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Influence of FRP wrapping techniques on the compressive behavior of concrete prisms

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Abstract

Results of an experimental investigation on the compressive behavior of concrete prisms with square cross-section, externally wrapped with carbon fiber reinforced plastic (CFRP) sheets are presented. The effects of the following parameters were analyzed: local reinforcement at the corners and continuous layers; horizontal and vertical discontinuous strips; number of continuous *layers*—length of specimens.

An analytical model is proposed to determine the maximum bearing capacity of compressed concrete members with square cross-section and externally wrapped with FRP for the different configurations examined, and also able to consider the strength reduction with the length increase of concrete members. Analytical results are then compared with the experimental *data* available in the literature, showing good agreement.

Keywords: Compressive test; Load-shortening curves; Confinement; CFRP wrap; Local reinforcements; Length effect

1. Introduction

Interest in the use of flexible fiber reinforced plastic (FRP) sheets for the external wrapping of concrete compressed members is today a very popular theme, especially as regards estimating the effectiveness of this reinforcing technique in increasing the strength and ductility of members in seismic areas.

Several advantages are observed in using FRP wraps compared to the most common other techniques based on the use of steel reinforcements such as: the high-mechanical properties of the material (tensile strength and elasticity modulus) compared with its lightness; its insensitivity to corrosion; the ease of applying the reinforcing material; etc.

Referring to the case of confinement effects of compressed members externally wrapped with FRP unidirectional sheets, several theoretical and experimental investigations given in literature [1–17] have stressed that the effectiveness of the reinforcing technique, in terms of both strength and ductility increases, is related to: the choice of the best type of reinforcing material and its thickness; the shape of the transverse cross-section to be wrapped; the length of the members; the grade of concrete and the presence of traditional steel reinforcements constituted by longitudinal and transverse steel bars; the presence of round fillets at the corners of square or rectangular cross-sections; the local strengthening technique at the corners with single strips of FRP before continuous wrapping.

These studies have shown that the best performances are obtained in members with circular cross-sections compared to members with square or rectangular cross-sections. The presence of sharp corners in cross-section or sections being too slender (ratio between the two sides higher than two) causes a reduction in the effectiveness of the wrapping technique because of the low flexural stiffness of the reinforcing package and because of the stress concentration at the corners. Moreover, the ineffectiveness of this reinforcing

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Nomenclature

B	side of square cross-section
d	diameter of confined core
D	outsider diameter of wrapped cylindrical members
E_c	modulus of elasticity of concrete
E_f	modulus of elasticity of FRP
f'_c	compressive strength of unconfined concrete
f'_{cc}	compressive strength (peak stress) of confined concrete
f_l	lateral confining stress on concrete core from FRP transverse reinforcement
f'_l	effective lateral confining stress
f_r	stress of FRP composite
f_u	ultimate strength of FRP wraps
f_{ud}	ultimate allowable stress of FRP
L	length of the specimen
P	axial force in compression
r	corner radius of cross-section
P_c	compressive peak load
t	thickness of FRP layer
k_e	confinement effectiveness coefficient for FRP confined cross-section
k_v	equivalent stiffness of concrete shell
k	reduction factor of ultimate stress in FRP
k_1	concrete strength enhancement coefficient
k_2	reduction factor for discontinuous wraps
β	parameter describing the stiffness of FRP—concrete shell
ε_{ct}	ultimate strain of concrete in tension
ε_{ud}	ultimate allowable strain of FRP
δ	axial displacement of concrete specimen
δ_c	shortening at peak load
ν_c	Poisson ratio of concrete
ρ_f	transverse FRP reinforcement ratio

technique can also be related to: imperfect adhesion of the reinforcing package; loading of the fibers in their perpendicular direction; delamination phenomena of multilayer; etc.

The implementation of round corners in square or rectangular cross-sections, before the application of a continuous FRP layer, is a very effective technique to reduce stress concentration and to improve confinement effects such as *suggested* in Yan et al. [15] and in Yamakawa et al. [16], but this technique involves additional costs and often cannot be used (e.g. when a reduced cover is present in an existing reinforced concrete member to be retrofitted). In these cases the use of single strips of FRP locally applied at the sharp corners before the continuous wrapping of the transverse cross-section could be a good alternative technique, to avoid premature collapse due to local stress peaks in the FRP sheets, as suggested in Campione et al. [17].

From the theoretical point of view, several studies highlight the fact that it is possible to predict the maximum compressive strength and the stress–strain response of wrapped compressed members. Some of these studies are of a semi-empirical nature (see e.g. in literature researches [18–23]), while others are based on the plasticity approach such as in Karabinis and Rousakis [24] or on simplified mechanical model given in Campione et al. [25]. Very few studies focus on the size effect inducing reduction in maximum compressive strength with an increase in the size of wrapped compressed members as in Theriault et al. [13].

Based on these considerations, the paper experimentally and theoretically analyses the confinement effects due to FRP wrap in members with sharp corner or round fillets.

In the first part of the paper, an experimental investigation is presented and discussed referring to the behavior of compressed concrete prisms having square cross-section and externally wrapped with FRP. The focus is on the effect of different wrapping techniques, such as the use of single strips applied at the corners before the continuous wrapping and the use of discontinuous wraps; also the effect of the slenderness of specimens is examined.

In the second part of the paper, an analytical model able to determine the maximum bearing capacity of concrete members with square cross-section (with sharp or round corners) for the different configurations examined is presented; moreover a new expression for maximum strength prediction including strength reduction with slenderness increasing is presented and verified against current experimental data and those available in the literature.

2. Experimental investigation

2.1. Experimental program

The experimental research carried out refers to the compressive behavior of low strength concrete members with square cross-section externally wrapped with unidirectional flexible high-strength, high-modulus carbon fiber sheets. FRP wraps were constituted by unidirectional carbon fiber and they were glued to the external concrete surface with an epoxy resin. The characteristics given by the manufacturer were: weight density 1820 kg/m^3; thickness t of 0.165 mm; elasticity modulus E_f of 230 GPa—tensile strength f_u of 3430 MPa; and ultimate strain in tension of 1.5%.

The parameters investigated, *on a total of 22 specimens,* were: the wrapping technique of concrete members with discontinuous horizontal and vertical strips; the presence of local reinforcements constituted by single strips at the corners applied preliminarily to the wrapping with continuous layers; the number of layers; the length of the specimens.

2.2. Constituent materials

The concrete utilized was obtained by using the following dosages: 250 kg/m^3 of Portland cement, 1050 kg/m^3 of aggregates with maximum size 15 mm, 850 kg/m^3 of sand and 150 l of water. This concrete had compressive cylindrical strength at 28 days (measured on 100 × 200 mm specimens) of $f'_c \approx 13$ MPa. Although this compressive strength is acceptable only for non-structural concrete in most countries, the choice of a very low concrete strength aims to show the effectiveness of the CFRP wrapping technique on the behavior of a concrete member in compression having low bearing capacity, such as it is common to have in several existing reinforced concrete structures like those mentioned in Ilki and Kumbasar [5].

Specimens with square cross-sections of side 150 mm with length 150, 300 and 450 mm, respectively were analyzed.

For the casting of fresh concrete, rigid wooden moulds were utilized and the concrete was compacted manually in the moulds. Specimens were cured without particular attention to curing conditions (humidity of 60% and temperature of 20 °C) in order to reproduce the worst conditions in the field and produce a decay in compressive strength. Specimens were rectified at the ends with a thin layer of high-strength mortar and tested after 28 days of curing. Cylindrical specimens of dimensions 100 × 200 mm were also prepared in order to test the material for compressive strength.

Some of the prismatic specimens were wrapped with unidirectional continuous layer of FRP, an overlap length of 100 mm being adopted. The fillet radius at the corners was a few millimeters, but in any case there was no guarantee of a minimum radius, e.g. 20 mm, as suggested in CEB-FIP [26]. The aim was to reproduce the most disadvantageous conditions and to verify whether the local reinforcing technique at sharp corners is a good alternative to the smoothing of sharp corners as discussed in Campione et al. [17]. In the case of discontinuous horizontal wraps (see Fig. 1) one layer of 60 mm depth at a pitch of 90 mm was adopted; preliminarily single strips were placed vertically to wrap the corners of the square cross-section. These fibers had an anchorage length of 50 mm for each side of the section. The technique of local reinforcement at the corners with single strips is also studied in Campione et al. [25], where on the basis of experimental and analytical studies it is suggested that the highest concentration of stresses in FRP arises at the corners. On the basis of these considerations, in all cases examined in the present work referring to the study of the effect of the number of reinforcing layers and of the length of the specimens, preliminary reinforcement at the corners with single strips was undertaken before continuous wrapping.

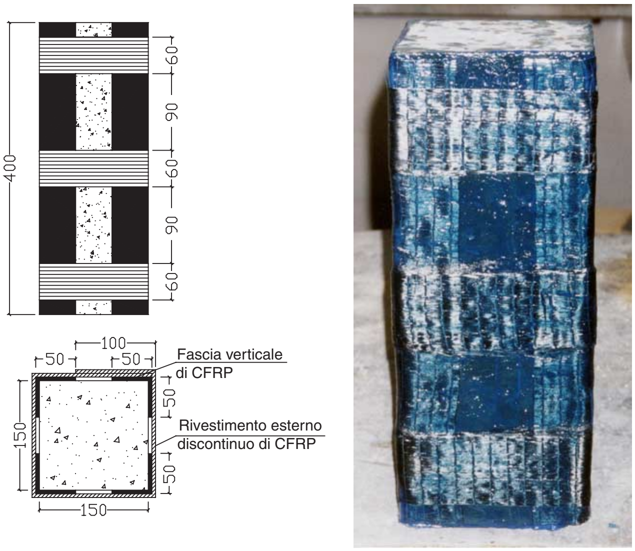

Fig. 1. CFRP arrangement for specimens with single horizontal and vertical strips.

2.3. Test set-up

Compressive tests were carried out using a testing machine with 3000 kN bearing capacity having at the top a spherical joint and operating in a controlled displacement mode at a slow displacement rate. A load cell recorded the external load P, while the axial shortening values were acquired by means of three LVDTs with a gauge length equal to the entire length of the specimens, as also specified in Campione et al. [17]. The three LVDTs were located in the plan in such a way as to form an angle of 120° with one another. Because of the spherical joints and of the location of LVDTs average shortening values were accurate such as if four LVDTs should be utilized. During the tests very reduced eccentricities in loading were observed also for slender specimens, as confirmed by the very close readings of the three LVDTs.

Load and axial shortening values were collected by means of a high-speed acquisition data system. The shortening value δ given in the following graphs is the average value of the reading of the three LVDTs for each load level. Specimens were loaded monotonically and stiff steel plates were placed between their ends and the platen of the loading machine. No strain gauges were applied in the FRP wraps during the tests.

3. Experimental results

In this section, the results of monotonic compressive tests are given in term of compressive load versus axial shortening values. For each type investigated two specimens were tested for and the average response curve of the two specimens is represented. A very low scattering of results (less than 5%) between each specimen and the average ones was observed.

Average values of maximum compressive load P_c and corresponding shortening δ_c are given in Table 1 for the different types of specimens examined (numbers of layers n and local reinforcement).

3.1. Effects of reinforcing techniques

Fig. 2 shows load-shortening curves referring to specimens of side 150 mm and length 450 mm in the absence and presence of FRP. A minimum fillet radius at the corner of 3 mm was adopted. For wrapped specimens the following cases are presented: one or two layers of continuous wraps; single strips at the corners and one continuous layer; horizontal and vertical strips.

From the graph it emerges that by wrapping the specimen with one layer of CFRP the bearing capacity increases compared to plain concrete up to 27%, and this increase is accompanied by a moderate increase in the corresponding shortening value.

By adding a second layer of CFRP the measured increase in the bearing capacity was up to 42%, accompanied by a very high increase in the corresponding shortening value.

In the case of a discontinuous wrapping technique, the results are very close to those obtained using one continuous layer. Moreover, in this case more brittleness was observed in the failure mode corresponding to the failure of FRP sheets compared to that of specimens wrapped with one layer of continuous FRP.

For specimens locally reinforced at the corner and wrapped with one layer of continuous layer, performance, in terms of both maximum strength and axial shortening values, is very similar to those of specimens confined with two continuous layers. This aspect highlights the effectiveness of this reinforcing technique, also because it allows a reduction in the cost of material if compared with continuous layers. Moreover, the solution with local reinforcement allows one an over-strength at the comers and it determines the rupture of the FRP wraps along the flat portion of the specimens with a more progressive failure mode compared to those relating to the case of a continuous wrap. By contrast, the presence of sharp corners without local reinforcement determines brittle rupture of FRP at the corners (see Fig. 3).

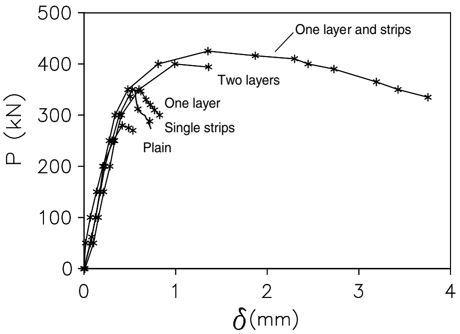

Fig. 2. Load-shortening curves for wrapped 150 × 150 × 450 mm specimens with different strengthening techniques.

Table 1
Mechanical properties of specimens tested

Number of layers	Local reinforcement	Length (mm)	P_c (kN)	δ_c (mm)
0	No	450	270	0.33
1	No	450	339	0.55
2	No	450	400	1.10
Discontinuous wraps	Yes	450	344	0.61
1	Yes	450	397	1.43
2	Yes	450	409	2.10
3	Yes	450	463	7.85
/	/	150	319	0.90
1	Yes	150	439	3.80
/	/	300	295	0.65
1	Yes	300	379	0.80

Referring to specimens wrapped discontinuously, the failure mode (see Fig. 4) was characterized by more brittleness if compared to the effect of local reinforcement and continuous wraps, but in this case too over-strength at the corners is observed.

Based on the above-mentioned considerations, in the following sections all cases presented will refer to specimens preliminarily reinforced at the corners with one layer of CFRP and then wrapped with a continuous layer.

Fig. 5 shows load-shortening curves for wrapped specimens with local reinforcement at the corners and one, two or three plies of CFRP. The results show an increase in the bearing capacity and in the strain capacity not proportional to the increase in the numbers of plies. The increase in the number of plies changes the load-shortening response shape that from a quasi-brittle type with one layer becomes a plastic type for three layers.

The failure mechanism observed with the variation in the number of plies is almost the same, and is characterized

Fig. 3. Failure mode of CFRP continuously wrapped specimens.

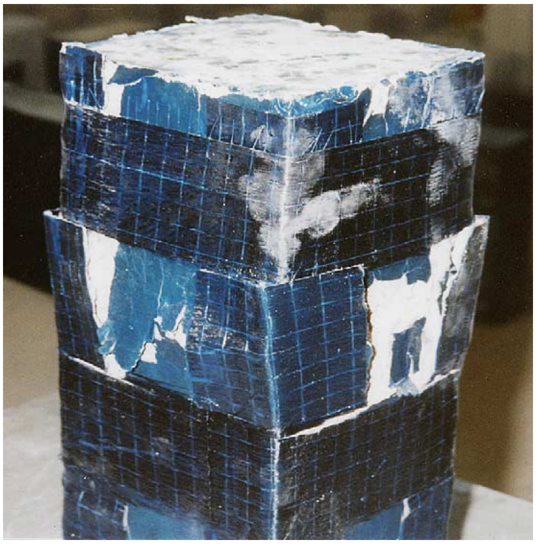

Fig. 4. Failure mode of CFRP discontinuously wrapped specimens.

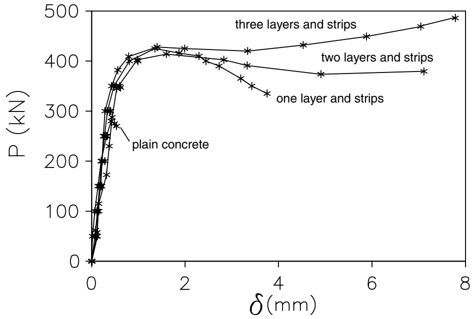

Fig. 5. Load-shortening curves for wrapped 150 × 150 × 450 mm specimens with different layers of CFRP.

by a failure in tension of FRP occurring after the peak load in concrete and involves the failure of fiber outside the comers of the specimens.

3.2. Slenderness effect

Referring to the slenderness effect it has to be observed that several recent analytical and experimental investigations given in the literature [13,14] highlight the fact that the variation in the shape and length of wrapped compressed concrete members strongly influences the maximum strength and the strain capacities of wrapped members. Specifically, with an increase in length or in the dimensions of the cross-section (for equal geometrical ratios of transverse reinforcements) the compressive strength is reduced. Most analytical studies focus on the importance of the effect of the shape of the transverse cross-section, but very few data and analytical models are able to predict the effects of length and more in general of size. In the literature, the effects mentioned are seen to be clearly understood for concrete members confined with steel reinforcements. Recently, for members wrapped with FRP too, an analytical study based on non-linear finite elements analyzed these effects such as observed by Yeh and Chang [27]. The latter study presents a parametric analysis correlating the strength and strain capacity properties of the confined material with the size of the members and with the variation in the parameters governing the confinement effects of wrapped compressed members.

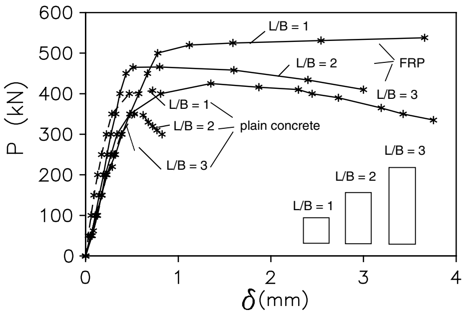

Fig. 6. Load-shortening curves for plain concrete and CFRP wrapped square specimens having different lengths.

In the present paper referring to the current investigation, Fig. 6 shows load-shortening curves of wrapped members with variation in the length of the specimens.

The graph refers to unconfined specimens and wrapped specimens with single strips at the corner and one continuous layer of CFRP. From the graph it emerges that with increases in length the strength decreases and more brittleness in the overall response is observed. This effect, which is well known for plain and steel reinforced members (see [20]), was also observed and discussed for members wrapped with FRP having circular and square cross-sections such as suggested in the literature [13,14]. Moreover, it was observed that the variation between the length increase and the strength decrease is non-linear, as also observed in Mirmiran et al. [1].

4. Analytical modeling

In this section, the attention is essentially on the determination of the maximum compressive strength of externally wrapped compressed concrete prisms referring to the FRP configuration presented in the previous section.

The first part of this section is addressed to the shape effect in plan for wrapped member with square cross-section; while the second part of this section is focused on the slenderness effect.

4.1. Shape effects

To determine the maximum compressive strength of confined concrete members wrapped with FRP, neglecting the size effects, the following formula, originally given in Richard et al. [28], can be utilized:

$$f'_{cc} = f'_c + k_1 \cdot f'_l \tag{1}$$

f'_l being the effective confinement pressure at concrete failure, f'_c the strength of unconfined concrete and k_1 an experimental coefficient generally assumed for normal strength concrete to be equal to 4.1.

To obtain the effective confinement pressures exercised by FRP on concrete core, due the constrained lateral expansion of concrete core, it is possible to consider the recent model proposed by Campione et al. [25] which express the effective confinement pressures as

$$f_l' = k_e \cdot \bar{f}_l \tag{2}$$

in which: k_e is the effectiveness coefficient having the expression suggested in CEB-FIP Bulletin no. 14 [26], taking into account the effect of the geometry of the transverse cross-section and the presence of round fillets at the corners having radius r; $\bar{f}_l$ is the reduced confinement pressure at concrete rupture exercised by the FRP package on the concrete core (see Fig. 8).

The reduced confinement pressure $\bar{f}_l$ is expressed as a share of the maximum confinement pressure f_l, having expression

$$f_l = \frac{2 \cdot t \cdot f_{ud}}{B} \tag{3}$$

With B the side of the square cross-section.

This analytical reduction factor of the uniform confinement pressure distribution, denoted in the following as k, takes into account the effective axial and flexural stiffness of the FRP package and the stiffness of the concrete core, occurring at concrete failure.

It has to be observed that the maximum confinement pressure f_l was obtained referring to the rigid body equilibrium of the transverse cross-section subjected to the distributed uniform pressure f_l and to the localized forces in FRP at the stresses f_{ud}.

The stress f_{ud} is the available ultimate stress in FRP, which is related to the strain ε_{ud} by means of the elasticity modulus of fibers, E_f being $f_{ud} = E_f\,\varepsilon_{ud}$. The strain ε_{ud} is the maximum strain value reached in circular members wrapped with FRP at rupture of the concrete core. Analytical research (see [18]) and experimental research (see [1]) have shown that the ε_{ud} strain is lower than the ultimate strain given by the manufacturer and in general it depends on the FRP characteristics and its value is generally between 0.004 and 0.008.

As already mentioned, the k factor and f_l confinement pressure are related to the equivalent average pressure $\bar{f}_l$ by means of

$$\bar{f}_l = k \cdot f_l \tag{4}$$

As shown in Campione et al. [25], it is possible to determine the k coefficient by considering a simplified one-dimensional model able to reproduce the three-dimensional problem of interaction between concrete core and FRP wraps due to the lateral expansion.

In the cases of members with sharp corners and wrapped with continuous layers of FRP the k coefficient has expression

$$k = \frac{2 \cdot \varepsilon_{ct} \cdot k_v \cdot E_f \cdot t}{f_l(4 \cdot E_f \cdot t \cdot \beta + k_v \cdot B)} \tag{5}$$

with k_v and β defined, as suggested in Campione et al. [25], as

$$k_v = \frac{2 \cdot E_c}{B \cdot (1 - 2 \cdot \nu_c)} \quad \beta = \sqrt[4]{\frac{3k_v}{t^3 \cdot E_f}} \tag{6}$$

being k_v the stiffness of the concrete shell in the plane of the cross-section; E_c the modulus of elasticity of concrete; ε_{ct} the ultimate strain in tension of unconfined concrete and ν_c its Poisson's coefficient.

Eq. (4) shows that effectively confinement pressure, expressed as a percentage of ultimate uniform confining pressure, depends not only on the characteristics of fiber (modulus of elasticity and axial stiffness related to t), but also on the characteristics of the concrete core. Similar conclusions, but of empirical nature, are also given in Chaallal et al. [20], in which was mentioned that the gain in strength of concrete depends not only on the number of FRP layer, but also on the concrete properties.

In the case of cross-sections with local reinforcement at the corners (single strips applied before the continuous wrapping) higher average confined pressures develop because of the higher stiffness of the FRP package and the k coefficient increases with respect to the case of single strips. In this case, more complex expression of the k factor can be obtained as suggested in Campione et al. [25].

In the case of a square cross-section with round fillets, as shown in Fig. 7, an increase in the radius of round fillets produced more uniform confinement pressure distribution; this involves, an increase in the confinement pressures. Although the variation in the stresses in the FRP package (depending on the effective confinement pressure distribution) is not linear with the variation in the radius of the corner r (especially for a high numbers of layers) it can be assumed in a conservative way that the variation in the stresses in FRP is linear with the variation in the corner radius.

Therefore the following expressions of the stress reduction factor in FRP can be obtained:

$$c_r = \frac{f_r}{\varepsilon_{ud} \cdot E_f} = k + (1 - k) \cdot \frac{2 \cdot r}{B} \tag{7}$$

being f_r the stress in FRP at maximum compressive strength.

Form Eq. (7) it emerges clearly that c_r gives the reduction of FRP stress with the decreases in the radius of fillet r. It also includes the section with sharp corners for which c_r is equal to k.

Similar equations are also suggested and calibrated on the basis of experimental data in the literature [7,13,29]. According to Manfredi and Realfonso [29] the stress reduction factor in FRP can be expressed as

$$c_r = 0.10 + 0.59 \cdot \frac{2 \cdot r}{B} \tag{8}$$

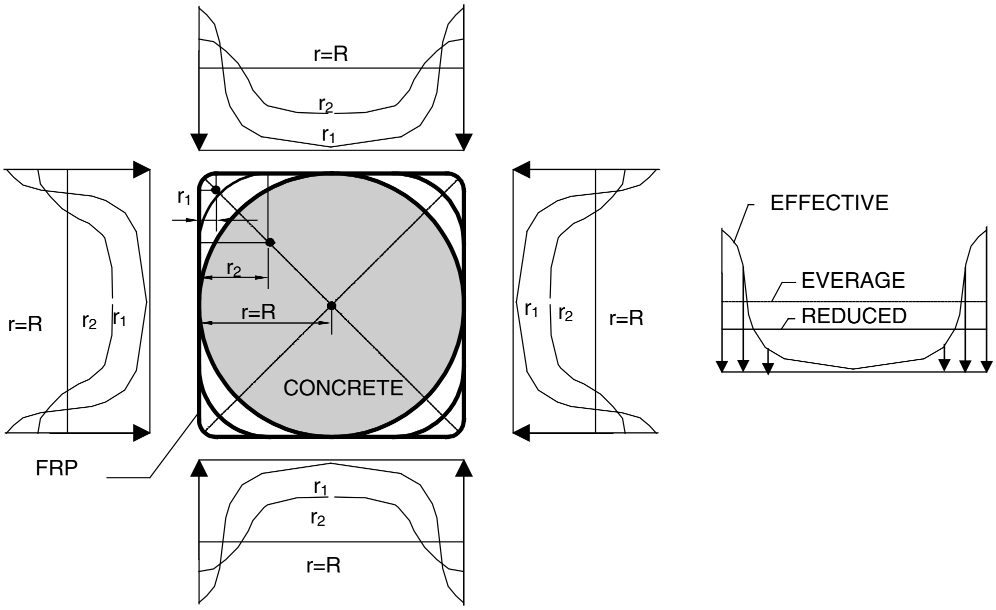

Fig. 7. Variation in confinement pressures distribution with variation in the corner radius.

From Eq. (8) it emerges that for a square cross-section c_{cr} is equal to 0.1 and its value does not depend on the properties of FRP (material type, number of layers) and concrete core, while using Eq. (7) the dependence is evident.

Fig. 8 shows the variation in c_r with the ratio $2r/B$ in accordance with expressions given in the literature [7,13,29]. If Eq. (7) is used with reference to a member with a square cross-section having $B = 150$ mm and wrapped with one and ten plies of wraps with high-strength and high-modulus ($E_f = 230$ GPa), two different values of k equal to 0.07 and 0.135 were obtained, showing the sensitivity of the k parameters to the fiber characteristics.

In the presence of discontinuous horizontal and vertical wraps a further reduction in the effectively confined concrete has to be considered along with the height, because the single wraps are placed at pitch s with net spacing s' between horizontal strips; therefore, the confinement pressures determined by the analysis of the transverse cross-sections can be reduced by means of a coefficient k_2 defined as $k_2 = 1 - \frac{s'}{2 \cdot B}$, as was suggested by Tan an Yip [30].

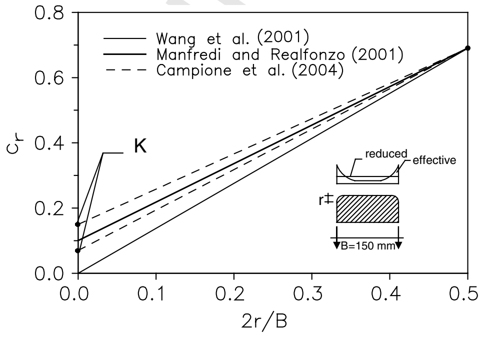

Fig. 8. c_r variation with $2r/B$ variation.

4.2. Length effect

If the length effect has to be considered in order to reproduce the reduction in maximum compressive strength observed experimentally, it is possible to adopt, adequately rearranged, the analytical expression given in Kim et al. [31] referring to the case of high-strength concrete compressed members with circular cross-sections and confined with very close steel spirals. The expression given in Kim et al. [31] found mechanical explication in the size effect law primarily given for members in tension by Bazant [32]. The size effect law given in Kim et al. [31] has the following expression:

$$f'_{co} = 0.8 \cdot f'_c + \frac{0.4 \cdot f'_c}{\sqrt{1 + \frac{L-d}{50}\left[1 - \frac{8000 \cdot A_{sp} \cdot (1-s/d)}{d \cdot s \cdot f'_c}\right]}} + \frac{2.8 \cdot 2 \cdot A_{sp} \cdot f'_y}{d \cdot s} \cdot \left(1 - \frac{s}{d}\right) \quad \text{(in MPa)} \tag{9}$$

L being the length of the cylindrical member, d the diameter of confined core, s and A_{sp} the pitch and the transverse area of the steel spiral and f_y the yielding stress of the spiral.

In Eq. (9) the coefficient 2.8 is the k_1 value assumed to take into account the high-strength concrete type. In the present investigation, as in Campione et al. [25], k_1 is assumed to be equal to 4.1 for normal strength concrete.

In Eq. (9) the first term takes into account the length effect for unconfined concrete in accordance with the literature researches [33,34], the second term takes into account the size effect in the case of confinement pressure and finally the third term takes into account the strength increase due to the confinement pressure.

If we consider that in the case of cylindrical concrete members confined with steel spirals placed at close pitch the effective confinement pressure is expressed by $f_1' = \frac{2 \cdot A_{sp} \cdot f_y}{d}$, it is possible express the square root term in Eq. (9) as a function of the effective confinement pressure as follows:

$$\frac{8000 \cdot A_{sp}(1 - s/d)}{dsf_c'} \cong 4000 \cdot \frac{f_1'}{f_y f_c'} \tag{10}$$

where the term $1 - s/d$ was not considered in the case of no cover and also in the case of concrete members externally wrapped with FRP.

In the case of members with square cross-sections and externally wrapped with FRP, supposing that the failure mechanisms involved in the size effect have the same weight as those involved in members with circular cross-sections and confined by steel spirals, Eq. (9) can be rearranged in the following form:

$$f_{co}' = 0.8 \cdot f_c' + \frac{0.4 \cdot f_c'}{\sqrt{1 + \frac{L-B}{50}\left[1 - \frac{4000 \cdot k_e \cdot c_r \cdot f_l}{\varepsilon_{ud} \cdot E_f \cdot f_c'}\right]}} + k_1 \cdot k_e \cdot c_r \cdot f_l \quad \text{(in MPa)} \tag{11}$$

obtained substituting Eq. (10) by means of Eq. (2) in Eq. (9).

In the case of members with circular cross-sections, Eq. (11) becomes

$$f_{co}' \cong 0.8 \cdot f_c' + \frac{0.4 \cdot f_c'}{\sqrt{1 + \frac{L-D}{50}\left[1 - \frac{4000 \cdot \rho_f}{f_c'}\right]}} + 2 \cdot \rho_f \cdot E_f \cdot \varepsilon_{ud} \quad \text{(in MPa)} \tag{12}$$

obtained considering that $B = D$, $k_e = 1$, $f_r = f_{ud}$, $f_l = \frac{2 \cdot t \cdot f_{ud}}{D}$, ρ_f being the geometrical ratio of the fibers in the cross-section ($\rho_f = 4 \cdot t/D$) and D the outer diameter of the columns to be wrapped.

In order to validate Eq. (11) experimental data given in Mirmiran et al. [1] and also given in the current investigation are considered.

In Mirmiran et al. [1] the dependence of the compressive strength on the variation in the length of the specimens with square cross-sections with round fillets and wrapped with glass sheets was observed; the analytical law fitting the experimental results was suggested in the following form:

$$f_{co}' = f_{c2:1}' \cdot \left[0.0288 \cdot \left(\frac{L}{B}\right)^2 - 0.263 \cdot \left(\frac{L}{B}\right) + 1.418\right] \tag{13}$$

f_{co}' being the strength of the concrete in the size considered, L and B the length and the side of the specimen and $f_{c2:1}'$ the strength of the concrete cylinder with a ratio between length and diameter equal to 2.

From Eq. (13) it emerges that the variation between the compressive strength and the length of the specimen is non-linear, but it does not emerge that it is also sensitive to the number of layers and to the shape of the transverse cross-section, as is evident from experimental observations and as is also observed using Eq. (11).

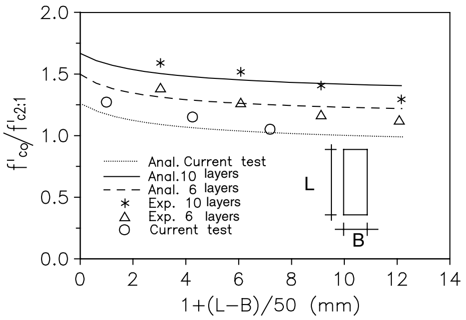

Fig. 9. Strength reduction with an increase in size.

Fig. 9 shows the variation in the compressive strength with the variation in the size of the specimen expressed with the parameter $1 + (L - B)/50$ as is done in Kim et al. [31]. The same graph provides some of the experimental results given in the literature by Mirmiran et al. [4] (denoted in Fig. 9 as Exp. 6 layers and Exp. 10 layers), and those object of the current investigation and referring to specimens wrapped with one layer of continuous wrap and locally reinforced at the corners. The comparison shows the acceptable agreement between experimental and predicted values.

5. Conclusions

Experimental compressive tests on concrete specimens externally wrapped with carbon fiber sheets have shown that:

- local reinforcement at the corners with CFRP strips before the application of continuous layers avoids possible fiber cutting at the corners, ensuring bearing capacity comparable with the cases of two continuous layers;
- local reinforcement with single horizontal strips and local reinforcements at the corners produce effects comparable to those of continuous wrapping and avoid possible fiber cutting at the corners;
- an increase in the number of reinforcing layers produces an increase in maximum compressive strength and significant increases in maximum strain capacities, but the effect is not directly proportional to the number of layers;
- an increase in the height of the specimens produces a reduction in maximum strength.

This study also presents a theoretical model for predicting the maximum strength, taking into account the effects of the shape of the cross-section and those of the length of the specimens.

The model is able to consider that:

- confinement pressure distributions are not uniform along the sides of the transverse cross-section and maximum values occur at the corners, leading to very low average confining pressure because of the low flexural stiffness of the reinforcing package;

- at peak load the effective distribution of the confinement pressure can be replaced considering a uniform value by means of a reduction factor.

Finally, the analytical law giving the strength reduction with an increase in the length of the specimen is given and is validated with the available experimental data.

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