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Review

Interfacial stresses in damaged RC beams strengthened with externally bonded CFRP plate

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Abstract

A theoretical method to predict the interfacial stresses in the adhesive layer of damaged reinforced concrete beams strengthened with externally bonded carbon fiber-reinforced polymer (CFRP) plate is presented. The adopted model is developed including the adherend shear deformations by assuming a linear shear stress through the depth of the RC beam [A. Tounsi, Int. J. Solids Struct., in press], while all existing solutions neglect this effect [e.g. S. Benyoucef, A. Tounsi, S.A. Meftah, E.A. Adda Bedia, Compos. Interfaces, in press; S.T. Smith, J.G. Teng, Eng. Struct. 23 (7) (2001) 857–871; T.M. Roberts, Struct. Eng. 67 (12) (1989) 229–233; A. Tounsi, S. Benyoucef, Int. J. Adhes. Adhes., in press; T. Stratford, J. Cadei, Construct. Building Mater. 20 (2006) 34–35]. In addition, in the present study the anisotropic damage model is adopted to describe the damage of the RC beams. It is shown that the damage has a significant effect on the interfacial stresses in FRP-damaged RC beam.

Keywords: Damaged concrete beam; Interfacial stresses; Strengthening; Composite plates; Adherend shear deformations

Contents

1. Introduction

One method of restoring the integrity of damaged concrete structures is that patch repair in which the concrete in damaged localities is strengthened with one of a wide range of repair materials. Bonding of steel plates to the tension faces of bent members is one of the solutions that have been proposed in the late sixties and early seventies for strengthening existing bridges [7,8]. However, one of the main disadvantages of this retrofitting method is corrosion and weight of the steel plate. These two problems can be avoided by the use of composite materials thanks to the high strength-to-weight and stiffness-to-weight ratios as well as the corrosion resistance of these materials. Their low density leads to an easy handling which counterbalances their very high cost compared to steel. Many studies on this theme have been carried out since the early 1990s

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[9–23]. In such retrofitted beams, debonding of the soffit plate from the beam is an important failure mode as it prevents the full ultimate flexural capacity of the retrofitted beam from being achieved. It is thus important to be able to predict the debonding failure load. Debonding failures depend largely on the interfacial shear and normal stresses between the beam and the bonded composite plate. Such stresses have been studied by experimental and theoretical methods. The experimental technologies were applied to test the interfacial stresses [24,25]. A peel test was developed to demonstrate the debonding process of the interface [26]. However, the experimental test of interfacial stress fields seems to be difficult because of the complicated distribution of local stresses. The analytical studies [1–6] tend to develop approximate models and provide closed-form solutions for the interfacial shear and normal stresses. It is shown that almost all existing solutions neglect the adherend shears deformations. Recently, A. Tounsi [1] developed an improved theoretical interfacial stress analysis for simply supported concrete beam bonded with a FRP plate in which the adherend shear deformations have been included by assuming a linear shear stress through the depth of the RC beam. In this paper, we have developed an improved theoretical method which takes this effect for damaged RC beams. In the analytical formulation, the damaged concrete member is described by an elastic linear beam governed by classical beam theory (Bernoulli–Euler assumption) with assuming a linear shear stress through the depth of the damaged RC beam. A damaged state is described through the incorporation of damage variables in the same way as is described by Shen et al. [27] Ghosh and Sinha [28]. The FRP strip is modeled as an ordinary laminated beam using lamination theory. The adopted model describes better the actual response of the FRP-damaged RC hybrid beam and permits the evaluation of the interfacial stresses, the knowledge of which is very important in the design such structures.

2. Theoretical analysis and solutions procedure

2.1. Material properties of damaged plates

Voyiadjis and Kattan [29] proposed an anisotropic damage model, in which the elastic energy configuration of deformed and damaged state is equivalent to the elastic energy configuration of deformed but undamaged state. Based on this assumption, the relations of elastic constants of damaged state and undamaged state can be expressed as:

$$\begin{cases} \tilde{E}_{11} = E_{11}(1-\Phi_{11})^2; \qquad \tilde{E}_{22} = E_{22}(1-\Phi_{22})^2 \\ \tilde{G}_{12} = 4G_{12}\left(\dfrac{(1-\Phi_{11})(1-\Phi_{22})}{(1-\Phi_{11})+(1-\Phi_{22})}\right)^2 \\ \tilde{\nu}_{12} = \nu_{12}\dfrac{(1-\Phi_{11})}{(1-\Phi_{22})}; \qquad \tilde{\nu}_{21} = \nu_{21}\dfrac{(1-\Phi_{22})}{(1-\Phi_{11})} \end{cases} \tag{1}$$

where $\tilde{E}_{11}$,$\tilde{E}_{22}$,$\tilde{G}_{12}$,$\tilde{\nu}_{12}$, $\tilde{\nu}_{21}$ and E_{11}, E_{22}, G_{12}, ν_{12}, ν_{21} are the elastic constants of damaged and undamaged state, respectively, and Φ_{11} and Φ_{22} are damaged variables. Hence, the material properties of the damaged beam can be represented by replacing the above elastic constants with the effective ones defined in Eq. (1). A convenient way to determining Φ_{11} and Φ_{22} is to utilize the damage law postulated by Yu et al. [30] for concrete. It given as:

$$\Phi_{22} = \frac{1}{2N_C+1}\left[\frac{\varepsilon_2}{\varepsilon_f^c}\right]^{N_C} \tag{2a}$$

$$\Phi_{11} = H\Phi_{22}(H > 1) \tag{2b}$$

$$N_C = \frac{\sqrt{E_f^c}}{2(\sqrt{E_c}-\sqrt{E_f^c})} \tag{3}$$

where E_f^c is the tangential elastic modulus when the stress reaches its peak, E_c is the initial elastic modulus and ε_f^c is the failure strain and ε_2 is the current state of strain. H is a constant determined by experiments, for example, when $E_c = 49.49$ GPa, $N_C = 3.65$, $H = 3$ and $\nu = 0.2$, then $\Phi_{22} = 0.12048(\varepsilon_2/\varepsilon_f^c)^{3.65}$.

2.2. Solutions procedure

A differential section dx, can be cut out from the FRP strengthened damaged RC beam (Fig. 1), as shown in Fig. 2. The composite beam is made from three materials: concrete, adhesive layer and FRP reinforcement. In the present analysis, linear elastic behaviour is regarded to be for all the materials; the adhesive is assumed to only play a role in transferring the

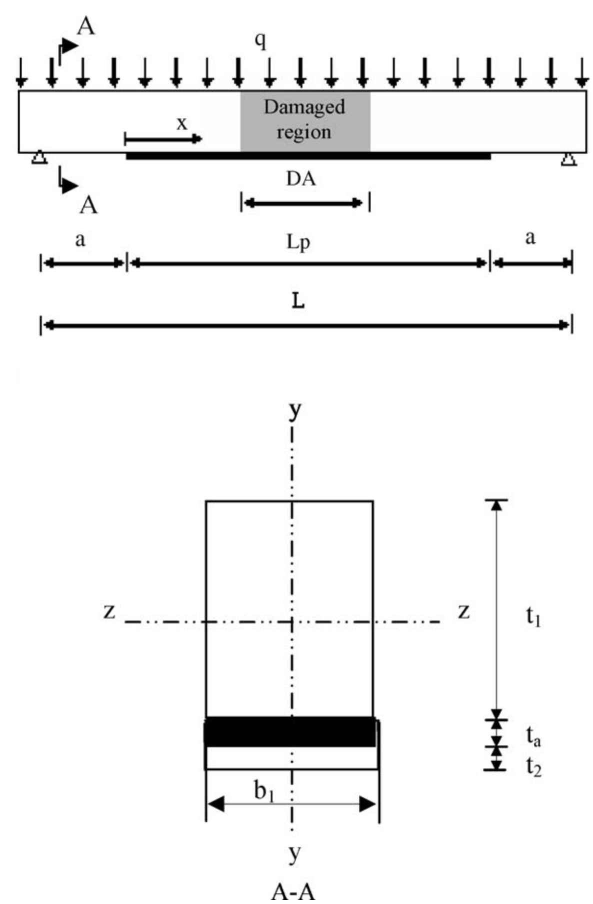

Fig. 1. Simply supported beam strengthened with bonded FRP plate.