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Boundary element analysis of CFRP reinforced steel plates

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ABSTRACT

This paper expands the studies on the fatigue behaviour of CFRP-sheet reinforced steel plates using the numerical method of boundary element analysis. The numerical software program BEASY was adopted in calculating stress intensity factors, crack propagation and fatigue lives. The composite patch and the cracked steel plate were simulated using surface elements, whereas the adhesive layer was simulated as interface elements to connect the patch and steel plate. This method was validated by the good agreement between the numerical and experimental results. The influences of bond length, bond width, patch configuration, CFRP layer number, the modulus of the composite patch and adhesive shear modulus on the stress intensity factors and their fatigue lives were then evaluated using the boundary element method.

1. Introduction

Examination of previous structural failures has revealed that many failures are due to fatigue fracture, which is common for metallic structures. Once fatigue crack initiates, they may propagate at an increasing rate and lead to catastrophic failure. Therefore it is very important to have the cracks repaired at an early stage. Recently CFRP (Carbon Fibre Reinforced Polymer) has become popular in strengthening metallic structures [1–3]. Experimental studies [4–13] have shown that composite repair is an efficient and cost-effective means to reduce crack growth rate and extend service life. By using composite patching techniques, some of the loads could be transferred to the composites by structural adhesives so that the strength or fatigue behaviour of the structures could be improved. Undoubtedly the behaviour of the patching techniques depends on the efficiency of the load transfer mechanisms, which is affected by many parameters, including the dimensions and material properties of the repaired structure, the composite patch and the structural adhesive. Therefore their effects on the bond integrity need to be studied if efficient bonded patches are to be designed. Experimental testing is an essential but expensive part of this development. In recent years, numerical methods have been generally used in the design of composite repairs because of the convenience and efficiency of computer analysis.

Of the different numerical approaches, finite element method (FEM) is the most commonly used technique for stress analysis because it can model extremely complex configurations and easily determine the response at any desired point of a structure. The problems involving nonfracture-driven plasticity, materials with significant inhomogeneities and shells may be adequately solved by the finite element method [14].

Mitchell et al. [15] appear to be the first to have carried out computer analysis of composite-reinforced metal sheets. They used a two-dimensional finite element method (FEM) to predict the strains and good agreement with the experimental observations was achieved. Ratwani et al. [16,17] and Anderson et al. [18] also made thorough attempts by using two-dimensional finite elements towards the analytical understanding of crack growth behaviour in composite-bonded metallic structures. Jones and Callinan [19,20] proposed an element stiffness matrix and implemented it in a standard finite element program to analyse cracking in composite-repaired metal sheets. Following their pioneering work, further numerical studies on composite-reinforced metallic structures were conducted and more methods were developed [21–30].

Similar to the finite element method, the boundary element method is another frequently used and well-established numerical technique [31]. It has been widely adopted to analyse composite-repaired metallic structures. It was first applied to crack growth analysis by Cruse and Besuner [32]. Ingraffea et al. [33] also used it in the analysis of crack extension problems. Dowrick et al. [34], Young et al. [35,36] and Wen et al. [37,38] used BEM in the analysis of reinforced cracked sheets, in which the patch and cracked sheet were modelled using two-dimensional boundary elements and the adhesive was simulated as shear springs. Mi and Aliabadi [39,40] and Mashiri et al. [41] applied the method to the analysis of three-dimensional mixed-mode crack growth. The boundary

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Nomenclature

a	crack half-length
E_a	elastic modulus of the structural adhesive
E_C	equivalent modulus of the composites
γ	Poisson's ratio of the adhesive
G_a	shear modulus of the structural adhesive
k_n	stiffness of out-of-lane spring in the BEASY models
k_p	constant obtained in the parametric study
k_t, k_u	stiffness of in-plane spring in the BEASY models
L	bond length of CFRP-sheets reinforced steel plate
L_{op}	optimal bond length of CFRP-sheets reinforced steel plate
N_1	experimental fatigue life
$N_{1,s}$	experimental fatigue life of unpatched steel plate
N_2	fatigue life obtained using BEASY
N_p	predicted fatigue life
t_a	thickness of one layer of structural adhesive
t_c	total thickness of the composites

element method has been shown to be an accurate and versatile technique [42–46].

In comparison with previous analytical methods and experimental data, both numerical methods are able to provide reasonably accurate analysis of composite repairs [16–30,34–38]. When used to analyse problems involving crack propagation, BEM may be more efficient [41]. One of the main advantages of BEM is that only a mesh of the surfaces is required, making it easier to use and often more efficient. Because this method requires only boundary discretization, re-meshing work for the simulation of the crack growth process is reduced compared to FEM, especially for three-dimensional analysis. BEM is therefore a powerful alternative to FEM for problems involving cracks [41–46].

This paper details the use of the boundary element method to carry out numerical and parametric studies for CFRP-sheet reinforced steel plates. The computer program BEASY [47] was adopted. The composite patch and the cracked steel plate were simulated using surface elements, whereas the adhesive layer was simulated as interface springs to connect the patch and steel plate. The numerical results are compared with the experimental findings reported in Liu et al. [13]. Good agreement is achieved for both double-sided and single-sided repairs. A parametric study is carried out to quantify the influences of bond length, bond width, patch configuration, CFRP layer number, the modulus of the composites patch and adhesive shear modulus on the stress intensity factors and their fatigue lives.

2. Brief summary of experimental program

A series of tests were conducted by Liu et al. [13] to investigate the fatigue behaviour of cracked steel plates strengthened by CFRP. Basic data relevant to the BE numerical simulations are summarised in this section to assist the readers. They include repair configurations, specimen dimensions, material properties, load ranges, graphs showing crack length versus number of fatigue cycles and fatigue lives.

The specimens were made of CFRP sheets bonded to cracked steel plates by epoxy adhesive. Typical geometry and configuration of the steel plates, adhesive layers and composite patches are shown in Fig. 1. The steel plates had uniform dimensions of 500 mm × 90 mm × 10 mm. They were all machined with a central notch consisting of a 5 mm hole and two initial slots. The slots were 1 mm long and 0.3 mm wide. The cracked plates were prepared according to ASTM E-647 specifications [48]. They were reinforced by three or five layers of carbon fibre sheets. Four types of patch configuration were designed, as shown in Fig. 2. Case A is the bare steel plate without any patch. These were tested as control specimens. Case B is the steel plate fully covered by composite patch. Case C is the steel plate bonded by two separate patches straddling the centre hole. Case D is the steel plate partially bonded by patches around the central part. The bond width was defined as the total width of CFRP patch and the bond length was defined as half the length of the CFRP patch.

The mechanical properties of the steel plates were determined through tensile coupon tests according to AS1391 [49]. The mean yield stress, tensile strength and Young's modulus are 297 MPa, 420 MPa and 200 GPa, respectively. Carbon fibre sheets, MBrace CF130 and MBrace CF530, were used as the patching systems. The fibres are uni-directional and are placed in the longitudinal direction of the plate. The measured elastic modulus, tensile strength and ultimate strain are 230 GPa, 2675 MPa and 1.2% for CF130, and 552 GPa, 1175 MPa and 0.2% for CF530 [50], respectively. In this study, MBrace CF130 and CF530 are referred to as normal modulus CFRP and high modulus CFRP, respectively. The structural adhesive Araldite 420 was used to join the CFRP and steel plate together. The measured tensile strength, elastic modulus and ultimate strain are 28.6 MPa, 1901 MPa and 2.4%, respectively [50].

All the specimens were subjected to uniform cyclic loading with a stress ratio of 0.1 until failure occurred. The stress ratio, defined as the ratio of minimum stress to maximum stress of the fatigue cycles, of 0.1 is commonly used in fatigue testing (e.g. Mashiri et al. [51]). The constant amplitude sine waves range from 13.5 kN to135 kN.

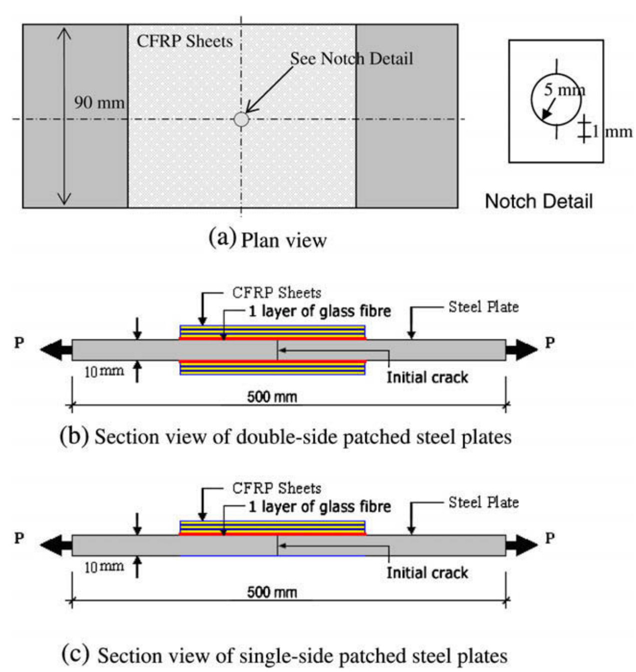

Fig. 1. Configuration of composites repaired steel plates (not to scale).