Composite Structures 158 (2016) 160–174

Contents lists available at ScienceDirect

Composite Structures

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

A lateral strain plasticity model for FRP confined concrete

Bambang Piscesa [a], Mario M. Attard [a,*], Ali Khajeh Samani [b]

[a] School of Civil Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[b] School of Civil Engineering, University of Waikato, Hamilton, New Zealand

ARTICLE INFO

Article history:
Received 20 August 2016
Accepted 13 September 2016
Available online 15 September 2016

Keywords:
Plasticity
Confined concrete
Stress-strain model
Dilation rate control

ABSTRACT

This paper presents a plasticity constitutive formulation for actively and passively confined concrete. The loading surface is based on Menetrey and Willam's model with an additional frictional driver parameter. The frictional driver parameter controls the prediction of the peak stress and the residual stress level. The proposed flow rule has a plastic dilation rate control parameter which is a function of the restraining device or the local lateral modulus. A non-constant plastic dilation rate formulation is proposed to improve the prediction of the lateral strain behaviour of concrete. The proposed plastic dilation rate formulation is able to model plastic volumetric compaction caused by the use of very stiff confining devices, as well as the initial plastic compaction after the onset of localized cracking. Furthermore, the formulation is able to distinguish between active and passive confinement by monitoring the local lateral modulus. The accuracy of the proposed plastic dilation rate formulation is verified by comparison with experimental results for specimens subjected to either active or passive confinement from a variety of concrete strengths. The comparison between the proposed plasticity model and the experimental results for concrete under passive confinement (specimens with FRP confining material) was excellent.

1. Introduction

Concrete is a quasi-brittle material whose strength and ductility can be greatly enhanced when subjected to sufficient amounts of confinement. To understand the behaviour of concrete under confinement, experimental testing using a triaxial cell with constant confining pressure (active confinement) have been carried out by many researchers. These studies have been used to develop constitutive models for concrete under confinement and then used to predict the capacity of reinforced concrete (RC) members. However, for RC members under compression, the state of confinement is not equivalent to a state of active confinement (constant pressure) until the steel ties are at yield. When the steel ties are not at yield, the confinement is proportional to the stiffness of the steel ties and the confinement is called passive. Hence, for reinforced concrete columns with steel ties, there can be two states of confinement during loading; passive when the ties are elastic and active when the ties are at yield. When other restraining material such as FRP are used to confine the concrete, the confinement condition is passive while the FRP remains intact and elastic.

The behaviour of concrete under active and passive confinement has different characteristics. A constitutive model that has been calibrated using experimental results under active confinement tends to overestimate the response prediction for concrete under passive confinement (especially if high stiffness confining material is used). Pantazopoulou and Mills [1] found that the behaviour of concrete was greatly affected by the restraint conditions. Furthermore, under passive confinement, the restraint imposed by the lateral devices affects the behaviour of the concrete [2,3]. Hence, to be able to predict the response of concrete under both active and passive confinement, a constitutive model that considers all the parameters that affect the behaviour of concrete is required. There are many constitutive models in the literature that are able to model both active or passive confinement. However, these constitutive models have different approaches in handling the restraint from the lateral confining device. These approaches can be divided into three categories; the first involves adjusting the failure surface obtained from actively confined concrete so it can be used for passively confined concrete; the second method involves adjusting the effective confining pressure and the third method involves adjusting the lateral strain response used to calculate the confining pressure.

Previous study on the peak failure surface of concrete under proportional loading conducted by Imran and Pantazopoulou [4] showed that the peak stress was not affected by the pattern of the applied confining pressure. Thus, it can be concluded that it is not necessary to adjust the failure surface at the peak stress

* Corresponding author.
E-mail address: m.attard@unsw.edu.au (M.M. Attard).

http://dx.doi.org/10.1016/j.compstruct.2016.09.028

Nomenclature

A, B	coefficient of plastic potential that calibrated in uniaxial/ triaxial and biaxial condition
a_1	parameter of axial stress in residual stress
α	frictional driver parameter
$\alpha_{peak}, \alpha_{res}$	frictional driver parameter that controlling the peak and residual stress
$d\lambda$	plastic multiplier
e	eccentricity of roundness in yielding function
$\varepsilon_v^p, \varepsilon_{vi}^p$	plastic volumetric strain at specific time step and at inflection point
$\varepsilon_{v,peak}^e, \varepsilon_{v,peak}^p$	elastic and plastic volumetric strain at peak uniaxial/triaxial compression
ε_{3u}	peak axial strain at uniaxial state
$\varepsilon_{3u}^p, \varepsilon_{1u}^p$	peak axial and lateral plastic strain at uniaxial state
ε_{3c}	peak axial strain at triaxial state
$\varepsilon_{3c}^p, \varepsilon_{1c}^p$	peak axial and lateral plastic strain at triaxial state
$\varepsilon_{3c}^e, \varepsilon_{1c}^e$	peak axial and lateral elastic strain at triaxial state
ε_{1b}	peak lateral strain biaxial state
$\varepsilon_{3b}^p, \varepsilon_{1b}^p$	peak axial and lateral plastic strain at biaxial state
E_a, E_b	parameter of ascending hardening function
D_{ijkl}	elastic tensor defined in term of elastic modulus (E_c) and poisson ratio (ν_c)
$f(\rho, \xi, \theta)$	yielding function
f_c, f_t	concrete compressive and tensile strength (MPa)
f_{cc}, f_{res}	peak axial and residual stress under certain amount of lateral pressure (MPa)
f_r	confinement pressure or lateral pressure (MPa)
$g, \dot{g} = \frac{\partial g}{\partial \sigma}$	plastic potential function and it first derivatives with respect to stress
k	ratio that defined the non-dimensional plastic volumetric incremental
k_1, k_2, k_3	parameter of peak and residual stress function
m	frictional parameter
m_{ij}^n	derivative of plastic potential (flow rule) with stress in specific time step
ψ_1, ψ_2	inclination of plastic potential in uniaxial/triaxial and biaxial case
ξ, ξ^p	hydrostatic length and its plastic part
ρ, ρ^p	deviatoric length and its plastic part
ρ_1, ρ_2	deviatoric length in uniaxial/triaxial and biaxial case
$r(\theta, e)$	elliptic function as the function of lode angle (θ) and eccentricity of roundness
$\sigma_{ij}^t, \sigma_{ij}^n$	elastic stress predictor and corrected stress at step-n (MPa)
q_h, q_s	hardening and softening parameter

obtained from actively confined concrete when used to predict the peak stress of passively confined concrete. The confining pressure under passive confinement for circular sections can be accurately estimated using the compatibility of the lateral dilation of the concrete core with the external confining device. The confining pressure estimated is thus reasonably accurate and therefore it would make no sense adjusting the confining pressure to achieve better predictions for passive confinement. For this study, the authors have used the third approach where the lateral confining pressure is best-determined using compatibility conditions and a good lateral strain model for concrete.

In this research, a plasticity based constitutive model is used. The total strains are decomposed into elastic and plastic parts. This allows the lateral strain model to be formulated as a function of the plastic dilation rate. The plastic dilation rate can be defined as the ratio of the incremental plastic principal lateral to axial strains. By knowing the plastic dilation rate, the rate of the plastic volumetric strain can be calculated. It is well known that under active confinement, when very high confining pressure is applied, the rate of the plastic volumetric strain is almost zero with no plastic volumetric compaction [5]. Furthermore, the plastic dilation rate asymptotes to approximately −0.5 for very high confinement (constant plastic volume change). However, under passive confinement with very stiff restraining devices, concrete can exhibit plastic volumetric compaction due to the collapse of the pore structures [6–8]. This plastic core compaction is identified when the value of the plastic volumetric compaction is less than zero ($\varepsilon_v^p < 0$). To achieve such condition, the value of the plastic dilation rate must be greater than −0.5. Subsequently, constitutive models based on experiments under active confinement will overestimate the peak strength of concrete under passive confinement. This is simply because the plastic dilation rate under active confinement is larger than the plastic dilation rate under passive confinement with very stiff restraining devices.

In this paper, a detailed study of the plastic dilation rate under passive confinement is presented. A study of the plastic dilation rate for active confinement has been carried out by the authors [5,9]. The proposed plastic dilation rate formulation is calibrated using experimental results from FRP wrapped concrete. The plastic dilation rate formulation is implemented into the flow rule proposed by Piscesa and Attard [9] which is able to incorporate constant and non-constant plastic dilation rate. In this paper, a non-constant plastic dilation rate is considered. There are two major contributions: Firstly, after the onset of localized cracking, the initial plastic compaction can be successfully modelled. This improvement addresses the limitation of some previous models developed by Papanikolaou and Kappos [10] and Červenka and Papanikolaou [11]. Secondly, plastic volumetric compaction is successfully implemented by introducing a lateral modulus (E_L) parameter into the plastic dilation rate formulation. With such features, the formulation is able to distinguish between active and passive confinement by observing the rate of the incremental stresses (in principle strain directions) divided by the rate of principal incremental strains.

A brief review of existing constitutive models for confined concrete including both empirical and plasticity formulations are presented. The empirical models considered are: the model of Samani and Attard [5]; Dong and Kwan [3]; Cui and Sheikh [12]; Lim and Ozbakkaloglu [2] and Teng and Huang [13]. The plasticity models considered are those of Papanikolaou and Kappos [10]; Bao and Long [14] and Piscesa and Attard [9].

The formulation of Piscesa and Attard [9] is then extended by incorporating a non-constant plastic dilation rate using a lateral modulus parameter related to the lateral stiffness of the confining environment. The plastic dilation rate is integrated into the plastic flow rule. The procedures for obtaining numerical incremental solutions using either the empirical or the plasticity models are then described and used to generate the stress-strain behaviour of confined concrete. The various models and the proposed formulation are compared with the selected experimental results. The performance of each model is accessed by looking at the stress-strain response, the volumetric strain, secant dilation ratio peak stress prediction and the plastic dilation rate for both active and passive confinement problems.