Materials and Structures
DOI 10.1617/s11527-014-0470-9

ORIGINAL ARTICLE

Shear strengthening of reinforced concrete T-beams under cyclic loading with TRM or FRP jackets

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Received: 6 July 2014 / Accepted: 3 November 2014

Abstract The paper presents a systematic investigation on the effectiveness of U-shaped textile-reinforced mortar (TRM) jackets as shear strengthening materials of reinforced concrete T-beams, by examining a number of parameters not studied before: cyclic loading; fixed support conditions; different types of textiles; different numbers of layers; anchors; the relative performance of TRM versus equivalent FRP systems; and different displacement amplitudes of the loading cycles. For beams without anchors it is concluded that the effectiveness of TRM increases non-proportionally with the number of layers and that, for the same total volume fraction of fibers in the jacket, one layer of textile is more effective than two. For beams with anchored TRM jackets it is concluded that the effectiveness of the strengthening system is quite high, as is the effectiveness of an anchored FRP system. The results are used to derive simple analytical models for the effective strain in anchored or non-anchored TRM jackets.

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Published online: 08 November 2014

Keywords Anchors · Cyclic loading · Fiber-reinforced polymers (FRP) · Reinforced concrete · Shear strengthening · T-beams · Textile-reinforced mortar (TRM)

1 Introduction and background

The use of externally applied composite materials as shear strengthening materials for reinforced concrete (RC) elements has become quite popular, due to the outstanding combination of properties (low weight, easy handling and application, high strength, immunity to corrosion, minimal disruption) offered by composites. A common field of application is that of externally applied jacketing in RC beams to enhance shear resistance. Investigations on shear strengthening of RC elements with polymer-based composites started in the 1990s (e.g. [11, 16]) and have been numerous since then. Shear strengthening projects in RC beams with composite materials are typically realized through the use of three-sided (U-shaped) jackets comprising polymer-impregnated unidirectional sheets (with fibers in the direction perpendicular to the member axis) wrapped around the web of T-beams. The effectiveness of U-shaped FRP jackets may be improved substantially by providing anchorage at the two ends of the U-shaped jacket. Anchorage systems typically involve the use of metallic elements (e.g. plates and bolts) or FRP anchors. Metallic anchorages have been investigated by [14, 15] and

[9]. FRP anchors comprise either near-surface mounted (NSM) bars placed at the re-entrant corners between slab and web (e.g. [8]) or resin-impregnated fiber rovings, often referred to as spike anchors. Spike anchors are more practical to use and have received the attention of investigators relatively recently [12, 13]. More details on the subject may be found in the review paper by [10].

Key advantage of shear strengthening with U-shaped FRP jackets is simplicity of application, whereas some drawbacks may be attributed to the polymeric resins used to impregnate the fibers, namely: poor behavior at high temperatures, high costs, inapplicability on wet surfaces, lack of vapour permeability and difficulty to conduct post-earthquake assessment behind FRP jackets. Such drawbacks may be eliminated by replacing polymers with inorganic mortars, which may be combined with fibers in the form of textile meshes (e.g. [18]). In the first studies on shear strengthening of RC elements, this class of materials was given the name "textile-reinforced mortar" (TRM) by [17] and "textile-reinforced concrete" (TRC) by Brueckner et al. [5, 6]. Triantafillou and Papanicolaou [17] investigated both experimentally and analytically simply supported RC beams with rectangular cross sections, under either monotonic or cyclic loading, and concluded that TRM jacketing in the shear spans, although less effective than FRP, is a highly promising solution for shear strengthening of RC elements. In their parallel study, Brueckner et al. [5, 6] investigated experimentally the shear strengthening of simply supported T-beams under monotonic loading through the use of U-shaped TRC jackets. In one of the test specimens in the studies of Brueckner et al. [5, 6] the jackets were combined with metallic anchors, which were proved to be quite effective in transferring stresses from the jacket to the slab. A few years later, [2] carried out experimental and numerical studies on the effectiveness of TRM as a means of increasing the shear capacity of small scale simply supported RC beams with rectangular cross sections. The beams, which were strengthened with TRM bonded on the two sides of the shear spans, were subjected to monotonic loading; the results, also confirmed by finite element analyses, proved once more the effectiveness of the method. More recently, [4] confirmed the above findings, through testing of simply supported beams with rectangular cross sections. In this study, the mortar-impregnated textile material was given the term FRCM (fabric-reinforced cementitious matrix composite system), which is more common in North American terminology (ACI [1]).

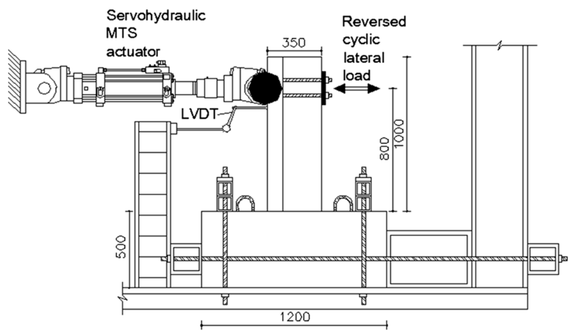

Fig. 1 Test set-up

From the literature survey presented above it is clear that studies on TRM shear strengthening are mainly limited to simply supported beams with rectangular cross sections under monotonic loading. The work of Brueckner et al. [5, 6] is the only one so far where TRM has been applied on (monotonically tested simply supported) T-beams, with mechanical anchors used in one of the specimens. In this paper the authors investigate systematically the shear strengthening of T-beams with TRM by examining a number of parameters not studied before: fixed support conditions, which simulate more realistically the end conditions of continuous beams, typically found in real structures; cyclic loading, which simulates seismic loads; different types of textiles and different numbers of layers; different configurations of mechanical anchors; the relative performance of TRM versus equivalent FRP systems; and different displacement amplitudes of the loading cycles. Details are provided in the following sections.

2 Experimental program

2.1 Test specimens and experimental parameters

The experimental program aimed to study three-sided (U-shaped) TRM jackets with or without anchors as shear strengthening materials of reinforced concrete T-beams subjected cyclic shear. A total of 13 specimens with the same geometry were constructed and tested as cantilevers (Fig. 1), in order to simulate realistic boundary conditions of continuous beams near their supports (columns). All beams were intentionally designed so that their flexural resistance exceeded the shear resistance not only before strengthening but also after, hence only shear failure could develop. As a result, the amounts of internal steel reinforcement are not representative of real beams, but they do serve the purpose of activating shear failure as the dominant failure mechanism. Details of beam geometry and reinforcement are given in Fig. 2.

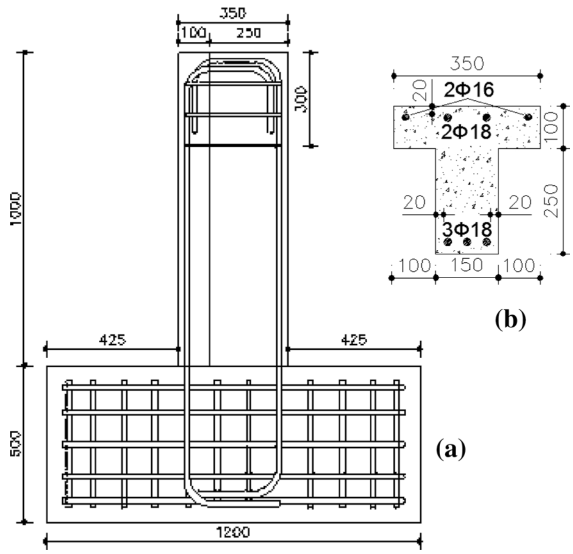

Fig. 2 **a** Beam geometry and reinforcement; **b** cross section (dimensions in mm)

The beams were designed such that the role of several parameters on the effectiveness of shear strengthening schemes could be investigated, namely the number of textile layers, the weight (i.e. the nominal thickness) of the textile, the use of anchors, the spacing of anchors, the use of mortar-based versus polymer-based (epoxy) matrix in the jackets and the displacement amplitude of the loading cycles. A description of the specimens follows next, supported by Fig. 3 and Table 1.

- One beam (**C**) was tested without shear strengthening, as control.
- Specimens **L1** and **L2** were strengthened with a TRM jacket comprising one and two layers, respectively, of a light-weight textile, without anchors (Fig. 3a).
- Specimens **H1** and **H2** were strengthened with a TRM jacket comprising one and two layers, respectively, of a heavy-weight textile, without anchors (Fig. 3a). This textile was two times heavier than the light-weight one.

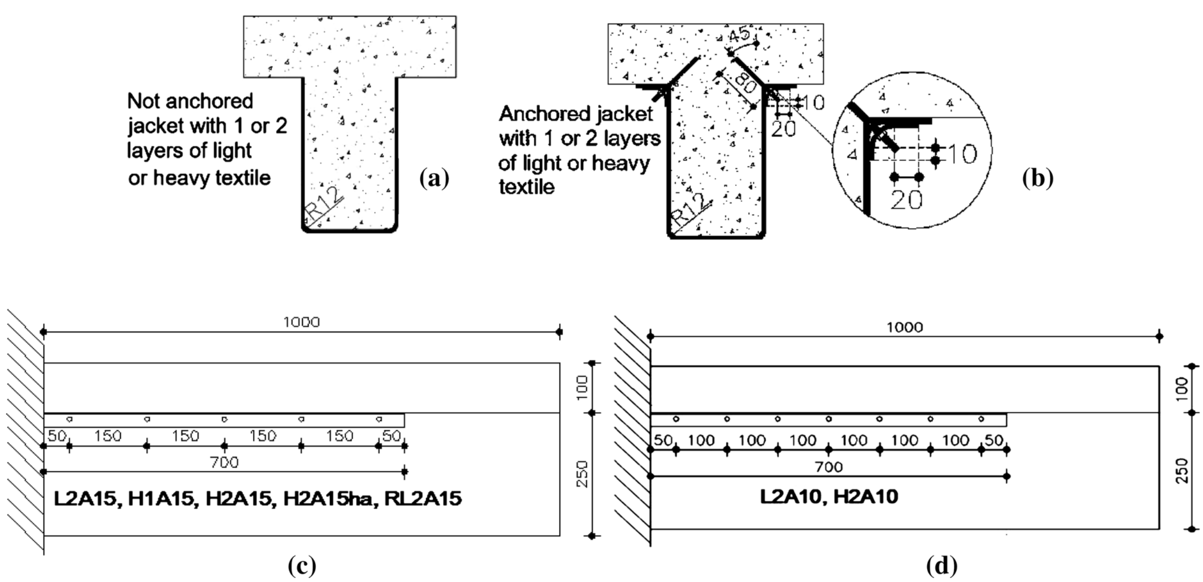

Fig. 3 Strengthening configuration for the beams tested. **a** Cross section of strengthened beams without anchors; **b** cross section of strengthened beams with anchors; **c** side view of steel section and bolts at spacing of 150 mm; **d** side view of steel section and bolts at spacing of 100 mm

Table 1 Description of strengthening schemes and concrete strength

Specimen notation	Strengthening scheme	Concrete strength f_c (MPa)
C	No strengthening	20.20
L1	1 layer of TRM, light textile	20.85
L2	2 layers of TRM, light textile	21.64
H1	1 layer of TRM, heavy textile	23.35
H2	2 layers of TRM, heavy textile	23.12
L2A15	2 layers of TRM, light textile, anchors at 150 mm	24.24
L2A15ha	2 layers of TRM, light textile, anchors at 150 mm, higher amplitude	23.18
L2A10	2 layers of TRM, light textile, anchors at 100 mm	12.58
H1A15	1 layer of TRM, heavy textile, anchors at 150 mm	13.39
H2A15	2 layers of TRM, heavy textile, anchors at 150 mm	13.88
H2A10	2 layers of TRM, heavy textile, anchors at 100 mm	25.06
RL2	2 layers of FRP, light textile	20.67
RL2A15	2 layers of FRP, light textile, anchors at 150 mm	24.66

- Specimen **L2A15** was strengthened with a TRM jacket comprising two layers of the light textile, anchored through the use of a longitudinally placed thin curved steel section fixed at the slab with mechanical anchors at spacing equal to 150 mm (Fig. 3b, c). Specimen **L2A10** was strengthened as L2A15, except that the spacing of anchors was equal to 100 mm (Fig. 3b, d).
- Specimens **H1A15** and **H2A15** were strengthened with a TRM jacket comprising one and two layers, respectively, of the heavy textile, anchored as in specimen L2A15. Specimen **H2A10** was strengthened as **H2A15**, except that the spacing of anchors was equal to 100 mm.
- Specimen **RL2** was identical to L2, except that the two layers of the light textile were impregnated with epoxy resin instead of mortar (FRP vs. TRM).
- Specimen **RL2A15** was identical to L2A15, except that the two layers of the light textile were impregnated with epoxy resin instead of mortar (anchored FRP vs. anchored TRM).
- Specimen **L2A15ha** was identical to **L2A15**. However, this specimen was tested with loading cycles of higher amplitude (5 mm) in comparison to all the other specimens (2 mm).

In summary, except for the control specimen (C), the specimens' notation is as follows: the first symbol denotes the weight of the textile (L for light, H for heavy); the second symbol denotes the number of layers (1 or 2); A denotes the use of anchors; the number following A denotes the spacing of anchors (15 or 10 for 150 or 100 mm, respectively); the symbol R as a first symbol denotes impregnation of the fibers with resin (FRP system); and the symbol ha denotes loading with cycles of higher amplitude in comparison to all other specimens.

2.2 Materials and strengthening procedures

Casting of the beams was made with two different batches of ready-mix concrete. The average compressive strength on the day of testing the beams, measured on 150 × 150 mm cubes (average values from three specimens), is given in Table 1. On the basis of concrete strengths, the beams were grouped in two series (corresponding to the two different batches): (a) The beams made of normal strength concrete, that is all beams except for L2A10, H1A15 and H2A15, with an average strength equal to 22.7 MPa; (b) beams L2A10, H1A15 and H2A15, with a (not intentionally) lower concrete strength, equal (on average) to 13.3 MPa. Strength properties (average values from three specimens) for the steel used for longitudinal reinforcement were as follows: yield stress 545 MPa, tensile strength 660 MPa.

For the specimens receiving jacketing, two different commercial textiles ("light" and "heavy") with equal quantity of carbon rovings in two orthogonal directions were used (Fig. 4a). Each roving was approximately 3 mm wide and the spacing between rovings (axis to axis) was 10 mm. The mass per unit area was 174 g/m^2 for the light textile and 348 g/m^2 for the heavy textile, resulting in a nominal thickness of each layer (based on the equivalent smeared distribution of fibers) equal to 0.048 and 0.096 mm for the light and the heavy textile, respectively. The guaranteed tensile strength and the elastic modulus of the carbon fibers, as taken from data sheets of the producer, were equal to 3,375 MPa and 225 GPa, respectively.

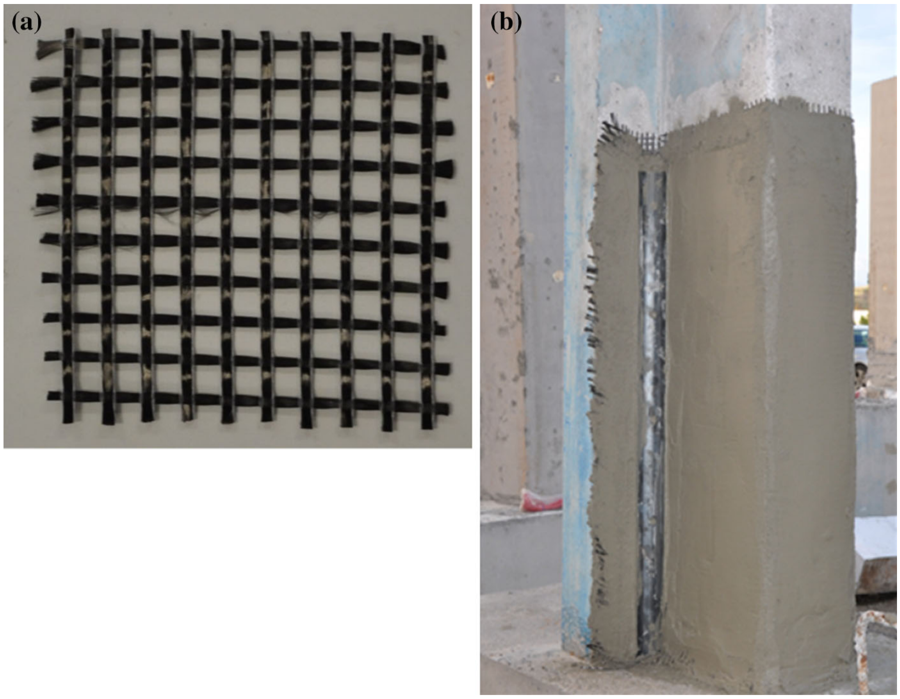

Fig. 4 **a** Textile architecture; **b** TRM jacket with anchorage

For the specimens receiving mortar as a binding material, a commercial cementitious dry binder mixed with re-dispersible polymers was used. The binder to water ratio was 5:1 by weight, resulting in plastic consistency and good workability. Application of the mortar was made in approximately 2 mm thick layers with a smooth metal trowel. Preparation of the concrete surface was done by mechanical grinding. 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 fiber rovings. The next mortar layer covered the textile completely and the operation was repeated until all textile layers were 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.

The flexural and compressive strength of the mortar was obtained according to EN-1015-11 [7], as average of 6 specimens. The mean compressive and flexural strength on the day of testing were 21.8 and 5 MPa, respectively. Standard deviations were 1.53 and 0.1 MPa for the compressive and the flexural strength, respectively.

For the specimens receiving adhesive bonding, a commercial low viscosity structural adhesive (two-part epoxy resin with a mixing ratio 3:1 by weight) with tensile strength of 22.7 MPa and an elastic modulus of 1.2 GPa was used; these values were provided by the manufacturer and were obtained according to ASTM D638 [3]. The adhesive had low viscosity such that complete wetting of the sheets was possible by using a plastic roller.

The anchorage system comprised 3 mm thick curved steel sections fixed at the slab with steel anchors (Figs. 3b–d, 4b). The steel sections were placed at the corners between the slab and the web, on top of the ends of the jacket, at a radius equal to 20 mm, while the mortar was still wet. The anchors were made of 6 mm diameter threaded rods, which were placed inside 45° holes drilled at a fixed spacing (150 or 100 mm). Holes were drilled into the slab with dimensions 80 mm in depth and 9 mm in diameter. The holes were filled with a two-part epoxy adhesive to half of their depths, the anchors were inserted into the holes, excessive resin was removed and the steel sections were fixed by tightening the bolts through the use of nuts, after hardening of the epoxy adhesive. This method of anchoring was selected on the basis of transferring the tension forces from the jacket into the slab.

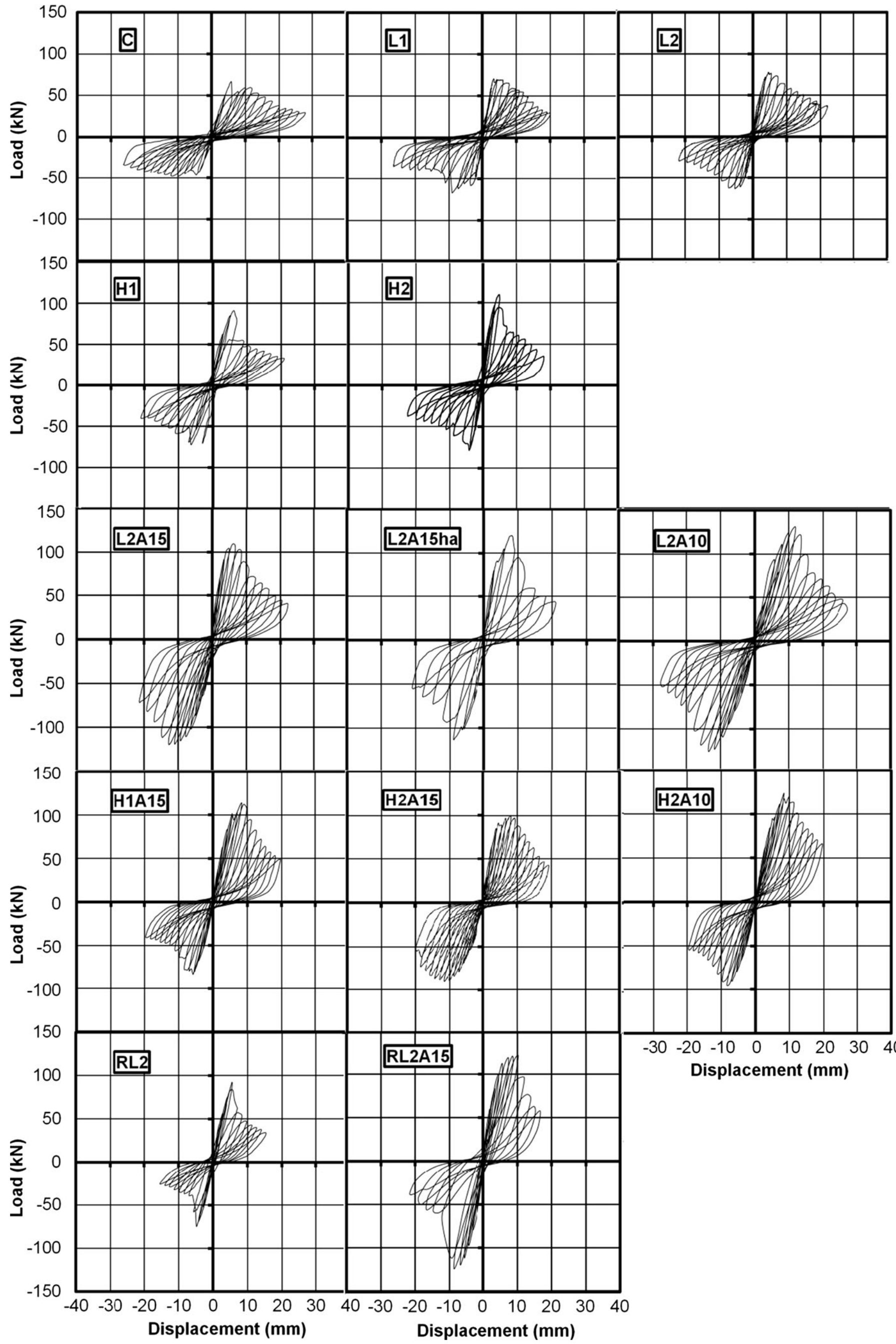

Fig. 5 Load versus displacement (at section of load application) curves

2.3 Experimental setup and procedure

All beams were subjected to lateral cyclic loading (Fig. 1) with a shear span of 0.8 m. Loading comprised successive cycles progressively increasing by fixed amplitudes (2 mm in all specimens, 5 mm in Specimen L2A15ha), at a rate equal to 0.2 mm/s. The load was applied using a horizontally positioned 250 kN MTS actuator. The transfer of force from the actuator to the specimen was achieved through two steel tubes (one on top of the flange and the other on the web of the beam) clamped together with two 26 mm diameter threaded rods (Fig. 1).

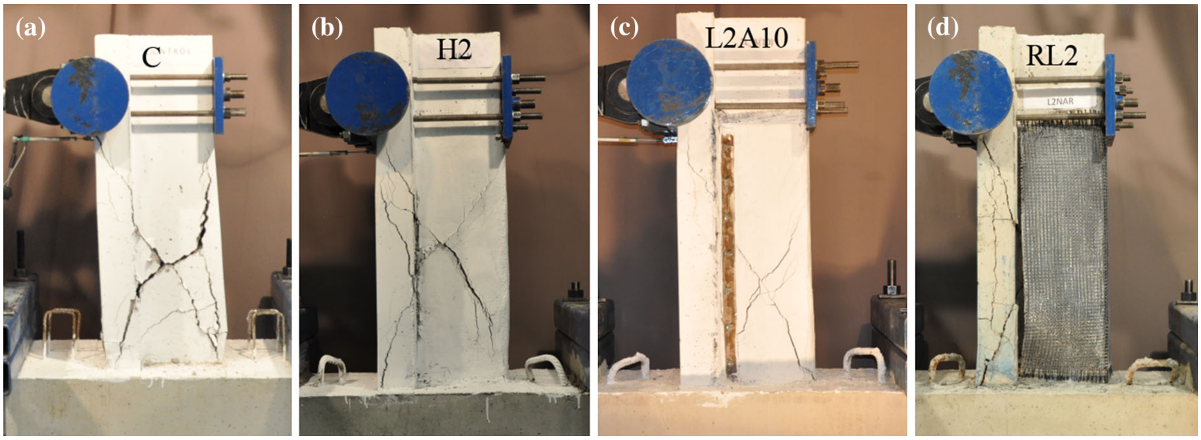

Fig. 6 Shear failure of beams **a** C, **b** H2, **c** L2A10 and **d** RL2

Displacements were measured at the end of the shear span using an external linear variable differential transducer (LVDT). Data from the load cell, the actuator's displacement transducer and the external LVDT were recorded using a fully computerized data acquisition system.

3 Experimental results and discussion

Figure 5 shows the load versus displacement at the section of load application of all the beams tested. All 13 specimens failed in shear, as expected, through the formation of diagonal cracks in the shear span (e.g. Fig. 6a–d, for beams C, H2, L2A10 and RL2). In the specimens strengthened with TRM the cracks were clearly visible on the jackets, due to the brittle nature of the inorganic matrix (cement-based mortar), which cracked too. Diagonal cracking in the FRP-strengthened specimens was confirmed by removing the jackets at the end of each test, as illustrated in Fig. 7a for Specimen RL2A15. For the sake of completeness, such confirmation was done for the TRM-strengthened specimens too (e.g. Fig. 7b for Specimen H1A15). All shear cracks formed an angle equal to 40°–45° with respect to the member axis.

The shear capacity of each beam, equal to the peak load, is given in Table 2 for both the "push" and the "pull" direction of loading. In all specimens, diagonal cracking resulted in failure of the jacket. In most cases, especially those where jackets were anchored, failure was evidenced by pull-out of the fiber bundles crossing the shear cracks (Fig. 8a); this failure mode occurred in Specimens L2A15, L2A15ha, L2A10, H1A15, H1A10 and H1. Another failure mode of the jackets was "debonding", which was either local, that is limited only adjacent to a few wide shear cracks (Specimens L1, L2 and H2), or full (Fig. 6d), corresponding to complete detachment of the jacket (Specimen RL2). A third failure mode, observed in Specimen H2A10, involved rupture of the fiber bundles near the contact with the anchored steel section (Fig. 8b). Finally, Specimen RL2A15 failed by pull-out of the anchors, followed by full debonding (Fig. 8c).

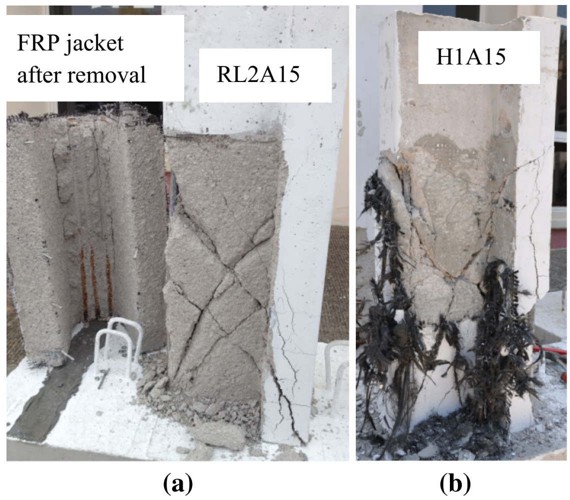

Fig. 7 Shear cracking as evidenced after removal of the **a** FRP and **b** the TRM jacket

Table 2 Summary of test results

Specimen	Peak shear force (kN)		Failure mode of the jacket	Shear force corresponding to the "concrete" contribution, V_{Rc} (kN)		Shear force resisted by the jacket, V_{Rj} (kN)		
	Push	Pull		Push	Pull	Push	Pull	Average
C	66.41	47.85	–	66.41	47.85	–	–	–
L1	69.82	65.55	Debonding (local)	66.41	47.85	3.41	17.70	10.56
L2	77.76	63.35	Debonding (local)	66.41	47.85	11.35	15.50	13.43
H1	90.70	71.90	Pull-out of rovings	66.41	47.85	24.29	24.05	24.17
H2	109.74	78.61	Debonding (local)	66.41	47.85	43.33	30.76	37.05
L2A15	109.50	119.26	Pull-out of rovings	66.41	47.85	43.09	71.41	57.25
L2A15ha	120.00	113.65	Pull-out of rovings	66.41	47.85	53.59	65.80	59.70
L2A10	130.62	128.17	Pull-out of rovings	50.83[a]	36.63[a]	79.79	91.54	85.66
H1A15	113.28	83.50	Pull-out of rovings	50.83[a]	36.63[a]	62.45	46.87	54.66
H2A15	99.98	90.70	Pull-out of rovings	50.83[a]	36.63[a]	49.15	54.07	51.61
H2A10	121.95	96.56	Fiber rupture	66.41	47.85	55.54	48.71	52.13
RL2	92.65	73.24	Debonding (full)	66.41	47.85	26.24	25.39	25.82
RL2A15	120.97	124.02	Pull-out of anchors and debonding	66.41	47.85	54.56	76.17	65.37

[a] Calculated by multiplying the value of V_{Rc} for beams with concrete of higher strength (22.7 MPa) by $\sqrt{13.3}/\sqrt{22.7} = 0.765$

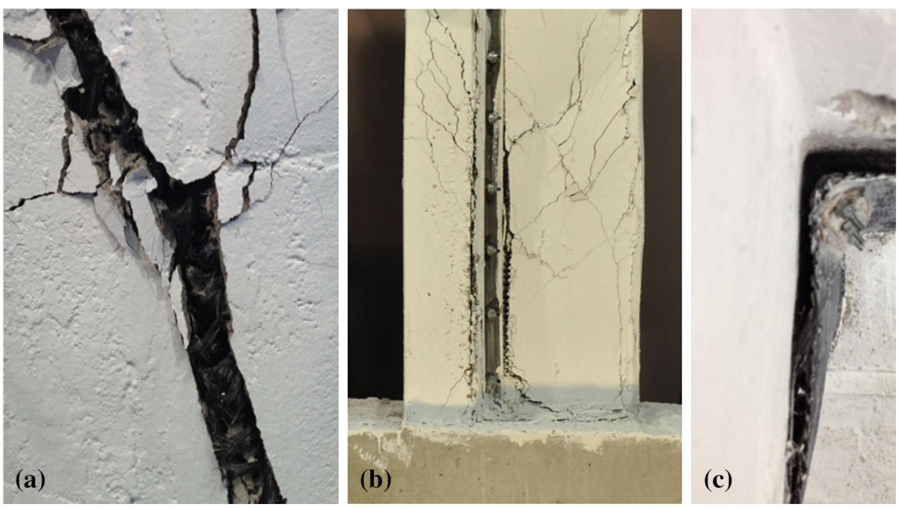

Fig. 8 **a** Pull-out of fiber bundles crossing a shear crack; **b** tensile rupture of the fiber bundles near the contact with the anchored steel section; **c** pull-out of the anchors, followed by debonding

In agreement with nearly all analytical models for the contribution of externally bonded reinforcement to the shear resistance, it is assumed that the shear resistance of a strengthened beam minus the resistance of the control specimen, V_{Rc}, gives the contribution of the strengthening system, V_{Rj}, to the total resistance. As none of the specimens contained internal shear reinforcement, the shear resistance of the control specimen depends heavily on the strength of concrete. In fact, according to most analytical models, the shear resistance of members without shear reinforcement is proportional to the square root of the compressive strength of concrete. On the basis of this assumption, the shear force corresponding to the "concrete" contribution, V_{Rc}, is equal to the shear resistance of specimen C, that is 66.41 and 47.85 kN in the "push"

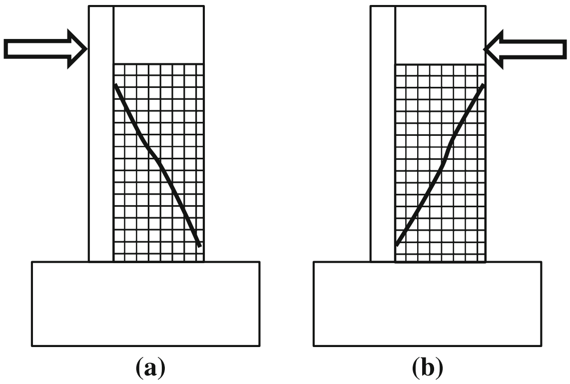

Fig. 9 Shear cracking and activation of the jacket in the **a** "push" and **b** "pull" direction

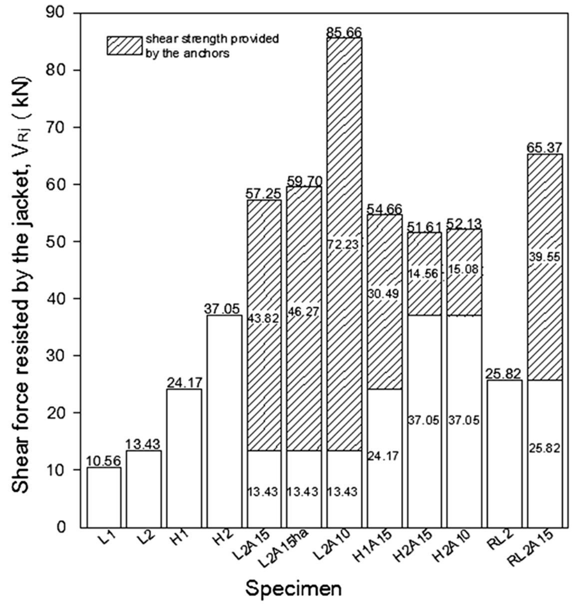

Fig. 10 Shear force resisted by the jacket

and "pull" direction, respectively, for all the beams with a concrete strength equal to that of Specimen C, that is 22.7 MPa. For the other specimens, that is L2A10, H1A15 and H2A15, which had a lower concrete strength, equal to 13.3 MPa, V_{Rc} may be estimated by multiplying the shear resistance of Specimen C by $\sqrt{13.3}/\sqrt{22.7} = 0.765$. The resulting value for V_{Rc} corresponding to Specimens L2A10, H1A15 and H2A15 is 50.83 and 36.63 kN in the "push" and "pull" direction, respectively. With V_{Rc} and the total shear resistance known, the contribution of the strengthening system, V_{Rj}, to the shear resistance may be calculated, as given in Table 2.

Regardless of the loading direction ("push" or "pull"), the jacket resists shear by approximately the same mechanism, that is stretching of fiber rovings crossing diagonal cracks in the web (Fig. 9). On the basis of this assumption, the average value of V_{Rj} in the "push" and "pull" direction (see last column in Table 2 and Fig. 10) may be used to draw conclusions regarding the effectiveness of the strengthening system for each beam, as described in the following.

By comparing V_{Rj} for beams L1 and L2 as well as for H1 and H2, it becomes clear that the shear carried by the TRM jacket (10.56 and 13.43 kN for L1 and L2, 24.17 and 37.05 kN for H1 and H2) does not increase proportionally to the number of layers. Moreover, the V_{Rj} values for Specimens L2 and H1 (13.43 and 24.17 kN, respectively), in which the jackets contain the same volume of fibers, indicate that one layer of a heavy textile is much more effective than two layers of a 50 % lighter textile.

A comparison of the results for beams L2 and L2A15 shows that the use of anchorage increases dramatically the effectiveness of the jacket, by more than 300 % [(57.25 − 13.43)/13.43 = 326 %]. However, if the comparison is made for beams H1 and H1A15, it is calculated that the use of anchorage increases the effectiveness of the jacket by approximately 125 % [(54.66 − 24.17)/24.17]. Finally, if the comparison is made for beams H2 and H2A15, it is calculated that the use of anchorage increases the effectiveness of the jacket by approximately 40 % [(51.61 − 37.05)/37.05]. Hence, the effectiveness of anchorage is always high but it decreases as the shear resisted by the jacket without anchorage increases.

The results for beams RL2 and L2 indicate that the use of epoxy resin instead of a cementitious matrix increases the effectiveness of a non-anchored jacket by about 90 % [(25.82 − 13.43)/13.43 = 92 %]. However, if the comparison is made for beams RL2A15 and L2A15, in which the jackets were anchored, it is calculated that the use of epoxy-based matrix instead of the cement-based one increases the effectiveness of the jacket by only 14 % [=(65.37 − 57.25)/57.25]. Hence, U-shaped TRM jackets in T-beams are substantially less effective than their FRP counterparts. However, the effectiveness of the two systems becomes comparable in the presence of anchorage.

The role of the spacing of the anchors may be investigated by comparing the results for beams L2A15 versus L2A10 and H2A15 versus H2A10. Reduction of the anchor spacing from 150 to 100 mm increased the effectiveness of the anchorage by about 50 % [(85.66 − 57.25)/57.25] in the beams with the light textile. This is attributed to the more uniform stretching of the fibers, which improves the performance of the TRM by reducing local overstressing and hence localized fiber pull-out. However, this increased effectiveness was marginal in the beams with the heavy textile, the reason being premature rupture of the fibers in specimen H2A10 near the contact with the anchored steel section.

Finally, a comparison of the results for beams L2A15 and L2A15ha indicates that increasing the displacement amplitude of the loading cycles from 2 to 5 mm had practically no effect on the results.

4 Analytical modelling

Modelling of the TRM jacket contribution to the shear resistance of T-beams may be based on the well-known truss analogy, as proposed in the past for closed TRM jackets in beams with rectangular cross sections [17]. Assuming that the textile is made of continuous rovings perpendicular and parallel to the member axis, as in this study, the TRM jacket contribution to shear resistance, V_{Rj}, can be written in the following simplified form:

$$V_{Rj} = 2t_j\, h_j f_j \cot\theta, \qquad (1)$$

where t_j = thickness of the jacket, h_j = height of the jacket (equal to height of the web), f_j = effective strength of the jacket and θ = angle between the shear crack and the member axis. The effective strength of the jacket may be thought of as an average stress in the fibers crossing the diagonal crack when shear failure of the member occurs. Application of Eq. (1) to all the beams tested in this study with $\theta = 45°$, $h_j = 250$ mm and t_j equal to the nominal thickness of the fibers, results in the values for f_j given in Table 3. By dividing f_j by the elastic modulus of the fibers (225 GPa), the effective strain ε_j in the fibers is obtained as given in Table 3. An overall conclusion here is that effective strains in all specimens with anchors, except for the ones with two layers of the heavy textile (H2A15, H2A10) which failed prematurely near the contact with the anchored steel section, exceed 0.5 %. In all specimens without anchors as well as in H2A15 and H2A10, the effective strain is lower, in the order of 0.2 %. Finally, values below 0.2 % were calculated in two specimens only, namely the ones with two layers of non-anchored TRM jackets (0.12 % for L2 and 0.17 % for H2).

Table 3 Effective strength and strain of the jacket

Specimen	Effective strength, f_j (MPa)	Effective strain, ε_j (%)
C	–	–
L1	440	0.20
L2	280	0.12
H1	504	0.22
H2	386	0.17
L2A15	1,193	0.53
L2A15ha	1,244	0.55
L2A10	1,785	0.79
H1A15	1,139	0.51
H2A15	538	0.24
H2A10	543	0.24
RL2	538	0.24
RL2A15	1,362	0.61

The values for ε_j obtained here are in good agreement with those calculated on the basis of (limited) tests performed by other researchers. In fact, the only published data for TRM-strengthened beams with U-shaped jackets made of carbon textiles at 0°/90°, as in the present study, are reported in [4], although they correspond to monotonic tests on beams with rectangular cross sections. These data refer to two beams, with notation UW-CT1 and UW-CT2, strengthened with one layer of textile with mass per unit area equal to 270 and 609 g/m^2, respectively. The corresponding values for ε_j were calculated equal to 0.12 and 0.24 %.

By looking at the effective strains for beams with anchors and the light textile, namely L2A15 (or L2A15ha) and L2A10, it is concluded that the effective strain decreases as the anchor spacing s_a increases. This is not surprising, as small anchor spacing implies more uniform activation and less local overstressing of the rovings. As already mentioned above, this conclusion does not apply if the textile

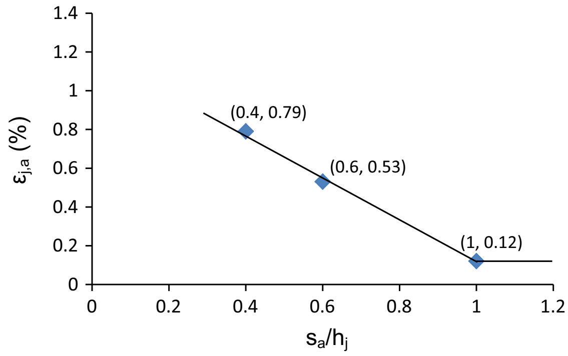

Fig. 11 Validation of linear trend between effective strain and anchor spacing

ruptures prematurely due to stress concentrations near the contact with the anchored steel section (specimen H2A10). Assuming that this premature rupture does not develop, it is reasonable to state that the effective strain decreases from a maximum value, corresponding to "dense" anchor spacing, to a minimum value, corresponding to the case where the anchor spacing becomes "large" enough so that the jacket behaves as if no anchors were used. It is reasonable to assume that "large" corresponds to the case where no anchor intercepts the shear crack, which is the case if $s_a \geq h_j$ (height of the jacket). On the basis of the above arguments and assuming that, for values of s_a exceeding a minimum value $s_{a,lim}$, the effective strain decreases linearly as the anchor spacing increases, the effective strain may be expressed as follows:

$$\varepsilon_{j,a} = \varepsilon_{j,fa} \quad \text{for} \quad \frac{s_a}{h_j} \leq \frac{s_{a,lim}}{h_j}, \tag{2}$$

$$\varepsilon_{j,a} = \varepsilon_{j,fa}\left(1 - k\frac{s_a}{h_j}\right) \quad \text{for} \quad \frac{s_{a,lim}}{h_j} \leq \frac{s_a}{h_j} \leq 1, \tag{3}$$

$$\varepsilon_{j,a} = \varepsilon_{j,na} \quad \text{for} \quad \frac{s_a}{h_j} \geq 1, \tag{4}$$

where $\varepsilon_{j,a}$ = effective strain of anchored jacket; $\varepsilon_{j,fa}$ = effective strain of fully anchored jacket, equal to the maximum possible effective strain corresponding to dense anchor spacing; $\varepsilon_{j,na}$ = effective strain of jacket with no anchors; and k = coefficient, to be determined from the condition that if $s_a = h_j$, then $\varepsilon_{j,a} = \varepsilon_{j,na}$. By imposing this condition, Eq. (3) becomes:

$$\frac{\varepsilon_{j,a}}{\varepsilon_{j,fa}} = 1 - \left(1 - \frac{\varepsilon_{j,na}}{\varepsilon_{j,fa}}\right)\frac{s_a}{h_j} \quad \text{for} \quad \frac{s_{a,lim}}{h_j} \leq \frac{s_a}{h_j} \leq 1. \tag{5}$$

Test results to validate Eqs. (2), (4), and (5) are only those for specimens L2 (no anchorage), L2A15 ($s_a/h_j = 150/250 = 0.6$) and L2A10 ($s_a/h_j = 100/250 = 0.4$). A plot of these results is shown in Fig. 11, which confirms fully the assumption made above for the linear relationship between effective strain and anchor spacing, expressed by Eq. (5).

5 Conclusions

The paper presents a systematic investigation on the effectiveness of U-shaped textile-reinforced TRM jackets as shear strengthening materials of RC T-beams, by examining a number of parameters not studied before: cyclic loading; fixed support conditions; different types of textiles; different numbers of layers; anchors; the relative performance of TRM versus equivalent FRP systems; and different displacement amplitudes of the loading cycles. The main conclusions are summarized as follows:

- The effectiveness of TRM jackets without anchorage increases non-proportionally to the number of textile layers. Moreover, for the same total volume fraction of fibers in the jacket, one layer is more effective than two.
- The anchorage system developed and tested in this study increases dramatically the effectiveness of TRM (and FRP) jackets.
- Non-anchored FRP jackets are nearly twice as effective as their TRM counterparts. However, if the jackets are anchored, the TRM system is marginally inferior to the FRP system.
- The spacing of anchors used in this study is related to the effectiveness of TRM jackets only in lightweight TRM systems.
- Increasing the displacement amplitude of the loading cycles (from 2 to 5 mm in this study) has practically no effect on the performance of the TRM strengthening system.
- On the basis of simple analytical modelling procedures, values for the effective stress and strain in the jackets can be estimated and used directly in the design of strengthening systems similar to the ones tested in this study.

Despite the reasonable number of tests presented herein, it is clear that the experimental database is far from complete and should be expanded (e.g. to larger scale beams), in order to increase the level of confidence, especially on the effective strain, and thus to allow the development of reliable design models.

Acknowledgments The authors wish to thank the students S. Maroudas, I. Marabeas, A. Michael, D. Sardeli, P. Katsapis and L. Koutas, for their assistance in the experimental program. Special thanks go to the technician K. Karlos. The research described in this paper has been co-financed by the European Union (European Social Fund—ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF)—Research Funding Program THALES—Investing in knowledge through the European Social Fund.

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