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A unified approach for the static and dynamic analyses of intermediate debonding in FRP-strengthened reinforced concrete beams

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ABSTRACT

A spectral method is proposed for solving static and dynamic problems in FRP-strengthened reinforced concrete beams in a unified way. In order to appropriately simulate the debonding failure a mechanical model considering nonlinear stress–strain relationships for concrete and steel is used. The FRP-to-concrete interface is modelled using a realistic bilinear local bond-slip law. Numerical results with the proposed model for the interfacial shear stress distribution and the load–displacement response are derived for beams statically tested. Using the same spectral model the influence of interfacial delaminations on the dynamic characteristics of the structures is studied. The feasibility of the proposed method for performing dynamic analyses for high frequency excitations in a very simple and non-expensive way makes this study very useful in non-destructive testing analyses as a tool for diagnoses and detection of debonding in its initial stage by monitoring the change in dynamic characteristics.

1. Introduction

Advanced composite materials are increasingly used in the strengthening of reinforced concrete (RC) structures [1–3]. The use of externally bonded strips made of fibre-reinforced plastics (FRP) as strengthening method has gained widespread acceptance in recent years since it has many advantages over the traditional techniques. However, unfortunately, this strengthening method is often associated with a brittle and sudden failure caused by some form of FRP bond failure, originated at the termination of the FRP material [4,5] or in the vicinity of flexural cracks in the RC beam [6–8]. Hence, flexural cracking of the RC beam has a major influence on the overall response of the strengthened member, and it affects the distribution of the stresses in the various constituents of the strengthened member [8–12]. In addition, this failure mode will affect the dynamic response of the beam by altering its natural frequencies. As a result, considerable analytical, numerical and experimental efforts should be made to capture these phenomena. Up to date, little effort has been made in the study of vibrations in FRP-strengthened RC beams and the influence of their failure modes over the dynamic properties, even though this effect might be used to predict a possible future debonding region in its initial instants that is not noticeable by simple visual observation. An early detection of this phenomenon might help in taking actions to prevent future catastrophes. To the authors' best knowledge, no model has been proposed up to date to represent the static and dynamic behaviour of this kind of strengthening in a unified way.

In the proposed approach in this paper, a spectral finite element (SFE) [13,14] is implemented in the framework of FRP-strengthened RC beams. Although the proposed approach is not a conventional finite element (FE) method, its structure is perfectly adaptable to displacement-based FE technique. For its application, the dynamic field equations are transformed to the frequency domain by using discrete Fourier transform (DFT) and then solved exactly or almost exactly in the frequency domain. The time domain response is obtained using inverse fast Fourier transform FFT. Unlike conventional FEM, the SFEM can give results in both the time and frequency domain in a single analysis. With this approach the method can be applied successfully to static and dynamic analyses since static response corresponds to dynamic computations when frequency tends to 0 Hz.

An interesting application of the proposed method is dynamic analysis for high frequency excitations. Unlike FEM, which would require a element size comparable to wavelengths which are very small in high frequencies, one spectral element would be enough to capture the highest frequencies. This gives to this method a large potential for use in the application of Structural Health Monitoring problems which can involve loading with high frequency content. By using high frequency measurements local damage can be detected [15–17] and, therefore, possible future debondings may be avoided.

In this work, taking as a reference the first-order shear deformation theory of Timoshenko with no contribution of the contractional mode, a one-dimensional SEM based model has been

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implemented for simulating the behaviour of reinforced concrete beams externally strengthened by FRP materials. Concrete-FRP phenomena are considered in a simplified way by the introduction of a characteristic variable within each element representing the relative slips between the RC beam and the FRP laminate [18,19]. Different nonlinear FRP-concrete interface laws might be used for determining the corresponding interface shear stress taking into account that a comprehensive way of modelling FRP–concrete debonding phenomena is not yet completely available [18,20–25]. For simplicity, in this work the well-established bilinear shear stress–slip relationship proposed by Lu et al. [23] is currently adopted.

The presentation of this work is organized as follows. Firstly, the dynamic equations simulating the behaviour of the RC beam strengthened with FRP laminates are derived. The application of the SFE method to this problem is shown in Section 3. In the following section, details of the nonlinear numerical procedure are shown. In Section 5, the static response predicted by the proposed method is compared with results from experimental tests for beams with intermediate debonding. Subsequently, a sensitivity study of the SFE method to capture the frequency changes provided by the progressive deterioration of the strengthened RC beam is performed. The paper is ended with conclusions and important remarks on future applications of the proposed approach.

The topic of structural health monitoring has been scarcely developed in FRP-strengthened RC beams in spite of its importance to prevent brittle failure modes. This work proposes a first approach to develop this topic which should be extended increasingly in the future.

2. Governing equations

In the present section the governing differential equations for the proposed problem are derived. On the basis of such equations the SFE method will be applied.

To solve the kinematics of the problem, firstly the partial interaction between RC beam and FRP plate is reflected by using an interface-slip s, which can be expressed as

$$s = u_{FRP\,top} - u_{C\,bot} \tag{1}$$

with $u_{FRP\,top}$ and $u_{C\,bot}$ denoting the axial displacements at the top of the FRP plate and at the bottom of the RC beam, respectively (Fig. 1).

According to the first-order shear deformation theory, the displacement field for axial and transverse motion is obtained by expanding the displacements in a Taylor series about the mid-plane displacements, $u_0(x,t)$ and $w(x,t)$, as

$$u_C(x,z,t) = u_0(x,t) - z\phi(x,t) \tag{2}$$
$$u_{FRP}(x,z,t) = u_0(x,t) - z\phi(x,t) + s(x,t) \tag{3}$$
$$w(x,z,t) = w(x,t) \tag{4}$$

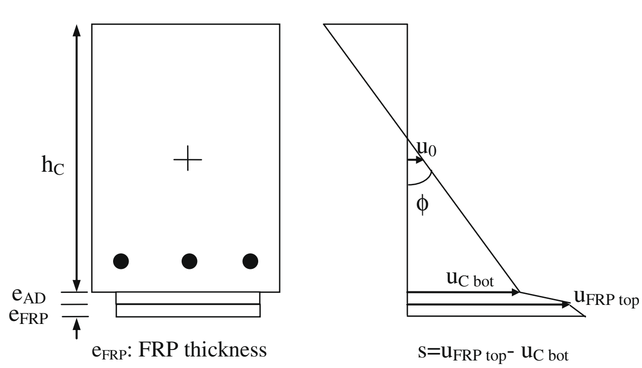

Fig. 1. Kinematic of the transverse section of FRP-strengthened RC beam.

where u_C, u_{FRP} and w are respectively the axial displacements in RC beam and FRP plate and the transverse displacement at a material point. ϕ is the curvature-independent rotation of the beam cross-section about the Y-axis. The coordinate z is measured from the mid-plane. These kinematic relationships are kept for the beam sections in which there is no FRP by removing the terms concerning the external reinforcement.

Using Eqs. (2)–(4), the linear strains can be written as

$$\varepsilon_{x\,C} = u_{0,x} - z\phi_{,x} \quad \gamma_{xz\,C} = w_{,x} - \phi \tag{5}$$
$$\varepsilon_{x\,FRP} = u_{0,x} - z\phi_{,x} + s_{,x} \quad \gamma_{xz\,FRP} = w_{,x} - \phi \tag{6}$$

where $\varepsilon_{x\,C}$, $\varepsilon_{x\,FRP}$, $\gamma_{xz\,C}$ and $\gamma_{xz\,FRP}$ are the longitudinal strains and the shear strains in the RC beam (C) and the FRP strip (FRP), respectively. Here the symbol $()_{,x}$ represents differentiation with respect to x.

Furthermore, the shear strain in the adhesive $\gamma_{xz\,AD}$ can be calculated from the interface-slip s and its thickness

$$\gamma_{xz\,AD} = s/e_{AD} \tag{7}$$

where e_{AD} denotes the thickness of the adhesive. Eq. (7) represents a simplification of the reality of variable shear strain through the adhesive thickness in the bond-critical zones [26].

The linear constitutive model for the concrete beam and the FRP plate can be expressed as

$$\sigma_{x\,C} = E_C\varepsilon_{x\,C} \quad \tau_{xz\,C} = G_C\gamma_{xz\,C} \tag{8}$$
$$\tau_{xz\,FRP} = G_{FRP}\gamma_{xz\,FRP} \tag{9}$$

where the material constants, E and G, are referred to the concrete beam (C) or the external plate (FRP) depending on the material considered; $\sigma_{x\,C}$, $\tau_{xz\,C}$ and $\tau_{xz\,FRP}$ are the longitudinal and the shear stresses in the RC beam and the shear stress in the FRP strip, respectively.

Calculation of bond shear stress between the FRP and concrete is very important in order to check the midspan debonding failure mode. Its value along a certain length of beam can be expressed as a function of the axial force acting on the FRP plate. The following relationship can be assumed (Fig. 2)

$$\tau_{xz\,AD}b_{AD} = F_{FRP,x} = ks = G_{AD}\gamma_{xz\,AD}b_{AD} \tag{10}$$

where $\tau_{xz\,AD}$ is the shear stress in the adhesive layer, F_{FRP} is the axial force in the plate, k is the stiffness constant which characterizes the adhesive interface which can be obtained by multiplying the adhesive slip modulus k_{AD} by the width b_{AD} of the adhesive layer and G_{AD} is the elastic shear modulus of the adhesive. Although in Eq. (10) a linear behaviour of the adhesive interface has been assumed, it does not involve any restriction for the application of the method since, as it will be seen in Section 4.2, when the elastic limit is reached the elastic moduli is replaced by the equivalent secant elastic moduli.

The strain energy for the strengthened sections is then given by

$$\begin{aligned} U = {} & \frac{1}{2}\int_L \int_{z_{1C}}^{z_{2C}} (\sigma_{x\,C}\varepsilon_{x\,C} + \tau_{xz\,C}\gamma_{xz\,C}) b_C \, dz\, dx \\ & + \frac{1}{2}\int_L \int_{z_{1FRP}}^{z_{2FRP}} (\sigma_{x\,FRP}\varepsilon_{x\,FRP} + \tau_{xz\,FRP}\gamma_{xz\,FRP}) b_{FRP} \, dz\, dx \\ & + \frac{1}{2}\int_L \int_{z_{1AD}}^{z_{2AD}} (\tau_{xz\,AD}\gamma_{xz\,AD}) b_{AD} \, dz\, dx \end{aligned} \tag{11}$$

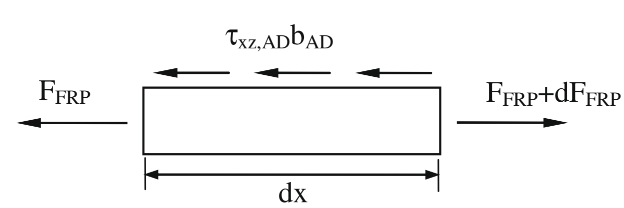

Fig. 2. Shear stress in the adhesive.