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Modelling bond of GFRP rebar and concrete

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HIGHLIGHTS

- Numerical modeling predicting the bond behavior of GFRP rebar and concrete.
- Two damage-based approaches were presented for GFRP rebar bond damage evolution.
- Results of FE modeling matched well with corresponding experimental measurements.

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ABSTRACT

The structural performance of concrete structures reinforced using glass-fiber-reinforced-polymer (GFRP) rebars is sometime compromised by debonding failure. For better analyzing the GFRP bar-concrete bond behavior, this study presents two damage-based approaches for assessing the bond damage evolution. One is the secant modulus-based model and other is exponential damage model. Using the exponential damage approach, a simplified analytical model based on only one curve fitting parameter was developed to predict the bond stress-slip relationship. Then, a 3D finite element (FE) model was developed and both proposed damage-based approaches were implemented, to simulate the GFRP bond behavior. The FE model considers the nonlinear behavior of the concrete and the GFRP bar-concrete interface. The analytical and numerical predictions of the GFRP bar-concrete bond behavior are validated by comparing with the relevant results of an experimental program focused on quasi-static pullout tests. At the end, a parametric study was carried out to numerically assess the influence of some critical parameters on the bond behavior.

1. Introduction

Concrete elements reinforced with conventional steel bars have been extensively used for construction purposes [1–3]. However, corrosion of the steel reinforcement limits the long-term performance of these type of elements. This problem causes the loss of structural serviceability by decreasing the steel-concrete bond strength and reducing the cross section of the reinforcements [4]. Accordingly, corrosion-free fiber reinforced polymer (FRP) materials have been developed, as an alternative to steel, to reinforce the concrete elements due to the several advantages associated with these composites. Among the available FRP composite materials in the market, glass fiber reinforced polymers (GFRP) have received considerable attention due to non-corrosive and non-conductive characteristics, high strength-to-weight ratio, relevant fatigue endurance and, last but not least, the cost competitiveness [5]. However, the research studies showed that the efficiency of FRP reinforcements in structural applications may be limited by the occurrence of FRP-concrete interface debonding, by means of premature failure modes [5,6]. In addition, the anisotropy nature of GFRPs introduces more complexity in understanding the GFRP-concrete bond behavior compared to the steel-concrete counterpart [7].

The literature review shows that several experimental investigations have been conducted to evaluate the influence of some parameters such as concrete strength, bar surface, bar diameters, and concrete cover, on the GFRP bar-concrete bond [5,8]. However, more experimental investigations are still needed to confirm with more certainty the influence of effective parameters in this context. Besides the experimental investigations, several attempts have been made to develop analytical models to predict the interfacial behavior of GFRP bars and concrete (e.g. [9]). The key parameters of the developed analytical models are determined using the curve fitting from experimental results. Usually, simplified analytical models depend on a reduced number of variables to be identified by the fitting approach and cannot consider the several

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parameters affecting the bond behavior. Hence, they are quite inaccurate with very conservative predictions [5].

Based on the existing experimental and analytical researches in the literature, limited resources are available for an accurate description of the bond damage evolution of GFRP bar-concrete during the pullout loading [7,10]. However, the interfacial damage features for GFRP bar-concrete bond are valuable aspects to better design the GFRP reinforced concrete structures [7]. Besides the available experimental researches, reliable numerical models are indispensable to investigate the influence of several parameters on the bond performance. Those are essential to reduce as much as possible the cost of experimental testing [11–13]. The complexities of numerical modeling the GFRP bar-concrete interface contact using the damage evolution approach justify the relatively small number of publication in this domain [7,10]. Numerical modeling of the relevant nonlinear phenomena requires sophisticated constitutive material and interface bond models to accurately simulate the GFRP bond behavior, which is an issue in this area that needs to be addressed.

This study intended, in the first part, to present two damage-based approaches for assessing the damage evolution of GFRP bar-concrete bond. One is the secant modulus-based model developed by [7] for damage assessing the GFRP bar-concrete bond. Other damage-based approach is exponential damage model developed with the aim of accounting for the interface deterioration of GFRP-concrete bond. Then, using this exponential damage model, a simplified analytical model based on only one curve fitting parameter was developed to predict the experimental bond stress-slip curves. Next, the results of an experimental program, organized with the purpose of assessing the influence of concrete characteristics and concrete cover thickness on the GFRP bond behavior, were represented. The experimental bond stress-slip curves of the tested pullout specimens were analytically predicted using the proposed simplified model. Furthermore, damage assessment of the experimental bond tests was carried out using the secant modulus-based damage model and exponential damage model. Both proposed damage-based approaches were implemented in a commercial finite element (FE) software [14]. Accordingly, in the second part, this study aimed to develop a 3D FE model to simulate the experimental GFRP bond behavior. This model considers the nonlinear behavior of the concrete and the GFRP bar-concrete interface. The definition of material constitutive parameters and properties of bond interfaces were explained in detail. Regarding the GFRP bar-concrete bond interface, the cohesive elements were adopted. At the end, the good predictive performance of the developed FE model was demonstrated in terms of bond stress-slip relation and concrete strain distribution. Then, a series of parametric study was carried out to numerically assess the influence of some critical parameters on the GFRP bond behavior.

2. Damage evolution for the gfrp bar-concrete bond

The nonlinear behavior of the bond between GFRP bar and concrete can be simulated by adopting the bond damage evolution approach. The bond damage process can be attributed to the reduction in terms of the adhesion and frictional resistances, and the mechanical interlock. The damage approach consists of two requirements: a damage initiation criterion and a damage evolution law. An initial linear response is assumed for the bond behavior until the maximum bond shear stress (τ_b). Once a damage initiation criterion occurs at the maximum bond stress, the damage propagation follows the adopted damage evolution law. In other words, the damage approaches allow for the damage mechanism development once the damage initiation criterion is met, and have no effect on the initial linear phase of bond response. Hence, this bond initial linear phase can be defined as an undamaged state. Accordingly, damage modeling enables to simulate the stiffness degradation and eventual pullout debonding and concrete cover splitting failures (as two main failure modes of pullout tests [5]) after the occurrence of the relevant damage initiation criterion. In the current model, two governed laws were described and adopted for the evolution of the damage variable (D) beyond the damage initiation. These laws are the secant modulus-based model and exponential softening branch. The damage variable (D) intends to include phenomenologically all the sources responsible for the bond deterioration, like adhesion and frictional resistances, and the mechanical interlock.

2.1. Secant modulus-based damage model

The damage approaches are characterized by defining a scalar damage evolution variable (D). This scalar variable ranges between 0 (denoting no damage) and 1 (denoting the limit stage of damage) ($0 < D < 1$, see Fig. 1a) [7]. In fact, upon further loading after damage initiation, the scalar damage evolution variable evolves from 0 to 1.

The bond shear stresses (τ_s) are affected by the corresponding damage as follows (e.g. see point "C" in Fig. 1a):

$$\tau_s = \begin{cases} \tau_e & \tau_e \leqslant \tau_b \rightarrow D = 0\text{, no damage} \\ (1-D).\tau_e & \tau_e > \tau_b \end{cases} \quad \text{where} \quad \tau_e = K_{be}.\delta \qquad (1)$$

where τ_e is the bond stress component predicted by elastic bond stress-slip relation without damage, considering the elastic bond stiffness (K_{be}) and the relevant slip (δ). K_{be} can be determined as $K_{be} = \tau_b/\delta_b$, where δ_b is the slip at the bond damage initiation.

The scalar damage evolution variable can be described by the degradation of bond stiffness based on Lemaitre-based damage model [7]. To take the advantage of this concept for the softening branch of GFRP bar-concrete bond, the variation of secant bond stiffness ($K'_{b\sec}$) in comparison to the elastic bond stiffness (K_{be}) can be adopted to represent the evolution of bond damage. This concept was schematically illustrated in Fig. 1a. Therefore, the bond damage evolution with respect to the corresponding slip can be determined as expressed in Eq. (2).

$$D = \begin{cases} 0 & \delta \leqslant \delta_b \\ 1-(K'_{b\sec}/K_{be}), & \delta > \delta_b \end{cases} \qquad (2)$$

Accordingly, using the scalar damage variable represented in Eq. (2), the bond damage evolution law is derived from the known bond shear stress-slip curves. It should be noted that a similar strategy for the evolution of bond damage can be adopted for the bond stresses in the normal direction (σ_n) when the corresponding bond normal stress-separation curves exist. However, in the present study, the evolution of bond damage for the normal direction was neglected due to the lack of relevant experimental data.

2.2. Exponential damage model

Another approach, adopted for the bond damage evolution in the current study, focuses on evolving an exponential function to describe the relation of GFRP-concrete bond shear stress vs. slip in post-peak phase. This function was inspired from the exponential damage model proposed by [14,15] for damage assessment. The exponential softening law defines the bond damage variable (D) as a function of the slip (δ) beyond the damage initiation. This bond damage variable (D), expressed in Eq. (3), is specified by a non-dimensional parameter (α) and the slip corresponding to com-