STRENGTHENING OF RC COLUMNS WITH FRP JACKETS

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ABSTRACT

During the occurrence of a seismic event, bridge and building columns are subjected to strong lateral loads. These actions may cause the failure of the columns due to an insufficient shear strength, flexural strength or ductility, especially for structures designed with old seismic codes. The confinement of these columns with FRP jackets improves its strength as well as its ductility providing, therefore, a suitable seismic retrofitting of the column. In this work, a numerical model based on Damage Mechanics is proposed to evaluate the seismic behavior of RC columns retrofitted with composite jackets.

1. INTRODUCTION

Reinforced concrete columns, particularly those built prior to the 1970s, have usually transverse steel details that provide little confinement to the concrete core or lateral support to the longitudinal reinforcing rebars. Traditionally, for poorly confined reinforced concrete columns retrofit systems consisting of concrete or steel jackets have been developed and experimentally validated [1]

In recent years, FRP composite jackets have been also used to provide confinement to reinforced concrete members. The strengthening of existing RC columns using steel or FRP jacketing is based on the fact that lateral confinement of concrete enhance its axial compressive strength and ductility. Furthermore, FRP column-jacketing systems speed up the installation of column jackets, reduce their maintenance and improve the durability.

Seismic design of FRP jackets for retrofitting of existing columns requires a prediction of the lateral load-displacement behavior of the confined concrete. In this paper, a simplified analytical model based on the application of Damage Mechanics to the plastic hinge models is used. In the model, it is defined a damage variable whose evolution allows to represent the progressive degradation experimented by a confined column subjected to flexural loading. The proposed model requires the stress-strain curves for the unconfined and FRP-confined concrete. For it, an analytical method proposed in the literature is adopted.

With the proposed model, numerical studies under cyclic loading are performed on RC circular columns

2. STRESS-STRAIN MODEL

To study the performance of fiber-reinforced polymer-wrapped reinforced concrete column under combined axial-flexural loading is necessary as input the stress-strain curve for the confined concrete. To obtain this curve the model proposed by Wang and Restrepo [2] has been used. This model is an extension to the case of FRP-confined reinforced concrete of the model proposed by Mander *et al.* [3] to calculate the increase in concrete compressive strength provided by transverse reinforcement in reinforced concrete columns. In this model the compressive load carried by concrete (P_c) is divided in three different regions: the unconfined concrete area (A_{cu}), the area of concrete confined by the FRP jacket only (A_{cFRP}) and the area confined by both the FRP jacket and the steel hoops ($A_{cFRP,S}$):

$$P_c = f_{co} A_{cu} + f_{cc,FRP} A_{cFRP} + f_{ccFRP,S} A_{cFRP,S} \tag{1}$$

where f_{co}, $f_{cc,FRP}$ and $f_{ccFRP,S}$ are the compressive stresses carried by the unconfined concrete area, by the concrete area confined only by the FRP jacket and by the concrete area confined by the FRP jacket and by the internal reinforcement simultaneously, respectively. These stresses are evaluated using the stress-strain model proposed by Mander *et al* [3]. According to this model the compressive stresses, f_c, are calculated as follows:

$$f_c = \frac{f'_{cc} x r}{r - 1 + x^r} \tag{2}$$

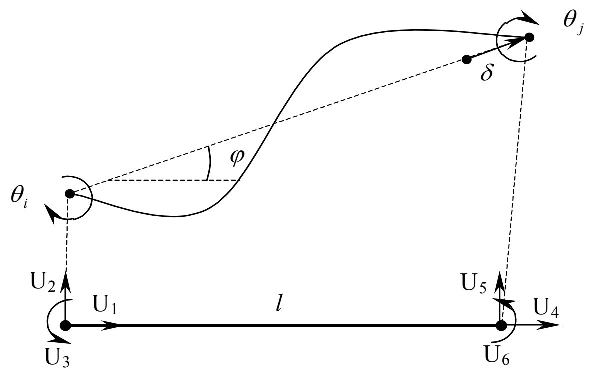
where f'_{cc} is the compressive strength of confined concrete and

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \qquad r = \frac{E_c}{E_c - E_{sec}}$$
$$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f'_{cc}}{f'_{co}} - 1\right)\right] \tag{3}$$

where E_c and E_{sec} = tangent modulus and the secant modulus of elasticity of concrete, respectively; ε_c = axial compressive strain of concrete; ε_{cc} = strain at maximum concrete stress of confined concrete; and f'_{co} and ε'_{co} = unconfined concrete strength and the corresponding strain, respectively.
When the model is applied to rectangular columns an arching confinement action appears for the FRP jacket due to the corners of the rectangular section. Because of it, it exists an unconfined concrete section. However, for circular columns, no arching action for the FRP jacket is considered and, therefore, all the concrete section is confined by either, FRP jacket only or by both FRP jacket and steel hoops.

3. DAMAGE MODEL

In this model, each member of the RC frame is represented as an assemblage of an elastic beam-column, flexural springs at the ends of the element and an axial spring. In this way, dissipative deformations (plastic and damage deformations) are lumped at its two ends. This model, adding the damage effect, is consistent with the traditional assumptions of plastic hinge (plastic rotation) and bar hinge (axial deformation). The stress distribution for each element is described by a three component vector $\{q\}^t = (M_i \quad M_j \quad N)$ that collects the bending moments at the two ends, M_i and M_j, and the axial force, N. The corresponding kinematic variable $u^t = \{\theta_i \quad \theta_j \quad \delta\}$ defines the deformed shape of the element excluding the rigid body motion (Figure 1).
According to the damage mechanics [4] the following relation is obtained for an axial element:



"**Fig. 1.** Generalized deformation for the beam/column model"

$$\delta_b^d = \frac{N_b L_b}{EA}\frac{d_a}{(1-d_a)} \tag{4}$$

where N_b and L_b are the axial force and the length of the element, respectively, and in which δ_b^d and d_a are the elongation due to damage and the axial damage, respectively. A similar relationship is postulated for flexural effects

$$\theta_i^d = \frac{d_i}{1-d_i}\frac{L_b}{4EI} M_i \tag{5}$$

$$\theta_j^d = \frac{d_j}{1-d_j}\frac{L_b}{4EI} M_j \tag{6}$$

where θ_i^d and θ_j^d the damage rotations at the ends of the element and d_i and d_j the damage variables due to flexural effects associated to each end of the member.

Considering damage and plastic deformations, if we denote $q=(M_i\ M_j\ N)^t$ and $u = \{\theta_i \quad \theta_j \quad \delta\}^t$, the constitutive law is given by

$$u - u^p = u^b + u^d = \lfloor F^o + F^d \rfloor q \tag{7}$$

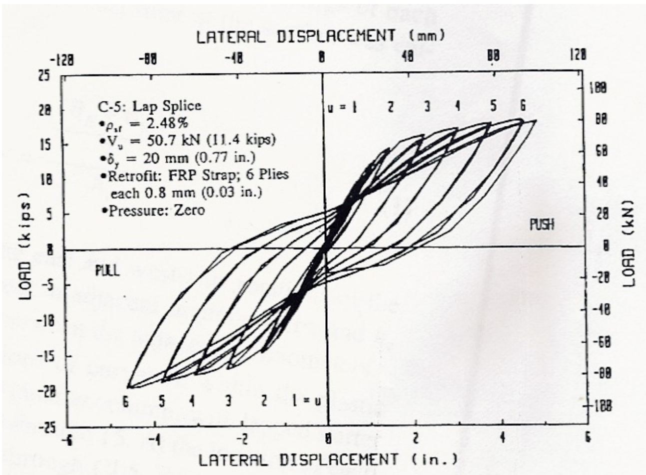
where u^b, u^p and u^d represent the elastic, plastic and damage deformations, respectively, and F^o the corresponding elastic flexibility matrix; F^d is the flexibility matrix due to damage and its expression, obtained from Eqs. (4), (5) and (6), is as follows:

$$F^o = \begin{pmatrix} \frac{d_a}{1-d_a}\frac{L_b}{EA} & & \\ & \frac{d_i}{1-d_i}\frac{L_b}{4EI} & \\ & & \frac{d_j}{1-d_j}\frac{L_b}{4EI} \end{pmatrix} \tag{8}$$

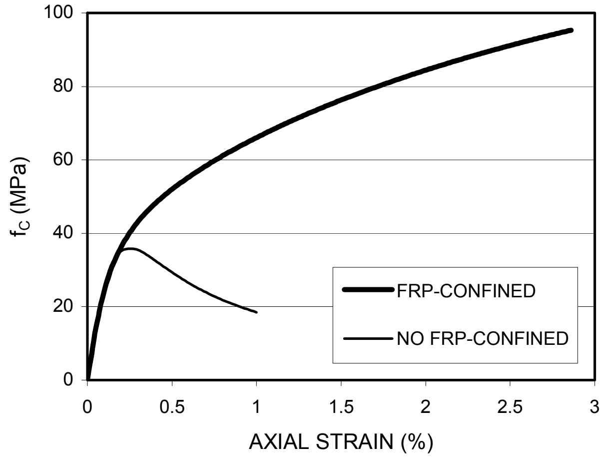
The damage and plastic variables evolution laws are defined according to the thermodynamics of irreversible processes through the definition of a damage potential, φ_d, and a plastic potential, φ_p [5]. These potentials are defined using significant limit states of the reinforced concrete cross-section through the stress-strain relationship of the confined concrete such as it was specified in the previous section.

4. NUMERICAL RESULTS

The model was calibrated with a circular cross section reinforced concrete column designed with pre-1971 codes for a high seismic risk area and tested by Saadatmanesh *et al* [6]. The column was wrapped with six layers of FRP composite straps only in the potential plastic hinge region resulting in a thickness of 0.005 m. The tensile strength and the modulus of elasticity of the jacket are 532 MPa and 18600 MPa, respectively.
The column was subjected to a constant axial load of 445 kN and to a cyclic lateral displacement history of increasing amplitude. The lateral load-displacement experimental curve is shown in Fig. 2.



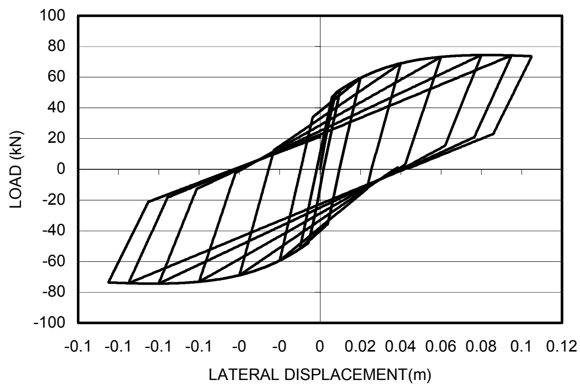
“**Fig. 2.** Experimental results”



“**Fig. 3.** Axial stress-strain response for circular column”

A numerical analysis was performed with the proposed model to simulate the lateral force-displacement response of the externally retrofitted circular column. For it, first of all, the stress-strain curve corresponding to the FRP confined concrete was obtained with the model proposed previously and is shown in Fig. 3. Then, the parameters of the damage model were determined using Eq. (5) which requires some values obtained from a moment-curvature analysis.

With the parameters of the damage model determined, the numerical analysis was performed considering the upper portion of the column as an elastic element and assuming a hinge at the bottom of the column. Applying a cyclic displacement history of increasing magnitude the numerical results predicted using the proposed model are shown in Fig. 4. The model predicts the experimental results of the FRP-confined circular column with reasonable accuracy. The displacement ductility predicted by the numerical analysis is practically the same to the ductility achieved by the test specimen. The maximum lateral load obtained with the model is a little lower but it is also very close to the measured value.



"**Fig. 4.** Numerical results"

5. CONCLUSIONS

A simplified numerical model based on Damage Mechanics has been proposed to simulate the seismic behavior of RC columns confined with FRP jackets. The approach combines the concepts of the lumped dissipation models with the notions of the Continuum Damage Mechanics and, therefore, the proposed formulation can be considered as simplified damage mechanics for frames.

From comparisons with some experimental results a good calibration has been obtained for the proposed model.

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