Construction and Building Materials 23 (2009) 1429–1437

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A practical approach for modeling FRP wrapped concrete columns

H.O. Koksal [a,*], B. Doran [a], T. Turgay [b]

[a] Department of Civil Engineering, Yıldız Technical University, 34349 Istanbul, Turkey
[b] Faculty of Architecture and Engineering, Abant İzzet Baysal University, 14280 Bolu, Turkey

ARTICLE INFO

Article history:
Received 7 February 2008
Received in revised form 18 June 2008
Accepted 2 July 2008
Available online 22 August 2008

Keywords:
Fiber reinforced polymer
Concrete
Column
Drucker–Prager
Plasticity
Finite element analysis

ABSTRACT

Fiber reinforced polymers (FRP) have gained rapid popularity in recent years as one of the strengthening techniques of structural concrete elements. Particularly, increase in the use of FRP composite materials for strengthening and retrofitting of reinforced concrete columns has urged the development of several approaches to determine their compressive strength. Although substantial experimental and analytical researches have been conducted to model and simulate the response of concrete confined with FRP jackets under concentric loading, there is still an apparent need for the detail analyses and efficient numerical models to further understand the stress–strain behavior and failure mechanisms of the confined concrete. In order to predict the compressive behavior of concrete even under high confinement pressures, this paper introduces new relations for calculation of the cohesion parameter of Drucker–Prager criterion in terms of cylindrical compressive strength only. These relations are developed from a parametric study of a large number of nonlinear finite element analyses (NLFFEA) of FRP wrapped concrete columns to account for the axial load level and the shape of the stress–strain curve. Incorporating a realistic one-parameter failure criterion of concrete, the failure cone of Drucker–Prager model is enforced to approximate and coincide with the whole compressive meridian of the criterion up to the analytically predicted point of the ultimate hydrostatic pressure in the analyses. Based on this failure cone, mainly seven different relations corresponding to the various levels of lateral pressure are proposed for the compressive meridian and the cohesion while keeping the internal friction angle as a constant value of 33°. The proposed approach is shown to fit quite well the experimental results of 42 specimens tested by eight different researchers, for various square and rectangular cross-sections under concentric loading.

1. Introduction

Although there have been several well documented experimental and analytical studies referring to the constitutive modeling of confined concrete in the last four decades, understanding and modeling the mechanical response of confined concrete to axial loading has still been a challenging issue. Most of the existing models have greater theoretical significance than practical implications since they can explain only some certain features of the concrete and can be applied to limited examples [1,2]. Considering the application of fiber reinforced polymers (FRP) to the reinforced concrete columns as an attractive solution for the enhancements of their strength and strain capacities, it can be easily observed that a great number of studies in the field of computational concrete mechanics has finally focused on the behavior of concrete confined with composites in the last decade [3–11]. However, the variety of factors including constitutive behavior of concrete, material properties of composites, effect of column size, cross-sectional geometry, corner radius, dilation ratio of concrete, and variation of confinement stiffness during loading make the proposed models complicated and difficult to implement in computer applications.

Beside that a constitutive model describes the behavior of confined concrete in an accurate manner, the material parameters of the model should also be easy to obtain. Furthermore, the implementation of the constitutive relations to the nonlinear analyses of concrete elements should be practical and numerically efficient. The scope of such models is mostly limited to the empirical relations of the ultimate strength of concrete specimens with circular cross-section under multi-axial compression [12]. Only a few of these models consists of the analytical expressions for the compressive strength of confined concrete in a very similar way to the form deduced from the well-known model of Mander et al. [13]. Mander model adopts William–Warnke failure surface [14] which is the most versatile and sophisticated failure model of concrete under multi-axial stress states. Unfortunately, in order to define the failure surface of William–Warnke model in principal stress space, there is a clear need for determination of five different material parameters through extensive testing of concrete: the concrete strength under uniaxial compression, uniaxial tension

* Corresponding author. Tel.: +90 212 383 2949; fax: +90 212 236 41 77.
E-mail address: hokoksal@yahoo.com (H.O. Koksal).

0950-0618/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2008.07.008

strength, equal biaxial compression and the two high-compressive stress points on the tensile meridian and compressive meridian respectively.

The elasto-plastic analyses of concrete structures usually refer to a simple solution instead of using a sophisticated model. This option could have been mostly the Drucker–Prager model because smooth surface representation of the yield criterion in principal stress space results in easy implementation of the criterion in computer programs [15–22]. In this paper, several aspects of the three-dimensional (3D) finite element modeling of FRP wrapped concrete columns under concentric loading are investigated. The emphasis is kept on the determination of the material parameters of Drucker–Prager criterion in order to predict the axial stress–strain behavior. Employing a realistic and practical failure model of concrete which only needs cylindrical compressive strength, the cohesion and the internal friction parameters of Drucker–Prager criterion have been adjusted through a parametric study. For this purpose, the Drucker–Prager cone is enforced to coincide with the whole compressive meridian of the concrete up to the failure point of hydrostatic pressure predicted by the model [20]. The comparison between the predictions of the present study and the experimental results of 42 specimens tested by eight different researchers are to be made for the validation of the present approach.

2. Finite element modeling of concrete columns

Concrete is modeled with an 8-noded 3D isoparametric solid element with an incompatible strain field in LUSAS software [23]. An optimum mesh size is chosen. Only the quarter of the column is modeled due to the symmetry of the load and geometry. All nodes in each plane of symmetry are fixed only in the direction normal to that plane. All nodes on the top surface of the model are restrained against the lateral displacements. FRP jacket is modeled by 4-noded two-dimensional thick shell element which is a family of shell elements for the analysis of arbitrarily thick and thin curved shell geometries [23]. Fig. 1 shows a typical FE meshing for a concrete element confined with FRP jackets. In addition, the top surface of the specimen is assumed to be in a rigid body displacement and defined in modeling process.

3. A modified Drucker–Prager approach for concrete modeling

Drucker–Prager type of plasticity is widely adopted in modeling constitutive behaviors of frictional materials, like concretes, soils and rocks [24]. Drucker–Prager yield criterion is a two-parameter model defined by cohesion, c and angle of internal friction, ϕ. It can be used to describe the behavior of concrete which are weak in tension and exhibit volumetric plastic strain. A parametric study has been performed to find out the effect of the material parameters of Drucker–Prager criterion on the response of confined concrete columns throughout the study. At the early stages of the present work, only a small number of test specimens were employed, and the previous studies of Mirmiran et al. [21] and Karakoc and Koksal [15] have been considered as suitable references for the choice of the cohesion and internal friction values. The angle of internal friction is approximately between 30° and 40°, which can be found by drawing various tangent lines to the compressive meridian obtained from the experimental data of concrete [15,16]. In this study, the internal friction angle of 33° is utilized as an average value [15,17,25]. The load carrying capacity and stress–strain behavior are continuously checked whether the NLFEA is sufficiently converged to the experimental results during the parametric study. As a result, the cohesion values are found out to be scattered between 3 and 10 MPa. The observed values are higher than the ones previously employed for the analyses of reinforced concrete beams by the first two authors of the present study [15,17]. Arslan [16] similarly recommends a relation for the cohesion, which outcomes are generally between 3 and 6 MPa for reinforced concrete beams. As a contradictory result, first analyses indicate that different values of cohesion should be used to predict the behavior for the test specimens having the same cylindrical concrete strength.

A similar procedure suitable for obtaining cohesion values is to draw tangent lines to the compressive meridian of concrete assuming a constant value for internal friction value. The use of a failure criterion of concrete, only needs cylindrical compressive strength and previously proposed by the first author [20], will be sufficient to plot the whole compressive meridians. The ultimate strength values predicted by the Koksal criterion [20,22] are used to determine the ultimate hydrostatic strength at failure as the end point of the meridian. The general formulation of this criterion is given in the following form:

$$f = \sqrt{6}\alpha(\xi)\xi + \rho - \sqrt{2}k(\sigma_1, \sigma_2, \sigma_3) = 0, \quad (1)$$

where ρ and ξ are deviatoric and hydrostatic lengths, respectively. In Eq. (1), k is considered as a function of the lateral confinement pressure, f_l and the cylindrical compressive strength of concrete, f_c':

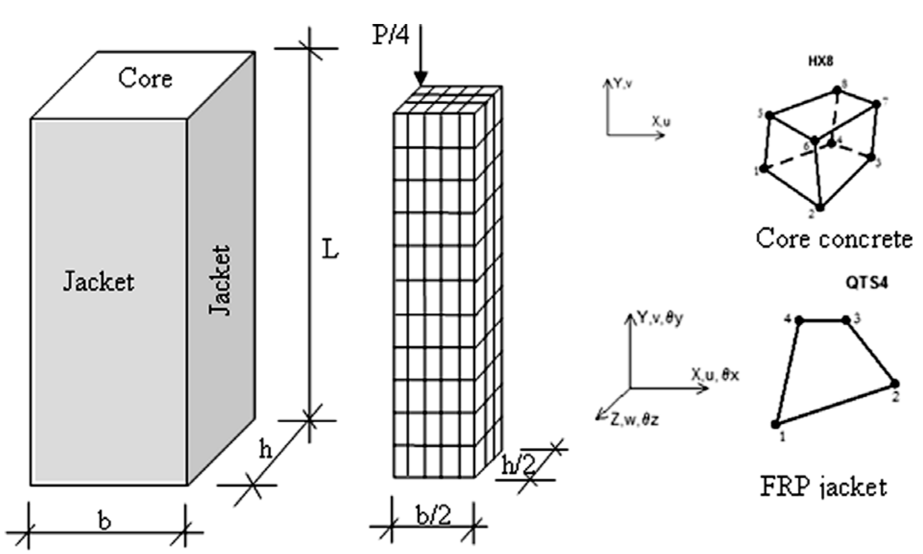

Fig. 1. FE meshing for a concrete element confined with FRP jackets.