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Flexural and interfacial behavior of metallic beams strengthened by prestressed bonded plates

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ABSTRACT

Closed form solutions for the flexural and the interfacial behavior of steel beams strengthened by prestressed bonded plates are presented. The method includes the shear deformation effect of the beam and is applied to three different load cases. The effect of different parameters such as the prestressing level, steel grade and geometric and mechanical properties of the plate on both the interfacial shear stress and the flexural behavior of the plated beam is discussed. The results show that while the geometric and mechanical properties of the plate have influence on the stiffness and the yield load capacity of the plated beam, prestressing does not affect the stiffness of the plated beam but increases the yield load capacity. The qualitative results of the analytical method presented in this paper are then compared with the experimental results of laboratory tests, which show good agreement between theory and practice. The experimental results show an increase in the yield and ultimate load carrying capacity of the beams strengthened by prestressed carbon fiber reinforced polymer (CFRP) plates.

1. Introduction

Reinforcement using a non-prestressed fiber reinforced polymer (FRP) plate has been used to strengthen flexural members; however, the permanent loads are not transferred into the strengthening element, and the FRP only acts against live loads. By strengthening with prestressed FRP plates (Fig. 1), a portion of the permanent load will be transmitted into the FRP. Although the strengthening of steel structures using carbon fiber reinforced polymer (CFRP) plates has attracted much research attention (e.g., [1–25]), there are relatively few studies that have theoretically investigated the behavior of steel beams strengthened with prestressed CFRP plates [19–21]. On the other hand, laboratory experiments from several studies have shown the effectiveness of using the prestressed CFRP plates to improve the yield and ultimate load carrying capacity of metallic structures; however, no theoretical research has focused on the flexural performance of such systems. The present paper uses an analytical approach to model the effect of prestressing on the stiffness, yield and ultimate load carrying capacity of the plated beams.

1.1. Methodology of existing theoretical approaches

As mentioned above, there are several studies that have treated the problem of plated beams. Basically, these studies can be divided into two general categories. The first category includes the analytical solutions that generate simple closed-form solutions as a result of the presumption of uniform stresses across the adhesive thickness (e.g., [17,19–21,26,27]); however, these solutions do not fulfill the condition of zero interfacial shear stress at the stress-free end of the plate. The second category includes the higher order solutions that satisfy the condition of zero interfacial shear stress at the end of the plate (e.g., [15,18,28]) but arrive at either inexplicit or explicit expressions that are much more complicated in practice than the solutions in the first category. Although the latter category gives more accurate results, the qualitative results are not easily attainable. In contrast, the former category presents the approximate closed-form solution, which can be easily used for design purposes. The method that is presented in this paper belongs to the first category and will generate simple closed-form solutions. The shortcomings associated with the lack of zero interfacial shear stress at the stress-free end of the plate are believed to be restricted only to the immediate vicinity of the plate end [26].

1.2. Existing solutions for steel beams reinforced with prestressed plates

In general, the governing equations of the beams reinforced with prestressed plates are the same as those for beams reinforced by non-prestressed plates. Nonetheless, there are some additional terms that should be taken into account in these solutions for the case of prestressed plates. There are few theoretical studies on the behavior of steel beams strengthened with prestressed CFRP plates [19–21], all belongs to the first solution category. Al-Emrani and Kliger [19] considered the effect of prestressing force on the

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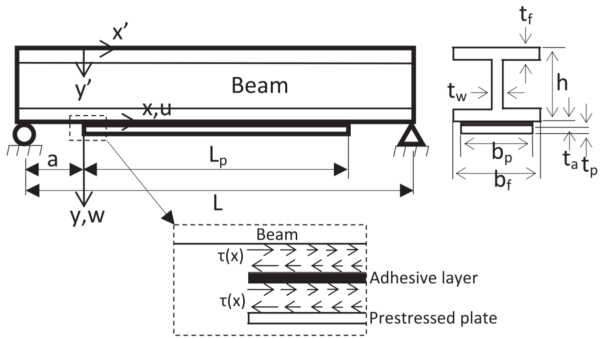

Fig. 1. Beam strengthened by a prestressed bonded plate.

interfacial shear stresses. Benachour et al. [20] developed the previous work [19] for different loading cases. Kerboua et al. [21] developed [20] to consider the shear deformation effect in their analysis. The accuracy of an assumption presumed in [20] has been questioned in [25]. Nonetheless, all the above solutions have generally been developed by focusing on the interfacial stresses at the adhesive layer. These solutions do not provide information on the flexural behavior of beams strengthened by prestressed plates, however different previous laboratory experiments have shown an improvement in the yield and ultimate load capacities of the prestressed plated beam. Hence, it is evident that there is a need for a series of solutions that study the effect of prestressing on the load–deflection behavior and the yield load capacity of plated beams.

In this paper, a closed-form solution for the interfacial stresses and flexural behavior of steel beams strengthened by prestressed plates, including the shear deformation effect, is presented. The paper gives closed-form expressions for the axial load distribution along the prestressed bonded plate and the vertical deflection of the beam. An approximate expression for the yield load of the plated beam as a function of the prestressing level is developed. A parametric study is performed to find the parameters that affect the stiffness and yield load of the plated beams. Finally, the qualitative results of the presented method are compared with the experimental results.

2. Governing equations

2.1. Basic assumptions

Linear elastic behavior for the beam, the plate and the adhesive layer is assumed. The beam behaves according to Euler–Bernoulli theory, and the curvature of the beam is assumed to be identical to that of the FRP plate. The bending deformation in the adhesive layer is neglected, and shear and normal stresses are constant across the adhesive thickness.

2.2. Governing differential equation of interfacial shear stress

Fig. 2 shows a differential segment dx of a plated steel I-beam. Note that the subscripts s and p denote the terms related to steel and the FRP plate, and the superscripts M and N are associated with the terms related to the bending and longitudinal forces at the neutral plane for each adherend. From Fig. 2, the axial force in the steel beam and in the FRP plate, N_s and N_p, are equal and are written as:

$$N_s(x) = N_p(x) = N(x). \tag{1}$$

The strains at the bottom flange of the steel beam and at the top of the FRP plate are expressed by:

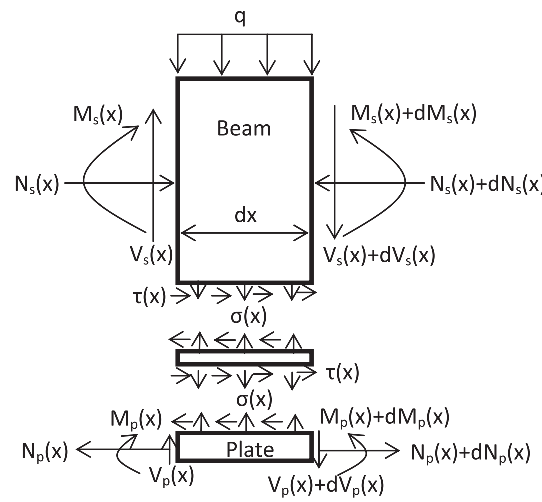

Fig. 2. Force equilibrium in an infinitesimal element dx.

$$\varepsilon_s(x) = \frac{du_s(x)}{dx} = \varepsilon_s^N(x) + \varepsilon_s^M(x) = -\frac{du_s^N(x)}{dx} + \frac{hM_s(x)}{2E_sI_s}, \tag{2}$$

$$\varepsilon_p(x) = \frac{du_p(x)}{dx} = \varepsilon_p^N(x) + \varepsilon_p^M(x) = \frac{du_p^N(x)}{dx} - \frac{t_pM_p(x)}{2E_pI_p}, \tag{3}$$

where $u_s(x)$ and $u_p(x)$ are the longitudinal displacements at the bottom flange of the steel beam and at the top of the FRP plate, $u_s^M(x)$ and $u_p^M(x)$ are the longitudinal displacements at the neutral plane of the steel I-beam, M_s and M_p represent the bending moment for the steel beam and the FRP plate, $\varepsilon_s^M(x)$ and $\varepsilon_p^M(x)$ are the strains induced by the bending moment at the steel beam and at the FRP plate and $\varepsilon_s^N(x)$ and $\varepsilon_p^N(x)$ are the strains induced by the bending moment at the steel beam and at the FRP plate. To determine the unknowns $\varepsilon_s^N(x)$ and $\varepsilon_p^N(x)$, a parabolic shear deformation function is assumed in the steel beam. Several studies [21,27] have used such a continuous function of shear deformation over the depth of the beam, which is zero at the outer surface of the upper edge. Moreover, there exist relevant studies on the strength and stability of the bonded joints [29–31]. A cubic variation of the longitudinal displacement is assumed in the steel beam as follows:

$$U_s^N(x, y') = A(x)y'^3 + B(x)y' + C(x), \tag{4}$$

where y' denotes a local coordinate system with an origin at the outer surface of the upper flange. Note that $x' = x$, and thus the formulations in this paper are derived based only on x. $A(x)$, $B(x)$ and $C(x)$ are coefficients that will be determined later. The shear stress in the steel beam is then expressed by:

$$\tau_{xy',s}(x, y') = G_s\gamma_{xy',s}(x, y'), \tag{5}$$

where G_s is the transverse shear modulus of the steel beam. The shear strain within the steel beam is given as:

$$\gamma_{xy',s}(x, y') = \frac{\partial U_s^N(x, y')}{\partial y'} + \frac{\partial W_s^N(x, y')}{\partial x}. \tag{6}$$

In Eq. (6), the first derivative of the transverse displacement, $W_s^N(x, y')$, with respect to the longitudinal coordinate, x, which originates from the longitudinal force, N, is assumed to be negligible. Therefore, Eq. (6) can be rewritten as:

$$\gamma_{xy',s}(x, y') = \frac{\partial U_s^N(x, y')}{\partial y'}. \tag{7}$$

Thus, Eq. (5) can be written as:

$$\tau_{xy',s}(x, y') = G_s(3A(x)y'^2 + B(x)). \tag{8}$$