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Shear strengthening of reinforced concrete members with textile reinforced mortar (TRM) jackets

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Abstract The application of textile reinforced mortar (TRM) as a means of increasing the shear resistance of reinforced concrete members is investigated in this study. TRM may be considered as an alternative to fiber reinforced polymers (FRP), providing solutions to many of the problems associated with application of the latter without compromising much the performance of strengthened members. Based on the experimental response of reinforced concrete members strengthened in shear it is concluded that textile-mortar jacketing provides substantial gain in shear resistance; this gain is higher as the number of layers increases and, depending on the number of layers, is sufficient to transform shear-type failure to flexural failure. TRM jackets were provided in this study either by conventional wrapping of fabrics or by helically applied strips. Both systems resulted in excellent results in terms of increasing the shear resistance. However, compared with their resin-impregnated counterparts, mortar-impregnated textiles may result in reduced effectiveness. Modelling of reinforced concrete members strengthened in shear with TRM jackets instead of FRP ones is presented by the authors as a rather straightforward procedure by the proper introduction of experimentally derived jacket effectiveness coefficients. From the limited results obtained in this study it is believed that TRM jacketing is an extremely promising solution for increasing the shear resistance of reinforced concrete members.

Résumé *Cet article décrit une recherche expérimentale sur l'application du mortier renforcé par textile (MRT) comme des moyens d'augmenter la résistance au cisaillement des membres en béton armé. MRT peut être considéré comme une solution de rechange aux polymères renforcés de fibres (PRF), fournissant des solutions à plusieurs des problèmes liés à l'application du dernier, sans compromettre beaucoup la conduit des membres renforcés. La conclusion dérivé de l'évaluation de la réaction expérimentale des membres renforcés au cisaillement est que la chemise au textile-mortier fournit un augmentation substantiel dans la résistance au cisaillement; cet augmentation est plus grand à mesure que le nombre de couches augmente et, selon le nombre de couches, est suffisant pour transformer l'échec au cisaillement à l'échec au fléchissement. Dans l'étude présentée ci-dessous les chemises MRT ont été fournies par emballage conventionnel des textiles ou par des bandes appliquées dans une manière hélicoïdale. Les deux systèmes ont eu des résultats excellents en termes d'augmentation de la résistance au cisaillement. Cependant, comparés à leurs contreparties imprégnées de résine, les textiles imprégnés du mortier peuvent résulter à une efficacité réduite. La modélisation des membres en béton armé renforcés au cisaillement avec des vestes de MRT au lieu de PRF est présenté par les auteurs dans une manière directe par l'introduction*

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appropriée des coefficients expérimentalement dérivés de l'efficacité de la chemise. Par les résultats obtenus en cette étude on croit que les chemises MRT introduit une solution extrêmement prometteuse pour augmenter la résistance au cisaillement des membres en béton armé.

1. Introduction and background

The need for upgrading existing structures has been enormous in the past years, both in non-seismic areas, due to deterioration and/or the introduction of more stringent design requirements, and in seismic areas, where structures designed according to old seismic codes have to meet performance levels demanded by current seismic design standards. One of the most common upgrading techniques for reinforced concrete members involves the use of jackets, which are aimed at increasing the shear resistance in regions with inadequate transverse reinforcement.

Among all jacketing techniques, the use of fiber reinforced polymers (FRP) has gained increasing popularity in the civil engineering community, due to the favourable properties possessed by these materials, namely: extremely high strength to weight ratio, corrosion resistance, ease and speed of application and minimal change in the geometry [1, 2]. Despite all these advantages, the FRP strengthening technique has a few drawbacks, which are attributed to the resins used to bind or impregnate the fibers. These drawbacks may be summarized as follows: (a) poor behaviour of epoxy resins at temperatures above the glass transition temperature, a fact which often calls for special and expensive fire protection measures; (b) relatively high cost of epoxies; (c) hazards for the manual worker, even though modern epoxies gradually become less hazardous due to smaller solvent contents; (d) inability to apply FRP on wet surfaces or at low temperatures; (e) lack of vapour permeability, which may cause damage to the concrete structure; (f) incompatibility of epoxy resins and substrate materials; and (g) difficulty to conduct post-earthquake assessment of the damage suffered by the reinforced concrete behind (undamaged) FRP jackets.

One possible solution to the above problems would be the replacement of organic with inorganic binders, e.g. cement-based mortars, leading to the replacement of FRP with fiber reinforced mortars (FRM). These materials have a relatively long-term record in structural engineering, especially in the development of thin section products [3], but they have problems too: As a consequence of the granularity of the mortar, penetration and impregnation of fiber sheets is very difficult to achieve; also, mortars cannot wet individual fibers, unlike resins. It is this property of epoxies, namely the ability to penetrate and wet the fibers, which results in excellent bond and tight interaction between fibers and matrix; hence, epoxy-impregnated continuous fiber sheets are used in a very efficient way. Despite the afore-mentioned bond-related problems, the use of composites with inorganic matrices (FRM) in the field of structural upgrading has not escaped the attention of the research community. The performance of carbon fiber sheets with an inorganic matrix made of aluminosilicate powder and a water-based activator has been evaluated by [4, 5]. These materials were used as externally bonded flexural strengthening reinforcement of concrete beams [4] or plain concrete prisms [5] and resulted in comparable performance with epoxy-impregnated sheets in terms of strength and stiffness, with some reduction in ductility. The fatigue performance of concrete beams strengthened in flexure with carbon fiber sheets bonded with the same inorganic matrix was evaluated in [6] and was found satisfactory. Large scale tests conducted by [7] on concrete beams strengthened in flexure or shear with externally bonded carbon sheets in a polymer-modified cementitious matrix have demonstrated that the technique is promising, albeit less effective compared with epoxy-based systems. In one study [8], unidirectional carbon sheets bonded with a cementitious binder were employed to confine small (100 × 200 mm) cylinders. Confined specimens in this study exhibited high strength and sufficient deformability, comparable to that of companion specimens wrapped with epoxy-impregnated carbon sheets.

Bond conditions in cementitious composites could be improved and fiber-matrix interactions could be made tighter when continuous fiber sheets are replaced by textiles. These materials comprise fabric meshes made of long woven, knitted or even unwoven fiber rovings in at least two (typically orthogonal) directions. The density, that is 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.

Although research on the use of textile meshes as reinforcement of cementitious products commenced in the early 1980s [9,10], developments in this field progressed rather slowly until the late 1990s. But during the past five years or so, the research community has put a considerable effort on the use of textiles as reinforcement of cement-based products, primarily in new constructions [11–20].

Studies on the use of textiles in the upgrading of concrete structures have been very limited: the work reported in [21] focused mainly on the bond between concrete and cement-based textile composites; the work in [22] presents test results on RC beams strengthened with two or three layers of alkaline resistant (AR) glass textile combined with cementitious mortar; and the work reported in [23] demonstrates the effectiveness of cement-based textile composites in the form of jackets to confine concrete in compression.

In the present study the authors: (a) provide test data on the use of carbon-based textiles in combination with inorganic (cement-based) binders, that is textile reinforced mortars (TRM), as shear strengthening materials of reinforced concrete members; (b) compare the effectiveness of these materials with their epoxy-bonded counterparts; and (c) present a simple model for the calculation of the shear resistance provided by TRM jackets in reinforced concrete members.

2. Experimental programme

2.1. Experimental method

The main objective of the experimental program was to provide a better understanding on the effectiveness of shear reinforcement offered by jackets made with continuous fiber (carbon) textiles in combination with an inorganic matrix material (cement-based mortar). 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 150 × 300 mm. 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" we imply that a single textile sheet was wrapped around the shear span until the desired number of layers was achieved (Fig. 1a). 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 (Fig. 1b). "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 (Fig. 1c). The two strips formed an angle of ±10° with respect to the transverse to the member axis.

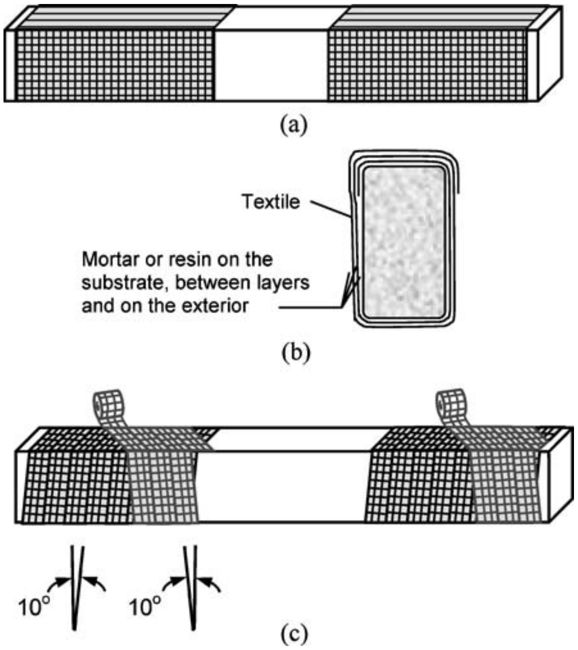


Fig. 1 Application of textile-reinforced mortar jackets in the shear spans: (a) conventional jacket, (b) layers of textile and mortar or resin, (c) spirally applied strips.

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.

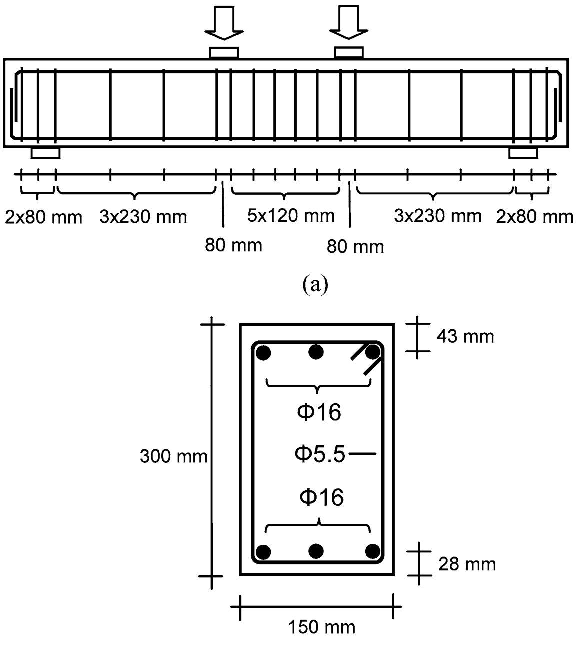
2.2. Test specimens and materials

All six beams were made from the same concrete batch. The beams were reinforced with three 16 mm diameter type S500s longitudinal rebars in each side (bottom and top).

Stirrups were hand-made using mild steel type S220, with a diameter of 5.5 mm; their spacing was 230 mm in the shear span, 120 mm in the constant moment region and 80 mm in the regions where concentrated loads were applied. It should be made clear that the spacing of stirrups in the shear span was increased intentionally, in order to ensure that failure of the RC members before strengthening would occur due to shear. Details of the reinforcement are shown in Figure 2.

Casting of the beams was made with ready-mix concrete in stiff steel moulds placed horizontally. The water:cement:sand:gravel proportions in the concrete mix were roughly 0.6:1:2.5:3.5 by weight. The specimens were cured using wet burlaps for about five days and then left in room conditions. Bonding of the jackets took place at a concrete age of about 30 days. In order to ensure a high bond quality between the concrete and the jackets, the specimens were thoroughly wire brushed, until any loose material was removed, and vacuumed. At the four edges in the shear span region, where the textile reinforcement was wrapped around, grinding of the concrete was provided to a radius of about 10 mm.

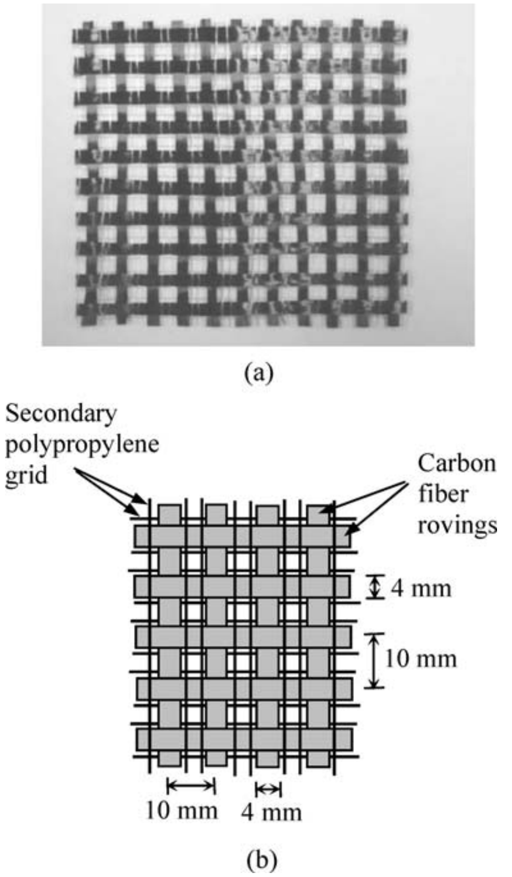
The outline of the jackets was marked on the specimens and the textile was cut to the required length. The textile contained equal quantity of high-strength carbon fiber rovings in two orthogonal directions (Fig. 3a). The rovings in each direction were simply placed one on top of the other and bonded on a secondary polypropylene grid (see Fig. 3b for the carbon textile architecture). Each roving was 4 mm wide and the clear spacing between rovings was 6 mm. The weight of carbon fibers in the textile was 168 g/m^2 and the nominal thickness of each layer (based on the equivalent smeared distri-



(a)

(b)

Fig. 2 Details of the reinforcement in the beams tested: (a) spacing of stirrups, (b) cross section.



(a)

(b)

Fig. 3 (a) Photograph and (b) architecture of bi-directional textile used in this study.

bution 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 taken from data sheets of the producer equal to 3350 MPa. The elastic modulus of carbon fibers was 225 GPa.

For the specimens receiving adhesive bonding a commercial structural adhesive (two-part epoxy resin with a mixing ratio 4:1 by weight) was used with a tensile strength of 30 MPa and an elastic modulus of 3.8 GPa (cured 7 days at 23°C). The adhesive was pasty with a viscosity such that complete wetting of the fibers in the textile was possible by using a plastic roller.

For the specimens receiving mortar as binding material, a commercial dry binder, consisting of cement and polymers at a ratio 10:1 by weight, was used. This binder contained fine cement and a low fraction of polymers. The binder to water ratio was 3:1 by weight, resulting in plastic consistency and good workability. Application of the mortar was made in approximately 1.5–2 mm thick layers with a smooth metal trowel. After application of the first mortar layer on the (dampened) concrete surface, the textile was applied and pressed slightly into the mortar, which protruded through all the perforations between rovings. The next mortar layer covered the textile completely and the operation was repeated until the required number of textile layers was applied and covered by the mortar. Of crucial importance in this method, as in the case of epoxy resins, was the application of each mortar layer while the previous one was still in a fresh state.

2.3. Testing procedure

The strength of mortar used in this study was obtained by flexural and compression testing according to [24], using a servohydraulic MTS testing machine. The average flexural and compressive strength values at 7 and 28 days for mortar are given in Table 1.

Table 1 Flexural and compressive strength of mortar

	Flexural strength (MPa)		Compressive strength (MPa)	
Mortar	Mean	Standard deviation	Mean	Standard deviation
7 days	3.02	0.61	27.45	1.65
28 days	4.24	0.78	30.61	1.83

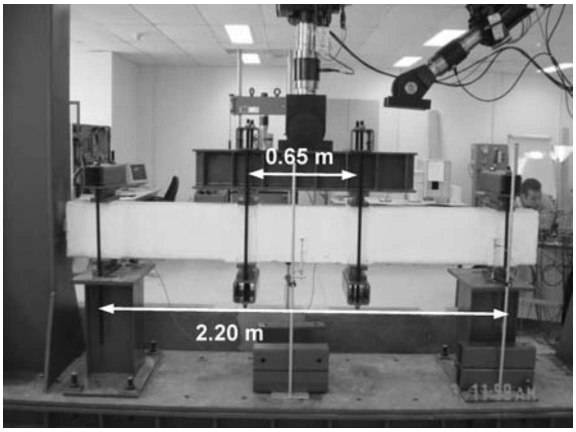


Fig. 4 Experimental setup for beam testing.

The compressive strength of concrete was determined from six 150 mm cubes taken during casting of the beams. The resulting value for the 28 day average compressive strength was 30.5 MPa. The steel used for longitudinal reinforcement had an average yield stress (determined from three specimens) equal to 575 MPa. The corresponding value for the steel used in stirrups was 275 MPa.

The six beams were subjected to transverse loading using a stiff steel frame as shown in Figure 4. The beams were loaded in four point bending at a total span of 2.20 m and a shear span of 0.775 m. The load was applied using a vertically positioned 500 kN MTS actuator. Four specimens (C, M2, R2 and M2-s) were tested monotonically (at an age of four months) at a displacement rate of 0.01 mm/sec and the remaining two specimens (M1, R1) were tested by applying the load in a quasistatic cyclic pattern of controlled displacements at a rate of 0.2 mm/sec. This enabled to access the performance of textile-based jackets not only in static but also in cyclic loading.

The loading sequence consisted of two cycles at a series of progressively increasing (by 1 mm) displacement amplitudes in each direction (push and pull), as illustrated in Figure 5. It is to be noted that beams M1 and R1 were strengthened after monotonic testing of the first four beams had taken place. Hence, testing of these two beams was done approximately two months after that for the first four beams (which were tested monotonically).

An important point during cyclic testing was the transfer of the force from the actuator to the beam. This was achieved through four pairs of steel tubes (placed at each load application point and at each sup-

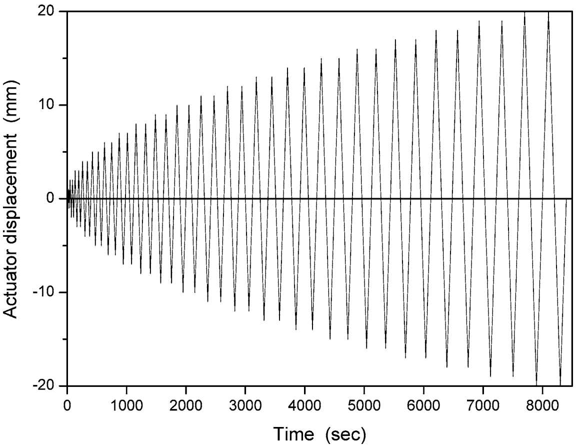


Fig. 5 Loading history for beams R1 and M1.

port, with one tube above and one below the concrete beam) clamped together with a set of two 28 mm diameter threaded rods.

Displacements were measured at mid-span using an external linear variable differential transducer (LVDT) mounted on the side of the concrete beam. Additional measurements of displacements were made at the supports, in order to make corrections accounting for the stiffness of the loading system. Data from the load cell, the actuator's displacement transducer and the external LVDTs were recorded using a fully computerized data acquisition system. From the applied load and displacement measurements the load versus mid-span displacement curves were obtained for each test.

Some of the beams (those tested monotonically) were also instrumented with acoustic emission (AE) sensors, in order to assess the evolution of damage during loading. Although the details of the AE study are outside the scope of the present paper, some of the basic results will be given in the next section. To record the AE signals, the 24-channel system DiSP of Physical Acoustics Corp. was used. The system was equipped with 14 PAC R15 sensors (having a resonance frequency of 150 kHz), six on each side of the beams and two at the ends (Fig. 6). A voltage threshold of 40 dB was applied. The number of AE events and other parameters including the number of counts, energy, duration etc. were recorded.

3. Results and discussion

Figure 7a shows the load versus mid-span displacement response of the four beams tested monotoni-

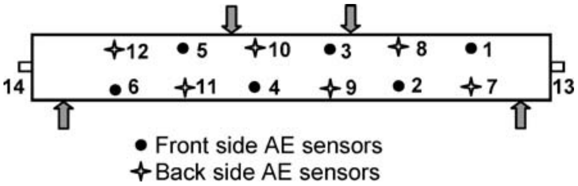


Fig. 6 Location of AE sensors.

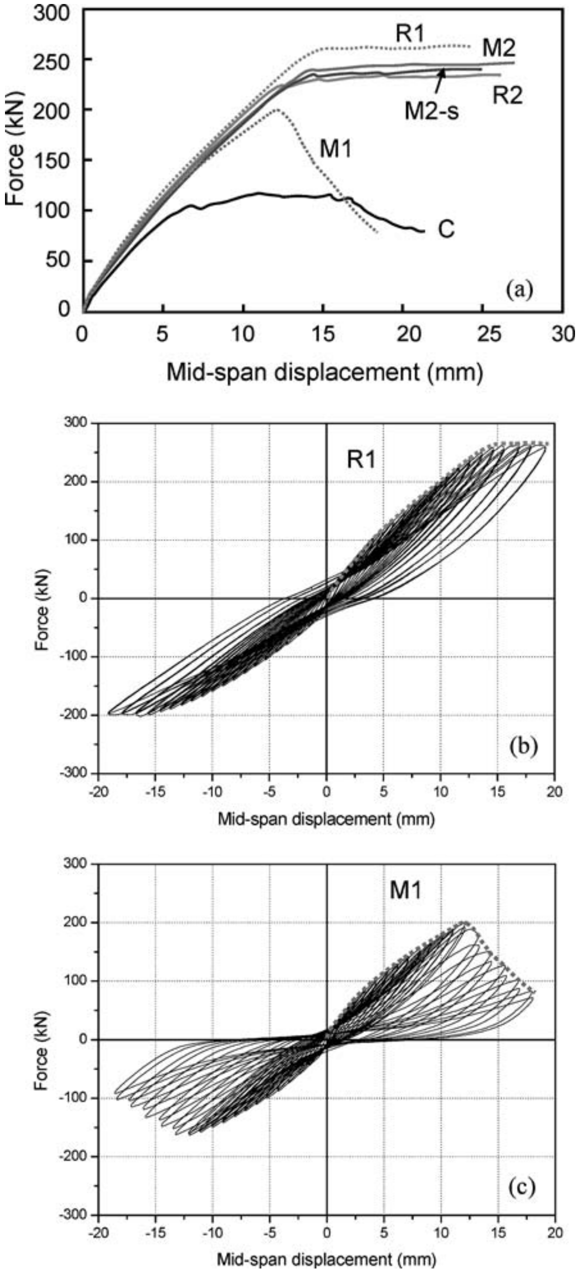


Fig. 7 Force–mid-span displacement curves: (a) for all beams tested (for beams subjected to cyclic loading the envelope curves in the push direction are given); (b) for beam R1; (c) for beam M1.

Table 2 Summary of test results

Specimen	Peak force (kN)	Failure mode
C	116.5	Shear
R2	233.4	Flexure
M2	243.8	Flexure
M2-s	237.7	Flexure
R1	261.9	Flexure
M1	200.1	Shear

cally as well as the envelope curve (dotted lines) in the push direction (so that it may be directly comparable with the monotonic testing curves) of the two beams tested cyclically. The force-deflection loops of the latter are given in Figure 7b,c. A summary of peak loads and failure modes for each specimen is given in Table 2.

The control beam (C) failed in shear, as expected, through the formation of diagonal cracks in the shear spans (Fig. 8a). 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 16 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 (see, for instance, Fig. 8b) 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, which 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 jacket (with two layers of textile reinforcement) in terms of suppressing the shear failure.

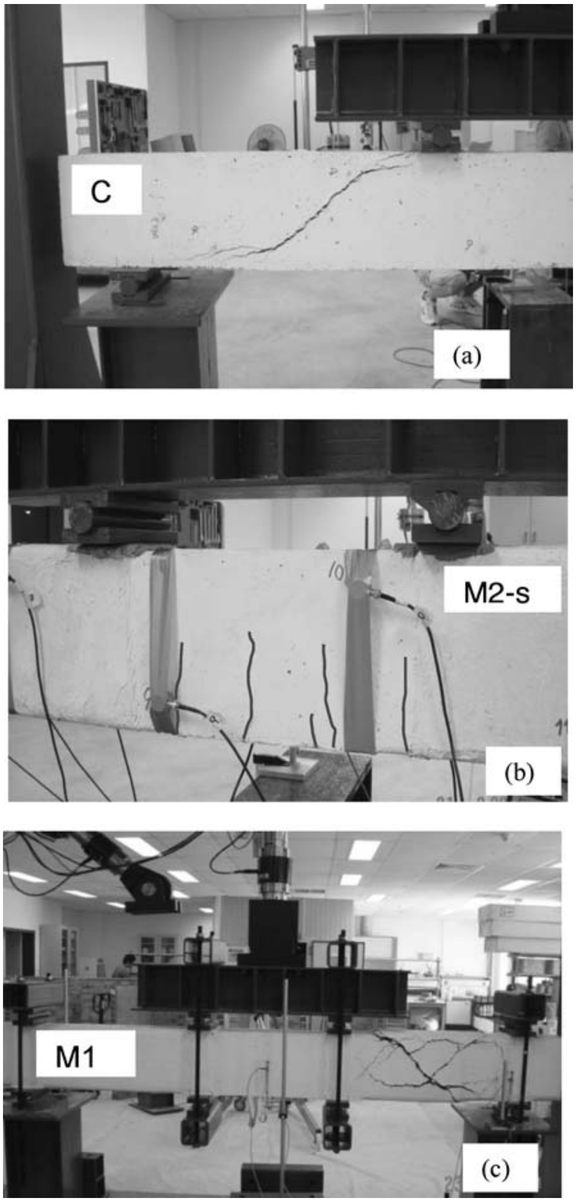


Fig. 8 Failure of beams tested: (a) diagonal shear, (b) flexural cracking, (c) diagonal shear (due to cyclic loading).

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. 2b). Specimen M1 failed in shear; this was evident by diagonal cracking in the shear span (Fig. 8f) 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 have 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 the maximum 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 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.

As one of the main AE findings we report here that the distribution of damage due to cracking in the beams was different in specimens with different types of jackets. Comparing the response of specimen R2 with that of specimen M2, in terms of the relative energy release (in dimensionless MARSE units – MARSE standing for Measured Area of the Rectified Signal Envelope) versus time, it was concluded that cracking in the (jacketed) shear spans was not arrested as effectively in specimen M2 as in specimen R2 (e.g. Fig. 9 for the right shear span). But on the other hand, as a result of this, cracking in the flexural span was much more intense in specimen R2 and less severe in specimen M2.

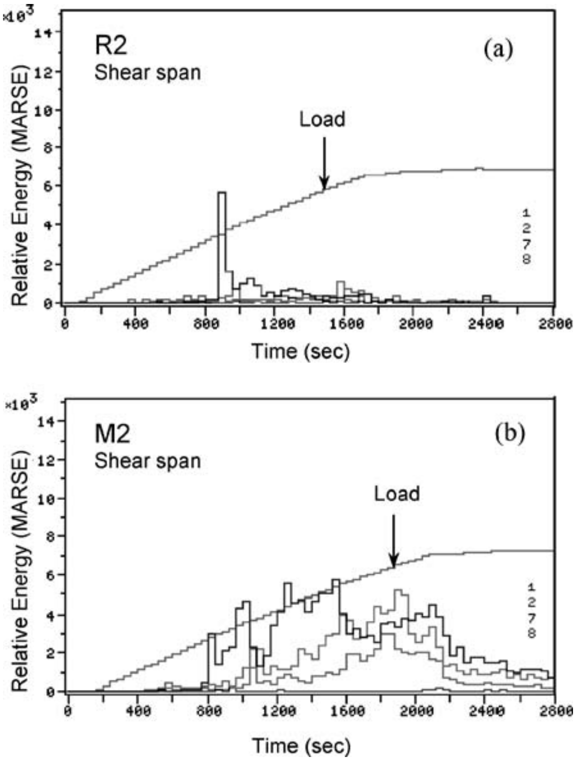


Fig. 9 Energy versus time in the right shear span as recorded by sensors 1, 2, 7 and 8 in specimens (a) R2 and (b) M2.

4. 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 [e.g. 1, 25–27]. 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. 10), the TRM jacket contribution to shear resistance, V_t, can be written in the following simplified form:

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

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

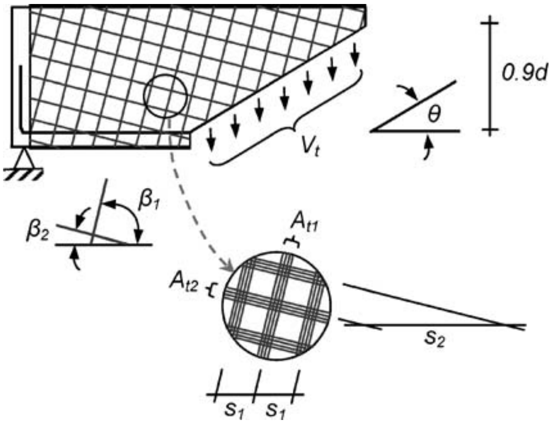


Fig. 10 Contribution of textiles with fibers in two orthogonal directions to shear resistance.

between the inclined shear crack and the member axis. Equation (1) 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 for resin-based (FRP) jackets (ε_{fe}) 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 $\theta = 45°$, $\beta_1 = 90°$ (fibers perpendicular to the member axis), $\beta_2 = 0°$ (fibers parallel to the member axis), $d = 272$ mm, $E_{fib} = 225$ GPa, $A_{t1}/s_1 = 2 \times 0.047 = 0.094$ mm, $A_{t2}/s_2 = 0$ ($s_2 = \infty$) and $V_t = 0.5 \times (200.1 \text{ kN} - 116.5 \text{ kN}) = 41.8$ kN, the effective strain in the TRM jacket at shear failure is obtained from eq. (1) equal to 0.8%. When the same analysis applies to beam R1 (the resin counterpart of beam M1) with contribution of the FRP jacket to the shear resistance at least equal to $0.5 \times (261.9 \text{ kN} - 116.5 \text{ kN}) = 72.7$ 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% (0.8% divided by 1.6%), with 57% (0.8% divided by 1.4%) being an upper bound. Hence we conclude 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.

5. Conclusions

On the basis of the test results presented in this paper we conclude that closed-type textile-reinforced mortar jackets provide substantial gain in the shear capacity of reinforced concrete members. Two layers of mortar-impregnated textile reinforcement (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 about 55% as effective as the FRP one.

Modelling of reinforced concrete members strengthened in shear with TRM jackets is a straightforward task, which can be performed in analogy to FRP jacketing, through the introduction of experimentally derived jacket effectiveness coefficients. Of course, obtaining reliable values for such coefficients would imply extensive testing.

From the relatively limited results obtained in this study the authors believe that TRM jacketing is an extremely promising solution for increasing the shear capacity of reinforced concrete members. Further investigation is needed not only to enhance the experimental database but also to optimize the mortar properties and to obtain a better understanding of textile reinforcement behavior.

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