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Modified force method for the nonlinear analysis of FRP reinforced concrete beams

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ABSTRACT

Among the different techniques adopted to retrofit structures that had become inadequate, the use of fiber reinforced composite materials (FRP) has gained more and more popularity for their relevant properties such as high strength to weight ratio and excellent corrosion resistance. However, debonding of FRP lamina from the substrate, made of either concrete or steel, may prevent the achievement of the full load bearing capacity of the reinforced element. In this paper a numerical method, able to follow the complete equilibrium path of a reinforced concrete beam externally strengthened by means of FRP sheets up to the complete detachment of the external reinforcement, is proposed. According to this method, the FRP sheets are separated from the reinforced concrete substructure by displaying the interface stresses that are taken into account by means of the corresponding interface slips (which are the primary unknowns). Compatibility equations are then imposed at the interface in order to restore the behavior of the externally reinforced beam. The method is first validated by benchmarking experimental results taken from literature and then exploited to perform a parametric analysis in order to point out the effect of the main design parameters on the response of the reinforced beam.

1. Introduction

Advanced fiber reinforced composite materials have been used for many years in civil engineering for structural retrofitting of both reinforced concrete and steel elements, in view of their particularly useful properties: corrosion resistance, high strength, low dead weight and hence ease-to-use which avoids the cumbersome work associated with traditional retrofitting techniques, see [1–4].

Composite materials may be used for different purposes: flexural strengthening of both reinforced concrete (RC) and steel beams, as in [5–7]; shear strengthening of RC elements, see [8–10]; prevent local buckling of steel beams web, see [11]; strengthening of tensile steel elements under fatigue and static loading, as in [12–15] and confinement of RC columns, see [16,17].

When dealing with this type of strengthening, one of the main issues, which may prevent to achieve the full load bearing capacity of the retrofitted element, is the debonding of the CFRP lamina from the substrate. In addition, even before failure, significant slip occurs at the interface, (see, e.g. [18–21]), which affects the service behavior of the retrofitted elements and prevents from analyzing them according to the usual hypothesis of conservation of plane section, unless simplified and safe assumptions are formulated, as in [22,23].

Different numerical studies, that take into account the partial interaction between CFRP reinforcement and substrate, based on 1D (see for instance [24]), 2D (see [25,26]) and 3D (see [27–29]) finite element formulations exist in literature. Partial interaction modeling is also considered in composite beams to take into account separately the behavior of both concrete slab and steel beam, see for instance [30,31]. All the approaches, proposed to model externally reinforced beams, predict fairly well the behavior under service loads, but most of them fail in the prediction of the ultimate load or highlight the impossibility in following the debonding phenomena occurring at the interface up to the complete detachment of the reinforcement lamina.

This paper presents a novel numerical approach, based on the force method, in which the response of an externally reinforced beam is derived by enforcing compatibility along the interface between concrete and CFRP lamina. However, in view of the softening nature of the cohesive law governing the response of the interface, the usual approach to the force method was modified and the problem was formulated assuming as primary unknowns the interface slips, instead of the interface shear stresses. It is demonstrated that this approach is stable enough to follow, unless snap-back occurs, the complete equilibrium path from the

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response of the strengthened beam to that of the original one after the debonding of the external reinforcement and the consequent and sudden load drop.

The problem formulation brings to a set of nonlinear equations, which are solved within a classical Newton–Raphson scheme, whose corresponding consistent tangent operator is derived.

The paper is organized as follows: Section 2 describes the numerical method proposed to compute the response of an externally reinforced beam. Then results of the modeling of benchmarking experimental tests taken from literature are derived in Section 3 in order to validate the proposed numerical approach. Section 4 presents some parametric analyses aimed at showing the effect of the main design parameters on the overall behavior of a RC beam retrofitted by a CFRP lamina. Finally, conclusion, highlighting potentialities and limitation of the proposed method, are drawn in Section 5.

2. Numerical method

The numerical method, proposed to model an externally reinforced concrete beam, see Fig. 1, is based on the following assumptions:

- beam sections possess an axis of symmetry perpendicular to moment axis and remain plane during deformation;
- perfect bond is assumed between concrete and steel rebars;
- slips occurring at the interface between the concrete substrate and the external reinforcement are governed by a cohesive law with softening behavior;
- concrete, steel rebars and external reinforcement behave as nonlinear materials;
- bending stiffness of external reinforcement is negligible.

2.1. Constitutive equations

A brittle nonlinear elastic constitutive behavior is assumed for the external reinforcement (usually a Carbon Fibre Reinforced Polymer, or a Glass Fibre Reinforced Polymer), see Fig. 2:

$$\sigma_r = \begin{cases} H(\varepsilon_r)\cdot E_r\varepsilon_r & \text{if } \varepsilon_r \leqslant \varepsilon_{ru} \\ 0 & \text{if } \varepsilon_r > \varepsilon_{ru} \end{cases} \tag{1}$$

where: σ_r and ε_r are the axial stress and strain, respectively, E_r is the corresponding Young modulus, ε_{ru} is the ultimate strain and $H(\varepsilon_r)$ is the Heaviside step function.

Reference is made to reinforced concrete beams to formulate the proposed approach. For concrete in compression the classical parabola-rectangle stress–strain relationship, see [32], is considered, while the behavior of concrete under tensile stress is assumed to be linear elastic up to the tensile strength f_{ct} and then it drops to zero, see Eq. (2) and Fig. 3:

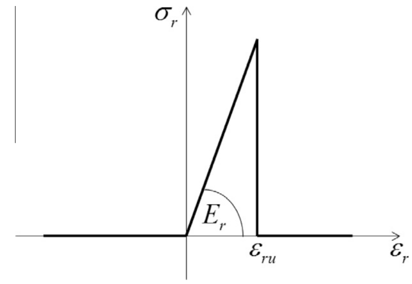

Fig. 2. Stress–strain relationship assumed for FRP.

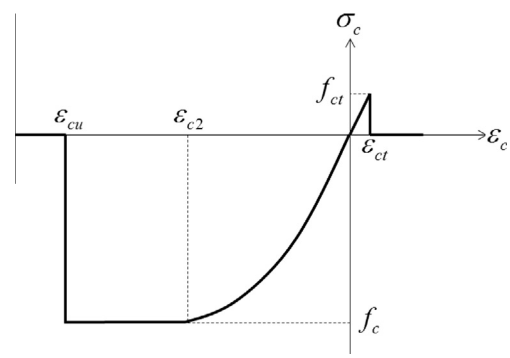

Fig. 3. Stress–strain relationship assumed for concrete.

$$\sigma_c = \begin{cases} 0 & \text{if } \varepsilon_c > \varepsilon_{ct} \\ E_c\varepsilon_c & \text{if } 0 \leqslant \varepsilon_c \leqslant \varepsilon_{ct} \\ \dfrac{\varepsilon_c}{\varepsilon_{c2}}\left(2+\dfrac{\varepsilon_c}{\varepsilon_{c2}}\right)f_c & \text{if } -\varepsilon_{c2} \leqslant \varepsilon_c < 0 \\ -f_c & \text{if } -\varepsilon_{cu} \leqslant \varepsilon_c < -\varepsilon_{c2} \\ 0 & \text{if } \varepsilon_c < -\varepsilon_{cu} \end{cases} \tag{2}$$

where: $\varepsilon_{c2} = 0.002$ is the strain at the end of the parabola, ε_{cu} is the ultimate compressive strain and $\varepsilon_{ct} = f_{ct}/E_c$ represents the tensile mechanical strain at the peak stress f_{ct}.

For internal steel reinforcement a classical elasto-plastic constitutive law is adopted with isotropic linear hardening, that is:

$$\sigma_s = \begin{cases} E_s\varepsilon_s & \text{if } |\varepsilon_s| \leqslant f_{sy}/E_s \\ \left[f_{sy} + H_s\left(|\varepsilon_s| - f_{sy}/E_s\right)\right]\cdot\dfrac{\varepsilon_s}{|\varepsilon_s|} & \text{if } f_{sy}/E_s \leqslant |\varepsilon_s| \leqslant \varepsilon_{su} \\ 0 & \text{if } |\varepsilon_s| > \varepsilon_{su} \end{cases} \tag{3}$$

where: σ_s and ε_s are the steel axial stress and strain, respectively, f_{sy} the yield stress and E_s, H_s the steel Young modulus and the linear hardening coefficient, respectively.

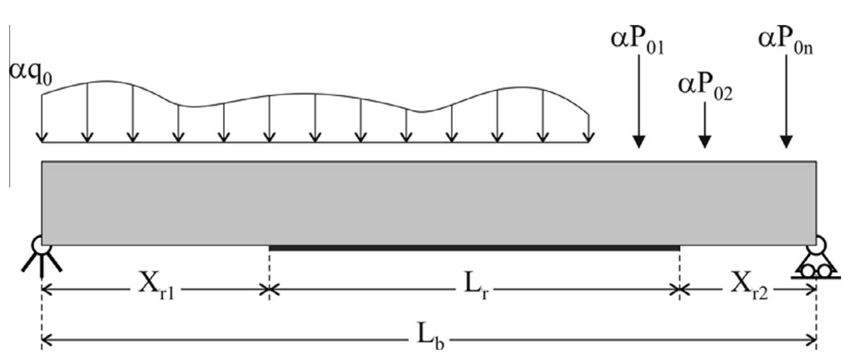

Fig. 1. Illustrative representation of a beam externally reinforced in bending with a CFRP lamina.