HIGH-CYCLE FATIGUE NUMERICAL MODELLING OF BOND BETWEEN FRP REBAR AND CONCRETE

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Abstract
Experimental studies have evidenced that the use of Fibre Reinforced Polymer (FRP) composite materials to reinforce or strengthen the RC structures exposed to repeated cyclic loading can improve their fatigue life. To exploit the good fatigue performance of these composite materials, the bond between the FRP reinforcement and the concrete must remain effective. The current study aims to simulate the nonlinearity in the bond of FRP rebar and concrete under high-cycle fatigue, firstly, by developing a damage-based model for reproducing the bond stiffness degradation and residual slip growth due to fatigue load effects, and then, developing a 3D finite element (FE) model in a commercial software. The FE model considers the nonlinear behaviour of the materials coupled with the developed damage-based model to simulate the bond deterioration due to high number of cycles. Moreover, to reduce the computational cost for modelling each cyclic loading, a cycle jump approach is implemented in the FE model. The developed numerical model is validated by comparing with the relevant results of an experimental program involving eccentric pull-out fatigue tests.

1. Introduction

Fiber reinforced polymer (FRP) reinforcement is one of the most recent type of composite materials for the reinforcing and strengthening purposes of reinforced concrete (RC) structures due to the several advantages offering by the FRP composites [1]. One of these advantages is providing a good resistance in terms of service life and failure of RC structures strengthened or reinforced using FRP materials subjected to repeated cyclic loading [2]. In this regard, the repeated cyclic loading has the most significant effects on the bond between the FRP materials and concrete, causing a reduction of the bond strength and an acceleration of bond deterioration, as the number of cycles increase.

Beside the available experimental data (see e.g. [3]), there is a growing need for accurate models to predict the fatigue life and behavior of the bond between FRP and concrete. However, the prediction of the bond performance under cyclic loading has several complexities needing to account for variation of the materials properties and of the bond interface with cycles. Therefore, more studies are still needed to develop models with the capability of providing accurate numerical simulations of concrete structures reinforced with the different type of FRPs (such as FRP bars). Such models can increase the confidence level in adopting FRP composite materials as reinforcements when the structures are under mechanical fatigue loading.

In this context, the main objectives of the current investigation is to develop a damage-based model and its implementation in a commercial FE software to numerically predict the mechanical behavior of the bond between FRP bars and concrete under high-cycle fatigue loading. The model considers the bond deterioration due to the fatigue using two separate measures of the damage: the bond stiffness degradation and the residual slip growth by the fatigue cycles. The developed fatigue model was combined with the 'cycle jump' technique and implemented in a 3D FE code, with the aim of assessing the potentialities for structural applications. For this purpose, the results of available experimental pullout tests considering the bond between Glass Fiber reinforced Polymer (GFRP) bar and concrete under repeated high-cycle fatigue loads was numerically simulated.

2. Model for the high-cycle fatigue of the bond between FRP bar and concrete

2.1. Development of damage models

The nonlinear fatigue behavior of FRP and concrete bond deterioration under cyclic loading can be phenomenologically simulated by adopting damage evolution approaches. In general, damage approaches consist of two requirements: a damage initiation criterion and a damage evolution law [4]. The damage initiation criterion for the static and fatigue behaviors of the bond between FRP bar and concrete is defined by the maximum quasi-static bond average shear stress ($\tau_{s,b}$) and the maximum fatigue bond average shear stress ($\tau_{f,\max}$) in each cycle, respectively (Fig. 1a). In the current study, to simplify the prediction process of the high-cycle fatigue bond behavior, the bond slip vs. fatigue cycle ($\delta - N$) and the bond stiffness ratio vs. fatigue cycle ($\kappa - N$, where κ is the ratio between the bond stiffness at a certain loading cycle (K_N) to the initial bond stiffness (K_0)) relations were assumed to be trilinear diagrams as schematically represented in Fig. 1c and 1d, as evidenced experimentally in [5]. Those can be obtained using fitting of the relevant experimental data.

The two measures of the FRP-concrete bond deterioration due to fatigue cycles, i.e. the bond stiffness and the bond residual slip, are schematically represented in Fig. 1a. The residual slip is the unrecovered slip after removing the applied fatigue load. The slip corresponding to the minimum fatigue bond shear stress ($\tau_{f,\min}$) in the cycle was assumed as the residual slips ($\delta_{res.}$) in the present model (Fig. 1b). The two components of the fatigue bond deterioration can be taken into account using a damage approach. Hence, in the current model, to simulate the nonlinearity in the fatigue behavior of bond, two separate damage laws were developed for reproducing the bond stiffness degradation and residual slip growth. Concerning the two requirements of a damage approach, the maximum fatigue bond shear stress ($\tau_{f,\max}$) is assumed as the damage initiation criterion for all fatigue cycles, while both bond damage evolution parameters are cycles dependent as detailed below.

The bond stiffness degradation and the residual slip growth during cyclic loading are considered uncoupled assuming two distinct scalar damage evolution variables (D_κ and $D_{res.}$). The scalar variable ranges between 0 (denoting no damage) and 1 (denoting the limit stage of damage). For the degradation of bond stiffness with fatigue cycles, the damage variable (D_κ) is defined considering the variation of bond shear stiffness along the fatigue cycles (K_N) in comparison to the initial bond stiffness (K_0). Therefore, the bond stiffness degradation in each fatigue cycle ($D_{\kappa,N}$) can be determined using the bond stiffness ratio ($\kappa_N = K_N / K_0 \leq 1$), as in Eqn. (1).

$$D_{\kappa,N} = 1 - \kappa_N \;\rightarrow\; 0 \leq D_{\kappa,N} \leq 1 \quad (1)$$

Accordingly, the bond damage variable $D_{\kappa,N}$ is derived from the experimentally known fatigue bond average shear stress-slip curves using Eqn. (1).

The present approach also considers the residual slip growth with fatigue cycles, focusing on the definition of residual slip bond damage variable ($D_{res.,N}$) as function of residual slip in the cycle ($\delta_{res.,N}$) compared to the maximum residual slip at the corresponding fatigue life ($\delta_{res.,f}$), as follows:

$$D_{res.,N} = 1 - \left(\frac{\delta_{res.,f} - \delta_{res.,N}}{\delta_{res.,f}} \right)^{p} \rightarrow 0 \le D_{res.,N} \le 1 \tag{2}$$

Therefore, the fatigue bond damage variable $D_{res.,N}$ is determined knowing fatigue bond shear stress-slip curves for $\delta_{res.,N}$ and $\delta_{res.,f}$, and p parameter by the curve fitting of the relevant experimental data.

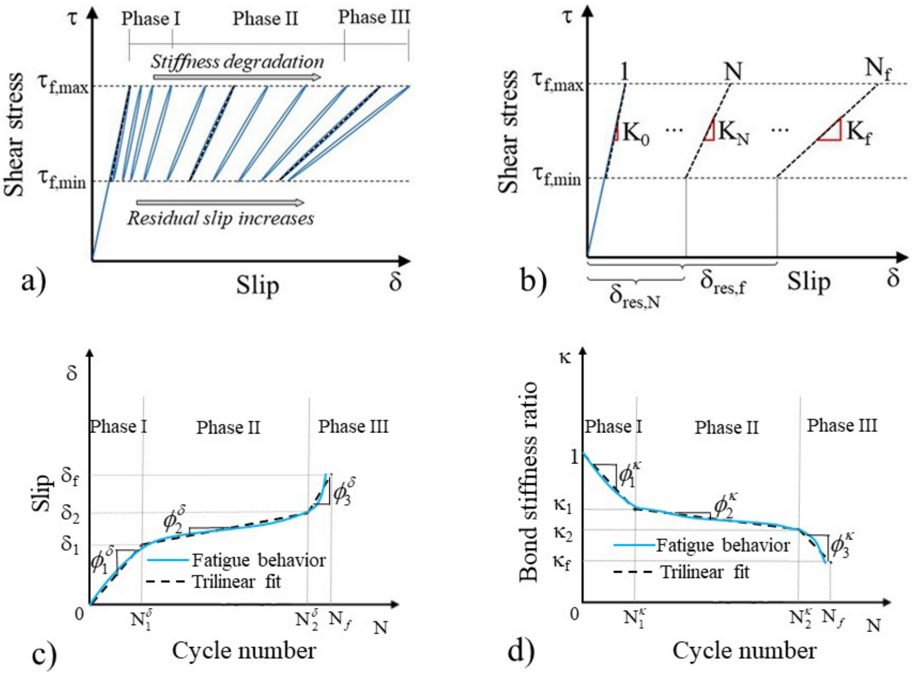

Figure 1. a) Bond deterioration due to fatigue cycles, b) bond stiffness degradation and residual slip increase with fatigue cycles, c) trilinear curve fitting of fatigue bond slip, d) trilinear curve fitting of fatigue bond stiffness degradation.

As far fatigue behavior of concrete and FRP bar, in the present numerical modeling, the degradation of the modulus of elasticity of concrete with fatigue cycles is considered following the proposal of Holmen [6]. Moreover, literature review evidences that when the strains in FRPs have relatively low levels (like for the FRP pullout tests adopted in the present investigation [5]), the strength of FRP is not affected by fatigue loading [7]. Hence, the effect of fatigue on the mechanical properties of FRP bars are neglected in the present model.

2.2. Cycle jump approach for modeling high-cycle fatigue

Modeling each cycle of the fatigue behavior has a huge computational cost and, depending on the available computational resources, it may be time consuming. To reduce the computation time, the 'cycle jump' technique allows performing numerical analyses selecting only a proper set of loading cycles. This is considered in the present fatigue FE modeling. According to the 'cycle jump' technique, the computation is done for a certain number of loading cycles, and the bond deterioration is determined by extrapolation strategy [8]. The selection of the simulated loading cycles, according to the 'cycle jump' technique, is made using a damage function D ranging between zero and one, and having positive gradient ($dD/dN \geq 0$) [9]. The 'cycle jump' implementation in a FE model has two requirements: (i) selection of loading cycles to provide a fast and computationally efficient numerical analysis; (ii) accumulation of the bond damage and redistribution of the stress state, beside the prediction of stiffness degradation and residual slip after a certain number of cycles.The schematic representation of the 'cycle jump' is shown in Fig. 2a. In the figure, the continuous line cycles are simulated for the fatigue response prediction, while the cycles with dash-line denote the cycle jumps.

In the present investigation, the estimation of the cycle jumps (NJUMP) is based on the damage curve of fatigue bond stiffness degradation (D_κ).The size of NJUMP varies between one and a certain upper limit defined as a maximum number of cycles that can be jumped over with the purpose of extrapolation the damage state toward the loading cycle , within acceptable limit of accuracy.

To simultaneously consider the two requirements of the 'cycle jump' approach, the fatigue bond modeling of the selected cycles consists of two steps. In the first step, the maximum fatigue load ($P_{f,\max}$) was statically applied and kept constant up to the end of fatigue analysis. In the second step, both damage variables of fatigue bond stiffness degradation (D_κ) and residual slip ($D_{res.}$) of the simulated cycles are introduced into the model and updated according to the corresponding damage law considering the relevant fatigue cycle number. Namely, an envelope of maximum fatigue loads is applied and the obtained results represent an envelope of the maximum slip (Fig. 2b and 2c).

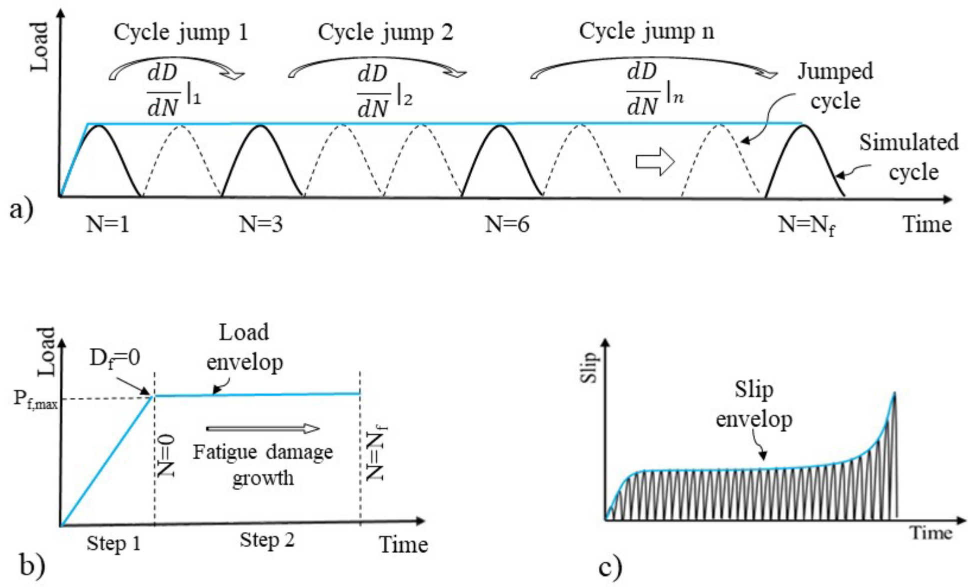

Figure 2. a) Schematic representation of the 'cycle jump' approach, b) amplitude of the applied load for fatigue modeling, c) envelop of bond slip.

3 Numerical modeling features

An experimental program detained in [5], comprised of eccentric pullout tests to assess bond characteristics between Glass Fiber reinforced Polymer (GFRP) bar and concrete under fatigue loadings, was considered to assess the predictive performance of the developed fatigue model. In the current paper, only one bar type and diameter (ComBAR® GFRP bar, diameter $d_f = 8\,\text{mm}$, with ribbed surface, Fig.

3a) was selected in combination with two fatigue load levels corresponding to $\tau_{f,\max}/\tau_{s,b}$ ratios of 60% and 70%. Mechanical properties in the bar (fibers) direction are assumed, according to producer's catalogue, as follows: tensile strength of 1500 MPa and modulus of elasticity of 60 GPa. The bars were embedded in concrete specimens of 200×200×150 mm (Fig. 3c) with an embedded length of $5d_f$ (40 mm) (see Fig. 3d). Tables 1 lists the mechanical properties of concrete and identifications of two selected fatigue pull-out configurations for the assessment of the proposed fatigue modeling.

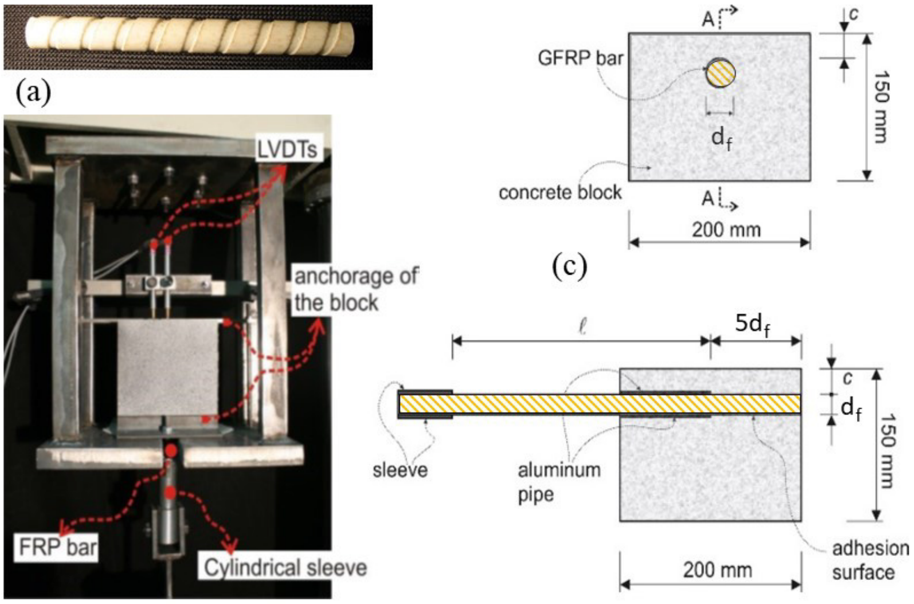

Figure 3. a) GFRP rebar ComBAR, d_f = 8mm. b) Experimental setup. Pullout specimen geometry: (c) top view, (d) longitudinal section A-A.

Table 1. Specimen ID and features

Specimen ID	Concrete compressive strength (MPa)	Concrete cover c (mm)	Fatigue load level $\frac{\tau_{f,\max}}{\tau_{s,b}}$ (%)
S1	20.3	10	60
S2	32.9	10	70

In order to numerically simulate the described experimental fatigue pullout tests using the developed fatigue model, a 3D FE model using a commercial software [10] was developed and described herein. Taking into account one symmetry plane of the experimental fatigue pullout specimen (Fig. 4), one-half was modeled applying the corresponding boundary conditions aiming to reduce the computational time of analysis (see Fig. 4b). Concerning the fatigue loading conditions, a load representative of an envelope of maximum fatigue loads was statically applied on the loaded-end of the bar according to the 'cycle jump' approach.

In the present investigation, the nonlinearity in concrete was modeled by using the nonlinear concrete damage plasticity (CDP) model available in [10]. According to the CDP model, the concrete inelastic behavior is simulated by applying an isotropic damaged elasticity concept in conjunction with isotropic tensile and compressive plasticity [10, 11]. The uniaxial behavior of concrete in tension and compression, before the crack initiation stage, was assumed to be linear up to concrete tensile strength and 0.4 of concrete compressive strength. After the concrete crack initiation, the uniaxial behavior is derived from the recommendations of CEB-FIP model code using a stress-crack opening and stress-strain relations in tension and compression zones, respectively.

A transversely isotropic linear elastic material model was used to characterize the GFRP bar up to its ultimate tensile strength considering the properties declared in producer's catalogue and the prediction of the elastic mechanical properties by the Chamis's formulae [12].

The bonded region of the fatigue pullout specimen was numerically simulated using cohesive elements (Fig. 4c) with a thickness close to zero (0.001 mm) by defining the relevant fatigue bond properties derived from the experimental data. Both main surfaces of cohesive element layer are tied to the surrounding components using a surface-based tie constraint, providing a perfect bond condition. A mixed mode of bond behavior including stress-separation (in the normal direction of the cohesive element plane) and shear stress-slip (on both tangential directions of the cohesive element plane) was defined for the cohesive elements (see details in [4]).

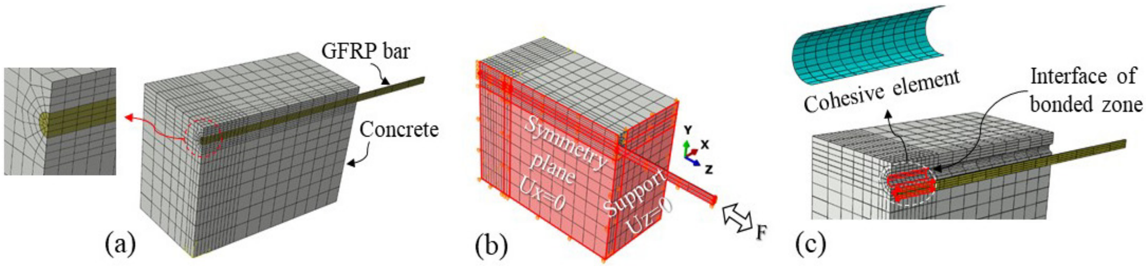

Figure 4. a) Meshing of the FE model, b) boundary conditions, c) interface of unbonded and bonded zones.

4. Assessment of predictive performance of the fatigue model

The potentialities of the proposed model to predict the high-cycle fatigue behavior of bond between FRP bar and concrete are assessed by comparison to the experimental measurements. The fatigue pullout specimens in Table 1 were numerically simulated using the 3D FE model. Both damage variables D_{κ} and $D_{res.}$ were adopted, and the p parameter of the damage variable of the residual slip (see Eqn. 2) was calibrated using the back analysis of the experimental data. It was determined $p = 2.5$ for all the simulated tests. However, it must be underlined that further investigations should be carried out to calibrate the p parameter for different type of FRP bars, other than the adopted GFRP rebar. Fig. 4 compares the experimental and predicted slip at maximum fatigue load vs. cycle number, showing a good predictive performance of the proposed model.

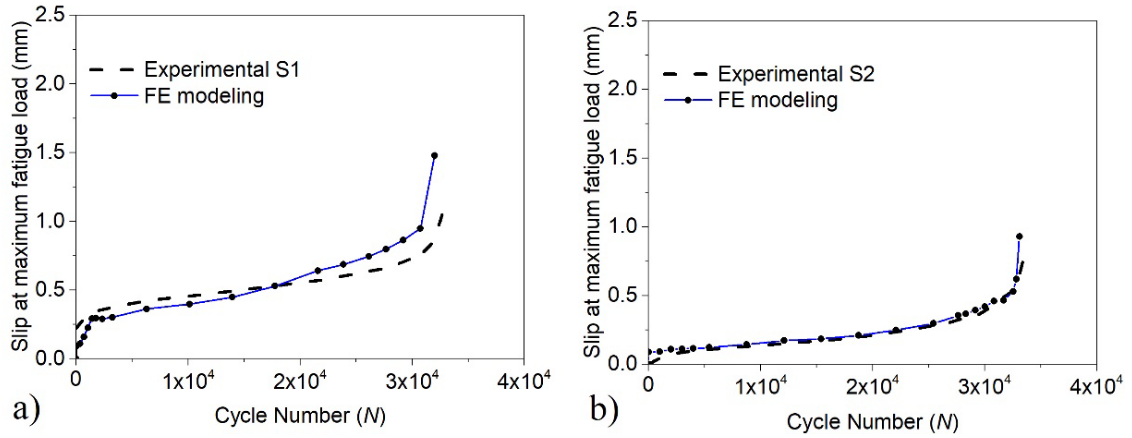

Figure 4. Comparison of the predicted and the experimental fatigue bond behavior of specimen: a) S1, b) S2.

5. Conclusions

A damage-based model was developed to predict the behavior of the bond between FRP bars and concrete under high-cycle fatigue loading. The nonlinearity in the fatigue behavior of FRP-concrete bond is simulated using two separate measures of the damage for reproducing the bond stiffness degradation and residual slip growth due to fatigue load effects. A 3D finite element (FE) model was developed combining the proposed damage-based fatigue model and the 'cycle jump' approach. The model considers the interfacial bonding behavior between the FRP bar and concrete using cohesive elements. Finaly, the accuracy of the model was confirmed by comparison to the relevant experimental results.

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