with the FEM to optimise this

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Nomenclature

β	degree of damage
a	half of crack length
N	number of fatigue cycles
C, n	material constants in Paris Law
ΔK	stress intensity factor range
a_i	initial crack length
a_f	final crack length
F	general correction factor
$\Delta\sigma$	nominal stress range
F_E	effect of elliptical crack fronts
F_S	effect of free surface
F_W	effect of finite width
F_G	effect of non-uniform opening stresses
b	width of specimen
K_t, K_u	shear spring stiffness
K_n	axial spring stiffness
E_a	Young's modulus of adhesive
G_a	shear modulus of adhesive
t_a	measured adhesive thickness
ν	Poisson's ratio of adhesive
R	stress ratio
p, q	empirically derived constants
f	crack opening function
ΔK_{th}	threshold stress intensity factor range
K_c	fracture toughness
N_e	tested fatigue cycles
N_p	predicted fatigue cycles
K_I	stress intensity factor in mode I
K_{II}	stress intensity factor in mode II
K_{III}	stress intensity factor in mode III
K_{CFRP}	stress intensity factor value of a specimen strengthened with CFRP
K_{plate}	stress intensity factor value of a bare steel specimen
S	stiffness ratio
E_f	Young's modulus of CFRP laminate
t_f	thickness of CFRP laminate
E_s	Young's modulus of steel plate
t_s	thickness of steel plate

strengthening method [16–24]. The effects of different parameters in the retrofitting system such as the shape, position, material properties of overlays on the fatigue behaviour of strengthened elements were investigated. Nevertheless, these studies mainly concentrated on the SIF values corresponding to a specified crack length. The numerical simulation of the full process of fatigue crack growth was limited. Although crack propagation analysis using mesh generation and cohesive elements has gained some favourable attention [25–29], these methods require a discretisation of three-dimensional volumes, which are complicated and time consuming.

Regarding the crack propagation analysis, the BEM is comparatively more efficient. It only needs to mesh the boundary of models, which reduces the dimension of the solution. Consequently, the mesh generation around the crack tip during the crack propagation process is also simplified. Young and Rooke [30] proposed a two dimensional boundary element model to analyse patched and stiffened cracked panels wherein they evaluated both the stress distribution and the SIF. Wen et al. [31] modelled the interaction between the plate and the overlay in the repair system as a distribution of forces, and examples were presented to demonstrate the accuracy and efficiency of the method. Mashiri et al. [32] and Chen et al. [33] carried out three-dimensional crack propagation analysis on different fillet welding joints. Liu et al. [34] investigated the SIF values, crack propagation and fatigue lives of CFRP sheet strengthened steel plates and demonstrated that the BEM was well suited for simulating fracture and crack propagation of CFRP sheet bonded steel plates.

In the present work, the BEM was employed to conduct a numerical simulation of CFRP laminate strengthened steel plates with different degrees of initial damage. The crack propagation analysis was conducted based on a commercial code (BEASY) [35] using the dual boundary element methodology (DBEM). The effect of retrofitting configuration and CFRP stiffness was also considered. The stress distribution, fatigue life and SIF value were evaluated. The numerical results were compared with the experimental findings reported in Yu et al. [36]. Good agreement of the fatigue life and crack propagation demonstrated that the BEM was reliable for crack propagation analysis of CFRP laminate retrofitted steel plates with different degrees of damage. The effect of bond length, bond width, CFRP stiffness and adhesive shear modulus on the SIF values were also evaluated using the BEM.

2. Boundary element method

2.1. Introduction to BEM

The BEM is well established and considered as an alternative to the FEM in a number of engineering fields since the 1970s [37]. The main attraction of the BEM is largely attributed to the reduction in the dimensionality of problems, which means that, in three dimensional problems, only surfaces are required to be modelled and meshed to perform the required integration when using the BEM in comparison with volumes when using the FEM, resulting in substantial savings in solving time.

Another considerable advantage of the BEM is the introduction of discontinuous elements. A discontinuous element is represented as an element where locations of a mesh point and a node are not coincident. Therefore, it is possible to model discontinuous stress results since problem variables are not forced to be continuous across elements. It makes the BEM especially useful in the simulation of fracture mechanics for the method achieves high accuracy where the stress field at the crack tip is extremely discontinuous. Moreover, the discontinuous elements offer more freedom to the mesh process.

2.2. Crack propagation analysis using BEM

The BEM is an ideal solution for fracture mechanics and crack growth simulation because high stress gradients at crack fronts can be accurately modelled [38]. However, direct application of the BEM to solutions of general crack problems cannot be achieved due to the coincidence of the crack surface, which gives rise to a singular system of the algebraic equation. Generally, the sub-region method [39] and the DBEM [40,41] are adopted to overcome this problem. The sub-region method defines artificial boundaries along the crack surfaces, thus creating several sub-regions without cracks. These artificial boundaries need to be introduced repeatedly for every increment of the crack extension during the analysis process. Also the boundaries differ from each other due to the geometry change during the crack propagation, which makes it hard to be performed automatically. The DBEM, which represents the crack by two elements occupying the same physical location, each element representing a face of the crack, was used in the adopted software (BEASY). Two independent