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Simple and efficient finite element modeling of reinforced concrete columns confined with fiber-reinforced polymers

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ABSTRACT

This paper presents a frame finite element (FE) that is able to accurately estimate the load-carrying capacity and ductility of reinforced concrete (RC) circular columns confined with externally-bonded fiber-reinforced polymers (FRP). This frame FE can model collapse mechanisms due to concrete crushing, reinforcement steel yielding, and FRP rupture. The adopted FE considers distributed plasticity with fiber discretization of the cross-sections in the context of a force-based formulation, and uses advanced nonlinear material constitutive models for reinforcing steel and unconfined, steel-confined, and FRP-confined concrete.

The adopted frame FE is validated through a comparison between numerical simulations and experimental results available in the literature of the load-carrying capacity of FRP-confined RC columns subjected to axial load only, and both axial and lateral load. The adopted FE is suitable for efficient and accurate modeling and analysis of FRP-confined RC columns, and thus it represents a step toward enabling analysis of real-world large-scale structures containing FRP-confined RC columns, for which more accurate three-dimensional models could be computationally prohibitive.

1. Introduction

Externally-bonded fiber-reinforced polymer (FRP) composites have found numerous applications in civil engineering structures due to their high strength-to-weight and stiffness-to-weight ratios, corrosion resistance, and high durability [1,2]. One of these applications is the FRP confinement of reinforced concrete (RC) columns to improve their structural performance in terms of ultimate load bearing capacity and ductility [3,4]. The FRP confinement of RC columns presents numerous advantages compared to other rehabilitation techniques, e.g., RC section enlargement and confinement using steel jackets. Some of these advantages include negligible increase in structural size and weight, easy transportation, and good resistance to corrosion and other degradation processes due to harsh environmental conditions [5]. This method has been widely used to retrofit bridges and buildings in the past two decades [6–8]. The proper use of this rehabilitation procedure requires the accurate prediction of the improved performance of the FRP-confined RC columns based on the specific geometry, material properties, and amount of FRP utilized. Numerous numerical tools have been developed to model the structural behavior of FRP-confined RC columns. These tools include (1) stress–strain models of FRP-confined concrete at the material level, (2) stress resultant-section deformation relations at the cross-section level, and (3) finite element (FE) models of structural components at the structural level.

Extensive studies available in the literature have been conducted to develop appropriate stress–strain relations for FRP-confined concrete. These stress–strain models can be classified into two categories: design-oriented and analysis-oriented models [9]. Design-oriented models [10–14] provide closed-form equations directly calibrated on experimental results for predicting the compressive strength, ultimate axial strain, and stress–strain behavior of FRP-confined concrete; whereas analysis-oriented models [15–18] derive stress–strain curves that are generated using incremental numerical procedures typically used within nonlinear FE models. A few models for sectional analysis of FRP-confined RC columns have been developed in the last decade. In [19], a fiber-section model was used to discretize the cross-section into fibers of unconfined concrete, confined concrete, steel rebars, and confining FRP. The structural force–deformation relation was derived by numerical integration of the stress–strain relation of the fibers at the column base section. In [20], a two-dimensional sectional analysis of RC columns confined with FRP was presented, in which the bending moment strength was determined through analytical

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integration of the stresses corresponding to material constitutive models used for design. The FE method has been widely used as a powerful tool to effectively model the behavior of FRP-confined RC columns. A significant number of previous FE studies employed refined FE meshes of three-dimensional solid elements using commercially available software, such as ANSYS [21], ABAQUS [22,23], and MARC™ [24], or research software such as DYNA3D [25], and FEMIX [26]. The computational cost of similar structural response analyses is usually extremely high, because of the large number of elements and degrees of freedom involved, and the need to use three-dimensional constitutive models for all materials considered in the FE analyses. In [27], appropriate material constitutive models were implemented in the framework of fiber-discretized frame elements using a displacement-based formulation. This computational model employed a variable confinement relation based on a non-uniform confinement distribution in the compression zone.

The efficient modeling of the structural behavior of FRP-confined RC columns through the FE method remains an active research field, due to the difficulties in understanding and predicting the complex interaction between confined and unconfined concrete, reinforcing steel, and confining FRP. The validation and calibration of FE models is made even more complex by the high cost and difficulties of producing test data from FRP-confined RC columns. The contribution of this study is the combination and implementation of existing modeling tools (i.e., force-based formulation for frame elements, fiber discretization of the cross-sections, and existing advanced material constitutive models for concrete and reinforcing steel) into a nonlinear frame FE that enables one to model the mechanical behavior of FRP-confined RC columns in an accurate and computationally efficient fashion, and that can be used for a computationally feasible nonlinear FE analysis of entire real-world structures, e.g., bridges subject to seismic excitation, for which more accurate three-dimensional models could be computationally prohibitive. To the authors' knowledge, this study employs for the first time a force-based frame FE with fiber-discretized cross-sections to model the structural response of FRP-confined RC columns. This paper focuses on RC columns with circular cross-section confined by externally-bonded FRP with fibers oriented along the hoop direction (i.e., orthogonal to the axis) of the columns.

2. Finite element modeling

2.1. Finite element formulation

This study adopted a two-node one-dimensional force-based frame FE [28] with Euler–Bernoulli kinematic assumptions under small deformations and small displacements (i.e., linear geometry) to model the structural response of FRP-confined RC columns. A fiber discretization was employed to evaluate the cross-section nonlinear behavior [28]. Realistic one-dimensional nonlinear constitutive models were employed to describe the stress–strain behavior of unconfined, steel-confined, and FRP-confined concrete, as well as of reinforcing steel. In this study, the element state determination was based on the non-iterative algorithm [29], whereas the integrals in the element formulation were evaluated numerically following a Gauss–Lobatto (G–L) integration scheme with a user-defined number of integration points (i.e., monitored cross-sections). It is noteworthy that other element state determination algorithms (e.g., the iterative algorithm proposed in [28]) and numerical integration schemes (e.g., Gauss–Legendre integration) can be also used in conjunction with the frame FE element developed in this study.

The outstanding features of the adopted frame FE include computational efficiency, high accuracy even when a coarse FE mesh is used, and ease of use. The computational efficiency of this frame element derives from the use of (1) the force-based formulation, which for frames imposes equilibrium exactly along the element axis and reduces the number of elements needed for an appropriate mesh of the FE model when compared to a displacement-based formulation [28,29]; and (2) the cross-section fiber discretization that allows the structural analyst to use one-dimensional material constitutive models only, which are computationally less demanding than their three-dimensional counterparts [28]. The accuracy of the adopted frame FE derives from the capability of the fiber-section models to closely represent the nonlinear interaction between axial forces and bending moments at the cross-section level, and the high fidelity of the one-dimensional material constitutive models in describing the actual stress–strain relations for the different materials used in FRP-confined RC columns. The ease of use of this frame FE is due to the fact that FE models built by using force-based frame elements are virtually mesh-independent, in the sense that the same mesh discretization can be used for linear and nonlinear FE analysis while equilibrium is enforced exactly along all members [28].

2.2. Material modeling and computation of cross-section stress resultants

In the adopted FE, the cross-section stress resultants (axial force and bending moment) are computed using a fiber discretization of the circular cross-section [19], as shown in Fig. 1. The concrete fibers are defined through a radial discretization (defined by parameters R_i = internal radius, R_e = external radius, R_c = confined radius, $n_{\mathrm{r}1}$ = number of steel-confined radial layers, and $n_{\mathrm{r}2}$ = number of unconfined radial layers) and an angular discretization (defined by parameters θ_i = initial angle, θ_e = end angle, and n_a = number of angular subdivision) of the cross-section. In addition, each reinforcing steel rebar corresponds to an additional fiber, which is described by the parameters A_{b_i} = area of the ith steel rebar, θ_{b_i} = angle for the ith steel rebar, and R_{b_i} = radius at which the ith steel rebar is located (with $i = 1, 2, \ldots, n_\mathrm{b}$, n_b = number of reinforcing steel bars). The nonlinear stress–strain response of each discretization fiber is described by appropriate one-dimensional nonlinear material constitutive models.

The constitutive behavior of the steel reinforcement was modeled using the one-dimensional Menegotto-Pinto plasticity model

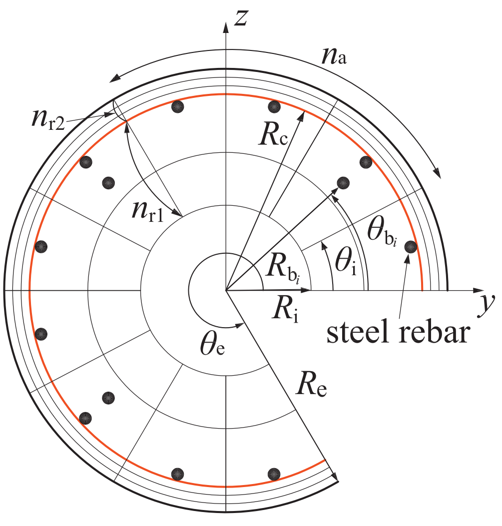

Fig. 1. Fiber discretization of a circular cross-section.