DUAL CONFINEMENT OF CIRCULAR CONCRETE COLUMNS CONSISTING OF CFRP SHEETS AND STEEL TIES OR SPIRALS

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ABSTRACT

It is well known, that confinement introduced by CFRP (Carbon Fiber Reinforced Polymer) sheets highly increases the ultimate compressive strength and ductility of concrete. The principal advantages of this technique are the high strength-to-weight ratio, good fatigue properties as well as noncorroding characteristics of the CFRP. On the other hand, the CFRP Material is very brittle and expensive. A high degree of safety is necessary. Various experimental research programs have been proposed to express the increase in strength and strain by the use of CFRP jackets, but, in the majority of cases, the additional effects of reinforcing elements, like stirrups or spirals, are not analyzed very well. This paper provides the investigations on wrapped, short concrete columns with and without stirrups and spirals. In an extensive research program the volumetric ratio of the CFRP jacket as well as the ratio of transverse reinforcement were varied. Thereby, columns with different geometrical shape, different CFRP thickness, and with different transverse reinforcement elements (stirrups and spirals) were produced and were tested in deflection controlled compression tests. The main results of these tests will be explained. Additionally, a comparison of the results with test series found in literature is given. Finally, new ways and possibilities for the design and use of CFRP confinements are shown.

Keywords: Confinement, Fiber Reinforced Polymer, Concrete Columns, Spiral, Strengthening.

1. INTRODUCTION

1.1. Strengthening of members subjected to axial force

Confinement is generally applied to members in compression with the goal to increase their strength and ductility. Besides conventional transverse tie reinforcing steel also advanced FRP (Fiber Reinforced Polymers) materials have recently recognized as favorable confinement devices. FRP consists of strengthening fibers (for example carbon fibers) in a resin system. The FRP or CFRP confinement appears by orienting the fibers transverse to the longitudinal axis of the concrete member. Through FRP strengthening by confinement, concrete's lateral expansion is efficiently restricted in cases of imposed axial compressive deformation; therefore, the elastic FRP resisting

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response generates an ever increasing lateral compressive stress state on concrete, leading to structural upgrade of the member core to provide sufficient deformability. If concrete cylinders are of interest, the confining pressure σ_l (also denoted as f_l) can be found from Eq. (1) (fib 2001).

$$\sigma_l = \frac{1}{2}\rho_j \cdot \sigma_j = \frac{1}{2}\rho_j \cdot E_j \cdot \varepsilon_j \quad \text{with} \quad \rho_j = \frac{4 \cdot t_j}{D} \tag{1}$$

where ρ_j = volumetric ratio of FRP jacket, $\sigma_j = f_l$ = stress in FRP jacket, E_j = modulus of composite material, ε_j = circumferential strain in FRP jacket (max $f_l \rightarrow \varepsilon_j = \varepsilon_{ju}$ = ultimate strain of FRP jacket), t_j = FRP thickness, and D = diameter concrete cylinder.

1.2. Stress-strain models of FRP-confined concrete

In the past, various experimental research programs had been carried out by other researchers to express the increase in strength and strain by the use of FRP or CFRP jackets.

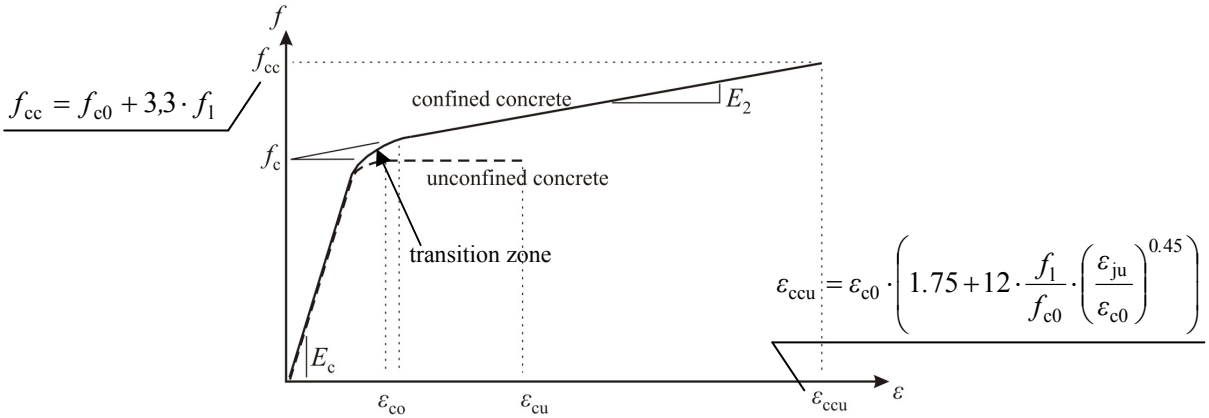

Figure 1: Stress-strain model for FRP confined concrete by Lam and Teng.

Some of them were adopted by design recommendations. Examples are the stress-strain model by (Lam and Teng 2003) in ACI 440.2R-08 (ACI 2008) or the model by (Spoelstra and Monti 1999) in technical report by the fib (fib 2001). The stress-strain model by Lam and Teng is illustrated in Figure 1.

2. EXPERIMENTAL STUDY

2.1. Emphases of research

In the majority of cases, the additional effects of reinforcing elements, like ties or spirals, are not analyzed very well. It results of the limited experimental evidence on the area of FRP confinement of real-size RC columns. Additionally, these limits have not allowed the appropriate implementation of key effects in the current models. Hence, the goals of the research work presented in this paper are:

• production and test of circular columns with different cross sections (from 15 up to 30 cm),
• thereby, production of RC elements with different steel ties and steel spirals,

• wrap with CFRP sheets of different thickness and of different manufactors,
• mainly increase the knowledge about dual confinement in RC columns.

2.2. Experimental program

In an extensive research program the volumetric ratio of the CFRP jacket ρ_j as well as the ratio of transverse reinforcement ρ_{st}, which are mainly accountable for effective confining pressure, were varied. Columns with different geometrical shape, different strength, different CFRP thickness, and with different transverse reinforcement elements (steel ties and spirals) were produced and tested.

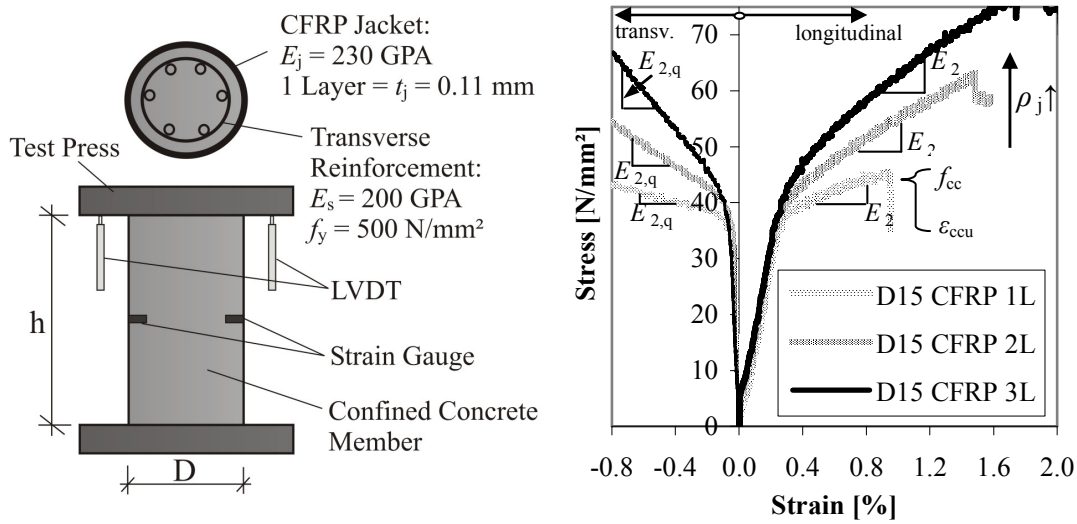

Figure 2: Experimental setup and derived stress-strain curves of confined concrete.

The whole research study is shown in Table I. During the tests two different measurement systems were used. In all the specimens, beside the strain gauges on the FRP jacket (at midheight), two LVDT's were fixed to two opposite sides of each specimen in order to measure the axial shortening. Figure 2 presents the experimental setup and the stress-strain curves in longitudinal and transverse direction derived from the compression tests. Thereby, the stress-strain curves of series D15 are illustrated. The stress-strain behavior (longitudinal and transverse) of the CFRP confined specimens was bilinear in general, and it was consisting of the three phase behavior reported in Figure 1. The second modulus E_2 could be observed in longitudinal (E_2) as well as in transverse ($E_{2,q}$) direction (cf. Figure 2). The failure of CFRP confined plain or steel reinforced specimens was 'explosive' due to the sudden and noisy fracture of CFRP sheets at ultimate strength f_{cc} and strain ε_{ccu}. Furthermore, Figure 2 also explains the interrelationship between the second modulus and the volumetric ratio of the CFRP jacket. More layers of CFRP produce higher volumetric ratios, and this circumstance results in higher second modulus and in higher ultimate states of strength and strain. These connections were used for the discussion of the compression tests in the next chapters.

Table 1: Tests on confinement with CFRP wrap and transverse steel reinforcement.

1 Series = 3 Specimens	Concrete	D	h	CFRP Wrap		Transverse Steel Reinf.		
		[mm]	[mm]	Layer	ρ_j [%]	Ø/s [mm]	ρ_{st} [%]	Type
D15 CFRP 1L	C30/37	150	300	1	0.29	-	-	-
D15 CFRP 2L	C30/37	150	300	2	0.59	-	-	-
D15 CFRP 2L C strength	C12/15	150	300	2	0.59	-	-	-
D15 CFRP 2L C strength	C35/45	150	300	2	0.59	-	-	-
D15 CFRP 2L C strength	C45/50	150	300	2	0.59	-	-	-
D15 CFRP 3L	C30/37	150	300	3	0.88	-	-	-
D15 6/10 CFRP 2L	C35/45	150	300	2	0.59	6 / 100	0.93	tie
D15 6/5 CFRP 2L	C35/45	150	300	2	0.59	6 / 50	1.87	tie
D20 CFRP 1L	C20/25	200	400	1	0.22	-	-	-
D20 CFRP 2L	C20/25	200	400	2	0.44	-	-	-
D20 CFRP 3L	C20/25	200	400	3	0.73	-	-	-
D20 CFRP 1L (240 GPA)	C20/25	200	400	1	0.22	-	-	-
D20 CFRP 2L (240 GPA)	C20/25	200	400	2	0.45	-	-	-
D20 CFRP 3L (240 GPA)	C20/25	200	400	3	0.67	-	-	-
D20 4/17,5 CFRP 2L	C20/25	200	400	2	0.44	4 / 175	0.17	tie
D20 6/17,5 CFRP 2L	C20/25	200	400	2	0.44	6 / 175	0.38	tie
D20 6/10 CFRP 2L	C20/25	200	400	2	0.44	6 / 100	0.66	tie
D20 6/5 CFRP 2L	C20/25	200	400	2	0.44	6 / 50	1.32	tie
D25 CFRP 1L	C20/25	250	500	1	0.18	-	-	-
D25 CFRP 2L	C30/37	250	500	2	0.35	-	-	-
D25 CFRP 3L	C30/37	250	500	3	0.53	-	-	-
D25 CFRP 4L	C25/30	250	500	4	0.70	-	-	-
D25 8/4 CFRP 1L	C25/30	250	500	1	0.18	8 / 40	2.27	spiral
D25 8/4 CFRP 2L	C30/37	250	500	2	0.35	8 / 40	2.27	spiral
D25 8/4 CFRP 3L	C30/37	250	500	3	0.53	8 / 40	2.27	spiral
D25 10/4 CFRP 2L	C25/30	250	500	2	0.35	10 / 40	3.60	spiral
D25 6/10 CFRP 2L	C25/30	250	500	2	0.35	6 / 100	0.53	tie
D25 6/10 CFRP 2L 1m	C25/30	250	1000	2	0.35	6 / 100	0.53	tie
D25 8/4 CFRP 2L 1m	C25/30	250	1000	2	0.35	8 / 40	2.27	spiral
D30 CFRP 2L	C25/30	300	600	2	0.29	-	-	-
D30 CFRP 3L	C25/30	300	600	3	0.44	-	-	-
D30 10/4 CFRP 2L	C25/30	300	600	2	0.29	10 / 40	2.93	spiral
D30 10/5.5 CFRP 2L	C25/30	300	600	2	0.29	10 / 55	2.13	spiral

3. RESULTS AND DISCUSSION

3.1. CFRP confined plain concrete

This chapter explains the results on confined plain concrete. Columns with different geometrical shape and different CFRP thickness were produced to vary the CFRP thickness t_j and the diameter of the column D. Both are responsible for the volumetric ratio of the CFRP jacket. The left diagram of Figure 3 describes the second modulus $E_{2,q}$ (transverse) as a function of the volumetric ratio of the CFRP jacket. It clearly can be seen, that there is a big influence of the volumetric ratio on the

second modulus. It is possible to find a regression curve for mathematical interpretation. Thereby, the volumetric ratio is able to take account of potential size effects. The regression curves of small (D15) and medium specimens (D20 and D25), and big specimens (D30) are almost the same. These results permit to conclude that there is no size effect on material behavior of confined specimens.

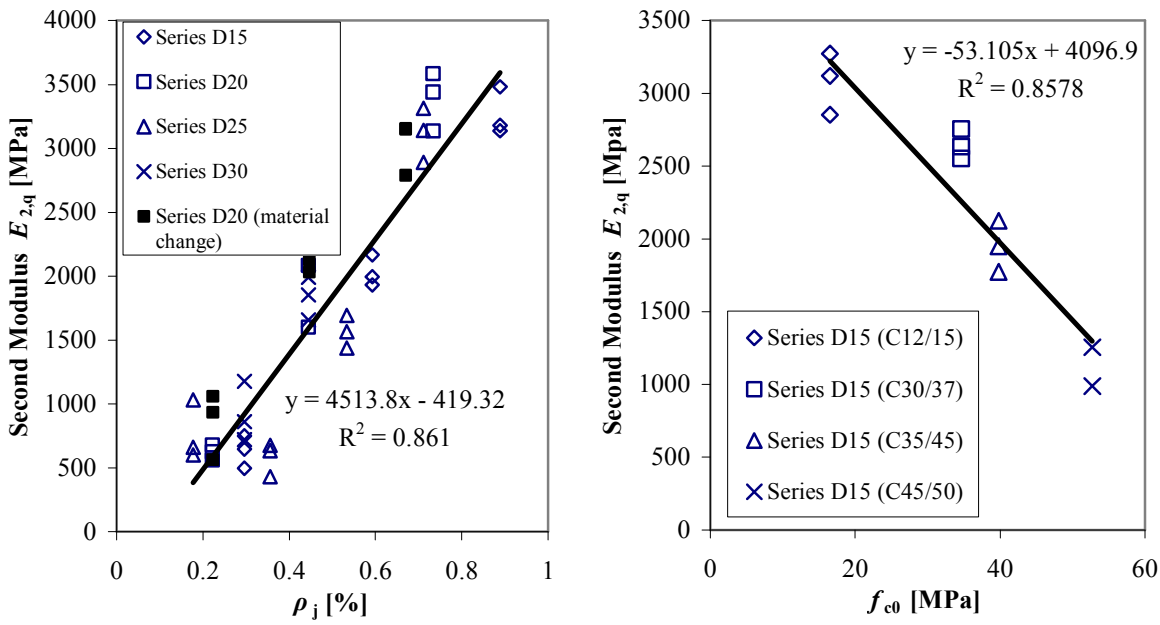

Figure 3: Second modulus $E_{2,q}$ as a function of ρ_j and as a function of unconfined concrete strength f_{c0}.

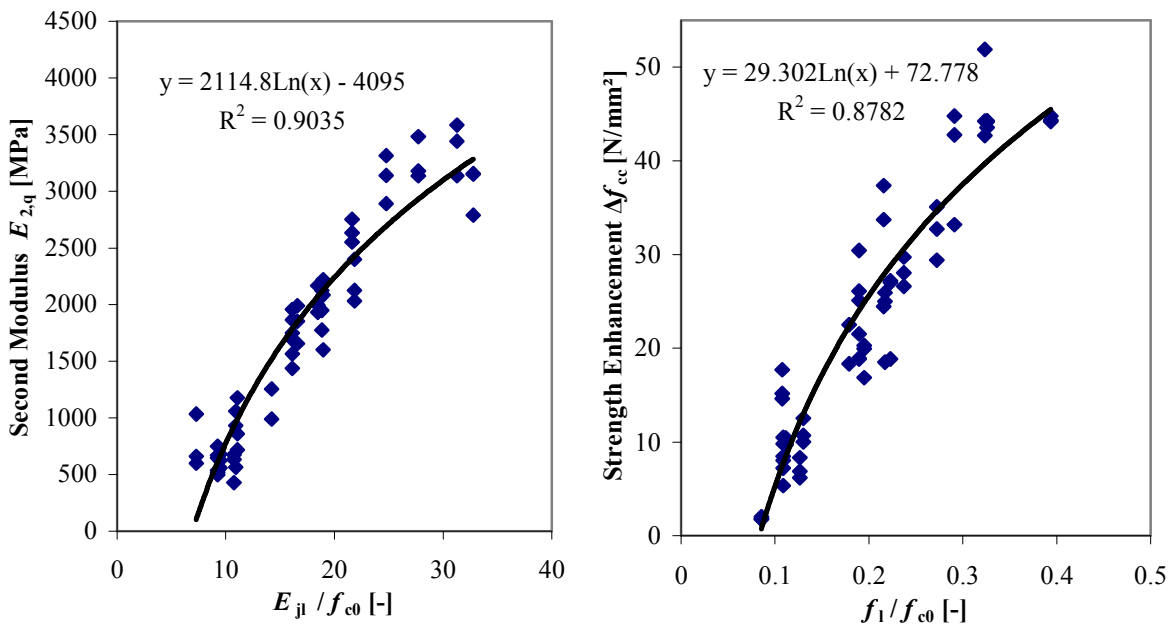

Figure 4: Second modulus $E_{2,q}$ as function of E_{jl}/f_{c0} and strength enhancement Δf_{cc} as function of the ratio between f_l and f_{c0}.

Figure 3 also explains the big dependency of $E_{2,q}$ on the unconfined concrete strength f_{c0}. Due to this fact, the proposal of (Xiao and Wu 2003) was used to involve the unconfined strength into analysis. If the confined modulus E_{jl} (cf. Eq. (2)) is deployed in relation to f_{c0}, very good regressions can be found to explain E_2 and $E_{2,q}$.

$$E_{jl} = \frac{1}{2}\rho_j \cdot E_j \tag{2}$$

An example is shown in the left diagram of Figure 4. In this sample, $E_{2,q}$ is described as a function of the ratio between E_{jl} and f_{c0}. The very high coefficient of determination clearly confirms the proposal of Xiao and Wu. Furthermore, by adding the ultimate strain ε_{ju} of the CFRP material it is possible to find proper regressions to calculate the ultimate stress f_{cc} and the ultimate strain ε_{ccu} of a confined concrete column (cf. Eq. (3)).

$$f_l = E_{jl} \cdot \varepsilon_{ju} \tag{3}$$

Figure 4 (right diagram) provides an example. Herein, the strength enhancement Δf_{cc} is now described as a function of the ratio between f_l and f_{c0}.

3.2. CFRP confined reinforced concrete

This chapter describes the results on confined reinforced concrete. Thereby, the effect of a dual confinement (consisting of transverse steel reinforcement and CFRP confinement) was the point of interest.

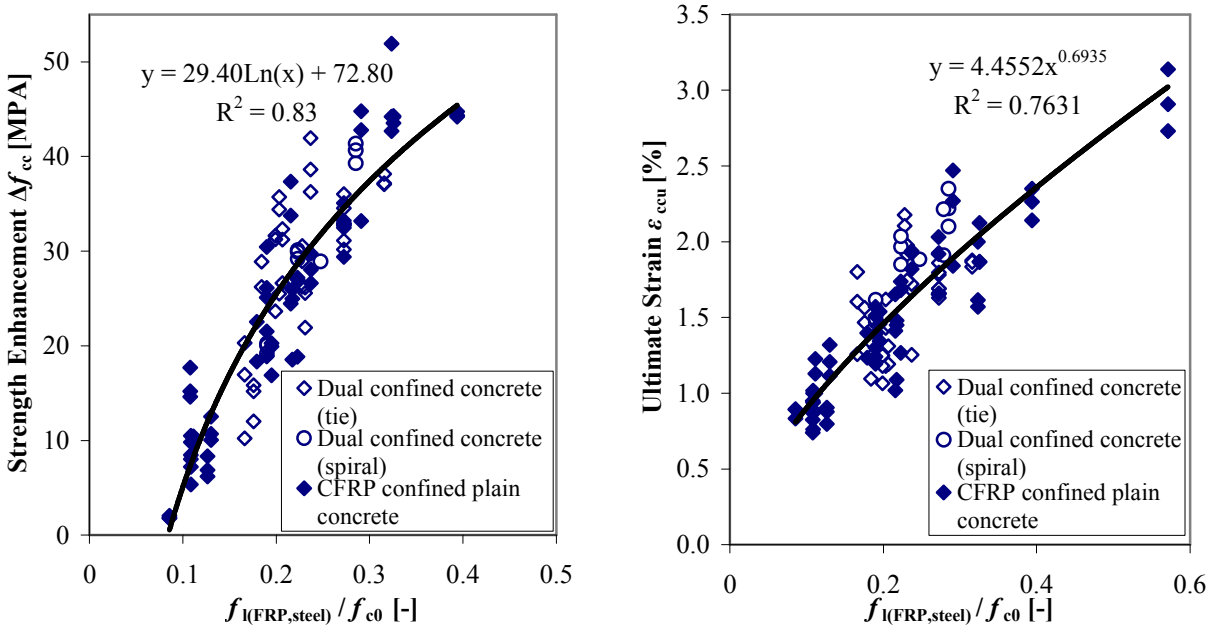

Figure 5: Strength enhancement Δf_{cc} and ultimate strain ε_{ccu} as functions of $f_{l(FRP,steel)}/f_{c0}$.

Dual confinement strongly increases the load bearing capacity in general. In doing so, it is possible to summarize the shares of the confinement pressures of CFRP and steel confinement.

$$f_{l(\mathrm{FRP,steel})} = \frac{1}{2}\rho_{\mathrm{j}} \cdot E_{\mathrm{j}} \cdot \varepsilon_{\mathrm{ju}} + \frac{1}{2}\rho_{\mathrm{st}} \cdot f_y \cdot k_{\mathrm{e}} \tag{4}$$

where ρ_{st} = transverse steel volumetric ratio, f_y = yield stress, and k_e= coefficient of lateral and vertical efficiency of transverse steel reinforcement.

In the diagrams of Figure 5, the strength enhancement as well as the reached ultimate strain of the confined plain concrete columns and of the reinforced ones are shown as functions of the ratio between $f_{l(FRP,steel)}$ and f_{c0}. Again, it is possible to find common regression curves for mathematical interpretation. Concerning the material behavior of reinforced specimens in axial direction, an analogous is obvious, where continuous decrease of specimens' axial rigidity occurs. However, this transition zone is more prolonged and smooth than plain FRP confined specimens showed. The following second modulus is similar to E_2 observed at confined plain concrete.

4. COMPARISON WITH EXPERIMENTAL RESULTS OF OTHER RESEARCH GROUPS

The own results for confined plain and reinforced concrete were compared with the test results of (Xiao and Wu 2003), (Lee et al. 2004), (Eid et al. 2009), (Lam and Teng 2004), and (Ilki et al. 2008). Figure 6 includes two samples. The left diagram describes the observed results for the strength enhancement Δf_{cc} of reinforced concrete columns as functions of the ratio between $f_{l(FRP,steel)}$ and f_{c0}.

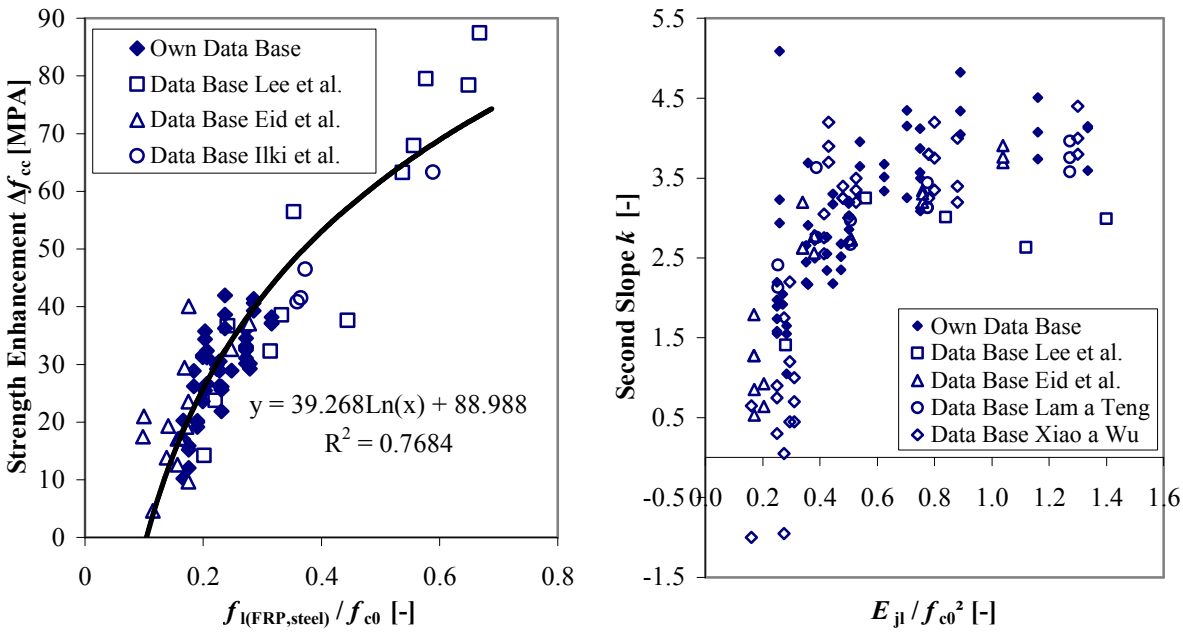

Figure 6: Strength enhancement Δf_{cc} as function of $f_{l(FRP,steel)}/f_{c0}$ and second slope k as function of E_{jl}/f_{c0}^2

The right diagram compares the own experimental results of confined plain concrete with the results of the other research groups with respect to the second slope k. These second slope appears if the axial stress is shown as a function of the confinement pressure σ_l; thereby, it explains the dependency of the axial stress on the confinement pressure.

Both diagrams attest a very good agreement between the different test series. It is possible to find proper and common regression curves despite the fact that different testing machines, test setups, and raw materials (for concrete and CFRP confinement) were deployed.

5. CONCLUSION

The FRP confinement can significantly increase the strength and ductility of concrete and reinforced concrete. The present study confirms the bilinear stress-strain model by Lam and Teng for confined plain and reinforced concrete. The proposal of Xiao and Wu to work with the ratio between confinement modulus E_{jl} and unconfined concrete strength f_{c0} also could be confirmed. Dual confinement effect of steel and CFRP confinement resulted as the total of transverse steel reinforcement and CFRP jacket. Thereby, it is possible to find regression curves in order to explain mathematically the influence of the confinement pressure, which is provided by CFRP and steel confinement, on the stress-strain behavior of wrapped concrete.

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