Textile Reinforced Mortars (TRM) versus Fiber Reinforced Polymers (FRP) as Strengthening Materials of Concrete Structures

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Synopsis: Fiber reinforced polymers (FRP) are investigated in this study in comparison with a new class of materials, textile reinforced mortars (TRM), for shear strengthening and/or seismic retrofitting of concrete structures. Textiles comprise fabric meshes made of long woven, knitted or even unwoven fiber rovings in at least two (typically orthogonal) directions. Mortars – serving as binders – contain polymeric additives in order to have improved strength properties. In this study, experimental investigations were carried out in order to provide a better understanding on the effectiveness of TRM versus FRP jackets as a means of increasing: (i) the axial capacity of concrete through confinement; and (ii) the load-carrying capacity of shear-critical reinforced concrete flexural members. From the results obtained it is strongly believed that the proposed TRM strengthening technique is a viable alternative to the already successful FRP strengthening technique.

Keywords: concrete; confinement; FRP; mortars; shear strengthening; textiles

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INTRODUCTION AND BACKGROUND

The use of fiber reinforced polymers (FRP) in strengthening and seismic retrofitting projects has gained increasing popularity among structural engineers, due to numerous attractive features of these materials, such as: high specific strength (i.e. strength to weight ratio), corrosion resistance, ease and speed of application and minimal change of cross sections. Despite its advantages over other methods, the FRP strengthening technique is not entirely problem-free. The organic resins used to bind and impregnate the fibers entail a number of drawbacks, namely: (a) poor behaviour at temperatures above the glass transition temperature; (b) relatively high cost of resins; (c) potential hazards for the manual worker; (d) non-applicability on wet surfaces or at low temperatures; (e) lack of vapour permeability; and (f) incompatibility of resins and substrate materials.

One possible course of action aiming at the alleviation of the afore-mentioned problems would be the replacement of organic binders with inorganic ones, e.g. cement-based mortars, leading to the substitution of FRP with fiber reinforced mortars (FRM). The problem arising from such a substitution would be the relatively poor bond conditions in the resulting cementitious composite as, due to the granularity of the mortar, penetration and impregnation of fiber sheets is very difficult to achieve. Fiber-matrix interactions could be enhanced when continuous fiber sheets are replaced by *textiles*. The latter comprise fabric meshes made of long woven, knitted or even unwoven fiber rovings in at least two (typically orthogonal) directions. The quantity and the spacing of rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the textile and the degree of penetration of the mortar matrix through the mesh openings. It is through this mechanical interlock that an effective composite action of the mortar-grid structure is achieved. For the cementitious matrix, the following requirements should be met: non-shrinkable; high workability (application should be possible using a trowel); high viscosity (application should not be problematic on vertical or overhead surfaces); low rate of workability loss (application of each mortar layer should be possile while the previous one is still in a fresh state); and sufficient shear (hence tensile) strength, in order to avoid premature debonding. In case E-glass fiber textiles are used, the cement-based matrix should be of low alkalinity.

Although research on the use of textile meshes as reinforcement of cementitious products commenced in the early 1980s (1), developments in this field progressed rather slowly until the late 1990s. But during the past five years or so, the research community has put considerable effort on the use of textiles as reinforcement of cement-based products, primarily in new constructions (2-9). Studies on the use of textiles in the upgrading of concrete structures have been very limited and focused on flexural or shear strengthening of beams under monotonic loading and on aspects of bond between concrete and cement-based textile composites (10-11). In the present study, the authors go a few steps further: First, textiles are combined with inorganic (cement-based) binders, named here textile reinforced mortars (TRM), to increase the strength and ductility of concrete through confinement. Next, TRM jackets are used to enhance the resistance of reinforced concrete members in shear (both monotonic and cyclic). Finally, TRM systems are compared with equivalent FRP systems, with a scope to quantify their effectiveness.

RESEARCH SIGNIFICANCE

Jacketing of reinforced concrete members in existing structures is an increasingly attractive strengthening and/or retrofit option both in non-seismic and in seismically prone areas. Among all jacketing techniques, the use of FRP has gained increasing popularity, due to the favorable properties possessed by these materials. However, certain problems associated with epoxy resins, e.g. poor behavior at high temperatures, high costs, incompatibility with substrates and inapplicability on wet surfaces, are still to be addressed. One possible solution would be the replacement of epoxies with inorganic binders, but impregnation of continuous fiber sheets with mortars is very difficult to achieve, resulting in rather poor bond between fibers and matrix. Bond conditions could be improved when textiles are used instead of fiber sheets, a concept leading to the use of textile reinforced mortar (TRM) jacketing as an alternative to FRP jacketing. It is this concept that the authors explore and study in this paper, for the confinement of concrete as well as for shear strengthening.

FRP VERSUS TRM IN CONCRETE CONFINEMENT

Test specimens and materials

The test plan included two types of specimens: (a) cylindrical specimens with diameter 150 mm and height 300 mm (Series A and B); (b) short column – type specimens with rectangular cross section 250x250 mm and height 700 mm (Series C). Each specimen series was cast using the same ready-mix concrete batch (but slightly different from series to series, in terms of water to cement ratio). All specimens were unreinforced, as the jacket – reinforcement interactions (e.g. prevention of rebar pull-out at lap splices or delay of rebar buckling) were not in the scope of the present study. The four corners of all rectangular prisms were rounded at a radius equal to 15 mm.

In the case of cylindrical specimens all confining systems were applied “as usual”, that is with a single textile sheet wrapped around each cylinder until the desired number of layers was achieved. The bonding agent was either epoxy resin or inorganic mortar, applied to the concrete surface, in between all layers and on top of the last layer. Jacketing of all rectangular columns was provided using a new concept, which involved the formation of each layer through the use of a single strip. The strip was wrapped around the column in a spiral (bandage-like) configuration, starting from one end (column top) and stopping at the other (column bottom), Fig. 1a. Each successive strip was wrapped in the direction opposite to that of the previous one (Fig. 1b). The strips were attached on the concrete either through full bond (that is with resin or mortar, as in the case of cylinders), or at the ends only, using a simple method, which involved wrapping and epoxy-bonding of another strip, applied laterally in two layers at each end (top and bottom) of the column (Fig. 1c). Application of the mortars was made in approximately 2 mm thick layers with a smooth metal trowel.

Specimens in Series A are given the notation A_XN, where X denotes the type of jacket (C for the unjacketed, that is the control specimens, MI for specimens with mortar type I jackets and MII for specimens with mortar type II jackets) and N denotes the number of layers. Series B included another five different designs: the control specimens, specimens wrapped with two or three layers of textile bonded with epoxy resin and their counterparts bonded with mortar type II. Moreover, the concrete strength was a bit higher in Series B compared to Series A (due to the different water to cement ratio in the two batches). The notation of specimens in Series B is B_XN, where X and N are defined as above (R is used to denote epoxy resin and MII is used to denote mortar type II). Finally, Series C included seven different designs of short rectangular column-type specimens, as follows: The control column, columns wrapped with two or four layers of textile bonded with an epoxy resin, their counterparts wrapped with two or four layers of textile bonded with mortar type II and two more columns with two or four layers of unbonded textile, anchored at the column ends using transverse wrapping (as in Fig. 1c). The notation of columns in Series C is C_XN, where, as above, N is the number of layers and X denotes the type of jacket (C for unjacketed, R for resin-based jackets, MII for Mortar II jackets and A for jackets made of unbonded strips with end anchorage). All types of specimens used in this study are summarized in the first column of Table 1. Three and two specimens for the case of cylinders and rectangular short columns, respectively, were considered sufficient for reasonable repeatability. As a result, a total of 44 specimens were tested.

For jacketing, a commercial unwoven textile with equal quantity of high-strength carbon fiber rovings in two orthogonal directions was used (Fig. 2). The mass of carbon fibers in the textile was 168 g/m^2 and the nominal thickness of each layer (corresponding to the equivalent smeared distribution of fibers) was 0.047 mm. The guaranteed tensile strength of the carbon fibers (as well as of the textile, when the nominal thickness is used) in each direction was 3350 MPa, and the elastic modulus was 225 GPa (both values were taken from data sheets of the producer). Mortar I was a commercial low cost dry inorganic binder (suitable for plastering) containing fine cement and a low fraction of polymers. Mortar II contained cement and polymers at a ratio 10:1 by mass (higher than in Mortar I). The binder to water ratio in Mortars I and II was 3.4:1 and 3:1 by mass, respectively, resulting in plastic consistency and good workability. The 28-day compressive and tensile strength was 8.56 and 30.61 MPa, respectively, for Mortar I; and 3.28 and 4.24 MPa, respectively, for Mortar II.

Test results

The response of all specimens in uniaxial compression was obtained through monotonically applied loading at a rate of 0.01 mm/s in displacement control, using a 4000 kN compression testing machine. Loads were measured from a load cell and displacements were obtained using external linear variable differential transducers (LVDT) mounted on two opposite sides, at a gauge length of 130 mm for the cylinders and 180 mm for the rectangular columns, in the middle part of each specimen. From the applied load and average displacement measurements the stress-strain curves were obtained for each test.

Series A - cylindrical specimens (Mortar I versus Mortar II) -- Typical stress-strain plots recorded for cylinders with jackets made of textile and two different types of inorganic binders (Mortar I and Mortar II) are given in Fig. 3a, along with results for control specimens. Peak stress (confined concrete strength) values, f_{cc}, and ultimate strains, ε_{ccu}, are given in Table 1 (mean values). With one single exception, all σ-ε plots for concrete with textile confinement are characterized by an ascending branch, which nearly coincides with that for unconfined concrete, followed by a second one, close to linear, which drops rather suddenly at a point where the jacket either fractured due to hoop stresses or started debonding from the end of the lap. This notable difference in the failure mechanisms is attributed to the different mortar strengths. It is believed that the property determining which of the two failure mechanisms will be activated first is the interlaminar shear strength of the textile-mortar composite, which is proportional to the tensile (that is the flexural) strength of mortar. Note that the relatively small difference in flexural strengths between the two mortars is in agreement with the marginally higher effectiveness of jackets with Mortar II compared to those with Mortar I. The term "effectiveness" is quantified here by the ratios of confined to unconfined strength and ultimate strain. Whereas in unconfined specimens the ultimate strain is taken equal to 0.002, in confined specimens it is defined either at the point where the slope of the σ-ε curve drops suddenly or at the point where the stress drops by 20% of the maximum value.

In specimens with two layers of textile-mortar jackets the gain in compressive strength was 36% and 57% for mortar type I and II, respectively. These numbers are found by dividing the difference between confined and unconfined strength by the unconfined strength, e.g. (20.77 – 15.24)/15.24 = 0.36 = 36% for specimen A_MI2. The corresponding values in specimens with three layers were 74% and 77%. Gains in ultimate strains were much higher, with effectiveness factors (defined above as the ratio of confined to unconfined ultimate strain) around 5 or 6. Overall, it may be concluded that textile-mortar confining jackets provide substantial gain in compressive strength and deformability. This gain is higher as the number of confining layers increases and depends on the tensile (that is the shear) strength of the mortar.

Series B - cylindrical specimens (mortar versus resin) -- Typical stress-strain plots for cylinders with jackets made of textile/epoxy (FRP) (specimens B_R2, B_R3) or textile/mortar (TRM) type II (B_MII2, B_MII3) are given in Fig. 3b, along with results for control specimens; peak stresses, f_{cc}, and ultimate strains, ε_{ccu}, are given in Table 1. Specimens with resin-impregnated textiles gave a nearly bilinear response with a transition curve and failed due to tensile fracture of the jackets in the hoop direction. In these specimens the strength increased by 53% or 92% and the ultimate strain increased by a factor which exceeded 8 or 12, when the jacket was made of two or three layers, respectively.

Similarly to specimens with textile-mortar (type II) jackets in Series A, the σ-ε plots for concrete with textile confinement (B_MII2, B_MII3) are characterized by an ascending branch, which nearly coincides with that for unconfined concrete, followed by a second one, close to linear, which drops rather suddenly at a point where the jacket fractured due to hoop stresses. A point of difference is that the σ-ε curve has a first local maximum, at strain $\varepsilon_{co} = 0.002$ where unconfined concrete failed, followed by a small descending branch, which picked-up rather quickly and became ascending, until final fracture of the jacket occurred. This distinct behavior was observed only in specimens with two confining layers (and in one specimen with three confining layers), in agreement with similar observations on concrete confined with FRP jackets of low stiffness. Compared with the control specimens, in those with two-layered textile-mortar jackets the strength increased by 25% and the ultimate strain by a factor of 4.9. In specimens with three-layered textile-mortar jackets the improvement in mechanical properties was even better: the strength increased by 49% and the ultimate strain by a factor of 5.4. It should be noted that these numbers are lower than those recorded when the same jackets (two or three layers of Mortar II) were used in specimens of Series A, where concrete was of lower strength, confirming that the effectiveness of TRM jackets increases as the unconfined concrete strength decreases; the same conclusion applies to classical FRP jacketing, as suggested in numerous studies found in the literature.

A comparison of the effectiveness of mortar versus resin in textile jackets can be made by dividing the effectiveness of mortar-based jackets to that of resin-based jackets. The average value of this ratio, given in the last two columns of Table 1, is around 0.8 and 0.5 for strength and ultimate strain, respectively, and appears to decrease only marginally as the number of confining layers increases from two to three (from 0.82 to 0.77 for strength and from 0.59 to 0.42 for strain).

Another interesting observation is that, contrary to FRP jackets, TRM jackets do not fail abruptly. Their fracture in the hoop direction initiates from a limited number of fiber bundles (when the tensile stress reaches their tensile capacity) and then propagates rather slowly in the neighboring bundles, resulting in a failure mechanism which may be characterized as more ductile (compared with FRP jacketing). This fact is also reflected in the σ-ε curves, where the point of maximum stress (and the associated ultimate strain) is followed by a descending branch which keeps a nearly constant slope for a large range of strain.

Overall, it may be concluded that textile-mortar confining jackets: (a) provide substantial gain in compressive strength and deformability and (b) are characterized by reduced effectiveness, when compared with FRP jackets. The reduction in effectiveness is quite small in terms of strength and more notable in terms of ultimate strain.

Series C – rectangular columns (mortar versus resin versus end anchorage) -- Typical stress-strain plots for short column-type specimens are given in Fig. 3c, for specimens confined with two or four layers of textile impregnated with resin (C_R2, C_R4), textile impregnated with mortar (C_MII2, C_MII4) and textile strips with end anchorage (C_A2, C_A4), respectively. For the sake of convenient comparison, each figure provides also the σ-ε curves of the control (unconfined) specimens. Peak stresses, ultimate strains (defined either at the point where the slope of the σ-ε curve drops suddenly or at the point where the stress drops by 20% of the maximum value) and effectiveness ratios are given in Table 1.

Columns with resin-impregnated textile (FRP) jackets exhibited a nearly bilinear response, until tensile fracture of the jackets occurred at the corners. The strength increased by 29% or 47% and the ultimate strain increased by a factor which exceeded 6 or 10, when the jacket was made of two or four layers, respectively. The behavior of columns confined with mortar-impregnated (TRM) jackets was quite similar. The strength increased by 40% or 51% and the ultimate strain increased by a factor a little less than 6 or 9, when the jacket was made of two or four layers, respectively. Specimens with four confining layers failed in a way very similar to the ones with resin-impregnated textile jackets, whereas in those with two layers failure was gradual, starting from a few fiber bundles and propagating slowly in the neighboring fibers; as a result, the σ-ε curves of these specimens do not contain a sudden drop, which is a characteristic of excessive fiber fracture in a rather large portion of the jacket height. With regards to relative effectiveness, mortar-impregnated textile jackets were found equally good to their resin-impregnated counterparts (in fact, they were superior by 3-9%, which may be attributed to statistical error) in strength terms and marginally inferior (by 5-13%) in ultimate strain terms.

Surprisingly, spirally confined columns with unbonded strips anchored at the ends only, behaved nearly as good as those confined with fully-bonded mortar-impregnated or resin-impregnated jackets, especially in the case of four layers. The strength increased by 39% or 45% and the ultimate strain increased by a factor a little less than 4 or 9, when the jacket was made of two or four layers, respectively. Failure in these specimens developed away from the anchorages and was characterized by gradual fracture of fiber bundles, as in the case of columns with fully-bonded mortar-impregnated textile jackets. With regards to relative effectiveness, spirally applied unbonded strips with end anchorages were found equally good to their resin-impregnated counterparts in strength terms and inferior by 36%-13% (depending on the number of layers) in ultimate strain terms. When effectiveness of unbonded jacketing is compared with that of mortar-impregnated jacketing, the results are nearly identical in the case of four layers and slightly inferior in terms of ultimate strain in the case of two layers.

Overall, it may be concluded that TRM jackets are quite effective in confining columns of rectangular cross sections for strength and axial deformability. When the effectiveness is compared with that of FRP jackets, it is found nearly equal in strength terms and slightly inferior in ultimate strain terms. The same conclusion applies in the case of spirally applied unbonded strips with end anchorages, except if the number of layers is quite low, which may affect adversely the deformability.

Simple confinement model

A typical approach towards modelling confinement is to assume that the confined strength f_{cc} and ultimate strain ε_{ccu} depend on the confining stress at failure, $\sigma_{\ell u}$ as follows (12-14) :

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \left(\frac{\sigma_{\ell u}}{f_{co}} \right)^m \tag{1}$$

$$\varepsilon_{ccu} = \varepsilon_{co} + k_2 \left(\frac{\sigma_{\ell u}}{f_{co}} \right)^n \tag{2}$$

where k_1, k_2, m and n are empirical constants. The reduced effectiveness provided by jackets other than resin-impregnated ones (textile reinforced mortar jackets or unbonded strips anchored at the ends, as used in this study) may be taken into account by splitting k_1 and k_2 in two terms, as follows:

$$k_1 = \alpha k_{1,R} \tag{3}$$

$$k_2 = \beta k_{2,R} \tag{4}$$

where $k_{1,R}$ and $k_{2,R}$ are the values of k_1 and k_2, respectively, if jackets are made with resin-impregnated fibers and α, β are "effectiveness coefficients", which depend on the specific jacketing system (say α_M, β_M for mortar-based jackets and α_A, β_A for unbonded jackets anchored at the ends) and can be derived experimentally.

The literature on the precise form of confinement models for concrete is vast. Some of these models, especially the older ones, are based on the assumption that the relationship between confined strength and ultimate strain and their unconfined counterparts is linear, that is m and n are both equal to one. In other models, especially in some of the most recent ones, m and n are taken less than – but still close to – one. Whereas the main advantage of the former approach is simplicity, the disadvantage is that linear relationships between $f_{cc} - \sigma_{\ell u}$ and $\varepsilon_{ccu} - \sigma_{\ell u}$ tend to overpredict both the confined strength and the confined ultimate strain for high confining stresses. As our objective in this paper is not to elaborate on confinement models for concrete, but rather to demonstrate the procedure regarding the use of the "effectiveness coefficients" α and β for the two alternative (to epoxy-bonded) jacketing systems, we make too, for the sake of simplicity, the assumption of linearity, that is we consider m and n equal to one; but the approach presented herein is applicable without difficulty for any set of values of m and n.

The confining stress $\sigma_{\ell u}$ at failure of the jacket is, in general, non-uniform, especially near the corners of rectangular cross sections. As an average for $\sigma_{\ell u}$ in a cross section with dimensions b and h one may write:

$$\sigma_{\ell u} = \frac{\sigma_{\ell u,h} + \sigma_{\ell u,b}}{2} = \frac{1}{2} k_e \left(\frac{2t_j f_{je}}{h} + \frac{2t_j f_{je}}{b} \right) = k_e \frac{(b+h)}{bh} t_j f_{je} \tag{5}$$

where t_j is the jacket thickness, f_{je}, is the effective jacket strength in the lateral direction and k_e is an effectiveness coefficient, which, for continuous jackets with fibers in the direction perpendicular to the member axis is defined as the ratio of effectively confined area to the total cross sectional area A_g (15) :

$$k_e = \frac{1 - \left[(b-2r_c)^2 + (b-2r_c)^2 \right]}{3A_g} \tag{6}$$

In Eq. (6) r_c is the radius at the corners of the rectangular section. Application of Eqs. (1) - (2) to the data obtained for the specimens of Series B and C (specimens in Series A were excluded because mortar-based jackets cannot be compared with their resin counterparts) results in the plots of f_{cc}/f_{co} and ε_{ccu} versus $\sigma_{\ell u}/f_{co}$ given in Fig. 4a and Fig. 4b, respectively. The best linear fit equations to these data yield $k_{1,R} = 2.79$ ($R^2 = 0.95$), $\alpha_M = 0.68$ ($R^2 = 0.69$), $\alpha_A = 0.84$ ($R^2 = 0.84$), $k_{2,R} = 0.082$ ($R^2 = 0.99$), $\beta_M = 0.57$ ($R^2 = 0.49$) and $\beta_A = 0.82$ ($R^2 = 0.98$), which may be used along with the aforementioned confinement model. The above values state that according to this simplified model the effectiveness of TRM jackets used in this study is roughly 70% in terms of strength and 55-60% in terms of ultimate strain; the corresponding values for unbonded jackets anchored at their ends are roughly 85% for strength and 80% for ultimate strain. Of course, these values should be considered as indicative, as the test data used for calibration are relatively limited. But the method presented for obtaining these effectiveness coefficients is quite general.

FRP VERSUS TRM IN SHEAR STRENGTHENING OF RC

Test specimens and materials

The next step in this investigation was to examine the effectiveness of TRM as externally applied strengthening reinforcement of shear-critical RC members. The investigation was carried out by testing six beams deficient in shear (with a large spacing of stirrups in the shear span) in four point bending. The beams were 2.60 m long and had a cross section of 150x300 mm. The geometry of the beams, the details of the reinforcement and the general set-up of the test are shown in Fig. 5.

Four of the beams were tested monotonically and two of them were subjected to cyclic loading. Three parameters were considered in the experimental investigation, namely the use of inorganic mortar versus resin-based matrix material for the textile reinforcement, the number of layers (one versus two) and the use of conventional wrapping versus "spirally applied" textiles. By "conventional wrapping" it is implied that a single textile sheet was wrapped around the shear span until the desired number of layers was achieved (Fig. 5c). The bonding agent was either epoxy resin or inorganic mortar, applied to the concrete surface, in between all layers and on top of the last layer. "Spirally applied" jacketing was implemented in one beam only and involved the formation of each layer through the use of a single strip, approximately 150 mm wide. The first strip was wrapped around the member in a spiral configuration, starting from one end of the shear span and stopping at the other, and the next strip was wrapped in the same configuration but in the direction opposite to that of the first one. The two strips formed an angle of $\pm 10^o$ with respect to the transverse to the member axis.

One of the six beams was tested without strengthening, as a control specimen (C). A second one was wrapped with two layers of mortar-based jacket in the shear span (M2). A third beam was identical to the second but with a resin-based matrix material for the textile reinforcement (R2). In the fourth beam jacketing was provided with spirally applied strips (M2-s). These four specimens were tested monotonically. The next two specimens were identical to the second and third, but with one layer (instead of two) of textile in a mortar-based (M1) and a resin-based (R1) matrix, respectively. These two specimens were subjected to cyclic loading.

Casting of the beams was made with ready-mix concrete of mean 28-day compressive strength equal to 30.5 MPa. The steel used for longitudinal reinforcement had an average yield stress equal to 575 MPa; the corresponding value for the steel used in stirrups being 275 MPa. Textile, mortar (type II) and resin matrices were the same materials as those in the experimental study involving confined specimens.

Test results

Specimens C, M2, R2 and M2-s were tested monotonically at a rate of 0.01 mm/s, whereas the remaining two were subjected to quasi-static cyclic loading (successive pairs of cycles progressively increasing by 1 mm of displacement amplitudes in each direction at a rate of 0.2 mm/s), all in displacement control. The load was applied using a vertically positioned 500 kN MTS actuator and the displacements were measured at mid-span using two external linear variable differential transducers mounted on both sides of the specimens. The load versus mid-span displacement curves for all specimens are given in Fig. 6.

The control beam (C) failed in shear, as expected, through the formation of diagonal cracks in the shear spans. The ultimate load was 116.5 kN. An interesting observation during this test was that no sudden drop in the load was recorded after diagonal cracking.

This is attributed to the considerable contribution to shear resistance provided by both the stirrups crossing the crack and the strong dowel action (activated by the three 160 mm diameter longitudinal rebars). The behaviour of beams R2, M2, M2-s and R1 indicated that shear failure was suppressed and that failure was controlled by flexure: cracks in the constant moment region became wide and yielding of the tension reinforcement (bottom layer in beams R2, M2 and M2-s, both layers in beams R1 and M1, depending on the sign of the force) resulted in a nearly horizontal branch of the force versus displacement curve. The maximum loads in specimens R2, M2 and M2-s were 233.4 kN, 243.8 kN and 237.7 kN, respectively, that is nearly the same. This confirms the fact that the shear strengthening scheme selected in this study did not affect the flexural resistance. But the increase in shear resistance was dramatic (more that 100%), regardless of the strengthening scheme: two layers of textile reinforcement (either in the form of continuous sheets or in the form of spirally applied strips) with the mortar binder performed equally well to the epoxy-bonded (FRP) jacket (with two layers of textile reinforcement).

Specimen R1 (one layer of textile bonded with epoxy) experienced a flexural yielding failure mode with unequal capacities in the push and pull directions (261.9 kN and 201.4 kN, respectively). This may be attributed to the (unintentionally) larger concrete cover at the top of each beam compared to the bottom (see Fig. 5b). Specimen M1 failed in shear; this was evident by diagonal cracking in the shear span as well as by the rather sudden strength and stiffness degradation. This specimen reached a peak load of 200.1 kN, corresponding to a substantial increase in shear capacity with respect to the control specimen, in the order of 70%. An interesting feature of specimen M1 was that fracture of the fibers in the mortar-based jacket was gradual, starting from a few fiber bundles and propagating slowly in the neighboring fibers. A second interesting feature was that beam cracking was clearly visible on the mortar-based jacket. This is an extremely desirable property, as it allows for immediate and easy inspection of damaged regions. Conventional FRP jackets in such regions would had been left intact after an extreme event (e.g. earthquake), thus making the assessment of damage a very difficult and rather expensive task (one that would require, for instance, non-destructive evaluation through the use of infrared thermography). When comparing these loads for specimens R1 and M1 with those of the others, it should be kept in mind that the former had, in general, slightly higher concrete strength, because they were tested a few months later. Furthermore, they were tested at a higher displacement rate.

Overall, it may be concluded that the mortar-impregnated textile jackets employed in this study were quite effective in increasing the shear resistance of reinforced concrete members. Two layers of textile reinforcement (with a nominal thickness per layer equal to only 0.047 mm in each of the principal fiber directions) were sufficient to prevent sudden shear failure, whereas one layer proved less effective compared to its resin-bonded counterpart, but still sufficient to provide a substantially increased resistance.

Modelling

Modelling of the textile-reinforced mortar jacket contribution to the shear resistance of flexural reinforced concrete members may be based on the well-known truss analogy, as proposed in the past for FRP jackets (15-18) . Assuming that the textile is made of continuous fiber rovings in two orthogonal directions (as in this study), with fibers in each direction i forming an angle β_i with the longitudinal axis of the member (Fig. 7), the TRM jacket contribution to shear resistance, V_t, can be written as

$$V_t = \sum_{i=1}^{2} \frac{A_{ti}}{s_i} \left(\varepsilon_{te,i} E_{fib} \right) 0.9d \left(\cot\theta + \cot\beta_i \right) \sin\beta_i \tag{7}$$

where $\varepsilon_{te,i}$ = "effective strain" of the TRM in the direction i, E_{fib} = elastic modulus of fibers, d = effective depth of the cross section, A_{ti} = twice the cross section area of each fiber roving in the direction i, s_i = spacing of rovings along the member axis and θ = angle between the inclined shear crack and the member axis. Equation (7) may be extended in a straightforward way to account for textiles with more complex geometry (e.g. with fiber rovings in more than two directions). Note that if the direction i is perpendicular to the member axis, the ratio A_{ti}/s_i in the above equation equals twice the nominal thickness t_{ti} of the textile (based on the equivalent smeared distribution of fibers) in this particular direction.

The effective strain $\varepsilon_{te,i}$ in the direction i may be thought of as the average strain in the fibers crossing the diagonal crack when shear failure of the member occurs. Studies on the effective strain(ε_{fe}) for resin-based (FRP) jackets have been numerous in the past and have led to the development of semi-empirical but rather reliable formulas, which express the effective strain as a fraction of the fracture strain for the fibers. The same approach could, of course, be adopted for TRM jackets, when a substantial set of test data becomes available. Alternatively, one may treat TRM jackets exactly as their FRP counterparts (those with resin-based instead of mortar-based matrix), by multiplying the effective strain (of the FRP-equivalent) by an "effectiveness coefficient", say k.

The simple model described above is applicable to only one of the beams tested in this study, namely beam M1, as this was the only strengthened specimen that failed in shear. With $\theta = 45^o$, $\beta_1 = 90^o$ (fibers perpendicular to the member axis), $\beta_2 = 0^o$ (fibers parallel to the member axis), d = 272 mm, E_{fib} = 225 GPa, A_{t1}/s_1 = 2x0.047 = 0.094 mm, A_{t2}/s_2 = 0 ($s_2 = \infty$) and V_t = 0.5x(200.1 kN – 116.5 kN) = 41.8 kN, the effective strain in the TRM jacket at shear failure is obtained from Eq. (7) equal to 0.8%. When the same analysis is applied to beam R1 (the resin counterpart of beam M1) with contribution of the FRP jacket to the shear resistance at least equal to 0.5x(261.9 kN – 116.5 kN) = 72.7 kN, a lower bound to the effective strain in the FRP is calculated as 1.4%. We may also note that the effective FRP strain in beam R1 has as an upper bound the fracture strain, which is about 1.5-1.6% (based on manufacturer's data). The effectiveness coefficient k of TRM versus FRP, based on the results for beams M1 and R1, can be obtained by dividing the TRM effective strain (0.8%) to the FRP effective strain (greater than 1.4% but at most equal to 1.5-1.6%); the value obtained is at least equal to 50%, with 57% being an upper bound. Hence it is concluded that the carbon fibers in the TRM jacket (with a single layer of textile reinforcement) were mobilized to a substantial degree - the average strain across the shear crack reached approximately 50% of the fracture strain of single fibers – and were a little more than 50% as efficient as their resin-impregnated counterparts. Of course, these values should be considered as indicative, until more test data become available. But the method described above for obtaining the effectiveness coefficients is quite general.

CONCLUSIONS

Based on the response of confined cylinders, it is concluded that: (a) Textile-reinforced mortar (named here TRM) confining jackets provide substantial gain in compressive strength and deformability. This gain is higher as the number of confining layers increases and depends on the tensile strength of the mortar, which determines whether failure of the jacket will occur due to fiber fracture or debonding. (b) Compared with their resin-impregnated counterparts (FRP), TRM jackets may result in reduced effectiveness, in the order of approximately 80% for strength and 50% for ultimate strain, for the specific mortar used in this study. It is believed that these numbers depend very much on the type of mortar and could be increased with proper modification of mortar composition. (c) Failure of mortar-impregnated textile jackets is less abrupt compared to that of their resin-impregnated counterparts, due to the slowly progressing fracture of individual fiber bundles.

From the response of rectangular columns it is concluded that TRM jackets are quite effective in confining columns of rectangular cross sections for strength and axial deformability. In comparison with their epoxy-based counterparts (FRP), mortar-impregnated textile jackets gave approximately the same effectiveness in strength terms and a slightly inferior one in ultimate strain terms. The same conclusion applies in the case of spirally applied unbonded strips with end anchorages, except if the number of layers is quite low, which may affect adversely the deformability. This concept of spirally applied unbonded jacketing appears to be quite interesting and certainly deserves further investigation.

From the response of RC members strengthened in shear it is concluded that closed-type TRM jackets provide substantial gain in the shear capacity. Two layers of mortar-impregnated textile reinforcement (based on carbon fibers with a nominal thickness per layer equal to 0.047 mm in each of the principal fiber directions) in the form of either conventional jackets or spirally applied strips were sufficient to increase the shear capacity of the beams tested by more than 60 kN, thus preventing sudden shear failures and allowing activation of flexural yielding (as was the case with the resin-based jacket). One layer of textile reinforcement proved less effective but still sufficient to provide a substantial shear resistance, which exceeded that of the unstrengthened beam by more than 40 kN. This corresponds to a good mobilization of the carbon fibers in the textile, at an average strain of 0.8%. However, when the performance of this jacket is compared with that of its resin-based counterpart, the TRM strengthening system is found a little more than 50% as effective as the FRP one.

Modeling of concrete confined or strengthened in shear with jackets other than resin-impregnated ones (FRP) becomes a rather straightforward procedure through the introduction of experimentally derived jacket “effectiveness coefficients”, a concept developed in this study in order to compare: (a) the confining action of mortar-based jackets or spirally applied unbonded jackets to their resin-based counterparts; (b) the contribution to shear resistance of TRM and FRP jackets.

From the results obtained in this study the authors believe that TRM jacketing is a promising solution for increasing the confinement as well as the shear capacity of reinforced concrete members, of crucial importance in seismic retrofit. Naturally, further investigation is needed (part of it is already under way) towards the optimization of mortar properties, the increase of the experimental database and the understanding of jacket-steel reinforcement interactions in column-type members.

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Table 1 – Strength and deformability of compression specimens.

Specimen notation	Compressive strength f_{cc}, MPa	Ultimate strain ε_{ccu}, (%)	$\frac{f_{cc}}{f_{co}}$	$\frac{\varepsilon_{ccu}}{\varepsilon_{co}}$	$\frac{f_{cc}}{f_{cc,R}}$	$\frac{\varepsilon_{ccu}}{\varepsilon_{ccu,R}}$
Series A						
A_C	15.24	0.20*	1.00	1.00	n.a.	n.a.
A_MI2	20.77	0.96	1.36	4.80	n.a.	n.a.
A_MII2	23.88	1.08	1.57	5.40	n.a.	n.a.
A_MI3	26.50	1.13	1.74	5.65	n.a.	n.a.
A_MII3	27.00	1.22	1.77	6.10	n.a.	n.a.
Series B						
B_C	21.81	0.20*	1.00	1.00	n.a.	n.a.
B_R2	33.47	1.67	1.53	8.35	1.00	1.00
B_MII2	27.36	0.98	1.25	4.90	0.82	0.59
B_R3	41.94	2.55	1.92	12.75	1.00	1.00
B_MII3	32.44	1.08	1.49	5.40	0.77	0.42
Series C						
C_C	14.25	0.20*	1.00	1.00	n.a.	n.a.
C_R2	18.41	1.24	1.29	6.20	1.00	1.00
C_MII2	20.00	1.18	1.40	5.90	1.09	0.95
C_A2	19.86	0.79	1.39	3.95	1.08	0.64
C_R4	20.97	2.03	1.47	10.15	1.00	1.00
C_MII4	21.56	1.76	1.51	8.80	1.03	0.87
C_A4	20.64	1.76	1.45	8.80	0.98	0.87

* The ultimate strain of control specimens is assumed equal to $\varepsilon_{co} = 0.2\%$, which agrees well with the mean value (0.22%) recorded at peak stress.

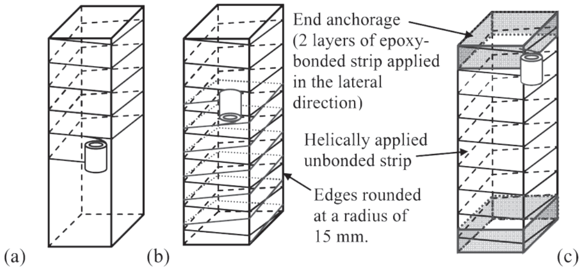

Figure 1 — Application of confining systems on rectangular specimens.

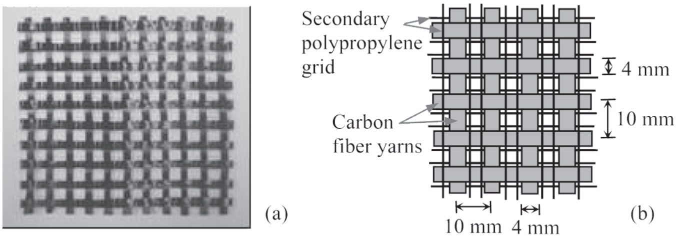

Figure 2 - (a) Photograph and (b) architecture of carbon fiber textile used in this study.

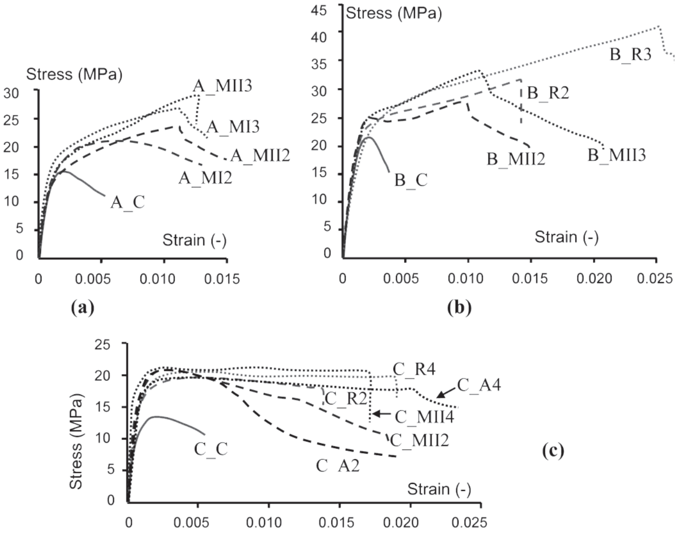

Figure 3 - Typical stress-strain curves for (a)-(b) cylinders,
(c) columns with rectangular cross sections.

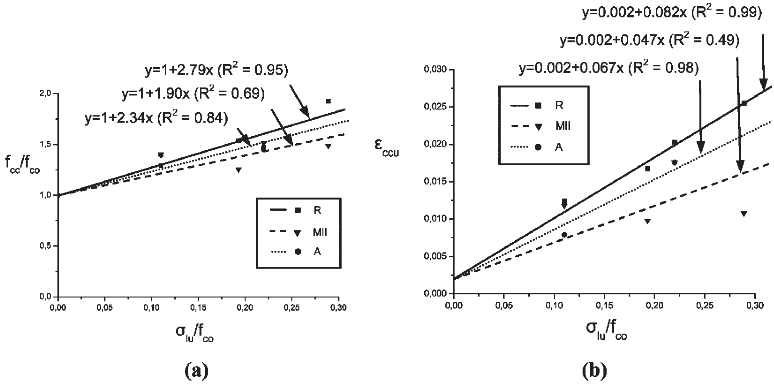

Figure 4 - (a) Normalized compressive strength and (b) ultimate compressive strain in terms of lateral confinement.

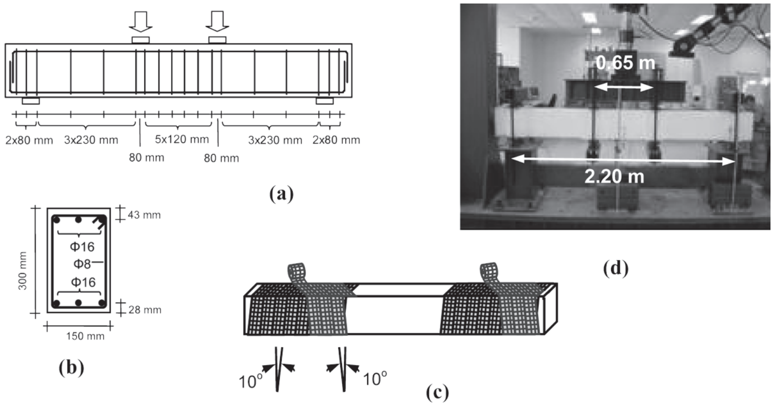

Figure 5 - (a)-(b) Geometry of the beams, (c) spiral application of strips at the shear spans and (d) general set-up of the test.

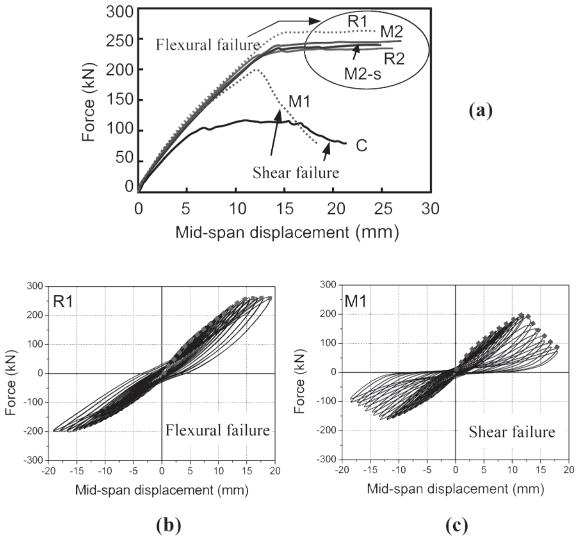

Figure 6 - Force – mid-span displacement curves: (a) for all beams tested (for beams subjected to cyclic loading the envelope curves in the push direction are given); (b) for beam R1; and (c) for beam M1.

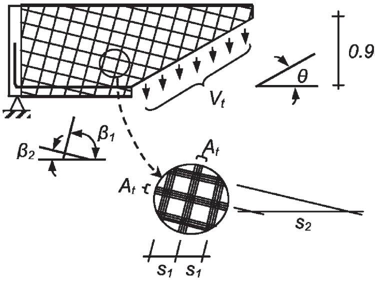

Figure 7 - Contribution of textiles with fibers in two orthogonal directions to shear resistance of RC members.