Three-Dimensional Finite Element Model for FRP-Confined Circular Concrete Cylinders under Axial Compression

Q.G. Xiao, J.G. Teng (cejgteng@inet.polyu.edu.hk), T. Yu & L. Lam
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China

ABSTRACT: This paper presents a 3D FE model for FRP-confined circular concrete cylinders based on a plastic-damage constitutive model for concrete recently proposed by Yu et al. (2010b). This 3D model is capable of modeling deformation non-uniformity in the axial direction due to factors such as end restraints. Numerical results obtained using the FE model for FRP-confined cylinders with end restraints or with a vertical gap in the FRP jacket conform to expected trends although their quantitative accuracy awaits confirmation by laboratory tests. This FE model has the potential for extension to more general cases of FRP-confined concrete columns (e.g. rectangular concrete columns) and can provide a useful tool for the exploration of confinement mechanisms in the development of simple stress-strain models for design use.

1 INTRODUCTION

A number of studies exist on the finite element (FE) modeling of fibre-reinforced polymer (FRP)-confined concrete using a Drucker-Prager (D-P) type plasticity model for the concrete (e.g. Mirmiran et al. 2000; Rousakis et al. 2007). In a recent study, Yu et al. (2010a, b) developed a new plastic-damage model for FRP-confined concrete in which the deficiencies of the previous D-P type plasticity models are eliminated. This model was formulated within the theoretical framework of the concrete damaged plasticity model (CDPM) provided in ABAQUS and was implemented in ABAQUS for the analysis of concrete cylinders whose deformation is assumed to be uniform along the height. This assumption means that the FE model needs to include only a horizontal slice of the column represented by a single-layer of solid elements. Such a slice model can closely represent the mid-height region of an FRP-confined cylinder but is incapable of capturing axial non-uniformity in deformation and stresses due to end constraints and other factors such as steel hoops. Provided axial non-uniformity is unimportant, this slice model provides an efficient approach for modeling interactions in the transverse plane. Yu et al. (2010b) has successfully employed the slice model in the nonlinear FE analysis of hybrid FRP-concrete-steel double-skin tubular columns (DSTCs).

In a slice model, the axial direction is always one of the principal directions for both stresses and strains, and the other two principal directions (i.e. lateral directions) are always perpendicular to the column axis. In addition, the principal stress and strain in the axial direction are normally larger than the principal stresses and strains in both lateral directions. This paper presents an extension of Yu et al.'s (2010b) slice model to a truly three-dimensional (3D) model for FRP-confined circular concrete cylinder with end effects appropriately captured. The necessary refinements to the plastic-damage model of Yu et al. (2010b) are first discussed. Numerical results from the 3D FE model are then presented to examine the capability of the FE model in capturing the effects of restraints against horizontal movements at the ends of the circular cylinder in an axial compression test. The effect of the existence of a mid-height vertical gap between the upper and lower parts of the FRP jacket on the behavior of confined concrete is also discussed using numerical results from the 3D FE model. In this paper, compressive stresses and strains are defined as positive while tensile stresses and strain are negative, unless otherwise specified.

2 PLASTIC-DAMAGE MODEL FOR CONFINED CONCRETE

In the plastic-damage model proposed by Yu et al. (2010b), the damage parameter, the strain-hardening/softening rule and the flow rule are all confinement-dependent and the yield surface reflects the effect of the third deviatoric stress invariant. In addition, the characteristics of non-uniformly confined concrete are included in this model by defining an effective confining pressure as follows:
where $f_{c0}$ is the compressive strength of unconfined concrete while $\sigma_2$ and $\sigma_3$ are the two principal lateral stresses respectively. Two methods have been explored in Yu et al. (2010b) for the flow rule of non-uniformly confined concrete, with the second method being adopted in the present study as it was deemed by Yu et al. (2010b) to be the more reliable approach. This method relates the flow rule $\dot{\varepsilon}_{pl}$ to the equivalent plastic strain and the term $\frac{\sigma_2 + \sigma_3}{2}$ whose absolute value represents confinement stiffness, with $\sigma_2$ and $\sigma_3$ being the two principal lateral strains respectively.

In a 3D FE model of an entire FRP-confined concrete cylinder/column, shear stresses generally develop between adjacent horizontal slices as a result of axial non-uniformity in deformation due to end constraints and other factors. As a result, the axial direction is not necessarily one of the principal directions. For a such more general stress state, the following assumptions are made in implementing Yu et al.’s (2010b) plastic-damage model without compromising the generality of the model for practical applications: (a) $\sigma_2$ and $\sigma_3$ in Eq. 1 are the two smaller principal stresses while $\sigma_1$ and $\sigma_3$ used in the flow rule are the two smaller principal strains; (b) $\sigma_2$ (or $\sigma_3$) is ignored in calculating $\varepsilon_{eff}$ if it becomes negative (i.e. or), as the effect of tensile stresses on confined concrete is unclear; (c) the term $\frac{\sigma_2 + \sigma_3}{2}$ is normally negative (i.e. tensile strains) due to the expansion of concrete, but if it is found to be positive or zero, it is taken as a very small negative value in determining the flow rule.

It should be noted that the analysis-oriented stress-strain model of Teng et al. (2007) was used in Yu et al. (2010b) in deriving the parameters for the plastic-damage model, while in the present study, Ji-ang & Teng’s (2007) model, which provides closer predictions for weakly confined concrete, was used.

3 FE MODEL

The FE model was implemented in ABAQUS to simulate the behavior of FRP-confined concrete cylinders. Circular concrete cylinders with a diameter (D) of 152 mm and a length (L) of 304 mm were initially considered; cylinders with other lengths were also considered in studying the effect of end restraints. The unconfined concrete had a compressive strength $f_{c0}$ of 30 MPa with a corresponding axial strain $e_{c0}$ of 0.0025. The plastic-damage model as described in the previous section was adopted as the constitutive model for concrete in the FE simula-

tions. The confining FRP jacket was modeled as an orthotropic elastic shell with the stiffness being mainly in the hoop direction; the axial elastic modulus of the FRP was assigned a very small value ($1 \times 10^5$ MPa). The Poisson’s ratio was set to be zero. The modulus of elasticity in the hoop direction $E_{frp}$, the thickness $t_{frp}$, and the hoop rupture strain of the FRP jacket were 80.1 GPa, 0.34 mm, and 1.3%, respectively. This simplified model for the FRP jacket means that it functions as a confining device in the FE model.

Considering the symmetry conditions of FRP-confined circular cylinders under axial compression, an axisymmetric model was used and only half of the column height was included in the FE simulation. The axisymmetric solid element CAX4 and the axisymmetric shell element SAX1 in ABAQUS were adopted for the concrete and the FRP jacket respectively. The concrete and the FRP jacket were tied together at their common nodes so that no relative slides were allowed at their interface. Both the concrete and the FRP jacket had elements size of about 5 mm chosen on the basis of a mesh convergence study. In all the FE analyses, axial displacements were uniformly imposed on the top surface of the concrete cylinder until the maximum lateral strain within the FRP jacket reached its rupture strain (i.e. 1.3%).

4 RESULTS AND DISCUSSIONS

4.1 Effect of end restraints

Circular concrete cylinders confined with a continuous FRP jacket, with or without end restraints, were analyzed. Figures 1 and 2 show that without end restraints, the distributions of both axial displacements and stresses are uniform; however, when the horizontal displacements at the end are prevented with restraints, the distributions of both axial displacements and axial stresses become highly non-uniform. The latter case is close to the actual situation of a laboratory test due to frictions between the end surfaces of the cylinder and the loading platens.

Figure 3 shows the axial stress-axial strain curves (referred to as stress-strain curves hereafter) and axial strain-lateral strain curves obtained from the FE analyses. For the case with end restraints, the FE results shown in Figure 3 are based on the following definitions: (a) the axial stress is the average axial stress over the cross-section; (b) the lateral strain is that of the outer surface of the concrete core at mid-height; and (c) the axial strain is the average strain defined in one of three different ways. The three definitions of the average axial strain are as follows: (I) the average displacement of the outer surface node of the concrete core at 60.8 mm divided by 60.8 mm; (II) the average axial displacement of all nodes of the concrete core at 60.8 mm divided by 60.8
mm; (III) the total axial shortening of the cylinder divided by the cylinder height.

It can be seen from Figures 3a and 3b that for the case without end restraints, the FE analysis produced almost the same stress-strain curve and axial strain-lateral strain curve as predicted by Jiang & Teng’s (2007) model. For the case with end restraints, the stress-strain curves based on axial strains of definitions (I) and (III) almost coincide with that predicted by Jiang and Teng’s (2007) model, but terminate at smaller ultimate axial strains. By contrast, the curve based on axial strains of definition (II) falls below that predicted by Jiang and Teng’s (2007) model, but the ultimate axial strain is nearly the same as that from Jiang and Teng’s (2007) model.

The FE results indicate that the compressive strength of confined concrete with end restraints is lower than that without end restraints (Figure 3a). This is in agreement with experimental results of unconfined concrete. It has been well established by laboratory tests that end restraints increase the observed compressive strength of concrete and this effect becomes more significant as the L/D ratio decreases (Sangha and Dhir 1972). However, FE results from the present study not shown here indicated that end constraints lead to a reduced confined concrete compressive strength for L/D ratios from 1 to 3, but this unfavorable effect of end restraints becomes insignificant when the L/D ratio exceeds 3.

The adverse effect of end restraints on the compressive strength of FRP-confined concrete cylinders can be explained as follows. End restraints prevent the FRP-confined cylinder from lateral expansion at the ends and lead to non-uniform straining of the FRP jacket along the height. When the FRP jacket reaches its hoop rupture strain at the mid-height, its hoop strain is still much smaller away from the mid-height and is equal to zero at the ends. As a result of this non-uniform straining of the jacket, the FRP-confined concrete reaches its ultimate axial stress earlier at a reduced total axial displacement [i.e. a smaller value of axial strain of definition (III), as shown in Fig. 3b]. Laboratory tests are needed to confirm the correctness of the above explanation.

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4.2 Effects of a gap in the FRP jacket

In certain practical applications (e.g. a column with a transverse beam), the column surface cannot be fully covered by a continuous FRP jacket and instead a vertical gap exists between the upper and lower parts of the FRP jacket. In addition, columns may be strengthened using discrete FRP rings (e.g. Wu et al. 2009) instead of a continuous FRP sheet where vertical gaps exist between rings. The FE model, being a truly 3D model, was employed to study the effect of a single vertical gap in the FRP
jacket on the behavior of confined circular concrete cylinders. End restraints were not specified in these FE analyses to simplify the situation based on the results discussed above. Two gap heights, 38mm and 76mm, were considered in the FE simulations.

Figure 4 shows that the distribution of axial stresses is highly non-uniform due to the presence of a vertical gap at the mid-height of the FRP jacket although the cylinder was uniformly loaded without end restraints. The effect of the gap on the stress-strain curve is shown in Figure 5, where the results for a continuous FRP jacket and for an unconfined cylinder are also shown for comparison. The axial strain is the average strain over the entire height of the cylinder. Figure 5 clearly indicates that a larger gap height leads to a greater reduction in the compressive strength of FRP-confined concrete. The stress-strain curve features a softening branch when the gap height is 76 mm. The results given in Figures 4 and 5 conform to expected trends and provides an initial indication that the FE model has captured the mechanics of the problem at least qualitatively. The quantitative accuracy of the FE results await confirmation by laboratory tests.

5 CONCLUDING REMARKS

A 3D FE model for FRP-confined circular concrete cylinders based on Yu et al.’s (2010b) plastic-damage model has been presented in this paper. This 3D model is capable of modeling deformation non-uniformity in the axial direction due to factors such as end restraints and a vertical gap in the FRP jacket. Numerical results obtained using the FE model have revealed that end restraints lead to highly non-uniform distributions of stresses and strains. FE results have also shown that a vertical gap in the FRP jacket leads to non-uniform distributions of stresses and strains and a reduction in the axial compressive strength. The FE model is currently being extended to more general cases of FRP-confined concrete columns such as FRP-confined rectangular concrete columns and eccentrically loaded concrete columns. The FE model with suitable verification can provide a useful tool for the exploration of confinement mechanisms in various FRP-confined concrete columns in the development of simple stress-strain models for use in design.

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7 REFERENCES


