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Numerical study on notched steel beams strengthened by CFRP plates

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HIGHLIGHTS

- Mixed-mode cohesive law was employed in simulation of notched steel beams strengthened by CFRP plate.
- Crack propagation and CFRP plate debonding processes were well simulated.
- Plastic behaviour of the CFRP strengthened notched steel beams was revealed.

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) externally bonding is an efficient and effective method to strengthen damaged steel beams, and thereby prolong their service life. However, debonding failure, which requires accurate predictions to ensure safety, can occur before the full usage of CFRP. In this study, the notched steel beams strengthened with CFRP plate were simulated by finite element method where the mixed-mode cohesive law was employed to determine the interfacial stress. The load–deflection curves and strain development at different load levels from experimental study were used to verify the validity of the numerical model. The interfacial stress distribution with increasing load was analysed, and good correlation with theoretical calculations at elastic stage was observed. In contrast to the previous elastic analytical study, the plastic behaviour of the CFRP strengthened notched steel beams was revealed. More importantly, interfacial crack initiation, propagation and debonding were accurately simulated. This simulation method can be used to predict debonding process in actual engineering applications. In addition, parametric analysis was conducted to assess the effects of notch depth, CFRP elastic modulus and CFRP thickness. The ultimate load and ductility decreased substantially with increasing notch depth. Furthermore, although increased bearing capacity was achieved by increasing the CFRP elastic modulus and thickness, ductility decreased and premature debonding failure occurred more easily.

1. Introduction

The use of fibre reinforced polymer (FRP) to strengthen concrete structures has been extensively studied in recent decades [8,11,21,53,54,55], while carbon fibre reinforced polymer (CFRP) is favoured for strengthening steel structures due to its higher stiffness [22,26,34,35,38,40,52]. The load capacity and stiffness of steel structures, as well as the fatigue life, can be improved by externally bonded with CFRP [14,27,39,49]. However, prior to the full usage of CFRP, premature debonding failure may occur [3,15,17,28,30,32,33], which limits the wide application of the strengthening technique. To clarify the debonding mechanism, researchers have studied the bond behaviour of the CFRP/steel interface [2,10,13,20,36,42,44,45,50]. The common debonding failure modes are cohesive failure (delamination of CFRP or adhesive) and adhesive failure (debonding between the adhesive layer and steel) [52]. Single lap [50] and double strap [18,19] shear tests were conducted to determine the bond-slip relationship, which is important for understanding of the adhesive debonding failure. While delamination failure was considered to occur mainly due to the shear stress concentration, the normal stress concentration is also an important factor [7,9,37,41]. Therefore, both of the slip and separation result in debonding failure, it is necessary to study the bond behaviour of CFRP and steel beams with consideration of the two effects. The mixed-mode cohesive law was applied to simulate the debonding failure of continuous steel beams strengthened by CFRP plates with consideration of both the shear and normal stress concentrations [6,41]. However, strengthened steel beams usually have defects and have different failure modes compared with the case of sound steel beams [15,16,25,56]. The mechanical performance of notched steel beams strengthened by CFRP plates requires further investigation.

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There are two main theoretical methods to predict the mechanical performance of steel structures strengthened by FRP: fracture mechanics and stress-based criteria [3]. For the latter, researchers have focused on steel plates and steel beams [24,48]; however, the theoretical analysis is limited to elastic stage, for which the stress concentration is overestimated [4,41]. Theoretical and experimental studies have also been conducted on notched steel beams [15]. The results basically agree in the elastic stage, but difference becomes obvious in the plastic stage. The actual debonding process cannot be predicted accurately. The theoretical result can be useful in simplifying the design, but it is inadequate for the mechanical performance evaluation. In contrast, fracture mechanics is considered as a more reliable debonding prediction method [29]. Numerical studies can be conducted based on the fracture mechanics. It could be a common useful method for debonding prediction because only typical cases have been considered in experimental study and the results are difficult to apply in practice [23,31,47,51].

In this study, the mixed-mode cohesive law was applied to simulate the stress distribution and debonding process of notched steel beams strengthened by CFRP plates. Previous theoretical and experimental results [15] were used to verify the numerical results. The purpose was to develop a numerical method to simulate the debonding failure of CFRP strengthened notched steel beams with consideration of plastic behaviour and to provide useful information for debonding prevention by parameter analysis.

2. Theoretical background

The most common failure mode of strengthened steel structures is debonding. As shown in Fig. 1, there are three types of fracture modes. Mode I, opening, usually occurs in the delamination of CFRP and cohesive failure of the adhesive layer. The fracture is due to the normal stress concentration. Mode II, shear cracking, is due to the shear stress concentration. Mode III, tearing cracking, is a mixture of Mode I and Mode II. The constitutive laws have been developed for Mode I, Mode II and Mode III (bond-separation model and bond-slip model for both shear directions), as shown in Fig. 2(a) and (b), respectively. According to the mixed-mode of interface debonding, both of the shear and normal stresses concentration were considered. For accurate prediction of debonding, the mixed-mode cohesive law was proposed for numerical simulation [41,43], in which pure Mode I, Mode II and Mode III can be simulated. The details of each model are described below.

2.1. Bond-separation model

The bi-linear bond-separation model followed the approach suggested by Camanho et al. [6] and Campilho et al. [7], as shown in Fig. 2(a). When the adhesive layer is damaged by pure tension, the damage of the adhesive layer initiates when the normal stress exceeds its tensile strength (f_t), which can be obtained from material test results. With increasing of crack opening, the normal traction stress (t_n) decreases gradually until reaching zero, and the corresponding displacement is defined as the final failure displacement (δ_n^f).

$$t_n = \begin{cases} K_n\delta_n & \text{if } \delta_n \leqslant \delta_n^0 \\ K_n\delta_n(1-d_n) & \text{if } \delta_n^0 < \delta_n \leqslant \delta_n^f \\ 0 & \text{if } \delta_n > \delta_n^f \end{cases}, \tag{1}$$

in which

$$K_n = \frac{E_a}{t_a};\ \delta_n^0 = \frac{f_t t_a}{E_a} \text{ and } d_n = \frac{\delta_n^f(\delta_n - \delta_n^0)}{\delta_n(\delta_n^f - \delta_n^0)}, \tag{2}$$

where K_i is the initial stiffness before cracking, δ_i is the opening displacement, δ_i^0 is the opening displacement at the point of initial interfacial cracking, δ_i^f is the final failure opening displacement when the normal traction force is zero, d_i is the damage factor due to the opening cracking (in the range of 0–1) (i = n,s, means normal and shear directions respectively), E_a is the elastic modulus of the adhesive layer, t_a is the thickness of the adhesive layer and f_t is the tensile strength of the adhesive layer.

Based on double cantilever beam tests, the final failure displacement can also be determined based on the interfacial fracture energy. The relationship was proposed by [1],

$$G_I = \frac{1}{2} f_t \delta_n^f, \tag{3}$$

where G_I is the interfacial fracture energy of Mode I failure.

2.2. Bond-slip model

Xia and Teng [46] proposed an interfacial bond-slip model to predict the bond behaviour of the steel-FRP interface, as shown in Fig. 2(b). Similar to the bond-separation model, it is also a bilinear relationship. We define the adhesive shear strength (τ_s) as the interfacial debonding strength, and it can be determined by the tensile strength of the adhesive layer ($0.8f_t$). The relationship of the shear traction stress (t_s) and slip displacement (δ_s) can be defined as

$$t_s = \begin{cases} K_s\delta_s & \text{if } \delta_s \leqslant \delta_s^0 \\ K_s\delta_s(1-d_s) & \text{if } \delta_s^0 < \delta_s \leqslant \delta_s^f \\ 0 & \text{if } \delta_s > \delta_s^f \end{cases}, \tag{4}$$

in which

$$K_s = \frac{G_a}{t_a};\delta_s^0 = \frac{f_t t_a}{G_a};\delta_s^f = \frac{2G_{II}}{\tau_s} = 62\left(\frac{f_t}{G_a}\right)^{0.56}\frac{t_a^{0.27}}{\tau_s} \text{ and } d_s = \frac{\delta_s^f(\delta_s - \delta_s^0)}{\delta_s(\delta_s^f - \delta_s^0)}, \tag{5}$$

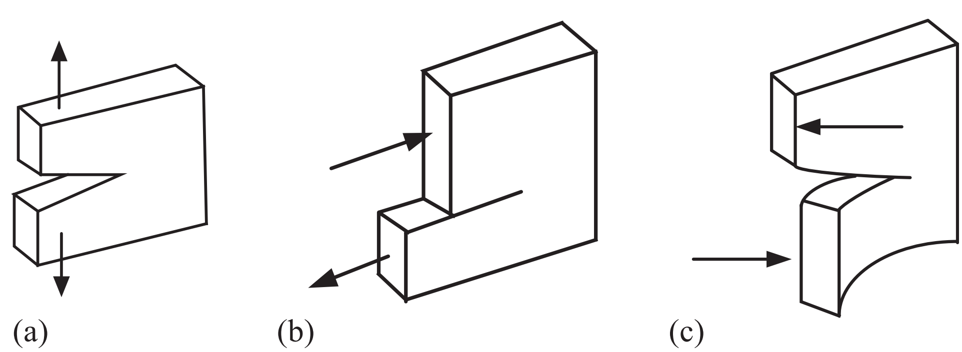

Fig. 1. Crack types: (a) Mode I; (b) Mode II; (c) Mode III.