Computational Materials Science 46 (2009) 15–20

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Approximate analysis of adhesive stresses in the adhesive layer of plated RC beams

Bachir Bouiadjra Mohamed, Tounsi Abdelouahed *, Benyoucef Samir, Adda Bedia El Abbas

Laboratoire des Matériaux et Hydrologie, Université de Sidi Bel Abbes, BP 89 Cité Ben M'hidi 22000 Sidi Bel Abbes, Algeria

ARTICLE INFO

Article history:
Received 4 January 2009
Received in revised form 23 January 2009
Accepted 27 January 2009
Available online 4 March 2009

Keywords:
Adhesive stress
Shrinkage
Creep
FRP plate
RC beam
Strengthening

ABSTRACT

A new popular method for retrofitting reinforced concrete beams is to bond fiber reinforced plastic (FRP) plates to the soffit. An important failure mode for such strengthened members is the debonding of the FRP plate from the member due to high interfacial stresses near the plate ends. As a result, previous researchers have developed several analytical methods to predict the interface performance of bonded repairs. In this paper, a theoretical interfacial stress analysis is presented, including creep and shrinkage effect for simply supported RC beams with a thin FRP composite plate. It explicitly considers the interface slip effect on the structural performance. The results agree reasonably well with those from the existing solutions. The influence of creep and shrinkage effect relative to the time of the casting and the time of the loading of the beams is taken into account. A parametric study has been conducted to investigate the sensitivity of interface behaviours to parameters such as the interface layer stiffness.

1. Introduction

In recent years, it has become increasingly common to strengthen reinforced concrete (RC) structures by using externally bonded fiber reinforced polymer plastic (FRP). This strengthening method has many advantages over the traditional techniques due to FRP high strength to weight ratio, ease of installation on site, and the improved durability and corrosion resistance of the composite material [1,2]. However, the application of this method is associated with considerable difficulties mainly due to undesired brittle failure mode of the strengthened member. If the repair is improperly designed, it could actually reduce the strength of the beam [3].

To mitigate the interfacial stresses near the ends of the repairing plates, different techniques, such as using anchor bolts and anchor plates, have been experimentally investigated [3–6].

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 Mukhpadhyaya and Swamy [7,8]; the shear-lag approach by Triantafillou and Deskovic [9], Ye [10] and Leung [11]; the staged analysis approach by Roberts [12], Roberts and Haji Kazemi [13] and deformation compatibility-based approach by Vilnay [14], Taljsten [15], Malek et al. [16], Tounsi et al. [17,18] and Smith and Teng [19].

The majority of the studies mentioned have focused on the short-term response characteristics of concrete beams strengthened with composites. The objective of this study is to develop a procedure that predicts the shear and peeling stresses in the interface between the beam and the repairing plate with a taking into account the creep and shrinkage effect. The model was compared with previous results, and then a parametric analysis was conducted.

2. Theoretical approach

A concrete model, which is designed for a concrete beam strengthened by an FRP plate on its tension surface subjecting to a three-point bending test, is used for present study. A schematic illustration of a theoretical model for evaluating the adhesive stress transfer properties for the current study is shown in Fig. 1. The following assumptions are used to simplify the calculations:

1. The concrete, adhesive, and FRP materials behave elastically, linearly, and isotropically.
2. The shear stress in the interface is proportional to the shear slip.
3. Since the thickness of the adhesive layer is small, both the shear and peeling stresses in the adhesive are assumed constant across its thickness.
4. The two bonded bodies have the same bending curvature at the same section. This assumption is also made commonly by other researchers [17–27].

2.1. Mathematical model for bonded repair considering interface slip

Adhesive shear failure is one of the most common failure patterns that may happen in plate-bonded concrete structures as shown in Fig. 2. An excess of applied shear stress in the adhesive layer leads to failure at the interface between the concrete beam

* Corresponding author.
E-mail address: tou_abdel@yahoo.com (T. Abdelouahed).

0927-0256/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.commatsci.2009.01.020

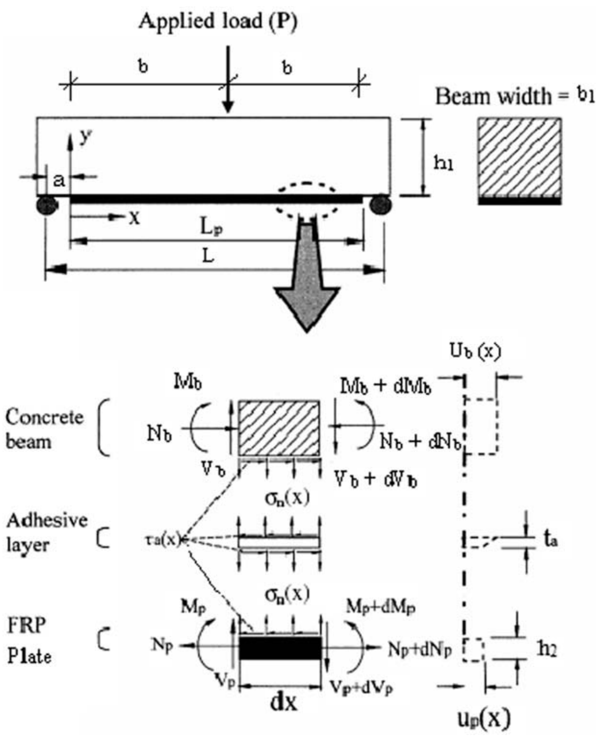

Fig. 1. Theoretical model for the present study (Stresses mechanics for the concrete strengthened by FRP laminates).

and the FRP plate and results in the reduction of the effective bending length of the plate. In Fig. 1, the compatibility expression for the shear stress in the adhesive layer at any section x is given by (assumption 2):

$$\tau = k_{as}S \tag{1}$$

where S the shear slip in the interface between the two bonded bodies, and k_{as} is the shear stiffness of adhesive which is given by:

$$k_{as} = \frac{G_a}{t_a} \tag{2}$$

G_a and t_a are the shear modulus and the thickness of adhesive, respectively.

Equilibrium of a differential segment dx (Fig. 1) in the horizontal direction requires:

$$\frac{dN_b(x)}{dx} = \frac{dN_p(x)}{dx} = b_a\tau \tag{3}$$

where N_b is compression in concrete beam; N_p is the tension in FRP plate; and b_a is width of adhesive along the direction of beam width.

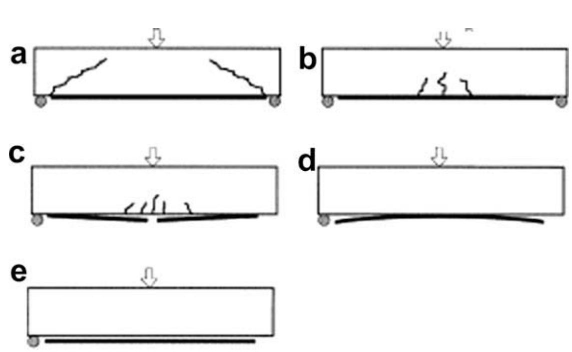

Fig. 2. Typical failure of plate-bonded concrete structures.

Equilibrium in the vertical direction gives:

$$V_b + V_p = V_T \tag{4}$$

where V_b is the shear force taken by beam; V_p the shear force taken by FRP plate; and V_T the total shear force of the section under consideration.

The moment equilibrium of the individual segment (concrete beam and FRP plate) about its centroid gives:

$$\frac{dM_b(x)}{dx} = V_b - b_a y_b \tau(x) \tag{5}$$

$$\frac{dM_p(x)}{dx} = V_p - b_a y_p \tau(x) \tag{6}$$

where M_b the moment taken by concrete beam; M_p the moment taken by FRP plate; y_b distance from the bottom of concrete beam to its neutral axis; and y_p distance from the bottom of FRP plate to its neutral axis.

The assumed curvature compatibility between the two bodies gives the curvature ϕ as:

$$\phi = \frac{M_b}{E_b I_b} = \frac{D'_{11} M_p}{b_2} \tag{7}$$

where D'_{11} is the element of the inverse of the stiffness flexural matrix of FRP laminate which is determined using classical laminate theory [28]. I_b is the moment of inertia of concrete beam; b_2 is width of FRP plate; and $E_b = E_b(t)$ is the time dependent tangent modulus of elasticity of the concrete beam given as (Trost and Wolff [29]).

$$E_b(t) = \frac{E_{bl}}{1 + \chi\varphi(t, t_b)} \tag{8}$$

where E_{bl} is the tangent modulus of elasticity of the beam at time t_{bl}; χ is an aging coefficient depending on strain development with time; and $t_b = t_{bl} - t_{bc}$ (t_{bc} is time of casting of beams and t_{bl} time at initial loading of beams); $\varphi(t, t_b)$ is the creep coefficient related to the elastic deformation at t_b days, which is defined as (Eurocode 2 Editorial Group [30]).

$$\varphi(t, t_b) = \phi_{RH}\beta(f_{cm})\beta(t_b)\beta_{cb}(t - t_b) \tag{9}$$

where $\phi_{RH}, \beta(f_{cm}), and \beta(t_b)$ are factors depending on the relative humidity, the concrete strength, and the concrete age loading, respectively, which are defined as

$$\phi_{RH} = 1 + \frac{1 - \frac{RH}{100}}{0.10\sqrt[3]{h_0}} \tag{10}$$

$$\beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}} \tag{11}$$

$$\beta(t_b) = \frac{1}{0.1 + t_b^{0.20}} \tag{12}$$

where RH is the relative humidity of the ambient environment in%; $h_0 = 2A_b/p_b$ is the notional size of the beam in mm; A_b is the area of the beam cross section; p_b is the beam perimeter in contact with the atmosphere; f_{cm} is the mean compressive strength of concrete in N/mm^2 at the age 28 days. Moreover, $\beta_{cb}(t - t_b)$ in Eq. (9) is a coefficient for the development of creep with time, which is estimated from

$$\beta_{cb}(t - t_b) = \left(\frac{t - t_b}{\beta_H + t - t_b}\right)^{0.3} \tag{13}$$

where β_H is a coefficient depending on the relative humidity RH, given as