Computational Modeling of Concrete with Internal (steel spirals) and External (FRP) Confinement

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SUMMARY:
This paper presents the results of a computational modeling to predict the compressive behavior of concrete cylinders internally reinforced by steel spirals and externally wrapped with FRP composites. The effect of internal and external confinement on compressive behavior of concrete are combined and it has also been investigated. In this study, concrete cylinders are modeled by ABAQUS software based on finite element technique. Modeling includes concrete strengthened with FRP jacket or concrete confined with just steel spiral and concrete with both FRP and spiral confinement. The numerical results have been verified with the available experimental data. Predicted stress-strain curves demonstrate an increase in compressive strength, ductility and energy absorption capacity in confined concrete specimens, either with steel spirals with various levels of confinement or FRP jackets with different number of layers. In presence of both confining systems, the enhancement for low level of internal confinement is considerable.

Keyword: Retrofitting, FRP Composites, Spiral Bars, Confined Concrete, Computational Modeling

1. INTRODUCTION

In recent years, the use of fiber reinforced polymer (FRP) jackets, as an external lateral confinement has found considerable attention in retrofitting and strengthening existing reinforced concrete (RC) columns in earthquake prone areas. The FRP composites have numerous advantages such as ease in application, high strength and stiffness-to-weight ratio, effective corrosion resistance and negligible changes in the member dimension.

Most of previous studies have concentrated on evaluation of the effect of confinement with spiral bars or FRP composites, separately. However, in practice both types of confinements exist in strengthening RC columns. These investigations demonstrated that lateral confinement increases compression strength, ductility and energy absorption capacity of concrete. Effective lateral confinement can be achieved by using spiral bars and wrapping FRP composites around concrete members.

Most of the proposed models for compressive strength and corresponding strain for confined concrete are based on the confinement model presented by Richart et al. (1928, 1929) Eqn. 1.1, Eqn. 1.2. This model demonstrated from experimental tests on specimens confined with hydrostatic pressure.

$$f'_{cc} = f'_{co}\left(1 + k_1 \frac{f'_l}{f'_{co}}\right) \tag{1.1}$$

$$\varepsilon_{cc} = \varepsilon_{co}\left(1 + k_2\left(\frac{f'_{cc}}{f'_{co}} - 1\right)\right) \tag{1.2}$$

Where f'_{cc} and ε_{cc} are the confined concrete compressive strength and corresponding strain; f'_{co} and ε_{co} are the compressive strength and corresponding strain of unconfined concrete; f'_l is the effective lateral

hydrostatic pressure; k_1 and k_2 are coefficients that are functions of concrete mix and the lateral confinement pressure. Richart et al. found the average value of $k_1 = 4.1$ and $k_2 = 5$ from experimental data.
One of the most well-known stress-strain models for steel confined concrete is proposed by Mander et al. (1988) Eqn. 1.3, Eqn. 1.4. The expressed model by mander et al. is based on an equation suggested by Popovics (1973).

$$f'_{cc} = f'_{co}(-1.254 + 2.254\sqrt{1 + \frac{7.94f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}) \tag{1.3}$$

$$\varepsilon_{cc} = \varepsilon_{co}(1 + 5\left(\frac{f'_{cc}}{f'_{co}} - 1\right)) \tag{1.4}$$

Different expressions are proposed for calculating f'_l that is a function of longitudinal and lateral steel and shape of column section. Mander et al. (1988) present following expression for effective lateral confinement pressure Eqn. 1.5, Eqn. 1.6.

$$f'_l = k_e f_l \tag{1.5}$$

$$f_l = \frac{1}{2}\rho_s f_y \tag{1.6}$$

Where f_l is lateral confinement pressure; ρ_s is ratio of the volume of transverse confining steel to the volume of confined concrete core; f_y is yield strength of the transverse reinforcement; k_e is effectiveness coefficient of lateral confinement pressure.

Several experimental and analytical confinement models for FRP confined concrete follow mander et al. confinement model; E.g. Saafi et al. (1999) proposed a model for FRP confined concrete based on the mander et al. model Eqn. 1.7, Eqn. 1.8.

$$f'_{cc} = f'_{co}\left(1 + k_1\frac{f'_l}{f'_c}\right) \tag{1.7}$$

$$k_1 = 2.2(\frac{f_l}{f'_{co}})^{-0.16} \tag{1.8}$$

Where f'_{cc} is the confined concrete compressive strength; f'_{co} is the compressive strength of unconfined concrete; f'_l is the effective lateral hydrostatic pressure; f_l is the lateral hydrostatic pressure; k_1 is effectiveness coefficient (refer to Eqn. 1.1).

Based on the lateral strain compatibility and stability force equilibriums of the concrete and FRP jacket, the lateral hydrostatic pressure of the FRP confinement for circular concrete sections is a function of volumetric ratio and lateral strain of the FRP jackets Eqn. 1.9, Eqn. 1.10.

$$f_l = \left(\frac{\rho_f E_f}{2}\right)\varepsilon_l \tag{1.9}$$

$$\rho_f = \frac{4n_f t_f}{D} \tag{1.10}$$

Where f_l is the lateral hydrostatic pressure; ρ_f is the volumetric ratio of the FRP jacket; E_f is elasticity modulus of FRP; ε_l is lateral strain of the FRP; n_f is number of applied FRP layers; t_f is the thickness of FRP layer; and D is the section diameter.

In recent years a few confinement models are proposed for concrete confined with both steel spirals and FRP jackets. A set of empirical equations is analytically proposed by J.-Y.Lee et al. (2009) Eqn. 1.11, Eqn. 1.12, and Eqn. 1.13.

$$f_c = E_c\varepsilon_c + (f'_c - E_c\varepsilon_{co})(\frac{\varepsilon_c}{\varepsilon_{co}})^2 \qquad \text{for} \quad 0 < \varepsilon_c \le \varepsilon_{co} \tag{1.11}$$

$$f_c = f'_c + (f'_{cs} - f'_c)(\frac{\varepsilon_c - \varepsilon_{co}}{\varepsilon_{cs} - \varepsilon_{co}})^{0.7} \qquad \text{for} \quad \varepsilon_{co} < \varepsilon_c \le \varepsilon_{cs} \tag{1.12}$$

$$f_c = f_{cs} + (f_{cu} - f_{cs})(\frac{\varepsilon_c - \varepsilon_{cs}}{\varepsilon_{cu} - \varepsilon_{cs}})^{0.7} \qquad \text{for} \quad \varepsilon_{cs} < \varepsilon_c \le \varepsilon_{cu} \tag{1.13}$$

Where f_c , ε_c are the stress and strain of confined concrete with both steel spirals and FRP jackets; E_c is elasticity modulus of concrete; f'_c , f'_{cs} and f'_{cu} are the strength of unconfined concrete, stress of confined concrete at the onset of yielding in the transverse steel and strength of concrete confined with both steel spirals and FRP jackets; ε_{co} , ε_{cs} and ε_{cu} are the concrete strain at the peak unconfined concrete stress (f'_c), the confined concrete strain at the onset of yielding in the transverse steel (corresponding to the f'_{cs}) and the concrete strain at the peak confined concrete stress(f'_{cu}).

2. RESEARCH SIGNIFICANCE

Computational modeling of concrete with both internal and external confinement by means of finite element techniques will assist in the study of strengthening and retrofitting of existing structures and the calibration of design techniques.

3. COMPRESSION FIELD MODELING OF CONCRETE

The constitutive material models used in the analysis of concrete with internal and external confinement are presented.

3.1. Compression Field of Unconfined Concrete

Modeling of unconfined concrete makes use of stress-strain curves generated by Hognestad (1951) Eqn. 3.1, Eqn. 3.2.

$$f_c = f'_{co}(2\frac{\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2) \qquad \text{for} \quad 0 < \varepsilon_c \le \varepsilon_{co} \tag{3.1}$$

$$f_c = f'_{co} - \left(\frac{0.15f'_{co}}{\varepsilon_{cu} - \varepsilon_{co}}\right)(\varepsilon_c - \varepsilon_{co}) \qquad \text{for} \quad \varepsilon_c > \varepsilon_{co} \tag{3.2}$$

Where f_c , ε_c are the stress and strain of unconfined concrete; f'_{co} and ε_{co} are the compressive strength and corresponding strain of unconfined concrete; ε_{cu} is the ultimate strain of unconfined concrete.

3.2. Compression Field of confined Concrete with Steel Spiral

For internally confined concrete with steel spirals, stress-strain curves generated by mander et al. (1988) were considered Eqn. 1.3, Eqn. 1.4, Eqn. 1.5, Eqn. 1.6, Eqn 3.3 and Eqn. 3.4.

$$k_e = \frac{1 - \frac{S'}{2d_s}}{1 - \rho_{cc}} \qquad \text{for circular steel spirals} \tag{3.3}$$

$$\rho_s = \frac{4A_{sp}}{d_s S} \tag{3.4}$$

Where k_e is the effectiveness coefficient of lateral confinement pressure; S' is clear vertical spacing between spiral or hoop bars; d_s is the diameter of spiral between bar centers; ρ_{cc} is the ratio of area of longitudinal reinforcement to area of core of section; ρ_s is the ratio of the volume of transverse confining steel to the volume of confined concrete core; A_{sp} is the area of transverse reinforcement bar; s is the center to center spacing or pitch of spiral.

3.3. Concrete in Tension

The tensile stress-strain curve of concrete includes an ascending linear elastic portion up to the tensile strength f_t , and a descending linear portion that simulates tension stiffening. The tensile strength of concrete obtains from ACI 318-11 Eqn. 3.5, Eqn. 3.6.

$$\mathrm{f_r} = 2\sqrt{\mathrm{f_c'}} \tag{3.5}$$
$$\mathrm{f_t} = (50 - 75)\%\mathrm{f_r} \tag{3.6}$$

Where $\mathrm{f_r}$ is the modulus of rupture; $\mathrm{f_c'}$ is the strength of concrete and $\mathrm{f_t}$ is the tensile strength of concrete. In this study, $\mathrm{f_t}$ considered to be $0.5\mathrm{f_r}$.

3.4. Steel

Based on the test a stress-strain curve consists of two ascending linear portion and a descending linear portion is used to model steel in compression and tension. Steel bar buckling is not considered and steel and concrete are assumed perfectly bounded.

3.5. Fiber Reinforced Polymer (FRP) Composites

A linear elastic stress-strain curve is used to model FRP composites. FRP jacket and concrete are assumed perfectly bounded and FRP fails just after reaching the rupture stress. Table 3.1 shows properties of two kinds of FRP used in this study.

Table 3.1. FRP Properties

FRP	Substance	Weight of 1 m^2 (gr)	Thickness (mm)	Modulus of Elasticity (MPa)	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain (%)
CFRP	carbon	245	0.156	$2.4 * 10^5$	3840	1.6
GFRP	glass	800	0.3	$0.77 * 10^5$	3619	4.5

4. STRESS-STRAIN CURVES

Modeled specimens are named with a three terms title; the first term is the compressive strength of concrete (MPa), second term is the internal confinement and the pitch of spiral (cm) and P means there is no internal confinement and the third one is the external confinement and the number of layers of FRP. E.g. 50-S5-2C means a specimen with compressive strength of 50 MPa and circular spiral with 5 cm pitches and 2 layers of CFRP.

Figure 4.1 shows the stress-strain curves obtain by Abaqus finite element program.

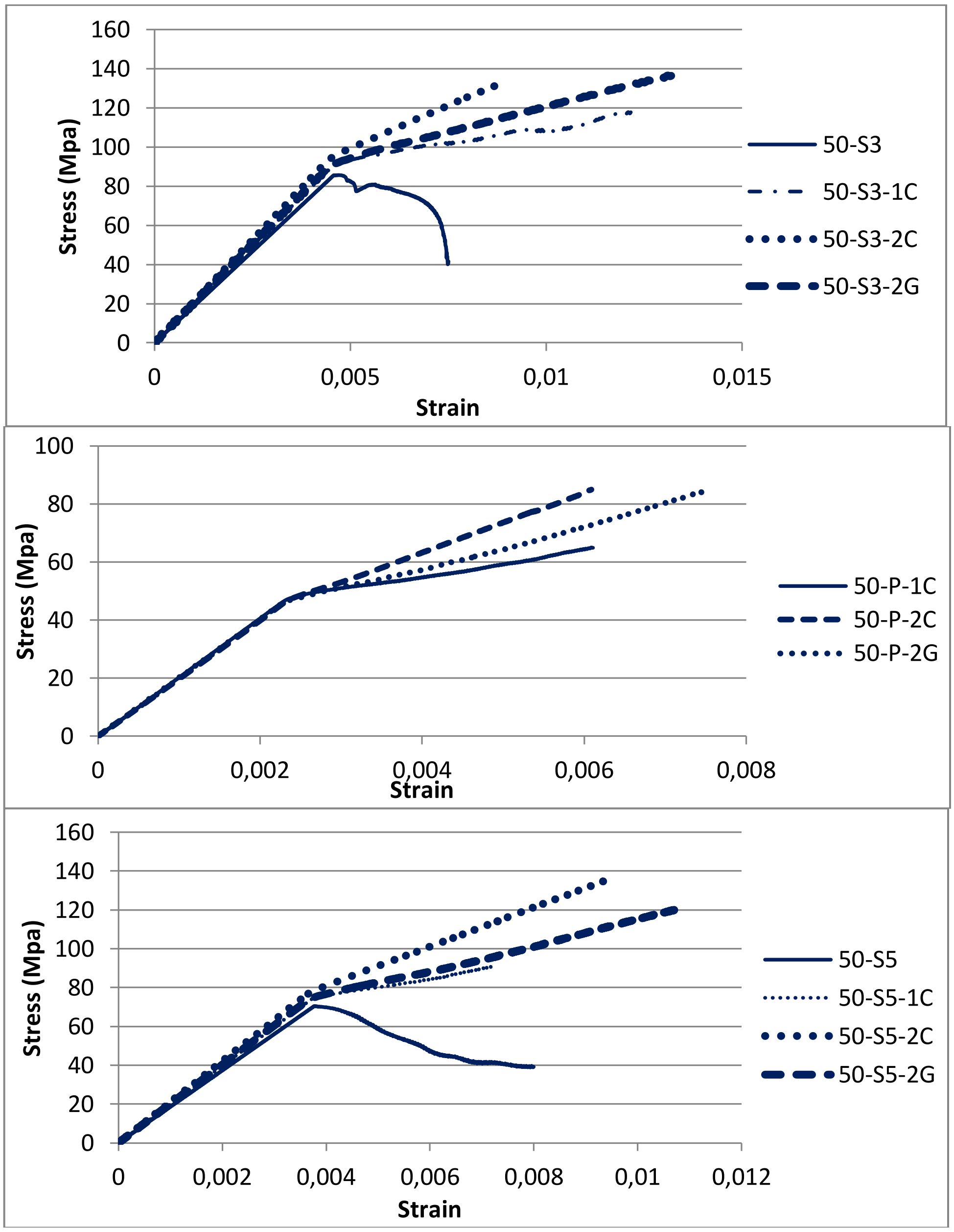

Figure 4.1. Axial stress-strain curves of confined concrete systems

5. COMPARISON WITH AVAILABLE EXPERIMENTAL DATA

Khaloo et al. based on their test results obtained complete stress-strain curves of the modeled 12×40 cm cylindrical specimens with the same internal and external confinement. In this section the present computational results are compared with the experimental data, see Figure 5.1.

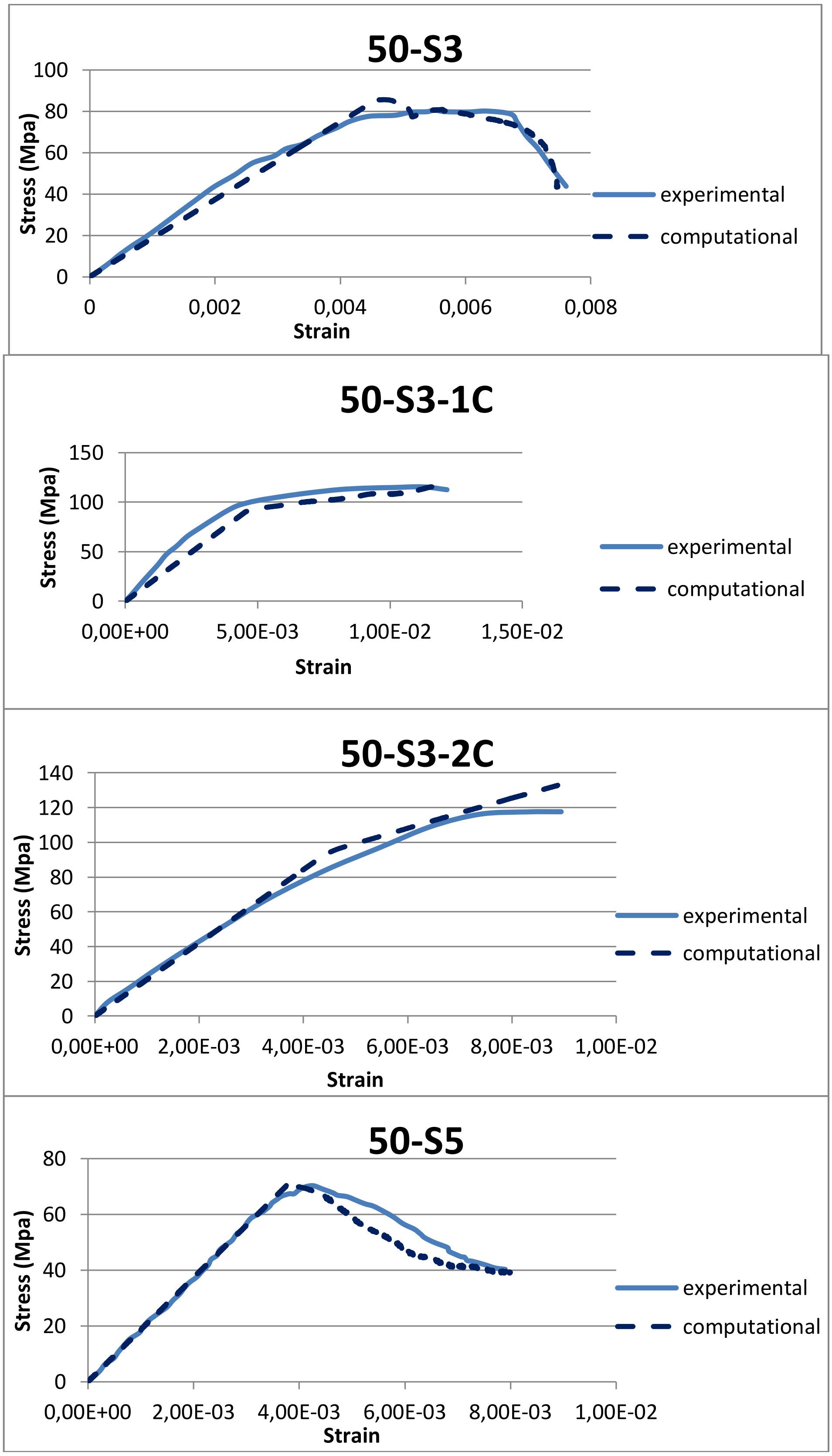

Figure 5.1. Comparisons with experimental results (continued)

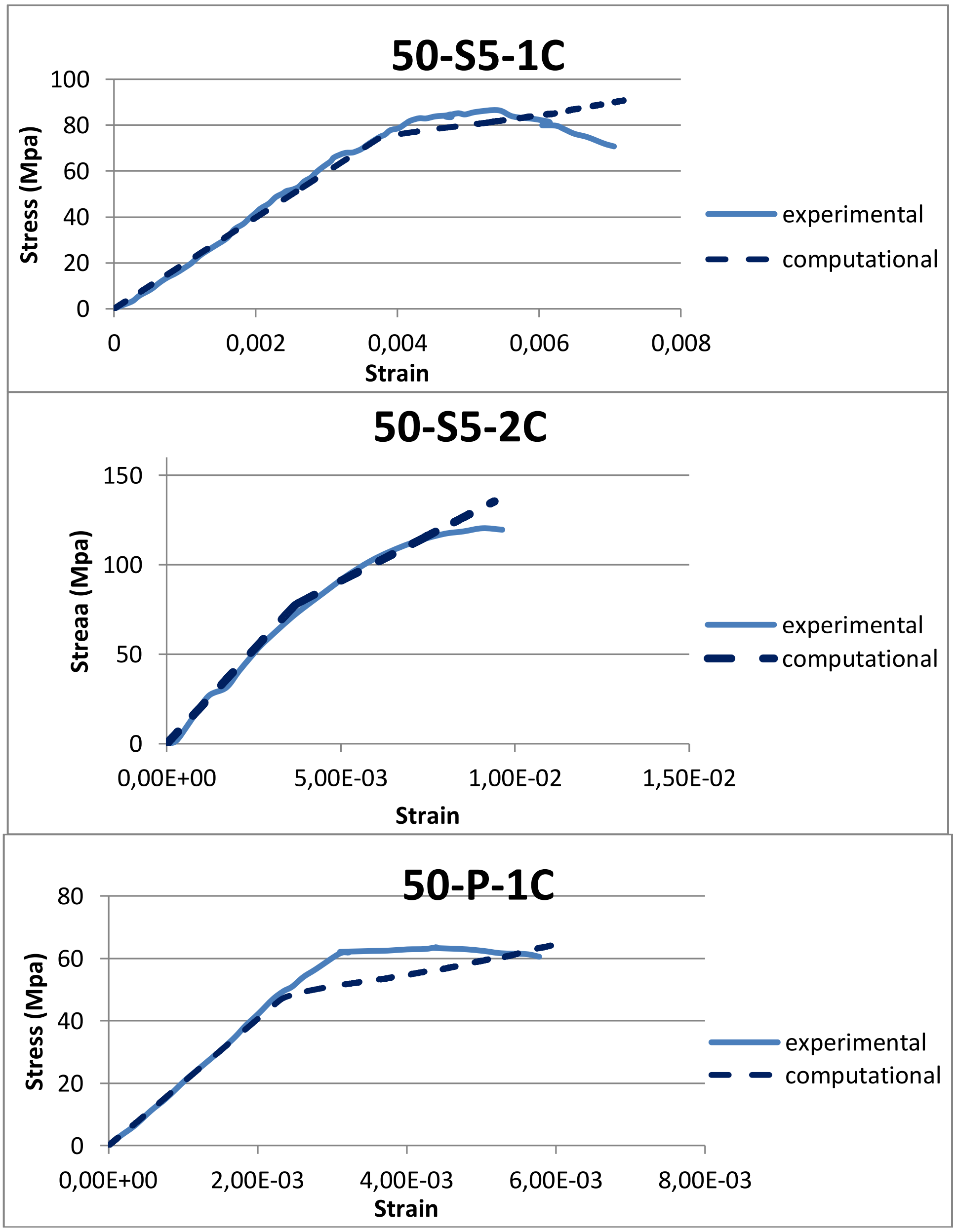

Figure 5.1. Comparisons with experimental results (continuation)
The comparisons between computational models and experimental data
shows that numerical model match the test results reasonably well.
The model shows good agreement with the behavior observed in experimental data.

7. CONCLUSION

The compressive behavior of concrete confined with both spiral bars as internal confinement and FRP jacket as external confinement is studied numerically in this research. Based on the computational results of this study, the following conclusions are drawn:

1. A confinement model capable of handling both internal and external confinement is introduced and implemented in the finite element program ABAQUS to analyze reinforced concrete columns confined with steel spirals and/or FRP layers. The computational approach shows good agreement with the available experimental data.

2. Predicted stress-strain curves demonstrate an increase in compressive strength, ductility and energy absorption capacity in confined concrete specimens, either with steel spirals with various levels of confinement or FRP jackets with different number of layers.
3. For given steel spiral volumetric ratio, the compressive strength of confined concrete and corresponding strain, increase with the increase in number of FRP layers.
4. For high level of steel spiral volumetric ratio as internal confinement the effect of external FRP confinement on the strength, ductility and energy absorption of confined concrete with spiral bars and FRP jackets is limited.
5. The confined concrete with GFRP layers is more ductile than confined concrete with CFRP layers.

Numerical model expresses acceptable prediction of compressive behavior of confined concrete with steel spirals as internal confinement and/or FRP jackets as external confinement. The objective is to calibrate a design formula for strengthening and retrofitting the existing structures. The existing structures have spiral bars before strengthening. This computational model could predict compressive behavior of existing concrete columns after retrofitting by FRP layers. So, the required amount of FRP layers based on the existing spiral bars of columns could be evaluated.

ACKNOWLEDGEMENT
Partial support of Center of Excellence in Structures and Earthquake Engineering in this research study is greatly appreciated.

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