Experimental Study of the Internal and External (FRP) Confinement Effect on Performance of Compressive Concrete Members

Alireza Khaloo[1] and Yousef Javid[2] and Mostafa Tazarv[3]

[1]*Professor, CE Dept., Center of Excellence in Structures and E/Q Eng., Sharif University of Technology, Tehran*

[2,3] *Graduate Student, CE Dept., Sharif University of Technology, Tehran*

Abstract

In this study, using an experimental study, it is desired to investigate the direct effect of external confinement (FRP) in presence of internal confinement and to determine some criteria in retrofitting and seismic strengthening design of existing structures and new constructions. Limited related report is presented in the literature so far. In this research, 12×40 cm cylindrical concrete specimens are tested under compression by universal testing machine with capability of strain controlled loading. Test Variables include compressive strength of concrete (30 & 50 MPa), type of FRP (CFRP & GFRP) and number of FRP layers (1 and 2), and spiral bar spacing in internal confinement (3 and 5 cm). Some specimens are used as control with no FRP jacketing and spiral confinement, some are strengthened with CFRP or GFRP, some have just spiral confinement, and finally some have both FRP strengthening and spiral confinements. Complete σ-ε curves are obtained from extensive test parameters indicate an increase in the strength and ductility in the confined case with either internal or external confinement. For high level of external confinement, the level of internal confinement has limited influence. Finally based on experimental data a new model is proposed to predict the performance of confined concrete.

Keywords: Strengthening, FRP, Spiral bars, Confined concrete, Model

Introduction

Many countries around the world, have tremendous need to repair and strengthen their existing infrastructure. Large numbers of existing structures, such as bridges, are deteriorating due to various problems related to marine environment, extensive use of deicing salts, increase in the number and the allowable weight of load-bearing trucks, and the design of old structures.

In recent decade, considerable attention has been focused on the use of fiber-reinforced polymer (FRP) composite materials for structural rehabilitation and strengthening. As a result, numerous papers on various aspects related to the subject have been published recently. If correctly applied, the use of FRP composites for strengthening reinforced concrete (RC) structures can result significant enhancements improved serviceability, ultimate strength, and ductility. Moreover, the FRP composites can generally be applied while the structure is in use, with negligible changes in the member dimensions. Other advantages include high strength and stiffness-weight ratios, a high degree of chemical inertness, controllable thermal expansion, damping characteristics, and electromagnetic neutrality.

Many experimental and analytical investigations have been conducted in recent years to evaluate the axial load capacity and stress-strain response of concrete confined with fiber-reinforced polymer (FRP) laminates (ACI Committee 440 2002). These investigations have clearly demonstrated that confining concrete with FRP jackets leads to substantial improvement of the axial strength and energy absorption capacity of concrete columns under both static and cyclic loading.(1-6)

Several confinement models were proposed in the literature to evaluate the axial strength and to describe the stress-strain response of FRP jacketed columns. A comprehensive review and assessment of existing models have been recently presented by Teng and Lam (2004). Most of the proposed stress-strain relationships are based on the following confinement model proposed by Richart et al. (1928, 1929) from tests conducted on concrete specimens confined with hydrostatic pressure

$$f'_{cc} = f'_c(1 + k_1 \frac{f'_l}{f'_c}) \quad (1) \qquad \varepsilon_{cc} = \varepsilon_{co}(1 + k_2(\frac{f'_{cc}}{f'_{co}} - 1)) \quad (2)$$

where f'_{cc} and ε_{cc} are the confined concrete compressive strength and corresponding strain, respectively; f'_c and ε_o are the compressive strength and corresponding strain for unconfined concrete; k_1 is the confinement effectiveness coefficient and f'_l is the lateral hydrostatic pressure. Based on their test results, Richart et al. (1928, 1929) found values for $k_1 = 4.1$ and $k_2 = 5$.

Spiral reinforcement in concrete columns was originally introduced by considere. Based on the result of an extensive experimental program, Richart , Brandtzaeg and Brown and Richart and Brown Proposed the Eq (1) for strength applied to both spirally reinforced and hydraulically confined columns.

Among the well-known expressions for evaluating the effect of confinement on the axial strength of concrete column is the one proposed by mander et al. (1988) for steel confined concrete. In this expression, the confined concrete compressive strength f'_{cc} and corresponding strain ε_{cc} calculated at the onset of yielding of the transverse steel, are expressed as a function of the effective constant lateral confining pressure f_l as follows

$$f'_{cc} = f'_c(-1.254 + 2.254\sqrt{1 + \frac{7.94 f_l}{f'_c}} - 2\frac{f_l}{f'_c}) \quad (3) \qquad \varepsilon_{cc} = \varepsilon_o[1 + 5(\frac{f'_{cc}}{f'_c} - 1)] \quad (4)$$

Different expressions were generated by Mander et al. (1998) for calculating f_l depending on the shape of the column section and configuration of longitudinal and lateral steel.[6-8]

Unlike confinement by steel hoops where the confinement pressure becomes theoretically constant beyond yielding of the hoops, the linear stress strain behavior of the FRP causes the confining pressure in FRP-confined concrete, associated with concrete dilation, to increase continuously with increasing lateral or axial strain. Provided there is a good bond between the concrete surface and FRP, the lateral strain in the FRP is often assumed to be equal to the lateral strain in concrete. Consequently, for FRP-confined circular column sections, the lateral confinement pressure f_l is calculated as a function of the volumetric ratio ρ_f and lateral strain ε_l of the FRP using the requirements of lateral strain compatibility and force equilibrium between the concrete and confining FRP jacket as follows

$$f_l = \left(\frac{\rho_f E_f}{2}\right)\varepsilon_l \quad (5) \qquad \text{Where} \quad \rho_f = \frac{4 n_f t_f}{D} \quad (6)$$

in which n_f is the number of applications (layers); t_f is the design thickness of the FRP fabric; and D is the column diameter.

Numerous analytical and experimentally based confinement models were proposed to calculate the confinement effectiveness coefficient k_1 (refer to Eq.(1)) for FRP confined concrete. A summary of some of the proposed expressions, including the k_1 equivalence of Eq.(3), is given in table 1.(8-12)

Table1- different models for confined concrete with FRP

Source	Karbhari And Gao (1997)	Samaan et al. (1998)	Miyauchi et al. (1999)	Saafi Et al. (1999)	Toutanji (1999)
Equation	$\frac{f'_{cc}}{f'_c} = 1 + k_1 \frac{f'_l}{f'_c}$				
K_1	$2.1(\frac{f_l}{f'_{co}})^{-0.13}$	$6.0 f_l^{-0.3}$	2.98	$2.2(\frac{f_l}{f'_{co}})^{-0.16}$	$3.5(\frac{f_l}{f'_{co}})^{-0.15}$

Research significance

Until now, all researches and experiments for evaluating the effect of confining with FRP, ignore the effect of the spiral bars. In other words, the concrete specimens which are strengthen with FRP, are tested without considering the effect of confinement with spiral bars in columns.

In this research the confinement that produced by FRP and also the confinement by means of spiral bars will be checked, not only separately but also in combination to each other, in order to achieve the proportion of each factor in confining the specimens.

Experimental program

Test parameters and test specimens

Thirty small-scale column specimens of 400 mm height and 120 mm diameter were tested. Specimens properties and details are provided in table 2.

Table 2- Summary of test parameters

No.	Specimen	f'_c MPa	Ttransverse Reinforcement	$\rho_{\min} = 0.12 \frac{f'_c}{f_y}$	ρ	FRP Reinforcement
1	30–P(A)	30	–	–	–	–
2	30–P(B)	30	–	–	–	–
3	30–P–1C	30	–	–	–	One Layer of CFRP
4	30–P–2C	30	–	–	–	Two Layers of CFRP
5	30–P–2G	30	–	–	–	Two Layers of GFRP
6	30–S5(A)	30	Φ6@ 50mm	0.0066	0.0188	–
7	30–S5(B)	30	Φ6@ 50mm	0.0066	0.0188	–
8	30–S5–1C	30	Φ6@ 50mm	0.0066	0.0188	One Layer of CFRP
9	30–S5–2C	30	Φ6@ 50mm	0.0066	0.0188	Two Layers of CFRP
10	30–S5–2G	30	Φ6@ 50mm	0.0066	0.0188	Two Layers of GFRP
11	30–S3(A)	30	Φ6@ 30mm	0.0066	0.0315	–
12	30–S3(B)	30	Φ6@ 30mm	0.0066	0.0315	–
13	30–S3–1C	30	Φ6@ 30mm	0.0066	0.0315	One Layer of CFRP
14	30–S3–2C	30	Φ6@ 30mm	0.0066	0.0315	Two Layers of CFRP
15	30–S3–2G	30	Φ6@ 30mm	0.0066	0.0315	Two Layers of GFRP
16	50–P(A)	50	–	–	–	–
17	50–P(B)	50	–	–	–	–
18	50–P–1C	50	–	–	–	One Layer of CFRP
19	50–P–2C	50	–	–	–	Two Layers of CFRP
20	50–P–2G	50	–	–	–	Two Layers of GFRP
21	50–S5(A)	50	Φ6@ 50mm	0.0111	0.0188	–
22	50–S5(B)	50	Φ6@ 50mm	0.0111	0.0188	–
23	50–S5–1C	50	Φ6@ 50mm	0.0111	0.0188	One Layer of CFRP
24	50–S5–2C	50	Φ6@ 50mm	0.0111	0.0188	Two Layers of CFRP

25	50-S5-2G	50	Φ6@ 50mm	0.0111	0.0188	Two Layers of GFRP
26	50-S3(A)	50	Φ6@ 30mm	0.0111	0.0315	-
27	50-S3(B)	50	Φ6@ 30mm	0.0111	0.0315	-
28	50-S3-1C	50	Φ6@ 30mm	0.0111	0.0315	One Layer of CFRP
29	50-S3-2C	50	Φ6@ 30mm	0.0111	0.0315	Two Layers of CFRP
30	50-S3-2G	50	Φ6@ 30mm	0.0111	0.0315	Two Layers of GFRP

Test set-up

Specimens were tested under strain-controlled condition. To gain complete stress-strain curves, the rate of imposed deformation was 0.05 mm/s. For each variable parameter, the stress-strain curves were plotted and results of the comparisons of the curves will be illustrated in next section. For convenience, special titles will be used for specimens that first term denotes the compressive strength of concrete, second term denotes the internal confinements where, for example S3 means internal confinement is spiral with 3cm pitches and P means there is no internal confinement. Last term shows external confinement where G is instead of GFRP and C is abbreviation of CFRP. For instance, phrase 300-S5-2G means a specimen with compressive strength of 300 kg/cm2, spiral with 5 centimeter pitches and 2 layers of GFRP.

Specimen's materials

According to ASTM C33, sands and gravels were gradated. Used cement was type 1-425 and Super plasticizer NSF was applied to reach to high strength concrete that was poured into mixture form 0.8 to 3 percent of weight of used cement. 30 concrete specimens were cylindrical with 12 cm diameter and 40 cm in height. Medium-high strength rebars (6mm diameter) were used as spiral with two different pitches, 3 and 5 centimeters, and external diameter of 11.6 cm. Table 3 shows properties of two different kinds of FRP.

Table 3- FRP properties

Fiber	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

Epoxy resin ML-506 and epoxy harder HA-11 that were blended in proportion of 100 to 15 were used as adhesive materials.

Stress-Strain curves

Figure 1 shows a variation of measured concrete strain with axial stress.

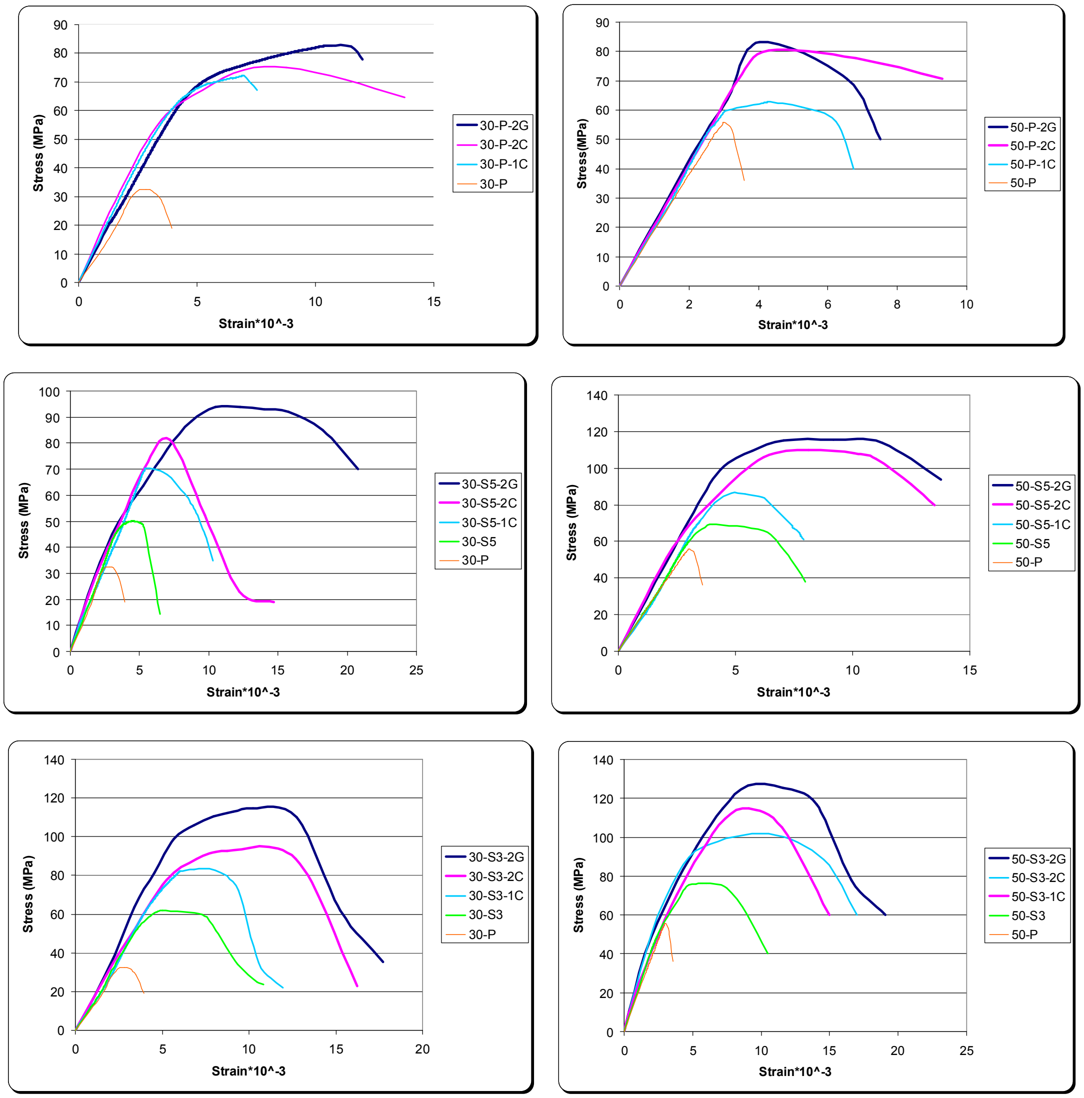

Fig 1- Axial stress - axial strain curves of various confinement system

Modified model for predicting maximum stress and proportioned strain:

External Confinement with FRP:

Based on the experimental studies, the equation 1 will be modifies with variable k_1 to predict the behavior of externally confined concrete with FRP. According to the Table 2, lateral confining pressure is computational as below:

$$f_l = \frac{2 f_{frp} . t_{frp}}{d} = \frac{2 \times 3840 \times 0.015}{12} = 9.6 \ MPa \qquad \text{one layer of CFRP} \qquad \textbf{(7)}$$

For two layers of CFRP and two layers of GFRP f_l will be 19.2 and 36.19 MPa respectively. By the use of statistical calculations, modified model for predicting the ultimate strength of externally confined concrete with FRP is proposed in Eq. 4.

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 \frac{f_l}{f'_{co}} \qquad \text{where} \qquad k_1 = 1.58\left(\frac{f_l}{f'_{co}}\right)^{-0.14} \qquad \textbf{(8)}$$

Strain at maximum stress would be derived by modified Richart equation that is as below

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 2.26\left(\frac{f'_{cc}}{f'_{co}} - 1\right) \qquad \textbf{(9)}$$

Internal Confinement with Spirals

Because of close pitches, confining pressure can be calculated by tensile force in the transverse reinforcements:

$$f_l = \frac{2F_y . A_{sp}}{d . s} \qquad \textbf{(10)}$$

Where d is diameter of spiral, Asp is cross section area of spiral, s is pitch and f_y is yielding stress of bar. So, f_l for confined concrete is 8.523 and 5.12 MPa for 3 and 5 cm pitches respectively. Equations 7 and 8 propose a modified model for predicting the ultimate strength and strain at the ultimate strength of internally confined concrete by spirals respectively.

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_2 \frac{f_l}{f'_{co}} \qquad \text{where} \qquad k_2 = 5.54\left(\frac{f_l}{f'_{co}}\right)^{0.3415} \qquad \textbf{(11)}$$

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 2\left(\frac{f'_{cc}}{f'_{co}} - 1\right) \qquad \textbf{(12)}$$

Combined Confinements

As mentioned before, there are some models to predict the behavior of externally and internally confined concrete separately, however there is no report for combined confinements. The lateral confining pressure assumed that is sum of two above-mentioned pressures.

Finally, by regression the available test data, modified model for predicting the ultimate strength and strain at the ultimate strength of combined confined concrete is represented in Eq. 10 and 11 respectively.

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_3 \frac{f_l}{f'_{co}} \qquad \text{where} \qquad k_3 = 1.94\left(\frac{f_l}{f'_{co}}\right)^{-0.28} \qquad \textbf{(13)}$$

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + 2.23\left(\frac{f'_{cc}}{f'_{co}} - 1\right) \qquad \textbf{(14)}$$

Conclusions

Based on the result of an extensive experimental study presented herein, it is concluded that at low level of internal confinement, strength and ductility enhancements due to FRP confinement are considerable. However, in case of relatively high level of internal confinement, External FRP strengthening has limited influence on strength and ductility increase. Also, with increase in concrete compressive strength, the effect of external confinement in presence of internal confinement is lower than lower strength concrete.

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