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Numerical investigation of concrete columns with external FRP jackets subjected to axial loads

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HIGHLIGHTS

- Damage model able to simulate the response of concrete columns under uniaxial load.
- Constitutive behaviour of concrete formulated via a modified Mazars' damage law.
- External FRP jackets performances related to the internal steel reinforcements.

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ABSTRACT

The application of fibre reinforced polymer (FRP) composites as an external reinforcement for concrete columns has proved to be an efficient method of confinement for strengthening and retrofitting existing structures needing a performance enhancement. In recent years, many different numerical models have been proposed to evaluate the behaviour of FRP confined concrete, also focusing on different constitutive laws for concrete. In this paper, a damage model has been developed to simulate and predict the response of concrete columns under uniaxial loading, externally confined with carbon FRP (CFRP) jackets, mainly focusing on the role of cross-section shape and internal steel bars in the strengthening intervention efficiency. Particularly, the constitutive behaviour of concrete has been here formulated via a modified Mazars' damage law, which allows to evaluate the three-dimensional confinement effects in the columns during monotonic axial compression loads. Many analytical models included in the design codes as well as previously developed numerical models do not relate the external FRP jackets performances to the internal steel reinforcements: the present study pursues this task, trying to understand the mechanisms from a detailed model. Its overall good agreement with experimental results gathered from literature proves the correctness of the suggested formulation.

1. Introduction

During the last decades various problems in terms of durability and consequent decrease in performance have been experienced by many existing concrete structures. Furthermore, the demanding strength and ductility increase in members under bending, shear and compression loads appears to be crucial for the seismic design, assessment and retrofitting of concrete. Under these circumstances, fibre reinforced polymers (FRP) composites have proven to be an effective strengthening and repair technique for reinforced concrete (RC) structures. Although confinement provided by external strengthening to inner concrete core have been thoroughly studied (see, among others [32,22,33,16,34,9,17,36,37]), the role of the mechanical interaction between internal steel reinforcements and externally bonded FRP does not seem to have been clearly understood yet. For a better understanding of the structural behaviour, the various non-linear mechanisms provided by internal steel reinforcements and externally bonded FRP should be specifically taken into account by analytical or numerical models, considered their strong influence on the efficiency of the strengthening technique [5,22].

According to Teng and Lam [33], most of the existing analytical models correlate the increase in strength and ductility with the passive confinement pressure provided by the external FRP sheets [31,21,29,8,11,2] without considering the contribution due to the internal transverse steel reinforcements. A few models (e.g. [10,7,18,4,22,9,12]) take into account that the global confining pressure is simultaneously due to the external FRP wrap and the internal steel stirrups. Furthermore, attention should be paid to the interaction between composite jacket and embedded longitudinal bars (e.g. [30,3,27,22]). If the stiffness of the external FRP

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jacketing is not enough to contrast the buckling of vertical steel bars, stress concentrations in the FRP can occur, causing its premature failure and a reduction in the efficiency of the FRP confining technique itself. Experimental tests have shown that longitudinal bars can be subjected to buckling, and columns post buckling behaviour was related to the jacket stiffness.

Another matter of interest is related to the shape of the column cross-section: most of the available stress–strain models have been proposed for circular confined concrete cylinders, but FRP confined concrete response in rectangular cross-sections lacks of sufficient investigation. Nevertheless some generalised analytical [17,28] and numerical [37,16] models have been proposed.

The Finite Element Method, capable of capturing complex stress variation in concrete, has been widely employed to model confined concrete. Many different constitutive models have been presented, including plasticity models [36,16], plastic-damage models and elastic-damage models [19,6]. Particularly, the Drucker-Prager Plasticity model has been extensively adopted because of its simplicity and suitability in describing concrete behaviour in structural members when its parameters are correctly calibrated. The modified Drucker-Prager model and the modified concrete damage-plasticity model proposed by Yu et al. [36,37] show that the following three features are needed for a plasticity model capable of predicting characteristics of both actively and passively confined concrete:

1. Yield criterion including the third deviatoric stress invariant.
2. Hardening/softening rule depending on the confining pressure.
3. Flow rule depending not only on the confining pressure but also on the confinement increase rate.

In case of damage-plasticity, a damage evolution law is also required. These models allow suitable simulation of the behaviour of externally confined plain concrete columns but they can not easily be applied to reinforced concrete columns including steel bars, mainly because of convergence problems due to the interactions between concrete and steel reinforcements.

This work aims to comprehensively evaluate the overall behaviour of FRP confined concrete columns, considering various types of cross-sections, corner radiuses in square cross-sections, types of external strengthening and internal steel bars. Three dimensional finite element models have been carried out using a modified Mazars' damage law for confined concrete. Often the isotropic damage theory is adopted to study concrete behaviour in unconfined conditions [19,24]. In this paper, confinement effects have been taken into account through the modification of Mazars' damage parameters, describing the stress increment in relation to the reinforcement type. The FRP jacket is modelled via orthotropic bi-dimensional elements and a specific contact algorithm [26,20] has been adopted for the interface between FRP sheets and concrete.

2. Concrete damage model

Mazars' damage model [19] is known to describe the strength loss in confined concrete columns. This model deals with an isotropic damage variable d, changing from 0 (no damaged material) to 1 (fully damaged material). The variable d describes the variation of the constitutive tensor $\boldsymbol{D}$ when damage occurs:

$$\boldsymbol{D}_s = (1-d)\boldsymbol{D} \tag{1}$$

Generally, $\boldsymbol{D}_s$ is named secant constitutive tensor.

The damage variation can be described through an internal variable k [15], representing the maximum strain level reached during the loading history, and a loading function f:

$$k(t) = \max_{\tau \leqslant t} \tilde{\varepsilon}(\tau) \tag{2}$$

where t is the time of analysis and τ is the time when the maximum equivalent strain $\tilde{\varepsilon}$ occurs. The equivalent strain $\tilde{\varepsilon}$ is a function of the strain tensor $\boldsymbol{\varepsilon}$. The loading function f is defined as $f = \tilde{\varepsilon} - k$.

Similarly to the elasto-plastic model, the loading-unloading condition can be written:

$$f < 0; \quad \dot{k} \geqslant 0; \quad \dot{k}f = 0 \tag{3}$$

The total stress–strain relation results as follows:

$$\boldsymbol{\sigma} = (1-d)\boldsymbol{D} : \boldsymbol{\varepsilon} \tag{4}$$

The total stress $\boldsymbol{\sigma}$ can be obtained as $\boldsymbol{\sigma} = (1-d)\bar{\boldsymbol{\sigma}}$ where $\bar{\boldsymbol{\sigma}}$ is the effective stress.

To evaluate the equivalent strain, the energy norm formulation [15] is taken into account:

$$\tilde{\varepsilon} = \sqrt{\frac{\boldsymbol{\varepsilon} : \boldsymbol{D} : \boldsymbol{\varepsilon}}{E_c}} \tag{5}$$

where E_c is the Young modulus of the virgin concrete material.

The aforementioned formulation for the equivalent strain evaluation leads to a symmetric tangent stiffness tensor $\boldsymbol{D}_t$, which allows an increase in the convergence velocity of the numerical analysis.

The damage function is composed by two parts, considering the different behaviour of concrete in tension and in compression [24]

$$d = \alpha_t d_t + \alpha_c d_c \tag{6}$$

where α_i (with $i = t,\ c$) are functions depending on the principal strain components and d_i are damage functions. For $k > \varepsilon_0$ (the elastic strain limit) the damage functions are defined as:

$$\begin{aligned} d_t &= 1 - (1-A_t)\frac{\varepsilon_0}{k} - A_t \exp\left[-B_t(k-\varepsilon_0)\right] \\ d_c &= 1 - (1-A_c)\frac{\varepsilon_0}{k} - A_c \exp\left[-B_c(k-\varepsilon_0)\right] \end{aligned} \tag{7}$$

where A_i, B_i are material parameters, experimentally determined.

Via a finite element formulation, the nonlinear material behaviour can be obtained from an incremental analysis, once the tangent stiffness tensor $\boldsymbol{D}_t$ is defined. The stress increment can be calculated following the incremental constitutive relation:

$$\dot{\boldsymbol{\sigma}} = (1-d)\boldsymbol{D} : \dot{\boldsymbol{\varepsilon}} - \boldsymbol{D} : \boldsymbol{\varepsilon}\dot{d} \tag{8}$$

where the damage time variation defined in Jiràsek [15]:

$$\dot{d} = \frac{\partial d}{\partial k}\dot{k} = \frac{\partial d}{\partial k}\dot{\tilde{\varepsilon}} = \frac{\partial d}{\partial k}\frac{\partial \tilde{\varepsilon}}{\partial \boldsymbol{\varepsilon}} : \dot{\boldsymbol{\varepsilon}} \tag{9}$$

If now $\boldsymbol{\eta}$ is the second order tensor $\partial\tilde{\varepsilon}/\partial\boldsymbol{\varepsilon}$, the tangent stiffness tensor is defined as:

$$\boldsymbol{D}_t = (1-d)\boldsymbol{D} - \frac{\partial d}{\partial k}\bar{\boldsymbol{\sigma}} \otimes \boldsymbol{\eta} = \boldsymbol{D}_s - \frac{\partial d}{\partial k}\bar{\boldsymbol{\sigma}} \otimes \boldsymbol{\eta} \tag{10}$$

2.1. Non local damage

In order to eliminate the issues of mesh-dependence emerging with the use of conventional damage theory models, a nonlocal damage approach has been adopted. A classical nonlocal damage theory has been used for damage stabilization [23], by introducing a characteristic length l_c equal to the average dimension of concrete aggregates. Through this approach, the equivalent strain $\tilde{\varepsilon}$ is modified into $\bar{\varepsilon}$, defined as:

$$\bar{\varepsilon} = \frac{1}{V_r(\boldsymbol{x})}\int_{\Omega} \psi(\boldsymbol{x}-\boldsymbol{s})\tilde{\varepsilon}(\boldsymbol{s})ds \tag{11}$$