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Creep response of intermediate flexural cracking behavior of reinforced concrete beam strengthened with an externally bonded FRP plate

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ABSTRACT

In this study, a creep response model for the long-term behavior of interfacial shear stresses induced by intermediate flexural crack of FRP-plated RC beams is developed. A theoretical model based on the bi-linear cohesive zone model for intermediate crack-induced debonding is established, with the unique feature of unifying debonding initiation and growth with time increments. The creep behavior of the RC beam, adhesive layer and FRP plate have been included by considering the time-dependent mechanical properties. The time-dependent stress-deformation relationship caused by creep is referred to as bond-slip law. Consequently, a new interfacial law which combines time-dependent mechanical properties of all retrofitted beam constituents is proposed by considering constant the total energy during the creep response with intermediate crack. Obtained results are in good agreement with those given in literature. A parametric study is carried out to demonstrate the effect of the mechanical properties and thickness variations of FRP, concrete and adhesive on interface debonding. Indeed, the creep behavior, activates the debonding process in long term. Size of the softening zone is reached quickly and the bearing capacity of the retrofitted beam will be relatively affected by the time increase.

1. Introduction

In recent years, applications of fiber reinforced polymer (FRP) materials for retrofitting and strengthening concrete structures have been rapidly growing around the world. It is generally accepted that the mechanical behavior of a FRP-confined concrete member under load depends on the stress strain relationship of the constituent materials (i.e. FRP and concrete). In most part of industrial applications, the stress strain relationship of retrofitted concrete beams under various load cases is often time-dependent generated by factors including ambient condition, creep, damage, fatigue, … etc. Therefore, the creep of a concrete beam, adhesive layer and FRP plate will considerably affect the mechanical behavior of the retrofitted beam. Unlike ambient condition (durability problem) and damage, however, the effect of creep on the stress strain relationship of all retrofitted beam constituents is considered in few studies (Mário et al., 2011).

In literature, several methods have been incorporating only the creep behavior of concrete in order to predict the long-term deflections of reinforced concrete. For that the effective modulus method, the mean stress method and the age-adjusted effective modulus method are mainly used (Tavares el al., 2002; Miàs et al., 2010; Solimanet al., 2012). These methods take into account some of the main parameters involved in the time-dependent behavior of reinforced concrete structures, such as the properties of the materials and the influence of environmental conditions by introducing the creep values of concrete. Using these methods, accurate predictions can be obtained and consequently the effective modulus method and the age-adjusted effective modulus method have been adopted in some national and international codes and recommendations (ACI Committee, 1995). Consequently, if the creep of FRP plate and adhesive layer is ignored, application of international codes and recommendations for rehabilitation or retrofitted concrete beams is easier.

The amount and evolution of the bond stresses between the laminate and the concrete along the time depend much on the remaining concrete creep strain after the FRP is applied. In many cases the FRP strengthening material is applied when the beam has been subjected to dead loads for quite a long time. In these

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cases, the effect of concrete creep in the interfacial bond stress and strength of cracked FRP-strengthened reinforced concrete beams was studied by Oller and Mari (2013). A simplified model to evaluate the short and long-term interfacial shear stress has been presented and checked through a non-linear time-dependent analysis model developed by the authors that includes a laminate debonding criterion. Within continuity, same authors (Marí et al., 2013) performed a theoretical study of the time-dependent behavior of FRP-strengthened reinforced concrete cracked sections subjected to sustained loading. Based on it, a simplified method for the calculation of long-term deflections has been proposed and verified with available experimental results. The method, which explicitly accounts for the most important parameters involved in the time-dependent behavior of concrete structures, has been used to study the influence of the FRP ratio on the short and long-term deflections on RC beams. It was concluded that the observed reduction of long-term deflections is mainly due to the reduction of short-term deflections due to the increment of stiffness caused by FRP laminates, and that the constraint produced by the FRP laminates to the long-term increment of curvature is small. Later, Miàs et al. (2013) made an experimental study of GFRP RC beams tested at service load, and subsequently subjected to sustained loading for 250 days. Two different amounts of GFRP reinforcement and two levels of sustained load were used to study the influence of these parameters on the increase of deflection due to creep and shrinkage. Both short-term and long-term deflections are presented and discussed. Both experimental and analytical investigations about the creep behavior of GFRP–concrete hybrid structures are proposed by Gonilha et al. (2013), in order to predict the long-term deformations of this type of structures. The analytical study showed that it is possible to predict experimental results with comprehensive material creep models. Furthermore, the analytical models proposed herein are able to predict the important effects of temperature and relative humidity changes observed experimentally provided that proper adaptations are made in the material creep models.

There are only a few existing studies that deal with the time-dependent interfacial shear stresses. Benyoucef et al. (2007) developed a theoretical formulation in the elastic range that took into account the rheological effects of concrete. A viscoelastic solution for the long-term interface stress distribution in a FRP plate strengthened reinforced concrete beam is developed by Zhang and Wang (2011). In this solution, the RC beam and the FRP plate are modeled as elastic materials; while the adhesive layer is modeled as a viscoelastic material using the standard linear solid model. Closed-form expressions of the interface stresses and deflection of the beam are obtained using Laplace transform and calculated using Zakian's numerical method. Diab and Wu presented a linear viscoelastic model in Diab and Wu (2007) for beams strengthened by FRP that was extended in Diab and Wu (2008) to a nonlinear model to simulate the interfacial time-dependent debonding along the FRP-concrete interface. Recently, Hamed and Bradford (2010, 2012) developed a model that considers creep, time dependent cracking and tension stiffening. However, none of these previous studies consider in a realistic manner the sequence of intervention (Hamed and Chang, 2013).

In all models presented above, interfacial shear stresses are predicted only in the elastic range (Benyoucef et al., 2007; Zhang and Wang, 2011; Diab and Wu, 2007, 2008) or by smeared simplified cracking with linear viscoelastic behavior in compression and brittle behavior in tension for the concrete (Hamed and Bradford, 2010, 2012). In other hand, very few studies have been conducted on the long-term stress distribution (Diab and Wu, 2007; Oller and Mari, 2013), which closely simulates the behavior of the intact (not pre-cracking) structures during the service-life. In this study, we develop a new viscoelastic model to study the creep behavior of the long-term interfacial stress distribution induced by intermediate flexural crack of the retrofitted concrete beam, by considering constant the total energy. In this model, the RC beam, the adhesive layer and the FRP plate are modeled as viscoelastic materials where creep coefficients of each material that depends on time and duration of loading. Using the cohesive zone model in three stages, only our model gives interfacial shear stresses in elastic, softening and debonding near the flexural crack with the time increments. Finally, some of the main parameters involved in the time-dependent behavior of retrofitted beam, such as the mechanical properties and thickness variations of FRP, concrete and the influence of environmental conditions, are evaluated by introducing the creep values.

2. Cohesive zone model in long-term behavior of mid-span cracked beam

Let us consider a simply-supported reinforced concrete beam, reinforced by an FRP plate subjected to point loads with a flexural crack at mid-span (Fig. 1). The geometry of the cross-section of the plated beam is similar to that proposed by many other researchers (Roberts and Haji-Kazemi, 1989; Smith and Teng 2001; Wang 2006a, b). Both the concrete beam and the FRP plate are modeled as linear elastic simple beams. The subscripts *1* and *2* denote the concrete beam and the FRP plate, respectively. Using elasticity laws, the axial forces N_i and bending moments M_i for these two beams ($i = 1, 2$) read:

$$N_i = E(t)_i A_i \frac{du_i}{dx}$$
$$M_i = -E(t)_i I_i \frac{d^2 w_i}{dx^2} \tag{1}$$

where u_i and w_i are respectively the axial and vertical displacements of beam i ($i = 1, 2$). $E(t)_i$, $A_i = b_i h_i$ and I_i are the adjusted time dependent elasticity modulus, cross sections and moments of inertia of beam i ($i = 1, 2$), respectively.

Displacement discontinuities caused by the flexural crack can be conventionally modeled as a rotational spring with infinitesimal thickness at the crack location (Fig. 1a). From, the rotational stiffness of the spring is determined by the fracture mechanics principle given by Paipetis and Dimarogonas (1986):

$$K_r = c(a, h_1) E_1(t) I_1 \tag{2}$$

Where h_1 and a are the thickness of the beam and the depth of the crack, respectively; $E_1(t)I_1$ is the time dependent bending stiffness of the whole concrete beam at the location of the crack at the time t, and $c(a, h_1)$ is determined by the crack geometry. For $a/h_1 < 0.6$, $c(a, h_1)$ is already given by Paipetis and Dimarogonas (1986). Considering a typical infinitesimal isolated body of the plated concrete beam as shown in Fig. 1c, the following equilibrium equations are established:

$$\begin{cases} \dfrac{dN_1}{dx} = b_2 \tau \\ \dfrac{dN_2}{dx} = -b_2 \tau \\ M = M_1 + M_2 + N_2(Y_1 + Y_2 + h_a) \end{cases} \tag{3}$$

Where N_i and M_i are the horizontal axial force and couple moment, respectively; τ is the interface shear stress; M is the total applied moment and Y_1 and Y_2 are the distances from the bottom of adherent 1 and the top of adherent 2 to their respective centroids, h_a is the thickness of the adhesive layer. For convenience, we assume that all the resulting applied forces (couple moment) act on the neutral axis of the concrete beam or the FRP plate.