

# Stress-Strain Model of Concrete Columns Externally Collared with Steel Angles Subjected to Axial Compression

*by Perpustakaan Referensi*

---

**Submission date:** 21-Sep-2024 08:42AM (UTC+0700)

**Submission ID:** 2460604741

**File name:** 007-Tavio\_def\_27973\_IRECE\_2015\_Vol\_15\_no\_3.pdf (2.1M)

**Word count:** 6387

**Character count:** 38274

# International Review of Civil Engineering (IRECE)

Contents:

<b>Computer Assisted Experimentation Influence of Straw on Thermal Properties of Clay Bricks for Thermal Comfort in the Building</b>	209
<i>by A. Echchikbi, S. Achouch, H. El Rhaleb, K. Gueraoui, F. Kijani-Sabban</i>	
<b>Utilizing Machine Learning Techniques for Safety Management and Severity of Accidents Forecasting in Construction Projects</b>	217
<i>by Ahmed Khatatbeh, Omar Qteishat, Issam Trrad, Fuad Al-Bataineh, Yazan Alzubi</i>	
<b>Comprehensive Study of Factors Governing Maintenance Operations for Public Office Buildings</b>	225
<i>by Hassanean S. H. Jassim, Amal H. Ali, Hadi Sarvari, Ali Khoshfetrat</i>	
<b>Study on Reinforcement of Block Masonry in Steel Buildings with Welded Joints</b>	243
<i>by Christian Mosquera, Marcos Rosero, Luis Hernández, Juan Velastegui, Christian Gómez</i>	
<b>Analyzing Road Freight Transport Choice in Bali</b>	257
<i>by Gusti Ayu Putu Candra Dharmayanti, Dewa Made Priyantha Wedagama</i>	
<b>Experimental Study of the Behavior of Self-Compacting Concrete Slabs Reinforced with Fibers Under Impact Loads</b>	266
<i>by Israa Kh. Jasim, Hadeel R. Khatab, Ali F. Saber</i>	
<b>Stress-Strain Model of Concrete Columns Externally Collared with Steel Angles Subjected to Axial Compression</b>	278
<i>by Tawio, P. Pudjisuryadi, A. Honestyo</i>	
<b>Effect of Steel Fiber and Confinement on Capacities of RC Columns in Dissipating Seismic Energy</b>	287
<i>by Bambang Sabariman, Tawio, Slamet Widodo</i>	



Praise Worthy Prize

# *International Review of Civil Engineering (IRECE)*

## *Editor-in-Chief:*

**Prof. K. M. Liew**  
Chair Professor of Civil Engineering  
Department of Civil and Architectural Engineering  
City University of Hong Kong  
Hong Kong SAR.

---

## **Editorial Board:**

<b>Abrams Daniel P.</b>	(U.S.A.)	University of Illinois
<b>Ansal Attila</b>	(Turkey)	Bogaziçi University
<b>Banthia Nemkumar</b>	(Canada)	University of British Columbia
<b>Berke Philip</b>	(U.S.A.)	College of Architecture, Texas A&M University
<b>Cai Steve C. S.</b>	(U.S.A.)	Louisiana State University
<b>Chan Siu-Lai</b>	(Hong Kong)	The Hong Kong Polytechnic University
<b>Dey Subhasish</b>	(India)	Indian Institute of Technology
<b>Dhakal Rajesh P.</b>	(New Zealand)	University of Canterbury
<b>Folić Radomir</b>	(Yugoslavia)	University of Novi Sad
<b>Kappos Andreas</b>	(U.K.)	City, University of London, Dept. of Civil Engineering
<b>Kovler Konstantin</b>	(Israel)	Israel Institute of Technology
<b>Liew Jat Yuen Richard</b>	(Singapore)	National University of Singapore
<b>Mang Herbert</b>	(Austria)	Vienna University of Technology
<b>Sapountzakis Evangelos J.</b>	(Greece)	National Technical University of Athens
<b>Tan Kiang Hwee</b>	(Singapore)	National University of Singapore
<b>Triantafillou Thanasis</b>	(Greece)	University of Patras
<b>Ye J.</b>	(U.K.)	University of Leeds

---

<sup>7</sup> The *International Review of Civil Engineering (IRECE)* is a publication of the **Praise Worthy Prize S.r.l.**  
The Review is published bimonthly, appearing on the last day of January, March, May, July, September, November.

Published and Printed in Italy by **Praise Worthy Prize S.r.l.**, May 31, 2024.

<sup>2</sup> Copyright © 2024 **Praise Worthy Prize S.r.l.** - All rights reserved.

This journal and the individual contributions contained in it are protected under copyright by **Praise Worthy Prize S.r.l.** and the following terms and conditions apply to their use:

Single photocopies of single articles may be made for personal use as allowed by national copyright laws.

Permission of the Publisher and payment of a fee is required for all other photocopying, including multiple or systematic copying, copying for advertising or promotional purposes, resale and all forms of document delivery. Permission may be sought directly from **Praise Worthy Prize S.r.l.** at the e-mail address:

[administration@praiseworthyprize.com](mailto:administration@praiseworthyprize.com)

Permission of the Publisher is required to store or use<sup>9</sup> electronically any material contained in this journal, including any article or part of an article. Except as outlined above, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without prior written permission of the Publisher. E-mail address permission request:

[administration@praiseworthyprize.com](mailto:administration@praiseworthyprize.com)

Responsibility for the contents rests upon the authors and not upon the **Praise Worthy Prize S.r.l.**

Statement and opinions expressed in the articles and communications are those of the individual contributors and not the statements and opinions of **Praise Worthy Prize S.r.l.** **Praise Worthy Prize S.r.l.** assumes no responsibility or liability for any damage or injury to persons or property arising out of the use of any materials, instructions, methods or ideas contained herein.

**Praise Worthy Prize S.r.l.** expressly disclaims any implied warranties of merchantability or fitness for a particular purpose. If expert assistance is required, the service of a competent professional person should be sought.

## 8 Stress-Strain Model of Concrete Columns Externally Collared with Steel Angles Subjected to Axial Compression

Tavio<sup>1</sup>, P. Pudjisuryadi<sup>2</sup>, A. Honestyo<sup>1</sup>

**Abstract** – RC structures with poorly confined columns have been known to have poor performance during earthquake events. Brittle failures of columns with low ductility can lead to progressive overall building collapses. Many confining techniques have been proven to be successful in retrofitting circular columns. However, for square or rectangular columns, providing effective confining stress by the external retrofitting method is not a simple task due to the high stress concentration occurring at the column's corners. In this paper, an analytical model for the axial stress-strain relationship of square concrete columns confined only by external steel collars has been developed. The combined effect of conventional internal stirrups and the external steel collars on the improved stress-strain relationship has been also developed analytically and proposed as the retrofit design approach. Comparison with experimental results has shown that the axial stress-strain relationship of square RC columns could be well predicted by the proposed retrofit design approach. Copyright © 2024 Praise Worthy Prize S.r.l. - All rights reserved.

**Keywords:** Analytical Model, Disaster Risk Reduction, External Retrofit, Square RC Columns

### Nomenclature

$P_{max}$	Specimen's maximum axial resistance
$P_{cmax}$	Concrete maximum axial resistance
$\epsilon_{Pmax}$	Axial strain consistent to $P_{max}$
$\epsilon_{cc}$	Axial strain consistent to $P_{cmax}$
$f'_{cc}$	Confined concrete compressive strength [MPa]
$\epsilon'_{cc}$	Confined concrete compressive strain
$\epsilon_{c0}$	Unconfined concrete compressive strain
$E_{sec}$	Confined concrete modulus of elasticity [MPa]
$r$	Constant
$E_c$	Plain concrete modulus of elasticity [MPa]
$\epsilon_c$	Strain of concrete

### I. Introduction

As seismic activity has been better understood, codes have become more demanding, necessitating the reinforcing and retrofitting of many old Reinforced Concrete (RC) structures. Liu et al. [1] have stated that the following deficiencies typically result from old, existing RC frame structures. A weak column can result in a mechanism of strong-column and weak-beam. Insufficient lap splices directly above floor levels can cause inelastic movements to concentrate with the higher flexural need.

Inadequate transverse reinforcement can confine the center of the column and prevent the longitudinal reinforcement buckling. Inadequate shear strength can develop the column's flexural capacity, or it can potentially degrade with increasing flexural ductility demand. Lastly, insufficient dimensions and detailings at

the beam-to-column joint can cause problems. Designing for the flexural mode of seismic energy dissipation in most framed structures is more cost-effective when plastic ductile hinges are formed in beams not in columns [2].

However, a failure of the single column can cause further failures and possibly result in the collapse of the entire building. Any structural building system would have columns as important members, and the building's ability to survive a seismic event is greatly impacted by how well it performs [1]. According to Mander et al. [3], having enough transverse reinforcement to confine the concrete, avoid the longitudinal reinforcement from buckling, and prevent brittle shear failure is crucial for the plastic hinge design of reinforced concrete columns.

Strength and ductility in concrete columns have been found to be improved by transverse confining stress [4], [5]. Numerous analytical models have been carried out to date to look at the impacts of confinement [6]-[9].

Typically, traditional transverse reinforcement (stirrups) provides confining stress in columns. Different methods to improve the performance of concrete, such as the use of high-strength steel bars as confinement, have been introduced [10]. The application of confinement has been extended as an interlocking system of multiple confinement [11], [12]. A combination with steel fiber has been also investigated to seek further the effectiveness of confinement [13]. Sections with square and circular columns have been studied in these investigations. The specimens have been subjected to axial and combined axial and bending loadings in both monotonic and cyclic patterns. Analytical models have only predicted the envelope curves in the situation of cyclic loading. The elements that have been found to be affecting the behavior

of confined concrete have included the volumetric proportion of side steel to the concrete central, the transverse reinforcement yield stress, the longitudinal steel proportion around the core perimeter, the resulting tie design, and the spacing tie. There is consensus regarding the differences between the enhanced relationship of stress-strain of confined concrete and that of unconfined concrete. These differences include the enhancement of compressive strength, the curve flatter post-peak descending branch, and the ultimate compressive strain increase (an increase in ductility). This has generally enhanced relationship between stress and strain in confined concrete is seen in Fig. 1. Here,  $f_t, f'_{c0}, f'_{cc}, \epsilon_t, \epsilon_{c0}, \epsilon_{cc}, \epsilon_{cu}, \epsilon_{sp}, E_c$  and  $s_{sc}$  represent its concrete's tensile strength, its compressive strength in an unconfined condition, its compressive strength in a confined condition, its rupture tensile strain, the concrete strains corresponding to the unconfined concrete's peak strength, the concrete strains corresponding to the confined concrete's peak strength, the ultimate compressive strain of the confined concrete, the strain at which the concrete cover is assumed completely spalled, the concrete's modulus of elasticity, and the secant modulus of confined concrete at peak stress, respectively.

Investigation on confined columns has recently been expanded for confinement that is applied externally, such as steel jacketing [14], Fiber-Reinforced Polymer (FRP) tubes [15], [16], and Fiber-Reinforced Polymer (FRP) jackets [17]-[19] for external confinement of concrete piers or columns. In order to make economic applications of FRP, GFRP straps have been introduced as confinement for concrete columns [20]. Other methods have been to implement light steel collars to improve the performance of concrete columns as a confining system [21], [22]. One of the primary reasons it is imperative that such an approach be created is the high demand for column retrofits. Experiments have demonstrated the effectiveness of several strategies for retrofitting circular columns [14]-[17]. It is difficult to provide effective confining stress via external retrofit for square and rectangular columns, nevertheless. This issue is found out to be addressed by a few experimental and sparsely analytical investigations [18]-[22].

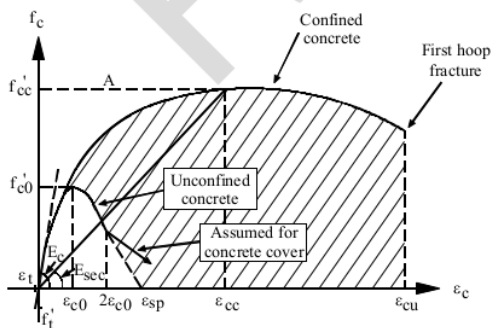


Fig. 1. Typically improved stress-strain curve of confined concrete (modified from [3])

The external steel collars confined square parts (Fig. 3) similarly experience the distribution of non-uniform stress (Fig. 2), which is like typical internal confinement. In addition to this comparable circumstance, the column behavior becomes more difficult when using the external confinement strategy. Compared to traditional stirrups, the mechanism of failure and behavior of contact between concrete and the element of external confinement may change. This paper presents an introduction and a discussion on the analytical approach. The work elaborates a suggested mathematical model for the curve prediction of axial stress-strain of external steel collars confined square columns. As a retrofit design strategy, the combined impact of external steel collars and traditional internal stirrups on the enhanced stress-strain relationship is also analytically suggested. From the investigation, it can be found out that the introduction of external steel collars has enhanced the performance of concrete columns. It can also be concluded that the more collars are used, the better the performance of the column is.

## II. Proposed Analytical Model

One of the most crucial aspects of modeling the axial stress-strain relationship of confined concrete analytically is predicting the transverse confining stress.

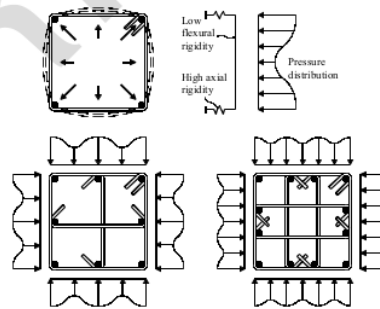


Fig. 2. Rectangular stirrups confined square column non-uniform confining stress (modified from [5])

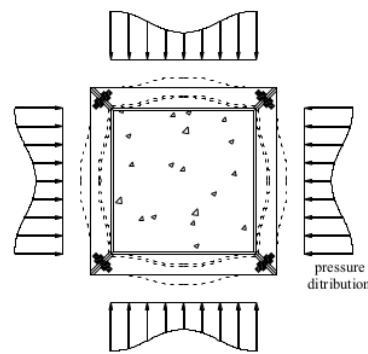


Fig. 3. Scheme of externally steel collars-confined square column non-uniform confining stress

Prior studies [3]-[6] have suggested confining stress models that are supplied on square, rectangular, and circular sections by internal confinement elements (ties and spirals). A retrofit design strategy for reinforced concrete columns with partly stiffened steel jackets has been suggested recently by Xiao and Wu [18]. The methods from earlier studies [3]-[6], [18] have been used in this investigation, with modifications made as needed for the external steel collar retrofitting methodology. The following parts provide an explanation of the model's evolution.

II.1. Main Effective Equivalent Uniform Confining Stress Provided by Steel Collars ( $f_{ie}$ )

A modified square concrete column with steel angle sections of steel collars is shown in Fig. 4. The notations  $b$ ,  $s_{sc}$ , and  $s_{scc}$  in the diagram stand for the concrete width, the steel collar spacing, and the clear steel collar spacing, respectively. As illustrated in Fig. 3, the stress of confining is ununiform in a column cross-section across the confinement device. Across the column section, this condition results in certain regions that are ineffectively contained. An ineffectively confined region  $b^2/6$  is produced for each parabola in Fig. 5(a) when the arced action is supposed to behave as a 45-degree initial tangent slope at the corners of second-degree parabolas [3], [5].

Equation (1) can be used to compute an ineffectively confined area expression ( $A_{par}$ ), which would account for the region of parabolic or the column section side:

$$A_{par} = \frac{2}{3}b^2 \tag{1}$$

As shown in Fig. 5(b), vertically positioned between neighboring confinement components are assumed to be the parabolic sections of ineffectively confined. Equation (2) gives the average effectively-confined cross-sectional area ( $A_e$ ) of Mander et al. [3] after considering both of vertical and horizontal directions of ineffective zones:

$$A_e = A_c \left( 1 - \frac{A_{par}}{A_c} \right) \left( 1 - \frac{s_{scc}}{2b} \right)^2 \tag{2}$$

where, in the case of externally restricted columns,  $A_c$  is the concrete core area, or the gross cross-sectional area of the column ( $=b^2$ ). Equation (3) proposes a confinement efficacy factor ( $k_e$ ), which is further discussed:

$$k_e = \frac{A_e}{A_{cc}} \tag{3}$$

where,  $A_{cc}$  is the columns' net core area (which is  $A_{cc}$  minus the size of any longitudinal bars). Equation (4) and Fig. 6 provide the uniform confining pressure of effective equivalent ( $f_{ie}$ ), which is modified by adding  $k_e$  to account for the actual non-uniform lateral confining pressure.

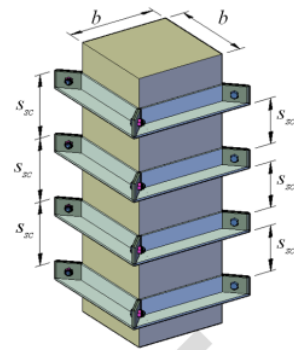
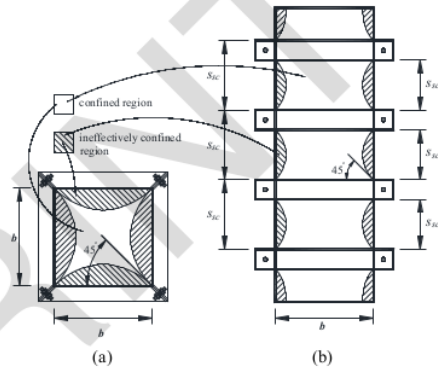


Fig. 4. Illustration of typical three-dimensional column specimens



Figs. 5. The region of ineffectively confined concrete at (a) cross-section; and (b) the column height

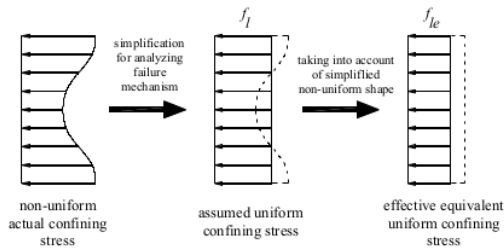


Fig. 6. Uniform confining stress of effective equivalent

The modification of  $f_l$ , which will be discussed later, results in the confining pressure of equivalent uniform ( $f_{ie}$ ):

$$f_{ie} = k_e f_l \tag{4}$$

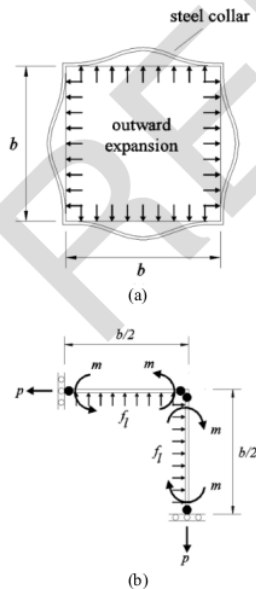
II.2. Confining Pressure Provided by Steel Collars ( $f_l$ )

Externally confined rectangular concrete columns frequently have confinement that is more efficient at the corners because of the stronger regions of the confinement elements [25], [26]. A comparable situation is also shown

by conservatively confined concrete with inside transverse reinforcement. Xiao and Wu [18] have claimed that external steel collars use an axial and combination bending mechanism to provide the confining pressure. Because of the comparatively moderate bending stiffness, this process differs from the statement for reinforcement of transverse, which solely relies on the action of the axial. First, Fig. 7(a) shows a concrete column with an externally retrofitted bulge under axial compressive stress. It is believed that the steel collars will flex in a way that preserves the concrete's ability to expand outward. It makes sense that the mid-sides would have more distortion than the corners. In the middle of the columns and at their corners, it is expected that the steel collars will break due to a combination of axial and bending mechanisms (plastic hinges are designed). By assuming uniformly generated confining pressure, simplified is the real non-uniform confining pressure generated. The forces in stability (the double symmetric condition only allows for analysis of 25% of the model) along the plane of cross-sectional are depicted in Fig. 7(b). Equations (5) and (6) allow for the expression of the axial  $p$  and bending moment  $m$  created in the steel collars as a function of the equal uniform confining pressure  $f_i$ , the breadth of the column section  $b$ , and the space of the steel collars  $s_{sc}$ . This is achieved by using force equilibrium.

$$p = f_i \frac{b}{2} s_{sc} \tag{5}$$

$$m = f_i \frac{b^2}{16} s_{sc} \tag{6}$$



Figs. 7. (a) Lateral expansion of concrete column and (b) Forces analyzed equilibrium

By using the combination of the steel collar's criterion for axial and bending failure (Eqs. (7)) from the Indonesian Structural Steel Code [23], it is possible to determine the steel collar's nominal capacities of axial and bending ( $p_n$  and  $m_n$ ). Reduction factors ( $\phi$ ) should be assumed to be 1.0 for determining the nominal capacity:

$$\frac{p}{\phi p_n} + \frac{8}{9} \frac{m}{\phi m_n} = 1.0 \text{ for } \frac{p}{\phi p_n} \geq 0.2 \tag{7-a}$$

$$\frac{p}{2\phi p_n} + \frac{m}{\phi m_n} = 1.0 \text{ for } \frac{p}{\phi p_n} < 0.2 \tag{7-b}$$

### II.3. Peak Strength of Confined Concrete ( $f'_{cc}$ )

All the specimens had their cross sections and heights fixed at  $200 \times 200 \text{ mm}^2$  and 600 mm, respectively. The employed clear concrete cover had a thickness of 20 mm.

The specimens have been configured with two 100 mm non-test portions at either end or a 400 mm intermediate test area. A 20 mm clear concrete cover has been employed. For all test specimens, normal concrete strength ( $f'_c = 20 \text{ MPa}$ ) has been utilized. Deformed bars have been used to strengthen the specimens for both transverse ( $f_y = 400 \text{ MPa}$ ) and longitudinal ( $f_{yt} = 400 \text{ MPa}$ ) purposes. Denser confinement than that of the test section has been intended for the non-test portions. Then the specimens were externally confined by the steel angle collars at 28 days post-casting. Four specimens with varying degrees of confinement have been designed while maintaining this configuration ( $f'_{c0}$ ). Initially, the specimen CS01 (Figure 8) was built without any confinement inside the test area, and the only longitudinal reinforcements utilized were 4-D10, or four 10-mm diameter deformed steel bars. The letters CS have been the first two digits of the specimen ID, then a number. The terms "Control" and "Specimen" are denoted by the letters "C" and "S," respectively. The last numbers are just the specimens' consecutive numbering, and the number "0" has denoted the monotonic axial compressive loading test.

The purpose of this specimen has been to provide the standard strength of untreated concrete ( $f'_{c0}$ ). Second, three representative specimens with the same dimensions and characteristics as Specimen CS01 have been further developed into Specimens S01, S03, and S05 (Figures 9).

Steel angle collars have been used to confine externally the specimens inside their test area. Steel collars constructed from steel angle sections have served as the external confinement elements (L40.40.4). For S01, S03, and S05, the volumetric ratios that have been intended for these specimens have been 3.84, 7.68, and 11.46 percent, respectively. The Structural Laboratory of the Research Center for Human Settlement, Ministry of Public Works, Indonesia, has been the site of the experimental tests. In order to find out the mechanical characteristics of steel bars and steel angle collars, tension tests have been carried out.

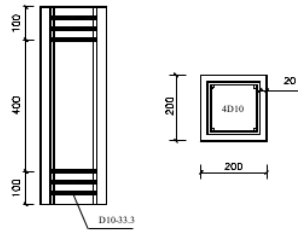
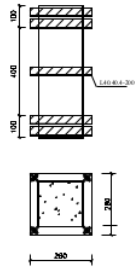
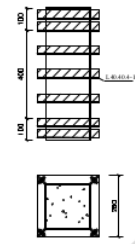


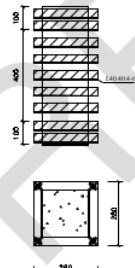
Fig. 8. Elevation and plan views of control specimen CS01



(a) S01



(b) S03



(c) S05

Figs. 9. Elevation and plan views of collared specimens: (a) S01; (b) S03; and (c) S05

With three samples with a nominal diameter of 9.5 mm, the specimen's formed bars (D10) had an average yield strength ( $f_y$ ) of 317 MPa with a standard deviation of 5.9 MPa. The equivalent standard deviation for the mean tensile strength (486 MPa) has been 3.8 MPa. A strip plate cut from the steel angle section has undergone a tension test, and the yield strength ( $f_{ysc}$ ) has been found to be 285 MPa. Figure 10 shows how the compression test is set up.

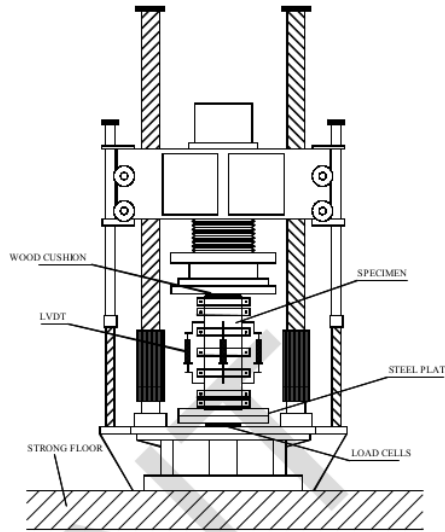


Fig. 10. Typical setup of the monotonic compression test

For the compression testing, four LVDTs have been utilized to measure the axial displacement and a load cell to measure the vertical load. A 5000 kN universal testing apparatus has been used to test each specimen. The specimens have undergone axial concentric loading that has been gradually increased. If any of the following conditions have been satisfied, the testing has been stopped: (1) specimen failure; (2) axial resistance falling below 50% of peak strength; or (3) LVDT capacity constraint. Important information from each specimen is enumerated in Table I. It has been discovered that the concrete strength has been 17.02 MPa from control specimen CS01. The unconfined strength of the concrete specimen is represented by the peak strength of CS01 ( $f'_{c0}$ ). The stress-strain curve is normalized (all stress values are split by) by using this strength in order to examine the impact of confinement on further specimens.

Figure 11 displays the initial set of tests' normalized stress-strain comparison.

Table II summarizes the strength increase and the failure notes. The predicted strength growth increments for the other collared specimens, S01, S03, and S05, have been 1.085, 1.209, and 1.422, respectively. By using regression analysis, the observed formula to predict the peak strength has been obtained.

TABLE I  
COMPRESSION TEST RESULTS

Parameters	CS01	S01	S03	S05
$P_{max}$ (kN)	762.9	822.9	906.9	1051.0
$P_{cmax}$ (kN)	675.8	733.0	817.1	961.2
$\epsilon_{Pmax}$ (%)	0.23	0.26	0.57	1.83
$\epsilon_{cc}$ (%)	0.23	0.26	0.57	1.83

Notes:  $P_{max}$  is the specimen's maximum axial resistance,  $P_{cmax}$  is the concrete maximum axial resistance  $\epsilon_{Pmax}$  is the axial strain corresponding to  $P_{max}$ ,  $\epsilon_{cc}$  is the axial strain corresponding to  $P_{cmax}$

The normalized effective equivalent uniform confining pressure ( $f_{le}/f'_{c0}$ ) and the normalized peak strength ( $f'_{cc}/f'_{c0}$ ) have been compared by using regression analysis. As seen in Figure 12, it has been discovered that the linear equation (correlation coefficient,  $R=0.992$ ) has accurately represented the relationship between the two parameters. Equation (8), which has been derived empirically, can be used to compute the peak strength once the effective equivalent uniform confining pressure has been established:

$$f'_{cc} = f'_{c0} \left( 1.0173 + 5.7558 \frac{f_{le}}{f'_{c0}} \right) \quad (8)$$

TABLE II  
THE SPECIMEN STRENGTH INCREASE AND FAILURE REMARKS

Specimen ID	$f'_{cc}/f'_{c0}$	Remark for descending brunch
CS01	1.000	60% of peak strength was lost following the descending branch (at strain 0.62%). It was noted that longitudinal bars buckled, and brittle diagonal failure occurred.
S01	1.085	At around 1.2% strain, strength fell below 50%. It was noted that longitudinal bars buckled, and brittle diagonal failure occurred.
S03	1.299	At a strain of roughly 7.4%, strength fell below 50% of peak strength. Longitudinal bar buckling was noted.
S05	1.422	There were two strength reductions because of broken collars 2 and 3, which occurred at 74% of peak strength (strain 8.60%) and 66% of peak strength (strain 11.64%), respectively. It was also noted that longitudinal bars buckled.

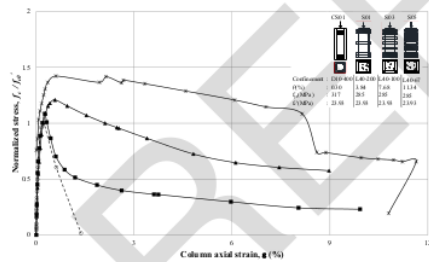


Fig. 11. The specimens' normalized axial stress-strain relationships

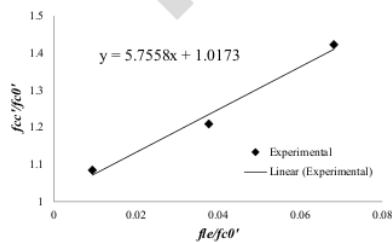


Fig. 12. Peak strength and effective uniform confining pressure linear relationship

#### II.4. Stress-Strain Relationship

Equations (9)-(12) show how the remainder of the model can adopt the Mander model [3] given the peak power provided by Equation (8):

$$\epsilon'_{cc} = \epsilon'_{c0} \left( 1 + 5 \left( \frac{f'_{cc}}{f'_{c0}} - 1 \right) \right) \quad (9)$$

$$E_{sec} = \frac{f'_{cc}}{\epsilon'_{cc}} \quad (10)$$

$$r = \frac{E_c}{E_c - E_{sec}} \quad (11)$$

$$f_c(\epsilon_c) = \frac{f'_{cc} \left( \frac{\epsilon_c}{\epsilon'_{cc}} \right)^r}{r - 1 + \left( \frac{\epsilon_c}{\epsilon'_{cc}} \right)^r} \quad (12)$$

where  $f'_{cc}$  is the confined concrete compressive strength (MPa),  $\epsilon'_{cc}$  is the confined concrete compressive strain corresponding to  $f'_{cc}$ ,  $\epsilon'_{c0}$  is the unconfined concrete compressive strain corresponding to  $f'_{c0}$ ,  $E_{sec}$  is the confined concrete modulus elasticity (MPa),  $r$  is a constant,  $E_c$  is the plain concrete modulus of elasticity (MPa),  $f_c(\epsilon_c)$  is the concrete stress as a function of concrete strain (MPa),  $\epsilon_c$  is the concrete strain. Figure 13 shows comparisons between the experimental data (S01, S03, and S05) and their analytical predictions. The suggested analytical models in the figure are indicated by the captions of the curves that end in "-Prop." It can be noted that the suggested analytical model can predict the normalized experimental stress-strain curves of Specimen S03 very well. The suggested model significantly overestimates the prediction for S01, while slightly underestimating the prediction for S05 prior to the first collar failure at a rather high axial strain value.

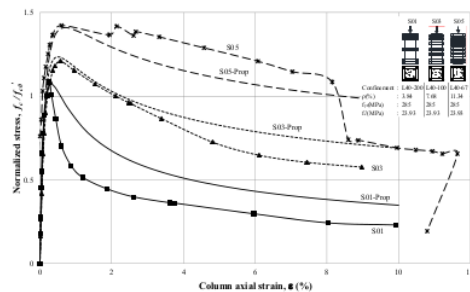


Fig. 13. Proposed analytical model normalized stress vs. axial strain and experimental results of S01, S03, and S05

II.5. Proposed Design Procedure for Strengthening Deficient Square RC Columns with External Steel Collar Retrofit

This segment presents a technique of design for retrofitting using the suggested exterior retrofit method.

Equations (13) and (14) [18] indicate the minimum confinement required of RC columns in the seismic area ensuring the rotational deformability of the possible plastic hinges near the column ends:

$$A_{sh1} = 0.09 \left( sb_c \frac{f_c'}{f_{yh}} \right) \tag{13}$$

$$A_{sh2} = 0.3 \left( sb_c \frac{f_c'}{f_{yh}} \right) \left( \frac{A_g}{A_{ch}} - 1 \right) \tag{14}$$

The underlying idea behind those statements is that constrained columns ought to keep their axial capacities even after the concrete cover spalls. In order to put it briefly, confinement needs to be set up so that the strength gained in the concrete core and the concrete cover are equal [24]. It is recommended that a column under consideration is given the corresponding confinement pressure for retrofit design [18]. Since the joint axial and the bending mechanisms of the steel collar parts are involved in this suggested retrofitting approach, achieving the desired equivalent confinement pressure is a difficult challenge (Equation (7)).

Additionally, as the method of retrofitting is typically applied to already existing inadequately restricted columns that already have traditional stirrups, the mathematical formulations will be more complicated. The existence of two coupled forms of exterior and inside confinement is the primary problem.

An algorithm to determine the combined effects of exterior and interior confinements is devised in this study.

The technique can be applied with the use of a computer, and the design of retrofit work can be easily simulated to meet a specific confinement target (such as the confinement mandated by a code). The basic concept is to superimpose the extra exterior confinement on top of the existing interior confinement effects. Assumed to be  $A_{ei}$  and  $A_{ee}$ , respectively, the effectively limited areas impacted by the internal and external confinements are shown in Figure 14.

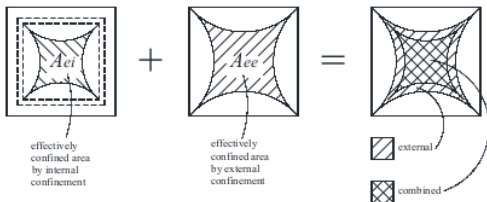


Fig. 14. Effectively Confined Area due to the internal and external confinement

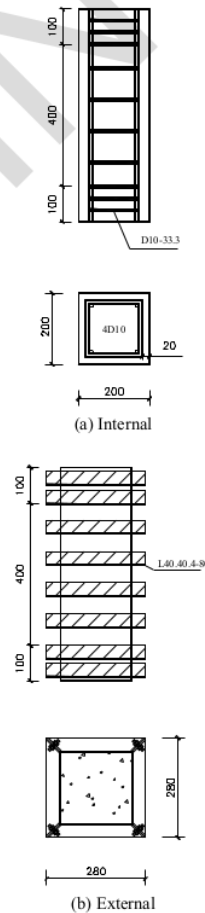
While the zone  $A_{ee}-A_{ei}$  solely feels the confining pressure from exterior confinement, the area  $A_{ei}$  feels the pressure from both internal and external confinements.

Equation (8) explains how to derive the confining pressure from the exterior confinement ( $f_{ie}$ ) by using the proposed analytical model, whereas the classic model presented by Mander et al. [3] can be used to determine the confining pressure from the interior confinement ( $f_{ii}$ ).

In order to syndicate these effects, it is planned to implement the average confining pressure ( $f_{icomb}$ ), which is relational to their affected zones as defined in Equation (15).

This confining pressure average can be used along with the proposed analytical model (Equations (9)-(12)) to express the axial stress-strain relationship because of both internal and external confinements:

$$f_{icomb} = \frac{(f_{ii} + f_{ie})A_{ei} + f_{ie}(A_{ee} - A_{ei})}{A_{ee}} \tag{15}$$



Figs. 15. Elevation view and cross-section of Specimens S04a: (a) reinforcement detail; and (b) external steel collars

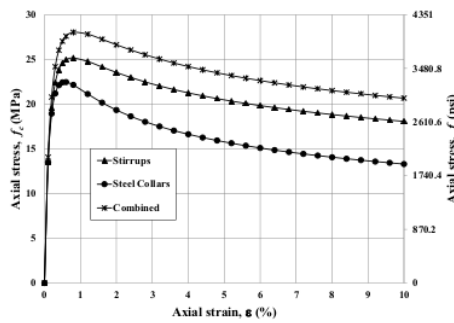


Fig. 16. Stress-strain relationship of S04a (retrofit design approach)

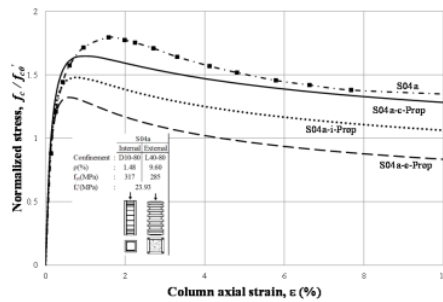


Fig. 17. Normalized stress vs axial strain of combined effect of internal and external confinement and experimental results of Specimen S04a

An additional specimen (S04a) has been constructed and tested by using the same experimental configuration to confirm the efficiency of the suggested design method.

The interior and the external confinement locations of the specimens have been arranged to coincide with one another. The example is shown in Figures 15.

### III. Discussion on Results

Figure 16 displays both the individual and the combined effects of internal and exterior confinement as well as the analytical stress-strain relationship curves. The normalized stress-strain relationships of experimental specimen S04a are compared with the suggested retrofit design model in Figure 17.

The outcome demonstrates that the analytical model has a reasonable ability to predict the observed behavior. It is discovered that the suggested method's results understate experimental data, yet this is still acceptable because it indicates that the design is safe and acceptable.

The suggested analytical model curve legends are designated as "S04ab-x-Prop." The impacts of the interior, exterior, and combined confinements for "i," "e," and "c" are shown by the index "x," respectively.

### IV. Conclusion

A proposed analytical model can be used to forecast the external steel collar's confined square concrete column's

peak stress. The primary suggestion of the model is to derive the corresponding effective uniform confining stress ( $f_{le}$ ) that external steel confining materials provide.

A collection of specimens was constructed and subjected to a constant compression load. The test's results have demonstrated a strong linear relationship between normalized equivalent effective uniform confining stress ( $f'_{cc}/f'_{c0}$ ) and normalized confined peak strength ( $f_{le}/f'_{c0}$ ). Additionally, a design retrofitting strategy is put forth. The influence of both internal and external confinement is combined in this analytical technique, which is explored. In order to validate the retrofit methodology, an additional specimen has been constructed and examined. The outcome has demonstrated a very good performance. More extensive research on the topic is recommended to further study the use of various parameters such as grouting and also bolts and stiffeners to provide better contact and strengthen or stiffen the steel collars.

### Acknowledgements

The authors gratefully acknowledge financial support from the Institut Teknologi Sepuluh Nopember for this work, under the project scheme of the Publication Writing and IPR Incentive Program (PPHKI) 2024.

### References

- [1] J. Driver R.G., and Lubell A.S. (2008), *Rehabilitation and Repair of Reinforced Concrete Short Columns with External Steel Collars*, Structural Engineering Report No.281, Department of Civil & Environmental Engineering, University of Alberta.
- [2] Sheikh, S.A., and Yeh, C.C. (1986), Flexural Behavior of Confined Concrete Columns, *ACI Journal*, pp. 389-404.
- [3] Mander, J. B., Priestley, M. J. N., and Park, R. (1988a), Theoretical Stress-Strain Model for Confined Concrete, *Journal of Structural Engineering*, ASCE, Vol. 114, No. 8, pp. 1824-1826.
- [4] Mander, J. B., Priestley, M. J. N., and Park, R. (1988b), Observed Stress-Strain Behavior of Confined Concrete, *Journal of Structural Engineering*, ASCE, Vol. 114, No. 8, pp. 1827-1849.
- [5] Saatcioglu, M., and Razvi, S. R. (1992), Strength and Ductility of Confined Concrete, *Journal of Structural Engineering*, ASCE, Vol. 118, No. 6, pp. 1590-1607.
- [6] Sheikh, S. A. (1982), A Comparative Study on Confinement Models, *ACI Journal*, Vol. 79, No. 4, pp. 296-306.
- [7] Hoshikusuma, J., Kawashima, K., Nagaya, K., and Taylor, A. W. (1997), Stress-Strain Model for Confined Reinforced Concrete in Bridge Piers, *Journal of Structural Engineering*, ASCE, Vol. 123, No. 5, pp. 624-633.
- [8] Tavio, and Kusuma, B. (2009), Stress-Strain Model for High-Strength Concrete Confined by Welded Wire Fabric, *Journal of Materials in Civil Engineering*, ASCE, Discussion, Vol. 21, No. 1, pp. 40-45.
- [9] Tabsh, S. W. (2007), Stress-Strain Model for High-Strength Concrete Confined by Welded Wire Fabric, *Journal of Materials in Civil Engineering*, ASCE, Vol. 19, No. 4, pp. 286-294.
- [10] Agustiar, Tavio, Raka, I G. P., and Anggraini, R. (2018), Behavior of Concrete Columns Reinforced and Confined by High-Strength Steel Bars, *International Journal of Civil Engineering and Technology*, Vol. 9, No. 7, pp. 1249-1257.
- [11] Machmoed, S. P., Tavio, and Raka, I G. P. (2020), Potential of New Innovative Confinement for Square Reinforced Concrete Columns, *Journal of Physics: Conference Series*, Vol. 1469, No. 012027, pp. 1-7.

- [12] 6vivo, T., Machmoed, S., Raka, I., Behavior of Square RC Columns Confined with Interlocking Square Spiral Under Axial Compressive Loading, (2022) *International Journal on Engineering Applications (IREA)*, 10 (5), pp. 322-335. doi: <https://doi.org/10.15866/irea.v10i5.20655>
- [13] Sabariman, B., Soehardjono, A., Wisnumurti, Wibowo, A., and 6vivo (2020), Stress-Strain Model for Confined Fiber-Reinforced Concrete under Axial Compression, *Archives of Civil Engineering*, Vol. 66, No. 2, pp. 119-133.
- [14] 1Jai, Y. H., Priestley, M. J. N., and Seible, F. (1994), Analytical Model for Steel-Jacketed RC Circular Bridge Columns, *Journal of Structural Engineering*, ASCE, Vol. 120, No. 8, pp. 2358-2376.
- [15] 1Jafi, M., Toutanji, H. A., and Li, Z. (1999), Behavior of Concrete Columns Confined with Fiber-Reinforced Polymer Tubes, *ACI Material Journal*, Vol. 96, No. 4, pp. 500-509.
- [16] 1Jin, A. Z., and Rizkalla, S. H. (2001), Confinement Model for Axially Loaded Concrete Confined by Circular Fiber-Reinforced Polymer Tubes, *ACI Structural Journal*, Vol. 98, No. 4, pp. 541-461.
- [17] 1Jury, S. A., and Harries, K. A. (2005), Axial Behavior and Modeling of Confined Small-, Medium-, and Large-Scale Circular Sections with Carbon Fiber-Reinforced Polymer Jackets, *ACI Structural Journal*, Vol. 102, No. 4, pp. 596-604.
- [18] Xiao, Y., and Wu, H. (2003), Retrofit of Reinforced Concrete Columns using Partially Stiffened Steel Jackets, *Journal of Structural Engineering*, ASCE, Vol. 129, No. 6, pp. 725-732.
- [19] Lee, C. S., Hegemier, G. A., and Phillip, D. J. (2010), Analytical Model for Fiber-Reinforced Polymer-Jacketed Square Concrete Columns in Axial Compression, *ACI Structural Journal*, Vol. 107, No. 2, pp. 208-217.
- [20] Pinto, D., Tavio, and Raka, I G. P. (2019), Axial Compressive Behavior of Square Concrete Columns Retrofitted with GFRP Straps, *International Journal of Civil Engineering and Technology*, Vol. 10, No. 1, pp. 2388-2400.
- [21] Hussain, M. A. and Driver, R. G. (2005), Experimental Investigation of External Confinement of Reinforced Concrete Columns by Hollow Structural Section Collars, *ACI Structural Journal*, Vol. 102, No. 2, pp. 242-251.
- [22] Pudjisuryadi, P., and Tavio (2016), Axial Compressive Behavior of Square Concrete Columns Externally Collared by Light Structural Steel Angle Sections, *International Journal of Applied Engineering Research*, Vol. 11, No. 7, pp. 4655-4666.
- [23] National Standardization Board (2020), *Specifications for Structural Steel Buildings (SNI 1729:2020)*, Indonesian National Standard, Jakarta, Indonesia, 254 pp. (in Indonesian).
- [24] Saatcioglu, M., and Razvi, S.R. (2002), Displacement-Based Design of Reinforced Concrete Columns for Confinement, *ACI Structural Journal*, Vol. 99, No. 1, pp. 3-11.
- [25] Shbeeb, N., Barham, W., Barsneeh, H., Nonlinear Finite Element Analysis of Concrete Columns Confined by Carbon Fiber Reinforced Polymer Sheets, (2022) *International Review of Civil Engineering (IRECE)*, 13 (4), pp. 275-289. doi:<https://doi.org/10.15866/irece.v13i4.19631>
- [26] Honestyo, A., Tavio, T., Ardhyananta, H., Axial Compressive Behavior of Bubble-Size Plastic Straw Waste FRP-Confined Circular Concrete, (2023) *International Journal on Engineering Applications (IREA)*, 11 (2), pp. 73-80. doi:<https://doi.org/10.15866/irea.v11i2.22603>

## 6 Authors' information

<sup>1</sup>Department of Civil Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia.

<sup>2</sup>Department of Civil Engineering, Universitas Kristen Petra, Surabaya, Indonesia.



**Tavio** (Corresponding Author) is a Professor at the Department of Civil Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia. His research interest includes forensic and retrofitting in civil engineering, analytical/numerical and experimental modeling for simulating the behavior and performance of reinforced and prestressed/ precast concrete members including composite and steel structures under seismic loading and fire conditions, concrete, steel, and rubber materials for structural use, dampers, and isolation systems for seismic mitigation.



**P. Pudjisuryadi** is an Associate Professor at the Department of Civil Engineering, Universitas Kristen Petra, Surabaya, Indonesia. He received his B.Eng., M.Eng., and Ph.D. in civil engineering from the Universitas Kristen Petra, Surabaya, Indonesia, the Asian Institute of Technology, Bangkok, Thailand, and the Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, respectively. His research interests include the seismic performance of reinforced concrete and steel structures.



**A. Honestyo** is a 25-year-old doctoral student majoring in civil engineering, at the Department of Civil Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia. His research interest includes forensics and retrofitting especially in the usage and development of environmentally friendly materials for concrete strengthening.

# ***International Review of Civil Engineering (IRECE)***

## **Aims and scope**

**7** The **International Review of Civil Engineering (IRECE)** is a peer-reviewed journal that publishes original theoretical papers, applied papers, review papers and case studies on all fields of civil engineering.

**10** The scope of the Journal encompasses, but is not limited to the following areas: *infrastructure engineering; transportation engineering; structural engineering (buildings innovative structures environmentally responsive structures bridges stadiums commercial and public buildings, transmission towers, television and telecommunication masts, cooling towers, plates and shells, suspension structures, smart structures, nuclear reactors, dams, pressure vessels, pipelines, tunnels and so on); earth quake, hazards, structural dynamics, risks and mitigation engineering; architectural engineering; environmental engineering; structure-fluid-soil interaction; wind engineering; fire engineering; multi-scale analysis; constitutive modeling and experimental testing; construction materials; composite materials in engineering structures (use, theoretical analysis and fabrication techniques); novel computational modeling techniques; engineering economics..*

*The Editorial policy is to maintain a reasonable balance between papers regarding different research areas so that the Journal will be useful to all interested scientific groups.*

The Journal also publishes short communications and discussions, book reviews, and a diary on international events related to any aspect of civil engineering.

---

## **Instructions for submitting a paper**

Contributions may consist of invited tutorials or critical reviews; original scientific research papers (regular paper); letters to the Editor and research notes which should also be original presenting proposals for a new research, reporting on research in progress or discussing the latest scientific results in advanced fields.

All papers will be subjected to a fast editorial process.

Any paper will be published within two months from the submitted date, if it has been accepted.

Papers must be correctly formatted, in order to be published.

Formatting instructions can be found in the last pages of the Review.

An **Author guidelines** template file can be found at the following web address:

**[www.praiseworthyprize.org/jsm/?journal=irece](http://www.praiseworthyprize.org/jsm/?journal=irece)**

Manuscripts should be sent via e-mail as attachment in .doc and .pdf formats to:

**[editorialstaff@praiseworthyprize.com](mailto:editorialstaff@praiseworthyprize.com)**

The regular paper page length limit is defined at **15** formatted Review pages, including illustrations, references and author(s) biographies.

***Pages 16 and above are charged 10 euros per page and payment is a prerequisite for publication.***

---

## **Abstracting and Indexing Information:**

**5**  
*Academic Search Complete - EBSCO Information Services*

*Cambridge Scientific Abstracts - CSA/CIG*

*Elsevier Bibliographic Database SCOPUS*

*Index Copernicus - IC Journal Master List 2022: ICV 124.08*

**Autorizzazione del Tribunale di Napoli n. 22 del 26/02/2010**

REPRINT



Praise Worthy Prize



2036-9913(202405)15:3;1-H

Copyright © 2024 Praise Worthy Prize S.r.l. - All rights reserved

# Stress-Strain Model of Concrete Columns Externally Collared with Steel Angles Subjected to Axial Compression

## ORIGINALITY REPORT

11%

SIMILARITY INDEX

8%

INTERNET SOURCES

5%

PUBLICATIONS

1%

STUDENT PAPERS

## PRIMARY SOURCES

1	<a href="http://core.ac.uk">core.ac.uk</a> Internet Source	2%
2	<a href="http://www.britannica.com">www.britannica.com</a> Internet Source	2%
3	Tienfuan Kerh, Chuhsiung Huang, David Gunaratnam. "Neural Network Approach for Analyzing Seismic Data to Identify Potentially Hazardous Bridges", Mathematical Problems in Engineering, 2011 Publication	1%
4	<a href="http://worldwidescience.org">worldwidescience.org</a> Internet Source	1%
5	Ramdan B. A. Koad, Ahmed Faheem Zobaa. "A Study of Non-Isolated DC-DC Converters for Photovoltaic Systems", International Journal on Energy Conversion (IRECON), 2013 Publication	1%
6	<a href="http://www.civilejournal.org">www.civilejournal.org</a> Internet Source	1%

7	temp.mickemedia.se.ext.levonline.com Internet Source	1 %
8	Yufei Wu. "Confined concrete", Elsevier BV, 2022 Publication	1 %
9	www.docstoc.com Internet Source	1 %
10	www.journals.elsevier.com Internet Source	1 %
11	"Editorial Board", Engineering Structures, 200810 Publication	1 %
12	journals.uokufa.edu.iq Internet Source	1 %

Exclude quotes  On

Exclude matches  < 1%

Exclude bibliography  On