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Interfacial shear stress in FRP-plated RC beams under symmetric loads

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Abstract

A recently popular method for retrofitting reinforced concrete (RC) beams is to bond fibre-reinforced polymer (FRP) plates to their soffits. An important failure mode of such plated beams is debonding of the FRP plates from the concrete due to high level interfacial stresses near the plate ends. A closed-form rigorous solution for the interfacial stresses in simply supported beams bonded with thin plates and subjected to arbitrary loads has been found, in which a non-uniform stress distribution in the adhesive layer was taken into account. This paper uses the rigorous solution to investigate the impact of symmetric loading configurations on the interfacial shear stress distributions, and concludes that the bending moments on the cross sections at the plate ends play a significant role in terms of stress concentration, while the shear forces on the same cross-section contribute little to the concentration. On the basis of this observation, this paper proposes a simplified approximate solution to the shear stress along the interface between concrete and adhesive layer. Compared with the rigorous and other approximate solutions, the simplified solution exhibits sufficient accuracy in terms of stress distribution and stress concentration localized near the plate ends. Due to its compact feature, the simplified solution is more suitable for engineering applications using a portable calculator and to be adopted in the codes of practices.

Keywords: Concrete beams; FRP plates; Interfacial shear stress

1. Introduction

As a nation's infrastructure ages, one of the major challenges the construction industry faces is that the number of deficient structures continues to grow. The applications of using externally bonded steel plates or fibre reinforced polymer (FRP) laminates to reinforced concrete (RC) structures have shown that the technique is sound and efficient and offers a practical solution to this pressing problem. Retrofitting using externally bonded plates is quick, easy with respect to material handling, causes minimal site disruption and produces only little changes in section size.

Central to the reinforcement effect of externally bonded concrete structures is the transferring of stresses from the concrete to the external reinforcement, which can cause the undesirable premature and brittle failure modes, such as debonding initiated from the cut-off ends of the bonded sheets/plates [30]. A good understanding of this problem is thus important for the development of suitable strength models. Extensive studies have been carried out during the last decade to investigate the interfacial stress distributions.

A number of experimental results showing the interfacial stresses can be found in the literature, e.g. the work reported by MacDonald and Calder [17], Jones et al. [14], Garden et al. [11], Etman and Beeby [10], Ahmed et al. [1] and Maalej and Bian [16]. Bonacci and Maalej [7] compiled an experimental database from the published results, where test results from a total of 127 specimens tested in 23 separate studies were included.

Numerical methods used in the determination of the interfacial stresses include the linear finite element methods

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Nomenclature

A	area of the cross section transformed to bonded plate material
B	breadth of RC beam
b	breadth of bonded plate and adhesive layer
E_c	elastic modulus of concrete
$E_x^{[i]}$, $E_y^{[i]}$	elastic moduli of the ith layer in the x and y directions, respectively
f_{cu}	cube strength of concrete
$G_{xy}^{[i]}$	shear modulus of the ith layer
h_0	distance from the neutral axis to the lower edge of the cross section transformed to bonded plate material
$h^{[i]}$	thickness of the ith layer
I	second moment of area of the cross section transformed to the bonded plate material
K	coefficient in the shear stress solution for the 1st group of loading
L	half span of beam
l	half length of bonded plate
M_0	applied bending moment
M_l	bending moment on the cross sections of RC beam at plate end
q	load intensity of UDL or magnitude of point load
$q(x)$	symmetrically distributed transverse load
Q_l	shear force on the cross sections of RC beam at the plate end
S_1, S_2, S_3	parameters defined by Eqs. (A2a–c) and the simplified versions by Eq. (9)–(11)
x^*	distance away from plate end where shear stress approaches the peak value
σ_{xy}	interfacial shear stress at the AC interface in plated beam
$[\sigma_{xy}]_{\max}$	maximum shear stress value
$\sigma_{xy,1}$, $\sigma_{xy,2}$	interfacial shear stress under 1st and 2nd group of loadings, respectively
σ^*	concrete fiber tensile stress at the middle span of RC beam
$\nu_{xy}^{[i]}$	Poisson's ratio of the ith layer
$\xi^{(1)}$	parameter defined by Eq. (A1a) and the simplified version by Eq. (4)
$\xi^{(2)}$	parameter defined by Eq. (A1b) and the simplified version by Eq. (6)
η	parameter defined by Eq. (A1c) and the simplified version by Eq. (7)
Θ	parameter defined by Eq. (A2f)
γ_1, γ_2	parameters defined by Eq. (A2d and e)

in Mays and Turnball [19], Hutchinson and Rahimi [13], Taljsten [28], Malek et al. [18], Rabinvich and Frostig [22] and Teng et al. [31]; the nonlinear finite element methods in Ziraba and Baluch [37], Ascione and Feo [6], Rahimi and Hutchinson [23] and Aprile et al. [2]; and the discrete section analyses in Arduini et al. [3], Arduini and Nanni [4], Arduini and Nanni [5] and Wang and Restrepo [33].

A number of approximate analytical solutions for calculating the interfacial stresses in simply supported FRP plated RC beams include the elastic shear stress analysis approach by Mukhopadhyaya and Swamy [20,21]; the shear-lag approach by Triantafillou and Deskovic [29], Ye [36] and Leung et al. [15]; the staged analysis approach by Roberts [24], Roberts and Haji-Kazemi [25] and the deformation compatibility-based approach by Vilnay [32], Taljsten [28], Malek et al. [18] and Smith and Teng [27]. These solutions were developed based on the assumption that shear and normal stresses are uniformly distributed across the thickness of the adhesive layer. Although this assumption reduces the complexity of the problem, leading to a relatively simple closed-form solution, it violates the traction free condition at the cut-off ends of the adhesive layer.

Rabinvich and Frostig [22] developed a high-order analysis in which the adhesive layer was treated as an elastic medium with negligible longitudinal stiffness. This leads to a uniformly distributed shear stress and a linearly distributed transverse normal stress across the thickness of the adhesive layer. The solution satisfies the traction free conditions at the ends of the adhesive layer. However, the solution does not give explicit expressions for the interfacial stresses. Shen et al. [26] proposed an alternative analytical approach which led to closed-form expressions. This analysis is limited to solve problems involving only uniformly distributed loads or/and symmetrical end moments. Yang et al. [35] extended their work to cover arbitrary loading configurations that are decomposed into symmetrical and antisymmetrical loads. However, this solution is very complex and cannot be used conveniently in the engineering practice. It is, therefore, imperative to revise the solution so that it is simple, practical and can still provide sufficient accuracy, compared with the original one.

To this end, this paper studies the general impact of symmetrically applied loads on the interfacial shear stress, and finds that the bending moments carried by the cross sections at the plate cut-off ends play a dominant role in generating stress concentration. The shear forces on the same cross sections contribute little towards the concentration, while their overall contribution to the shear stress distribution along the interface between concrete and adhesive layer can be calculated on the basis of the classic laminated beam theory.

2. Rigorous solution

As the rigorous solution of Yang et al. [35] is used to investigate the impact of load configurations to the interfa-