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# Boundary element analysis of edge cracked steel plates strengthened by CFRP laminates

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ABSTRACT

This paper presents a numerical study on the fatigue behaviour of edge cracked steel plates strengthened with carbon fibre reinforced polymer (CFRP) laminates based on the boundary element method. The models were first validated by a comparison with experimental data in the literature, followed by a further investigation into the effects of initial damage degree, bond configuration and crack type on the fatigue behaviour of retrofitted specimens. Results indicated that CFRP overlays could effectively slow down crack growth and extend fatigue life of edge cracked steel plates, regardless of the initial damage levels. It seems better to adopt an early repair considering the total fatigue life. Double-sided repair showed significant superiority over single-sided repair when equivalent composite materials were used. For the repair configuration presented herein, the strengthening was more efficient for edge cracked steel plates than centre cracked steel plates.



## 1. Introduction

Deterioration of aging steel structures such as bridges due to load and environmental effects is a world-wide problem as traffic volume demands continue to call for improved structural performance. Rehabilitation techniques provide an alternative way to replacement and reduce both time and economic costs. For fatigue crack repair in steel structures, when compared to traditional retrofitting methods like stop hole drilling and steel plate welding, bonded carbon fibre reinforced polymer (CFRP) approach becomes an attractive option. One benefit is that it is free from some drawbacks of conventional strengthening methods such as induction of new fatigue prone areas and complexity in construction.

Extensive research on CFRP-strengthened steel members has been conducted to investigate the strengthening efficiency of fatigue behaviour [1–3], and results have shown that composite materials have great potential in retarding crack propagation and extending fatigue life. However, most previous studies adopted specimens with a centre notch, which normally consisted of a hole and two slots [4–7] or just one slot [8,9], while studies on specimens with edge cracks strengthened by composite materials are less reported [10–12].

Jone and Civjan [10] presented an experimental and analytical study on the fatigue behaviour of CFRP bonded steel plates. Two types of initial notches were introduced, i.e., edge notch and centre hole. Variables such as bond length, bond area, single- or double-sided repair and applications prior or subsequent to crack propagation were considered. Results indicated that the fatigue life was considerably extended and some suggestions on this strengthening method were proposed. Monfared et al. [11] tested 15 steel plates with symmetrical edge notches on both sides. High modulus CFRP overlays were selected for the retrofitting system. Comparisons in terms of single- or double-sided bond, with or without prior surface preparation by sandblasting were presented. Fatigue life of the specimens was increased by 79% to 119%. Colombi et al. [12] gave emphasis to single-edge notched tension specimens strengthened by CFRP laminates on one side. Test results showed that fatigue life of the strengthened steel plates was increased by as much as 2.28 to 5.88 times that of the unstrengthened ones.

Besides experimental study which is comparatively expensive and time consuming, numerical analysis has also been conducted to study the fatigue and fracture behaviour of CFRP-strengthened steel structures. Finite element models were established to evaluate stress intensity factors (SIFs) at crack fronts of steel elements considering different retrofitting parameters [13–15]. The boundary element method also proved to be effective to predict crack propagation and fatigue life of CFRP strengthened steel plates and welded joints [16–19].

To the best of the authors' knowledge, few attempts have been

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**Nomenclature**

| | |
|---|---|
| $R$ | Stress ratio |
| $E_e$ | Young's modulus of equivalent composite layer |
| $E_c$ | Young's modulus of CFRP |
| $t_c$ | Thickness of CFRP |
| $E_a$ | Young's modulus of adhesive |
| $t_a$ | Thickness of adhesive layer |
| $N$ | Number of fatigue cycles |
| $a$ | Crack length (edge crack) |
| $\Delta K$ | Stress intensity factor range |
| $C$, $n$ | Material constants in Paris Law |
| $p$, $q$ | Empirically derived constants |
| $f$ | Crack opening function |
| $\Delta K_{th}$ | Threshold stress intensity factor range |
| $K_{Ic}$ | Fracture toughness |
| $K_I$ | Stress intensity factor in mode I |
| $K_{II}$ | Stress intensity factor in mode II |
| $K_{III}$ | Stress intensity factor in mode III |
| $M$ | Bulging correction factor |
| $f_w$ | Correction term in stress intensity factor for elliptical flaw |
| $M_m$ | Stress intensity magnification factor |
| $\sigma$ | Far field stress |
| $W$ | Plate width |
| $N_i$ | Initial fatigue cycle numbers |
| $N_{p\text{-}CFRP}$ | Fatigue crack propagation life of CFRP strengthened specimens |
| $N_{p\text{-}plate}$ | Fatigue crack propagation life of unstrengthened specimens |
| $a'$ | Half of crack length (centre crack) |
| $F$ | General correction factor |
| $F_E$ | Correction term in stress intensity factor for elliptical crack front |
| $F_S$ | Correction term in stress intensity factor for free surface |
| $F_W$ | Correction term in stress intensity factor for finite width |
| $F_G$ | Correction term in stress intensity factor for nonuniform opening stress |
| $a_1$ | Crack length on the unbonded side of single-sided strengthened specimens |
| $a_2$ | Crack length on the centreline of single-sided strengthened specimens |
| $a_3$ | Crack length on the bonded side of single-sided strengthened specimens |

made to perform a crack propagation analysis using numerical simulation on CFRP-strengthened steel plates with edge cracks. In this paper, a boundary element analysis was conducted on the fatigue behaviour of steel plates with edge cracks strengthened by CFRP laminates. The models were first validated by a comparison with the test data reported by Colombi et al. [12]. Afterwards, effects of initial damage degree, bond configuration and crack type were examined. The study presented in this paper extends the understanding of CFRP-repaired steel plates with edge cracks, and provides some useful suggestions for such strengthening method.

## 2. Test programme in the literature

### 2.1. Specimen geometry and dimensions

The basic geometry and dimensions of the specimens are shown in Fig. 1 [12]. They were edge cracked steel plates bonded by one or two layers of CFRP laminates on a single side. The steel plates had a mean yield strength and tensile strength of 330 MPa and 444 MPa, respectively. The Young's modulus was 208 GPa. Strengthening materials included one type of CFRP laminates and two types of structural adhesives. Based on the manufacturer's data sheet, the CFRP laminates had a tensile modulus greater than 200 GPa, a tensile strength greater than 2800 MPa and a laminate thickness of 1.4 mm. Adhesive 1 was used to bond CFRP laminates to steel plates while Adhesive 2 was specially selected for the two-layer CFRP repaired system to bond the CFRP laminates together. Adhesive 1 had a tensile modulus greater than 4.5 GPa and a tensile strength greater than 28.4 MPa; Adhesive 2 had a tensile modulus greater than 3.8 GPa and a tensile strength greater than 30 MPa. Two strengthening configurations were designed, i.e. CFRP laminates with full width (see configuration (a) in Fig. 1(a)) and half width (see configuration (b) in Fig. 1(b)) of the steel plate were used. Two lengths of initial cracks were introduced to investigate the effect of damage degree, i.e., 6 mm and 15 mm.

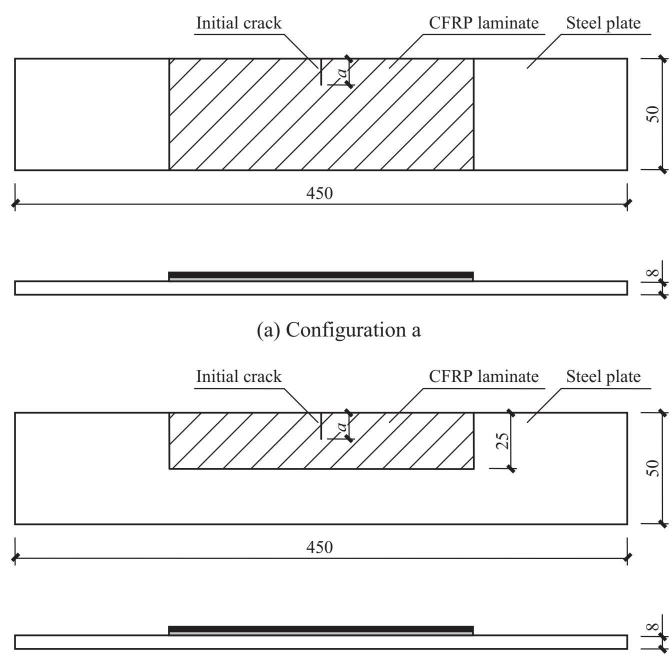


**Fig. 1.** Geometric configurations of steel plates (unit: mm, not to scale): (a) configuration a; (b) configuration b.

### 2.2. Fatigue loading and test results

Tensile cyclic loading was applied to all the specimens with a frequency of 10 Hz and a stress ratio $R$ of 0.4. The stress range was kept as 90 MPa in the nominal cross section of unstrengthened specimens. Details on the test results of Ref. [12] are given in Table 1.

## 3. Boundary element modelling

*BEASY* [20], a commercial software package, was employed in this study to analyse crack propagation and to predict fatigue life