Engineering Structures 113 (2016) 362–370

Contents lists available at ScienceDirect

Engineering Structures

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

Analytical compressive stress–strain model for high-strength concrete confined with cross-spirals

Jonathan West [a], Ahmed Ibrahim [b,*], Riyadh Hindi [c]

[a] Midwest Engineering Associates, 100 North Main St., Suite 301, East Peoria, IL 61611, USA
[b] Department of Civil Engineering, University of Idaho, Moscow, ID 83844, USA
[c] Parks College of Engineering, Aviation, and Technology, Saint Louis University, Saint Louis, MO 63103, USA

ARTICLE INFO

Article history:
Received 28 August 2014
Revised 28 September 2015
Accepted 25 January 2016

Keywords:
High strength concrete
Stress–strain
Compressive stress
Confined concrete
Cross spiral

ABSTRACT

The behavior of high-strength concrete members subjected to seismic loads is mainly based on the ultimate strength of concrete and its ductility. The ductility of reinforced concrete is defined by both axial stresses and strains, which could be represented by the total amount of energy that concrete can absorb before failure. Conventional spiral confinement increases the nominal compressive axial capacity of concrete due to the confinement action of the concrete core, which consequently provides increase in the crushing (failure) strain. The pitch (spacing) of spiral reinforcement has a significant effect on increasing the amount of energy that concrete can absorb. This paper presents a stress–strain model for the prediction of the confined compressive strength of high-strength concrete subjected to axial stress. The stress–strain model is based on confining concrete using cross-spirals. The main parameters were the spiral spacing, and the confinement technique either conventional or cross spirals. The model is based on the results of twenty-one high-strength reduced scale concrete columns that were tested under concentric compressive axial load. The proposed model was compared with two existing models where showed good agreement with the experimental results.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Reinforced concrete columns are the main load supporting elements of any structural system and have to be designed and detailed adequately to resist both gravity and lateral loads. Transverse reinforcements in concrete columns in the form of spirals play an important role in protection of columns, especially when they are subjected to strong earthquakes or accidental lateral loads. Columns are required in structural system to deform laterally and provide adequate ductility, ACI 318 [1]. Transverse reinforcement are recommended and specified by ACI 318 [1] for beams and columns to prevent buckling of longitudinal reinforcing bars, resist shear forces, avoid sudden shear failure, and to confine the concrete core to provide high ductile behavior and deformability. The transverse reinforcement are considered effective once the concrete at the concrete core starts to crack or spall. The engineering community is in need for precise models to predict the axial ductile behavior of reinforced concrete confined with new confinement techniques such as the one considered in this study (cross spirals). Existing confinement models found in the literature are mainly for conventional confinement techniques.

Lateral confinement in concrete columns has many different forms like: hoops, fiber-reinforced wrapping, wire mesh, high-strength pre-stressing strands, and various different schemes of spirals. Each of these methods is able to satisfy the requirements of ACI 318 [1] to enhance the maximum strength of concrete, but with each method, the geometry of the reinforcement changes and affects the ultimate strength of concrete. The progression of the models used to determine the effectiveness of the confinement strength of concrete has changed a lot. Table 1 summarizes most of the proposed equations to predict the ultimate axial strength of confined concrete with either ties or single-spirals.

The stress–strain behavior of axially loaded concrete is derived from the combination of the concrete's compressive strength and the rate at which the concrete cracks. As the concrete is loaded, the concrete deforms vertically, causing the column to also expand laterally. This is referred to as the Poisson phenomenon. As loading increases, the lateral expansion increases until micro-cracks start to form between the cement and aggregate interface. The crack propagation reduces the modulus of elasticity, which changes the stress–strain relationship from linear to non-linear. Two methods have been identified to increase the maximum strength of the

* Corresponding author.
E-mail addresses: jwest@mail.bradley.edu (J. West), aibrahim@uidaho.edu (A. Ibrahim), rhindi@slu.edu (R. Hindi).

http://dx.doi.org/10.1016/j.engstruct.2016.01.049
0141-0296/© 2016 Elsevier Ltd. All rights reserved.

Table 1
Confinement models for high strength concrete.

	Confinement method	Confined compressive stress model
Khaloo et al. [4]	Steel hoops and spirals	$f'_{cc} = f'_{co}\left(-0.413 + 1.413\sqrt{1 + \frac{11.4f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}\right)$
Bing et al. [5]	Steel hoops and spirals	$f'_{cc} = f'_{co}\left[-1.254 + 2.254\sqrt{1 + 7.94\alpha_s\frac{f'_l}{f'_{co}}} - 2\alpha_s\frac{f'_l}{f'_{co}}\right]$
		$\alpha_s = (21.2 - 0.35f'_{co})\frac{f'_l}{f'_{co}} \quad f'_{co} < 52$ MPa
		$\alpha_s = 3.1\frac{f'_l}{f'_{co}} \quad f'_{co} > 52$ MPa
Mander et al. [3]	Steel hoops and spirals	$f'_{cc} = f'_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}\right)$

$f'_{co} = unconfined\ compressive\ strength,\quad f'_{cc} = confined\ compressive\ strength$ and $f'_l = lateral\ confinement\ pressure.$

concrete; the first one is to increase f'_c (compressive strength of concrete); however, one major problem is as the strength of the concrete increases, the brittleness behavior increases. The second method is to reduce or prevent the lateral expansion by confining the concrete using lateral reinforcement, which will delay the crushing and increase the ductility and it will increase the crushing strength as well.

Hindi et al. [2] proposed the use of two opposing cross spirals in lieu of the conventional single spiral. The spacing of the cross spiral could be manipulated to either increase the behavioral characteristics of the column or to improve constructability. Where high ductility is needed, the cross spirals could be used a spacing of S, thus effectively doubling the volumetric lateral confinement ratio without violating the minimum spacing limitation by ACI 318 [1]. In areas where constructability is an issue, using a cross spiral with a spacing of $2S$ could be used. Cross-spirals were constructed using the same technique as the single-spiral except that two opposing spirals were lifted into place at the same time rather than one. As observed, the cross spirals were not any more difficult to tie in place than the traditional single one during construction.

The net effect would be to maintain the same volumetric confinement ratio with double the spacing. This would increase the constructability without altering the load carrying characteristics of the column.

Mander et al. [3] developed a model that predicts the strength of reinforced concrete circular or rectangular columns under axial loads. This model is limited only to normal-strength concrete and assumes that the transverse steel yielded before the concrete reaches its maximum strength, thus allowing the full strength of the transverse steel to be taken into account.

Khaloo et al. [4] reported that high-strength concrete behaves differently than normal-strength under axial concentric loads, and this is caused by the brittle nature of high-strength concrete. At the ultimate load, the concrete is not able to expand fully to engage the steel bars. Mander et al. [3] model gave a much higher strength estimate for columns than the actual testing showed. Khaloo et al. [4] developed a new equation that is based on the same parameters that Mander et al. [3] model had, but used the experimental data for high-strength concrete to propose a new equation for predicting the strength of the confined concrete. Bing et al. [5] used a combination of both [3,4] models and proposed modifications to the equation where the strength of concrete plays a larger role on the overall strength of concrete columns. This modification explains a good axial behavior for normal-strength concrete and high-strength concrete using hoops, ties, or single-spirals. Al-Qattawi [6] investigated the axial behavior of reinforced concrete circular columns confined with cross-spirals, and Marvel [7] reported experimentally the axial behavior of high-strength concrete columns confined with spirals. The present study is conducted to propose an analytical stress–strain model to predict the stress–strain behavior of high-strength concrete confined by cross-spirals, and the proposed analytical model is based on Marvel's [7,8] results. Many different studies related to the confined compressive strength of different concrete with various confinement techniques could be found in the literature [9–16].

2. Analytical model

The proposed analytical stress–strain model for high-strength concrete confined with cross-spirals is based on the results of the experimental program developed by Marvel [7,8]. The experiments included a reduced scale high-strength concrete columns reinforced by single and cross-spirals. Twenty-one concrete columns were tested; with seven columns using the conventional single-spirals configuration and seven columns using cross-spirals at the same pitch as the single-spirals. The final seven columns had a spiral pitch twice that of the original spacing. Table 2 summarizes all the specimens' dimensions, the concrete strength, and the spacing between all the spiral configurations. The concrete columns had a total diameter of 355 mm and a core diameter of 275 mm for the inner spirals and 285 mm for the outer spirals. Fig. 1 shows the specimen details. Mander et al. [3] model is used as a reference to be adapted and modified to describe the stress–strain behavior of high-strength confined concrete. All the results of the tested columns are used to verify and to ensure that they follow the same trend as predicted by [3] for normal-strength concrete and [5] for high-strength concrete. More details about the experimental results could be found on Marvel [7,8,10].

2.1. Effective area of confined concrete with single-spirals

As unconfined concrete experiences compressive axial loading, the concrete deforms vertically and laterally. The lateral expansion is reduced with the use of lateral confinement that introduces lateral stress. The confinement stress, along with reducing the lateral expansion also increases the maximum axial strength and overall reduction in the brittleness of the concrete. The increase in maximum axial strength and ductility of concrete is based on placing the concrete in a tri-axial compression stress-state compared to the uniaxial compression in unconfined concrete. The response of confined high-strength concrete using cross-spirals is based on many factors, which in consequence affect the stress–strain behavior. Some of those factors are vertical reinforcement spacing, reinforcement technique, transverse reinforcement volume, and the ratio and configuration of vertical reinforcement.

The stress–strain behavior under axial load of confined high-strength concrete is mainly affected by its brittleness and its maximum strength, which is achieved sooner especially when the spirals have been fully engaged. While the stress–strain behavior of confined concrete with single-spiral has already been established ACI 318 [1], the present study is performed to develop a stress–strain model for confined high-strength concrete with cross-spirals.

A significant difference has been found in the axial load capacity between the confined normal and high strength concrete with cross spirals. An average of a 41% increase in the ultimate strength is obtained and more details could be found at [18]. The basic equations for predicting the axial strength and the stress–strain behavior of high strength concrete due to confinement, the core effectiveness and the confinement pressure, need to be modified to include the effect of cross-spirals configuration. Mander et al. [3] stress–strain model is based on the relationship between the concrete core area before loading (A_{cc}) and the core area (effective area) at the ultimate load (A_e), and that model was derived only for normal strength concrete. The area of concrete core enclosed by the centerlines of the perimeter spirals is given as:

Download English Version:

https://daneshyari.com/en/article/6740164

Download Persian Version:

https://daneshyari.com/article/6740164

Daneshyari.com