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Debonding of a thin rubberised and fibre-reinforced cement-based repairs: Analytical and experimental study

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ABSTRACT

An analytical approach for the prediction of debonding initiation between a rubberised cement-based overlay and old concrete substrate under monotonous mechanical loading was applied. Based on the linear elastic fracture mechanics, a model has been developed taking into account the interlocking between two crack surfaces in the overlay. Assuming that the debonding initiation just occurs after the crack cutting the overlay layer reaches the overlay–substrate interface, the stress intensity factor of the debonding tip can be calculated, allowing prediction of stress fields near the interface debonding tip. Then with a criterion of debonding initiation and propagation depending on the interface tensile strength, the load associated could be determined and might be interesting for the design of thin bonded cement-based overlays. The adequateness of this analytical approach was verified by both experimental data and finite element calculations. It has been used to show the relevance of a cement-based material with low modulus of elasticity combined with a high residual post crack strength to achieve sustainable repairs.

1. Introduction

Numerous experimental studies have been devoted to the debonding propagation of thin bonded overlays. Granju [1] demonstrated that the debonding of overlays is mainly caused by the coupled effects of vertical cracking through the overlay and traffic loads. It is by restraining the crack opening that fibres enhance the bonding durability of overlays. Moreover, Beushausen and Alexander [2] showed that restrained shrinkage deformations is the main factor influencing the serviceability and durability of bonded concrete overlays. Failure mechanisms associated with differential shrinkage stresses are cracking and debonding. In parallel, several predictive models have already been proposed to predict the delamination of thin bonded overlays. Zhang and Wang [3] developed an interface fracture mechanics analysis for delamination of layered beam subject to general mechanical loads. A discrete crack model, allowing prediction of both crack growth and debonding propagation under monotonic loading has been developed [4]. Later, it has been improved to take into account the delayed effects and recently, it has been extended to the case of fatigue loading [5]. Although proved as a relevant tool for researchers in debonding modelling, the application of the numerical model for practitioner in design work of thin bonded cement-based overlays seemed to be onerous, due to numerous input data to be determined and to long duration of calculations, particularly for complicated structures. The aim of this paper is to apply a simple analytical approach allowing prediction of debonding initiation in the case of thin bonded steel fibre reinforced and rubberised cement-based overlays. The results from this analytical approach were confronted with already published experimental results from a parametric study on the impact of the properties of the repair material on the resistance to debonding [6]. This study showed the benefit of a material that has a high strain capacity before cracking localisation and a high post cracking residual strength. A cement-based material providing such properties has been developed by Nguyen et al. [7] thanks to a metal fibre-reinforcement and to the incorporation of rubber aggregates from shredding of used tyres. This material has been implemented and its effectiveness in achieving more sustainable repair has been validated. Needless to say, the approach has another advantage; help to maintain a clean environment by recycling old tyres.

2. Modelling fundamentals

Attentions will be paid on the durability of composite structures: a layer of overlay material on a substrate to be repaired. When mechanical load is applied to the composite system, cracks may be initiated in tension zone of the overlay and propagated towards the overlay-substrate interface. After the crack reaches the interface, two possibilities may occur:

1. If the strength of the overlay-substrate interface is high enough, crack will be propagated through the substrate layer. This corresponds to a monolithic behaviour.

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2. The interface tensile strength is such as the crack is deviated inducing the delamination of the repair layer from the substrate on which it was placed.

In the first situation, the overlay-substrate bond presents a good quality against debonding and the failure of substrate is not target of our investigation. The latter case will be considered in the current paper.

The singularity of stress fields near the debonding interface tip between two different materials has been analytically investigated in the literature. Colerto and Hogan [8] and Ozil and Carlsson [9] used elastic foundation models to account for the local deformation at the crack tip. Wang and Qiao [10] and Qiao and Wang [11] used sub-layer models in which each layer of the virgin beam at the joint is modelled as a single sub-beam and each layer has individual rotation. However, the implementation of these models is not easy due to a high number of parameters to be considered and related subsequent equations to be solved. In this work, a conventional composite beam model proposed by Suo and Hutchinson [12] and then developed by Li and Thouless [13] was used. The literature shows that, in the case of cement-based materials, debonding is always initiated by tension perpendicular to the interface [14]. Therefore, in this model, only the normal tensile stress near the debonding tip was involved.

2.1. Modelling fundamentals

The problem of a composite beam subjected to axial loads and bending moments was treated in 2D by Suo and Hutchinson [12] and presented in Fig. 1. The overlay (material #1) lies above the interface which coincides with the x_1-axis and the substrate (material #2) below. The thickness of two layers are h and H, respectively. The origin of x_1-axis is chosen at the tip of the interface debonding zone. The uncracked bimaterial layer can be regarded as a composite beam with a neutral axis lying a distance δ above the bottom of layer #2. The composite structure is assumed to be loaded as shown in Fig. 1a. By the principle of loading superposition, this problem can be treated if the problems in Fig. 1b and c can be solved. Note that in Fig. 1b, since $\sigma_{22} = \sigma_{12} = 0$ in the layers, a crack can be created anywhere paralleling the interface without

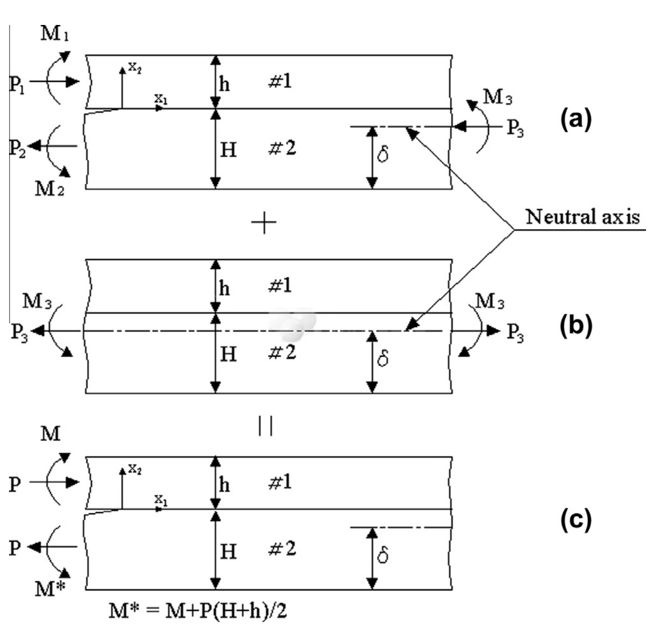

Fig. 1. Equivalent scheme for determination of peeling stresses near interface debonding tip due to axial loads and bending moments.

disturbing the peeling and shear stresses near the interface debonding tip. Therefore, the singularity of peeling and shear stresses for the problem in Fig. 1a is exactly the same as that in Fig. 1c, in which the number of load parameters controlling the debonding tip singularity is reduced to only two, P and M given in Eq. (1).

2.2. Basic equations

$$P = P_1 - C_1 P_3 - C_2 \frac{M_3}{h}$$
$$M = M_1 - C_3 M_3 \tag{1}$$

The C's are dimensionless parameters defined as follows:

$$C_1 = \frac{\Sigma}{A_0} >; \quad C_2 = \frac{\Sigma}{I_0}\left(\frac{1}{\eta} - \Delta + \frac{1}{2}\right) >; \quad C_3 = \frac{\Sigma}{12 I_0} \tag{2}$$

The determination of parameter Σ in Eq. (2) requires that the Dunders' coefficients α and β to be determined:

$$\alpha = \frac{\Gamma(\kappa_2 + 1) - (\kappa_1 + 1)}{\Gamma(\kappa_2 + 1) + (\kappa_1 + 1)} >; \quad \beta = \frac{\Gamma(\kappa_2 - 1) - (\kappa_1 - 1)}{\Gamma(\kappa_2 + 1) + (\kappa_1 + 1)} \tag{3}$$

in which subscripts 1 and 2 refer to the two materials in Fig. 1a. $\kappa = 3 - 4v$ for hypothesis of plane strains and $(3 - v)/(1 + v)$ for hypothesis of plane stresses. $\Gamma = E_1/E_2$, Young's modulus ratio between materials #1 and #2. Other parameters in Eq. (2) are defined as follows:

$$\eta = \frac{h}{H} \tag{4}$$

$$\Sigma = \frac{1 + \alpha}{1 - \alpha} \tag{5}$$

$$\Delta = \frac{1 + 2\Sigma\eta + \Sigma\eta^2}{2\eta(1 + \Sigma\eta)} \tag{6}$$

$$A_0 = \frac{1}{\eta} + \Sigma \tag{7}$$

$$I_0 = \frac{1}{3}\left\{\Sigma\left[3\left(\Delta - \frac{1}{\eta}\right)^2 - 3\left(\Delta - \frac{1}{\eta}\right) + 1\right] + 3\frac{\Delta}{\eta}\left(\Delta - \frac{1}{\eta}\right) + \frac{1}{\eta^3}\right\} \tag{8}$$

According to Rice [15] and Suo and Hutchinson [12], the singular stress field near the interface debonding tip can be determined through the complex stress intensity factor K (Eq. (9)).

$$\sigma_{22} + i\sigma_{12} = \frac{K}{\sqrt{2\pi r}} r^{i\epsilon} \tag{9}$$

in which σ_{22} and σ_{12} are peeling and shear stresses, perpendicular and parallel to the interface, respectively, at a distance r from the debonding tip. ϵ is a bi-material constant, defined as:

$$\epsilon = \frac{1}{2\pi} \ln \frac{1 - \beta}{1 + \beta} \tag{10}$$

The stress intensity factor K is given by Eq. (11)

$$K = K_P + K_M = \left(\frac{P}{\sqrt{Ah}} - ie^{i\gamma}\frac{M}{\sqrt{Ih^3}}\right)\frac{p}{\sqrt{2}} h^{i\epsilon} e^{i\omega} \tag{11}$$

where parameters A, I and p are defined as follows:

$$A = \frac{1}{1 + \Sigma(4\eta + 6\eta^2 + 3\eta^3)} \tag{12}$$