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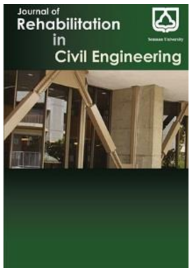

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Behavior Comparison of Uniaxial Cylindrical Columns Strengthened with CFRP

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ABSTRACT

In recent years application of CFRP sheets in the strengthening of the concrete circular column has increased numerously. Knowing the exact behavior of concrete cylindrical columns confined with CFRP is of the first order of importance. ISIS Code of Canada has given relations for strength increase of circular columns confined with CFRP sheets, these relations are defined for a specified range of confinement pressure, and for higher confinement pressures there are no relations describing the behavior of the confined specimen. In this paper, cylindrical specimens with different concrete strengths and a variable number of CFRP layers were used. They were modeled in finite element software. After verification of models with laboratory works; results of finite element modeling were compared with ISIS Canada. The analytical results show that with a change in concrete strength the results have a different error from ISIS results. Therefore, for confinement pressure of more than the permissible value of ISIS code, change in the amount of strength increases was studied.

1. Introduction

Concrete confinement imposes multi axial compressive stress on the concrete, and causes increase of its ultimate strength and ductility, consequently prevents it from early collapse of the concrete usually. Concrete confinement is done by perimeter turnings of CFRP sheets. FRP confining effect in structural members has been the subject of different studies [1-3]. Although in old buildings the retrofitting of concrete members were done by FRP confinement to restore or even to increase the strength capacity [4-6]. Some researches about effectiveness of FRP on axial stress–strain curve of confined concrete and cylindrical specimens load capacity of concrete also have been done [7-12].

In 2002, Li et al studied different rebar arrangements for strengthening of cyclic specimens strengthened with CFRP. They found out that compressive strength of cylindrical concrete specimen confined with CFRP is not related to rebar arrangements [13,14].

According to ISIS Canada Educational module 4 the compressive pressure of confinement, for a cylindrical column, is calculated using relations (1) to (3) [15]. In equation (1) N_b the number of layers, ϕ_{frp} perimeter reduction confinement, f_{frp} CFRP maximum strength, t_{frp} CFRP sheets thickness, and D_g is the specimen diameter. ϕ_c in relation (2) is the concrete resistance factor and w_w is the volumetric confinement ratio. f_{cc} in equation (3) is the ultimate strength of confined concrete, α_{pc} is a performance confinement (that depends on a number of factors such as FRP type, concrete strength, and member size). ISIS Design manual No. 4 currently recommends that α_{pc} be taken as 1.0. Fig (1) shows confinement mechanism for axial strengthening of circular reinforced concrete specimen using externally bounded FRP wraps.

$$f_{lfrp} = \frac{2\ N_b \phi_{frp} f_{frp} t_{frp}}{D_g} \qquad (1)$$

$$w_w = \frac{2\ f_{lfrp}}{\phi_c f_c} \qquad (2)$$

$$f_{cc} = f_c(1 + \alpha_{pc} w_w) \qquad (3)$$

$$f_{lfrp} \leq \frac{f_c'}{2\alpha_{pc}}\left(\frac{1}{k_e} - \phi_c\right) \qquad (4)$$

The maximum confinement pressure that ISIS code considers for the specimens confined with CFRP is calculated from relation (4). In this relation, considering k_e and ϕ_c, they are equal to 0.8 and 0.6, respectively, thus the allowable confinement pressure is calculated as $0.325 f_c'$.

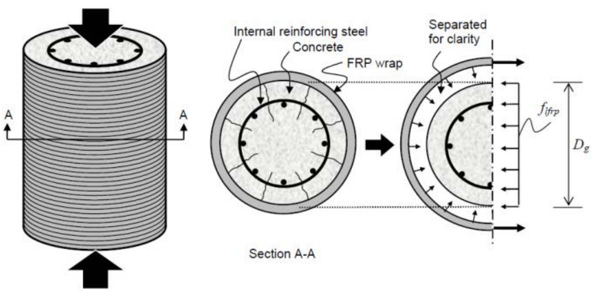

Fig (1) Mechanism for axial strengthening of circular reinforced concrete specimen using externally bounded FRP wraps [15].

In this article, a cylindrical concrete specimen was modeled and analyzed 3 dimensionally in Abaqus software. It was verified with experimental work of complete confinement and ISIS code's result. Also using CFRP with different number of layers and change in concrete strength was studied. At the end with increase in specimen's confinement pressure more than allowed ISIS value, we investigated this parameter in confining method.

2. Modeling

2.1. Concrete modeling

Concrete modeling was done with an eight-node cubic element (3D) in Abaqus software. By comparing relations for concrete behavior from Majewski [16], Euro code EN 1992-1-1[17] , Wang and Hsu [18], the EN 1992-1-1 model confirmed with the laboratory work very well. Therefore, to define the concrete behavior the relations of EN 1992-1-1 [17,19] were used. Then plasticity damage model for the concrete was defined with relations (5) through (11).

$$\sigma_c = f_{cm}\frac{k\eta - \eta^2}{1 + (k-2)\eta} \quad (5)$$

$$k = 1.05E_{cm}\frac{\varepsilon_{c1}}{f_{cm}}, \qquad \eta = \frac{\varepsilon_c}{\varepsilon_{c1}} \quad (6)$$

$$\varepsilon_{c1} = 0.7(f_{cm})^{0.31} \quad (7)$$

$$E_{cm} = 22(0.1f_{cm})^{0.3} \quad (8)$$

Compressive stress of concrete, up to $0.4f_{cm}$, is elastic and greater than that from relation (5) the stress is defined as non-linear. The maximum compressive stress of concrete is f_{cm}. The compressive stress (σ_c) is a function of variables η, k. These variables are calculated from relation (6). ε_c is the compressive strain for concrete, related to σ_c. Concrete strain at maximum compressive stress is ε_{c1}, f_{cm}, which is calculated from relation (7). Concrete elastic module is calculated from relation (8) a function of the maximum compressive stress of concrete. Fig. (2) shows the compressive behavior.

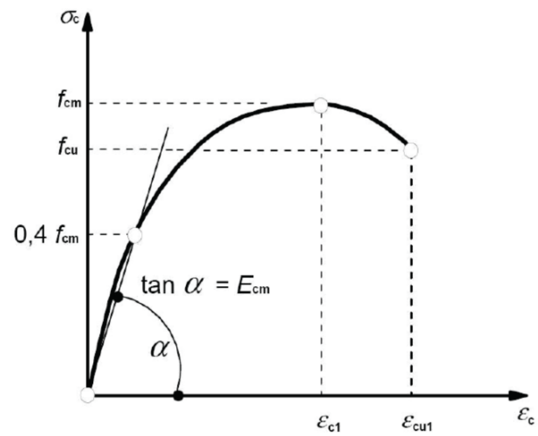

Fig.(2) Concrete compressive behavior.

$$f_{ctm} = 0.3f_{cm}^{(2/3)} \quad (9)$$

$$\sigma_t = E_c\varepsilon_t \qquad if \quad \varepsilon_t \le \varepsilon_{cr} \quad (10)$$

$$\sigma_t = f_{cm}\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right) \qquad if \quad \varepsilon_t > \varepsilon_{cr} \quad (11)$$

Maximum concrete tensile stress was obtained from relation (9). In relations (10-11), ε_{cr} is concrete strain at maximum tensile stress that have linear behavior up to f_{ctm} which is defined from relation (10) (region 1), and for strains more than ε_{cr} , tensile strain is determined from equation (11); at this step damage plasticity occurs (region 2). Fig.(3) shows tensile behavior of concrete and table (1) displays properties of concrete.

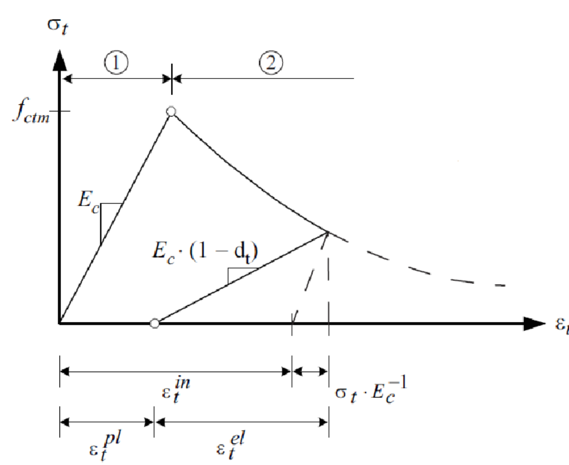

Fig.(3) Concrete tensile behavior.

Table (1) Concrete properties.

Compressive (MPa) stress	Density (kg/m^3)	Elasticity module (MPa)	Poison ratio
17.8	2400	26154	0.2
25	2400	28960	0.2
45	2400	34545	0.2

2.2. Modeling CFRP

All of CFRP sheets have lamina type and modeled with shell element [20] and have 10 cm width. Also in applying CFRP, resin applied has more strength than CFRP's, therefore in this modeling we neglect CFRP slips on concrete surface and its traction was defined as tie. Table (2) shows CFRP properties.

Table (2) CFRP properties.

Longitudinal tensile strength (MPa)	4100
Longitudinal compressive strength (MPa)	3206
Transvers tensile strength (MPa)	80.136
Transvers compressive strength (MPa)	240.4
Longitudinal shear strength (MPa)	80.136
Transvers shear strength (MPa)	120.246
Density (kg/m^3)	1536
Elastic module (GPa)	240
Poison ratio	0.25
Thickness (mm)	0.12

3. Strengthening specimens

All of specimens have 30 cm diameter and 60 cm height, numbering specimens from left to right represents, specimen's concrete strength that starts with S, and then total number of CFRP layers. Confinement details were explained in table (3). Uniaxial load may act perpendicular to CFRP jackets and causes the jacket to buckle rapidly, this situation occurs when CFRP jackets confines all external specimens' area, to stop occurring this we use a finite spacing of layers (5 mm) between jackets at the upper side or down side of specimens' surface, with this method confinement pressure is reached and jackets do not buckle rapidly.

Table (3) Strengthening details.

Specimen	Concrete strength (MPa)	Confinement type	No. of layers	Confinement pressure (MPa)
S17-0W S25-0W S45-0W	17.8 25 45	Without cover	-	-
S17-1W S25-1W S45-1W	17.8 25 45	Fully covered	1	3.28
S17-3W S25-3W S45-3W	17.8 25 45	Fully covered	3	9.84
S17-6W S25-6W S45-6W	17.8 25 45	Fully covered	6	19.68
S17-9W S25-9W S45-9W	17.8 25 45	Fully covered	9	29.52

4. Model verification and finite element results

Types of jackets have negligible effect on linear behavior of specimens. Specimens with different jackets in linear behavior are similar to each other, and since low stress concrete has low lateral expansion, jackets do not act. But in plastic region, increase in stress causes a lot of lateral expansion, and that causes confinement pressure creation [21, 22].

All specimens' results are shown in table (4). For specimen S60-0W ultimate uniaxial strength was measured 16.7 MPa, that was suitable for specimen built with 17.8 MPa concrete, and its error is from difference in uniaxial and biaxial strength for concrete, Figure (4) shows this [19].

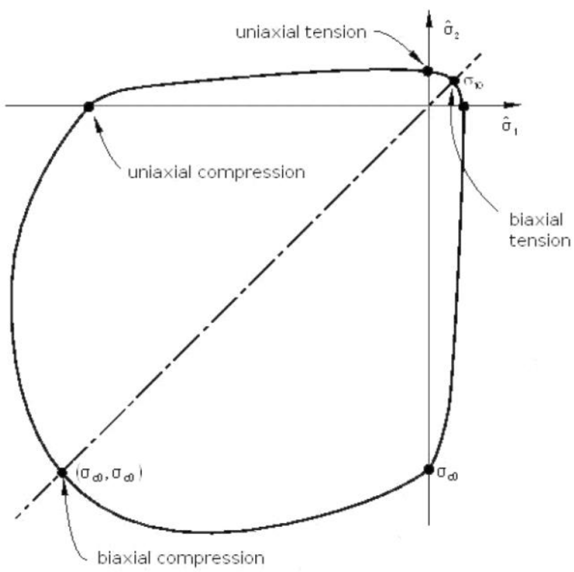

Fig.(4) Concrete behavior under uniaxial and biaxial stress [19].

In 2002 Li et al. tested cylindrical specimens, 30 cm in diameter and 60 cm in height, fully covered with one layer of CFRP jacket and the design concrete slump was 12 cm [14]. This test program was undertaken using a 4900 kN universal- testing machine, which the load is controlled, at the structural laboratory of the National Taipei University of Technology [14]. The experimental equipment includes load cells, a linear voltage displacement transformer, an analog/digital converter with a signal amplifier, and a personal computer [14]. The strength increase for 16.68 MPa concrete (uniaxial strength), was found to be 35 percent. It's important to represent the type of CFRP modeled in this study to be similar to li et al. laboratory work. With attention to figure (5) and comparison with experimental and analytical results, it indicates that the analytical results are satisfactory, and for assurance a comparison with ISIS code was done. With the aid of relation (2) and using one layer of CFRP on cylindrical specimens (30 cm in diameter), confinement pressure was found to be 3.28 MPa, 39% more than the unconfined specimen's strength.

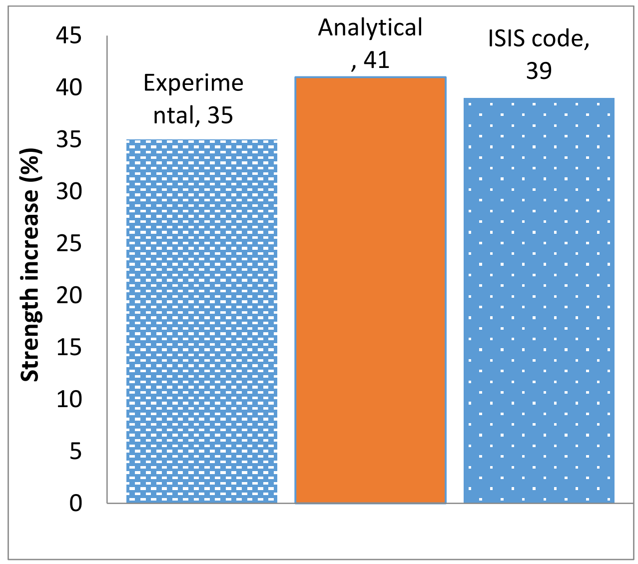

Fig.(5) Experimental, analytical and ISIS results.

Table (4) Specimens' results.

Specimen	Maximum strength (MPa)	Strength increase (%)	Strain	ISIS strength increase (%)
S17-0	16.73	-	0.0017	-
S25-0	23.53	-	0.0021	-
S-45-0	42.59	-	0.0016	-
S17-1W	23.61	41	0.0024	39
S25-1W	30.19	28	0.0027	28
S45-1W	48.74	14	0.003	15
S17-3W	36.14	116	0.004	117
S25-3W	42.2	79	0.0033	84
S45-3W	60.93	43	0.0037	46
S17-6W	45.64	172	0.0053	235
S25-6W	58.68	149	0.0044	167
S45-6W	80.86	90	0.004	93
S17-9W	51.56	208	0.0053	353
S25-9W	69.38	195	0.0049	251
S45-9W	98.35	131	0.0049	139

All specimens' analysis results are tabulated in table (4). Also, percent increases in specimens' strength were compared with the results. Stress-strain diagram, axial and radial strain, for strengthened specimens (17.8 MPa concrete) are shown in Fig.(6). According to the figure, for cylindrical specimen (17.8 MPa concrete) with 3 layers, increase in strength is very good; but for more than 3 layers, with increase in number of layers percent increase in strength is reduced greatly; and in case of 9 layers with confinement pressure of very much greater than the value specified in ISIS code we observed 208 percent increase in strength; this value is much more greater than the code value. This shows a great difference between values from the code, which is the result of high deviation for the relations not in the specified regions. Besides, using more layers and increasing confinement pressure more than the permissible value would cause increase in specimen's strength nonlinearly, and does not obey the linear relations of the code. Figure (9) illustrates this clearly.

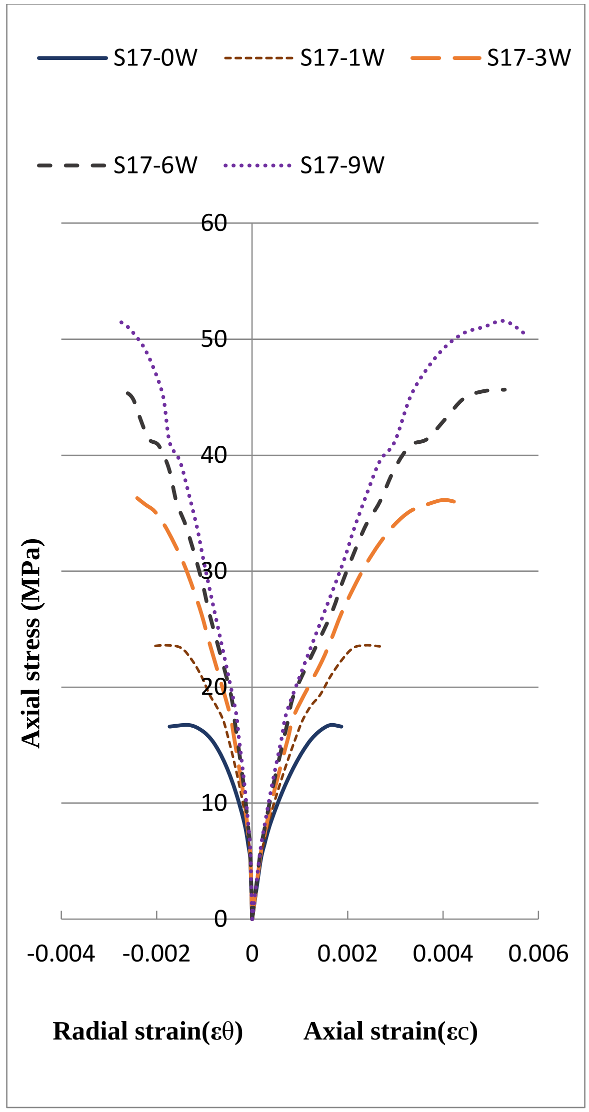

Fig.(6) Stress-strain diagrams for 17.8 MPa concrete.

Analytical results of cylindrical specimens, with 25 MPa concrete strengthened with 3 layers of CFRP, matches very well with results of ISIS code; but with increase in number of layers up to 6 layers the deviation reaches to 18% and for 9 layers this deviation is 56%.

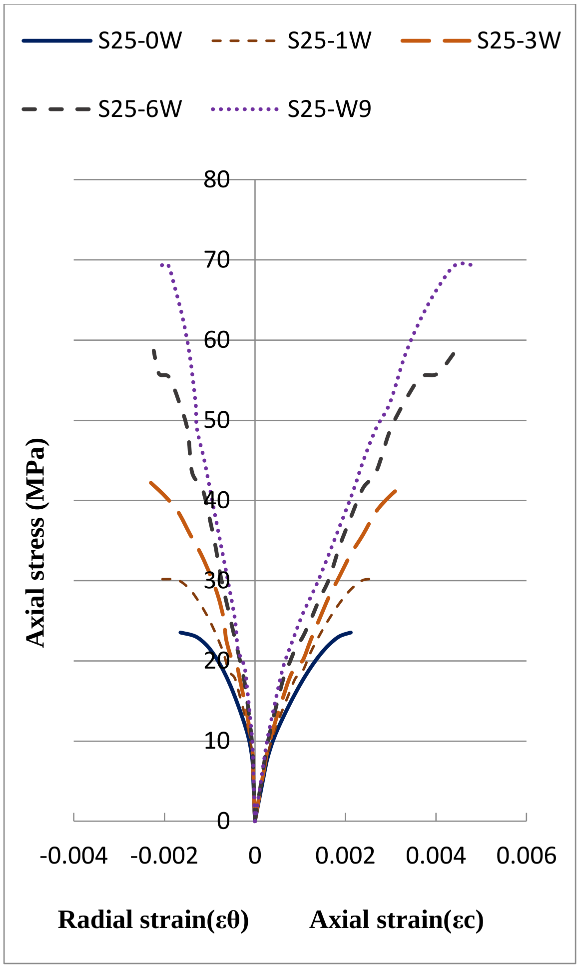

Fig.(7) Stress-strain diagrams for 25 MPa concrete.

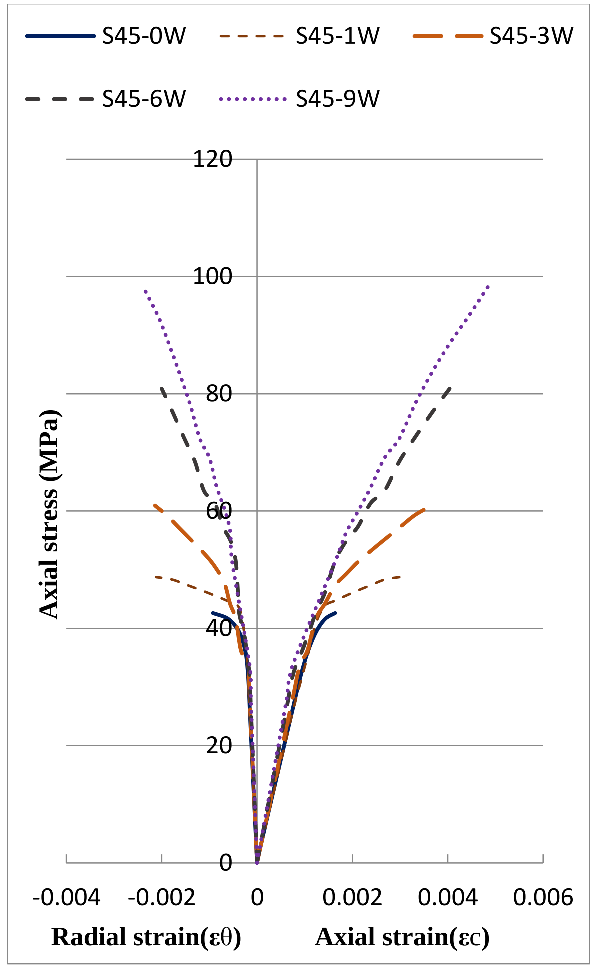

Fig.(8) Stress-strain diagrams for 45 MPa concrete.

Figure (8) shows the stress-strain curves of strengthened specimens of 45 MPa concrete. In all 45 MPa concrete specimens, with increase in number of layers, the results have a little deviation from the ones of the code. Axial strain values of specimens are increased with increase in number of layers; where it reaches its maximum value of 0.0047 for the case of 9 layers of CFRP.

The results tabulated in table (4) are from relations of ISIS code of Canada (without consideration of limits on confinement pressure). Figure (9) is an illustration of comparison between results of ISIS code of Canada and Abaqus results. According to this figure for 17.8 MPa concrete, for high confinement pressure, analytical result is deviated more from ISIS results than 25 MPa concrete. Also the strength reduction for 17.8 MPa is more. However, the deviation for 45 MPa concrete is much less than the other two types of concretes. This indicates we are able to use more layers on high strength concretes. In addition, all three types of concretes, in permissible range of confinement pressure, showed results which are according to ISIS code of Canada; this emphasizes the high accuracy of relations in predicting the ultimate strength of specimen in the permissible range.

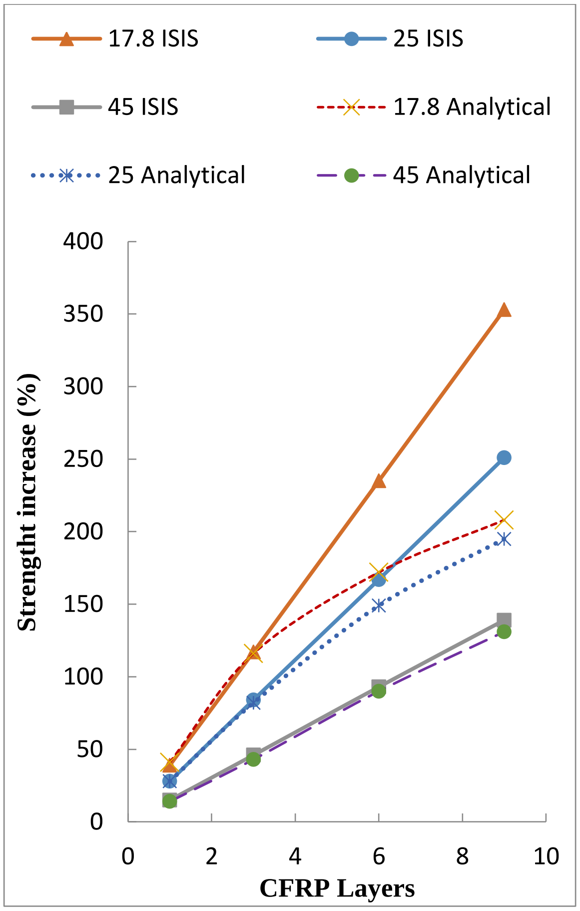

Fig.(9) Comparison of Abaqus results with ISIS code.

5. Conclusions

In this paper behavior of 15 cylindrical specimens, under uniaxial compressive force, were studied. The obtained results' values were compared with actual experimental results. In this study, dimensions of all specimens were constant and equal; and only with various numbers of layers, effect of different confinement pressure, on 3 kinds of concretes, were compared with ISIS code of Canada. The 15 specimens were divided into 5 groups: one group with no wraps, and the other four groups with one, three, six and nine layers were confined; each group consisted of 3 specimens. Comparing the outcome of analysis, following results were observed:

(1) For the permissible confinement pressure, the results from ISIS code of Canada and results of modeling of confined cylindrical specimens in Abaqus software are very close to each other. This indicates high accuracy of the results given in the code, for totally wrapped specimens with CFRP.

(2) For confinement pressures of more than the permissible value, the ISIS code of Canada calculates the percent increase in specimen's strength (with high strength concrete) with little error (deviation); but for lower strength concretes the deviation is much higher.

(3) A fully covered cylindrical specimen with CFRP causes considerable strength and increase in ductility. With increase in number of layers confinement pressure is increased greatly. It is noted that the strength increase, with layer increase, is not linear.

(4) ISIS code of Canada considers the maximum strength increase as twice the cylindrical specimens' primary strength, but this strength increase could be up to three times the concrete primary strength.

(5) Our model in finite element software, using relations in EN 1992-1-1, correctly predicts the behavior of cylindrical specimen.

(6) Lower strength concretes with respect to higher strength concretes, in higher confinement pressures, have more deviations.

(7) The permissible confinement pressure given in ISIS code of Canada is very conservative.

6. Refrences

[1] Kwan, AKH., Chau, SL., Au, FTK. (2006). "Improving flexural ductility of high-strength concrete beams". Proc ICE – Struct. Build, 159(6), pp. 339–347.

[2] Paultre, P., Legeron, F., Mongeau, D. (2001). "Influence of concrete strength and transverse reinforcement yield strength on behavior of high-strength concrete columns". ACI Struct. J., 98(4): pp. 490–501.

[3] Cusson, D., Paultre, P. (1994). "High-strength concrete columns confined by rectangular ties". J StructEng,120(3): pp. 783–804.

[4] Xiao, Y. (2004). "Applications of FRP composites in concrete columns". Adv. Struct. Eng., Vol.7(4): pp. 335–343.

[5] Xiao, Y., Ma, R. (1997). "Seismic retrofit of RC circular columns using prefabricated composite jacketing". J Struct. Eng., 123(10): pp. 1357–1364.

[6] Ilki, A., Peker, O., Karamuk, E., Demir, C., Kumbasar, N. (2008). "FRP retrofit of low and medium strength circular and rectangular reinforced concrete columns". J Mater Civ. Eng., 20(2): pp. 169–88.

[7] Ozbakkaloglu, T. (2013). "Compressive behavior of concrete-filled FRP tube columns: assessment of critical column parameters". Eng. Struct., 51: pp. 188–199.

[8] Xiao, Y., Wu, H. (2003). "Compressive behavior of concrete confined by various types of FRP composite jackets". J Reinf Plast Compos, 22(13): pp. 1187–1201.

[9] Rousakis, TC., Karabinis, AI., Kiousis, PD. (2007). "FRP-confined concrete members: axial compression experiments and plasticity modelling". Eng. Struct., 29(7): pp. 1343–1353.

[10] Ozbakkaloglu, T., Lim, JC., Vicent, T. (2013). "FRP-confined concrete in circular sections: review and assessment of stress–strain models". Eng. Struct., 49: pp. 1068–1088.

[11] Idris, Y., Ozbakkaloglu, T. (2013). "Seismic behavior of high-strength concrete-filled FRP tube columns". J. Compos. Constr., Vol. 17 (6) pp. 1943.

[12] Ozbakkaloglu, T. (2013). "Compressive behavior of concrete-filled FRP tube columns: assessment of critical column parameters". Eng. Struct., Vol. 51 pp. 188–199.

[13] Li, Y., Fang, T., Chern, C. (2003). "A Constitutive Model for Concrete Cylinder Confined by Steel Reinforcement and Carbon Fiber Sheet". pacific conference on earthquake engineering,.

[14] Li, Y., Lin, C., Sung, Y. (2003). "A constitutive model for concrete confined with carbon fiber reinforced plastics". Mechanics of Materials, Vol. 35, pp 603–619.

[15] ISIS educational module 4. (2004). "An introduction to FRP strengthening of concrete structures". prepared by ISIS Canada, February 2004.

[16] Majewski, S. (2003). "The mechanics of structural concrete in terms of elasto-plasticity". Silesian Polytechnic Publishing House, Gliwice,.

[17] EN 1992-1-1. (2004). " Eurocode 2 Design of concrete structures - Part 1-1: General rules and rules for buildings".

[18] Wang, T., Hsu, T.T.C. (2001). "Nonlinear finite element analysis of concrete structures using new constitutive models". Computers and Structures, Vol. 79, Iss. 32, , pp. 2781–2791.

[19] Kmiecik, P., Kaminski, M. (2011). "Modelling of reinforced concrete structures and composite structures with concrete strength degradation taken into consideration". Archives of civil and mechanical engineering, No. 3.

[20] Abaqus theory manual and users' manual, version 6.10. (2010).

[21] Bouchelaghem, H., Bezazi, A., Scarpa, F. (2011). "Compressive behavior of concrete cylindrical FRP-confined columns subjected to a new sequential loading technique". Composites: Part B, Vol. 42, pp 1987–1993.

[22] Uya, B., Taoa, Z., Hanc, L. (2011). "Behaviour of short and slender concrete-filled stainless steel tubular columns". Journal of Constructional Steel Research, Vol. 67, pp 360–378.