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Bond between textile-reinforced mortar (TRM) and concrete substrates: Experimental investigation

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ABSTRACT

This paper presents an extended experimental study on the bond behaviour between textile-reinforced mortar (TRM) and concrete substrates. The parameters examined include: (a) the bond length (from 50 mm to 450 mm); (b) the number of TRM layers (from one to four); (c) the concrete surface preparation (grinding versus sandblasting); (d) the concrete compressive strength (15 MPa or 30 MPa); (e) the textile coating; and (f) the anchorage through wrapping with TRM jackets. For this purpose, a total of 80 specimens were fabricated and tested under double-lap direct shear. It is mainly concluded that: (a) after a certain bond length (between 200 mm and 300 mm for any number of layers) the bond strength marginally increases; (b) by increasing the number of layers the bond capacity increases in a non-proportional way, whereas the failure mode is altered; (c) concrete sandblasting is equivalent to grinding in terms of bond capacity and failure mode; (d) concrete compressive strength has a marginal effect on the bond capacity; (e) the use of coated textiles alters the failure mode and significantly increases the bond strength; and (f) anchorage of TRM through wrapping with TRM jackets substantially increases the ultimate load capacity.

1. Introduction and background

The need for retrofitting the existing concrete infrastructure is progressively becoming more important due to their continuous deterioration as a result of ageing, environmental induced degradation, lack of maintenance or need to meet the current design requirements (i.e. Eurocodes). Replacing the deficient concrete structures in the near future with new is not a viable option as it would be prohibitively expensive. For this reason a shift from new construction towards renovation and modernization has been witnessed in the European construction sector, between 2004 and 2013, with practically 50% of the total construction output being renovation and structural rehabilitation. (i.e. €305bn turnover on rehabilitation and maintenance works in EU27 for 2012, see www.fiec.eu).

The use of externally bonded (EB) composite materials (such as fiber reinforced polymers – FRPs) is a common retrofitting technique usually employed by engineers. Almost a decade ago, an innovative cement-based composite material, the so-called textile-reinforced mortar (TRM), was introduced in the field of structural retrofitting [1,2] as an alternative to FRP solution, addressing cost and durability issues. Since then, TRM progressively attracts the interest of the structural engineering community.

TRM comprises high-strength fibers (i.e. carbon, glass or basalt) in form of textiles combined with inorganic matrices (such as cement-based mortars). The textiles that are used as reinforcement of the composite material typically comprise fiber rovings in two orthogonal directions, thus creating open-mesh geometry. TRM is an attractive retrofitting solution because it combines the outstanding properties of composite materials (e.g. high-strength, low weight, corrosion resistance) with the favourable characteristics offered by mortars and cannot be found in resins (e.g. fire resistance, low cost, ability to apply on wet surfaces and low temperatures, air permeability of the substrate). The same material is also referred in the literature as fabric-reinforced cementitious

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matrix (FRCM) (e.g. Ref. [3]).

Significant research effort has been put in the last decade to exploit TRM in several cases of retrofitting reinforced concrete (RC) structures; namely flexural (i.e. Ref. [4–7]), shear strengthening of RC elements (i.e. Ref. [8–11]), confinement of RC columns (i.e. Ref. [1, 2]), seismic retrofitting of RC columns (e.g. Refs. [2,12–16]), seismic retrofitting of infilled RC frames [17]. TRM has also been successfully used for retrofitting masonry structures (e.g. out-of-plane strengthening [18] and shear strengthening of masonry walls [19]). However the number of studies on the bond behaviour between TRM and concrete are relatively limited [20–27]. The study of the bond behaviour between TRM and concrete is of crucial importance as it helps understanding the complex mechanisms of transferring forces from the textile reinforcement to the surrounding matrix and eventually to the concrete substrate. It is also a fundamental step towards the development of design models to be used in strengthening applications.

Past studies on the bond between TRM and concrete were mainly focused on the behaviour of textiles comprising poly-paraphenylene benzobisoxazole (PBO) fibers, except for those in Refs. [21,23] where uncoated carbon and glass fibers [21] and coated carbon fibers [23] were used. With the maximum number of TRM layers investigated being equal to two, the common conclusion of past studies was that for bond lengths varying from 50 mm to 450 mm, failure occurs within the composite material, namely at the interface between the fibers and the surrounding mortar. This failure mode typically includes slippage of the fibers within the mortar and is usually described as debonding at fibers/matrix interface. Failure at the interface between the mortar and concrete substrate without involving though any part of the concrete cover was very rarely reported [25,26]. Ombres [26] attributed the alteration of the failure mode to the increase of the number of layers from one to two. Other parameters, such as the concrete compressive strength and the surface preparation, have been investigated only in Ref. [25] and it was found to have insignificant effect on the bond capacity of one PBO-TRM layer bonded to concrete.

From the literature survey it becomes clear that the subject of the bond behaviour between TRM and concrete has not sufficiently been covered. In this paper the authors investigate for the first time systematically a set of parameters, focusing on the load response and the failure modes of the EB TRM reinforcement, namely:

- the number of TRM layers, from one to four, which is beyond the current limit of two,
- the bond length, from 50 mm to 450 mm,
- the concrete surface preparation,
- the concrete compressive strength,
- the coating of the textile, which has not been investigated before in comparison with uncoated textiles, and
- the anchorage through wrapping with TRM jackets, which again is a parameter not previously investigated.

In addition, the textile used in this study comprises carbon fibers, which are commonly used in strengthening applications. Details are provided in the following sections.

2. Experimental programme

2.1. Test specimens and experimental parameters

The main objective of this study was to investigate the bond between TRM and concrete considering different parameters. A total of 80 specimens were fabricated and tested under double-lap direct shear. The geometry of the specimens is shown in Fig. 1. Each specimen comprised two 100 mm-square-section RC prisms connected only by TRM layers bonded on two opposite sides of the prisms. The length of the prisms was equal to 250 mm in all cases, except from two prisms that were constructed 500 mm long for examining a bond length of 450 mm. The bond width of TRM was the same for all the specimens and equal to 80 mm. Both prisms were reinforced with steel cages as illustrated in Fig. 1b.

The key investigated parameters of this study comprised:

a) the bond length;
b) the number of TRM layers;
c) the concrete surface preparation;
d) the concrete compressive strength;
e) the coating of the textile; and
f) the anchorage through wrapping with TRM jackets.

The 80 specimens comprised 40 twin specimens as a measure to reduce the scatter of the results. Parameters (a) and (b) were examined on 22 twin specimens (44 specimens in total), with the bond length varying from 50 to 450 mm and the number of layers from one to four. Six twin specimens were tested to investigate parameter (c), namely the effect of the concrete surface preparation (grinding or sandblasting), whereas other six twin specimens were used to evaluate the effect of the concrete compressive strength (15 or 30 MPa) on the results [parameter (d)]. Four twin specimens were tested to examine the influence textile coating on the ultimate load and failure mode [parameter (e)], and two twin specimens were used to investigate the effect of anchorage through wrapping with TRM jackets [parameter (f)].

The notation of specimens addressing parameters (a) and (b) was LX_N, where X is the bond length and N is the number of TRM layers. For the other specimens, the notation was LX_N_Y, with Y denoting the investigated parameter: S for concrete surface preparation; Ls for low concrete compressive strength; C for coated textile and W for TRM wrapping. Details of the different strengthening configurations and number of tested specimens for each parameter are listed in Table 1.

2.2. Materials and strengthening procedure

The RC prisms were cast in different groups and dates. For all

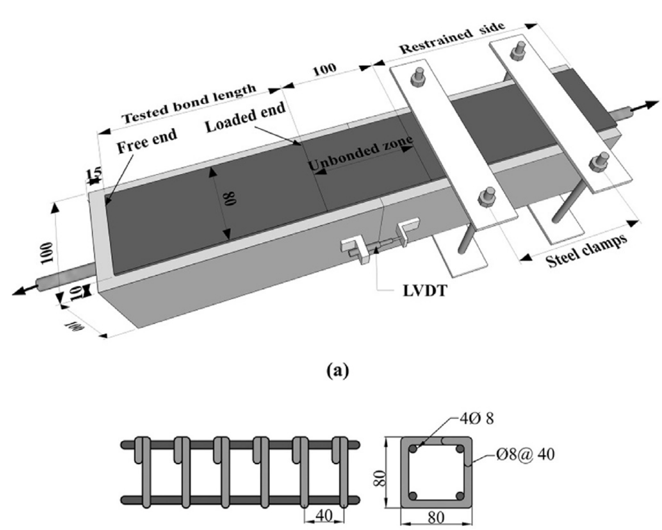

Fig. 1. Specimen details (dimensions in mm).

tested specimens, the targeted concrete compressive strength was 30 MPa, except for group LN_X_Ls (twelve specimens) where the targeted compressive strength was lower and equal to 15 MPa. The compressive strength of all specimens was measured on the day of the testing (average value of three 150 × 150 × 150 mm cubes) and is given in Table 1.

The strengthening system applied in this study comprised high-tensile strength carbon fiber textile embedded into cement-based mortar. The textile had equal quantity of carbon fibers in the two orthogonal directions with a mesh of 10 mm (Fig. 2). The weight of the carbon textile reinforcement was 348 g/m^2, whereas its nominal thickness (based on the equivalent smeared distribution of fibers) was 0.095 mm. According to the manufacturer datasheets, the tensile strength and modulus of elasticity of the carbon fibers were 3800 MPa and 225 GPa, respectively. The matrix consisted of an inorganic dry mortar comprising cement and polymers at a ratio of 8:1 by weight. The water-binder ratio of the mortar was 0.23:1 by weight, resulting in plastic consistency and good workability. The compressive and flexural strength of the mortar (average value from 3 prisms) were experimentally obtained on the day of testing using prisms with dimensions of 40 × 40 × 160 mm according to EN 1015-22 [28] and are given in Table 1.

The concrete surface was prepared prior to strengthening by removing a thin layer of concrete (with the use of a grinder) and creating a grid of groves (with a depth of approximately 3 mm – Fig. 3a). This procedure was followed for all specimens, except for those of group LX_N_S, where the concrete surface was sandblasted (Fig. 3b). After cleaning and dampening the concrete surface, the first layer of mortar with approximately 2 mm thickness was placed

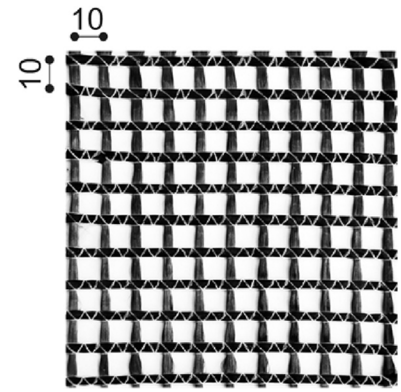

Fig. 2. Carbon textile used in this study (dimensions in mm).

Table 1
Specimens details, concrete compressive strength, and mortar properties on the day of testing.

Specimen notation	Specimens name	Bond length (mm)	Number of TRM layers	Additional remarks	Concrete	Mortar	
					Compressive strength (MPa)[a]	Flexural strength (MPa)[a]	Compressive strength (MPa)[a]
LX_N	L50_1 L50_2 L50_3 L50_4	50	1, 2, 3, 4	–	31.2 (0.56)	9.17 (0.92)	38.8 (0.60)
	L100_1 L100_2 L100_3 L100_4	100	1, 2, 3, 4	–	30.4 (0.63)	8.24 (0.94)	33.8 (0.56)
	L150_1 L150_2 L150_3 L150_4	150	1, 2, 3, 4	–	31.2 (0.22)	9.23 (0.49)	39.7 (1.33)
	L200_1 L200_2 L200_3 L200_4	200	1, 2, 3, 4	–	32.8 (0.66)	8.54 (1.26)	35.9 (0.27)
	L250_1 L250_2 L250_3 L250_4	250	1, 2, 3, 4	–	32.5 (0.32)	8.95 (0.37)	37.6 (0.90)
	L450_1 L450_2	450	1, 2	–	29.5 (0.37)	9.4 (0.81)	40.1 (1.23)
LX_N_S	L100_3_S L100_4_S L150_3_S L150_4_S L200_3_S L200_4_S	100, 150, 200	3, 4	S = Surface preparation	29.3 (0.73)	8.68 (0.77)	36.8 (0.45)
LX_N_Ls	L100_3_Ls L100_4_Ls L150_3_Ls L150_4_Ls L200_3_Ls L200_4_Ls	100, 150, 200	3, 4	Ls = Low concrete strength	14.7 (0.55)	8.98	35.2 (0.90)
LX_N_C	L150_1_C L150_2_C L200_1_C L200_2_C	150, 200	1, 2	C = Textile coating	30.4 (0.28)	8.35 (0.65)	32.7 (0.97)
LX_N_W	L100_3_W L100_4_W	100	3, 4	W = Anchorage through wrapping with TRM		8.35 (0.65)	32.7 (0.97)

[a] Standard deviation in parenthesis.

on the concrete surface using a metallic trowel (Fig. 4a). Then the first textile layer was applied and pressed slightly into the mortar, which protruded through the perforations between the fiber rovings as shown in Fig. 4b. This procedure was repeated until the required number of TRM layers was applied. Finally, an external layer of mortar with approximately 3 mm thickness was applied and levelled by trowel (Fig. 4c). Of crucial importance in this method was the application of each mortar layer while the previous one was still in a fresh state.

For the specimens retrofitted with coated textile (LX_N_C), an epoxy resin was used. The adhesive used for the coating was a low viscosity, two-part epoxy resin. The tensile strength and the elastic modulus of this adhesive were equal to 72.4 MPa and 3.18 GPa, respectively (taken from the manufacturer data sheets).

For the specimens received wrapping, namely the longitudinal TRM composite was anchored through TRM jackets wrapped around the concrete prism (group LX_N_W), additional surface preparation was made prior to strengthening including rounding of the prism corners to a radius of 10 mm. After applying the required number of longitudinal TRM layers, the prism side under investigation was wrapped with two TRM layers following the strengthening procedure previously described. The width of the textile used for wrapping was 100 mm which was equal to the bond length of the longitudinal TRM layers (Fig. 4d).

2.3. Experimental setup and procedure

All specimens were tested after a curing period of six weeks (same curing conditions were applied to all specimens). The experimental setup included two steel clamps which were fixed at one side (restrained side) of the specimen to ensure that failure would occur in the monitored side (Fig. 1a and Fig. 5). The TRM composite was left un-bonded at a 100 mm-long central zone (50 mm at each prism) of the specimen (Fig. 1a) to prevent concrete-edge failure which could have adverse effects. All tests were carried out using a universal tensile testing machine of 250 kN capacity. The specimens were griped to the tensile machine using the 16 mm steel bars fitted at the centre of each prism during casting (these bars were terminated at the interface between the two prisms- Fig. 6a). To ensure full alignment between the two prisms, two 10 mm diameter acrylic dowels were inserted into the concrete mass of the prisms (Fig. 6b) (after casting and prior to the strengthening application) at pre-made holes (Fig. 6a). The load was applied at a displacement control with rate of 0.2 mm/min. Two LVDTs were mounted to the unstrengthened sides of the specimens to record the displacement of the joint (Fig. 5).

In a number of previous studies the single-lap shear test set-up was used to investigate the bond of one TRM layer to concrete [21–22,25–26]. However, the double-lap shear test set-up was selected for this study, which is a modification of the set-up proposed in Ref. [29] for testing the bond between FRP composites and concrete. The selection of the double-lap shear test set-up was deemed necessary for testing more than one TRM layers, as with such a set up the stresses are transferred from the concrete to the composite material indirectly, simulating realistically real-word

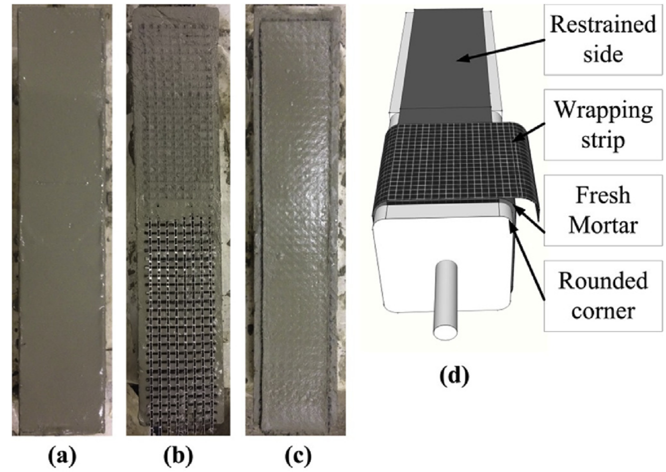

Fig. 4. (a) Application of the first layer of mortar; (b) application of the first layer of textile layer into the mortar; (c) application of the final layer of mortar; and (d) wrapping with TRM jacket at the side of specimen under examination.

Fig. 3. Different concrete surface preparation: (a) grinding and creating a grid of groves; and (b) sandblasting.

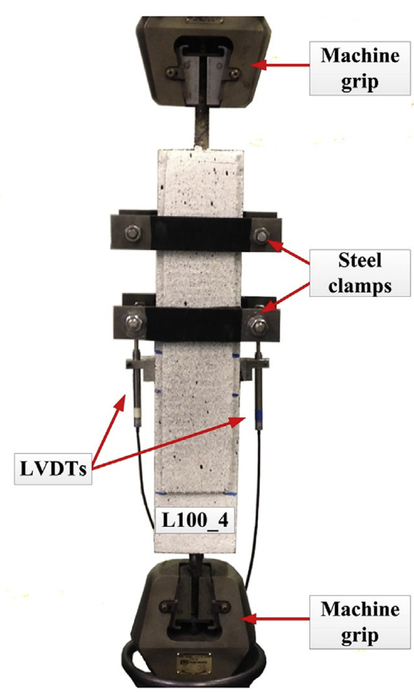

Fig. 5. Details of the test set-up.

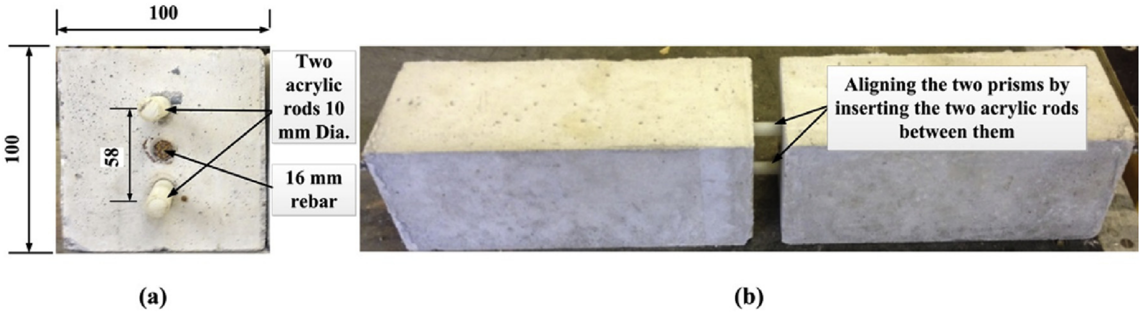

Fig. 6. Alignment of the two concrete prisms using two acrylic rods (Dimensions in mm).

applications. In contrast, in single-lap tests the load is applied directly to the composite material, which means that shear stresses between layers cannot be developed in case of more than one TRM layer.

3. Experimental results

Key results of all tested specimens are presented in Table 2 which includes:

(1) the maximum load (P_{max}) carried out by the TRM strips for both twin specimens S1 and S2,
(2) the displacement (average of two LVDTs readings) which corresponds to the maximum load (δ_{max}),
(3) the average load (P_{av}) of the two twin specimens,
(4) the average displacement (δ_{av}) of the two twin specimens,
(5) the corresponding average normal stress in the textile (σ_t), and
(6) the failure mode.

The value of normal stress was calculated using Eq. (1):

$$\sigma_t = \frac{(P_{av}/2)}{n^*t^*b} \tag{1}$$

where n is the number of TRM layers, t is the equivalent thickness of the textile in the longitudinal direction (t = 0.095 mm), and b is the bond width (b = 80 mm). Eq. (1) was used to calculate the normal stress of the fibers excluding the contribution of the mortar. This is typical in the case of TRM systems, and is valid for the ultimate capacity, since the matrix has been cracked. At this load level, all the tension is carried by the textile reinforcement.

Starting from the specimens LX_N that were strengthened with one up to four TRM layers at bond lengths of 50, 100, 150, 200 and 250 mm, the maximum load recorded (average from twin specimens) was (see also Table 2): (a) 7.7, 11.6, 12.2, 13.9, and 16.1, kN, respectively, for the specimens with one TRM layer, (b) 18.4, 23.5, 25.3, 28.1, and 29.4 kN, respectively, for the specimens with two TRM layers, (c) 22.6, 31.2, 35.1, 36.0, and 38.03 kN, respectively, for the specimens with three TRM layers, and (d) 27.9, 35.0, 37.9, 41.5, and 41.8 kN, respectively, for the specimens with four TRM layers. The bond length of 450 mm was investigated only for one and two TRM layers, with the corresponding maximum load equal to 17.4 and 31.6 kN, respectively.

Fig. 7 shows the load-displacement curves (average of the two LVDTs readings) recorded for specimens LX_N. For better illustration, only one of the twin specimens response curve is included, whereas they have been grouped according to the number of TRM layers applied. It is noted that the trend of the curves of twin specimens was similar in all the cases (see “S1” and “S2” columns in Table 2). A common characteristic of all curves is their behaviour up to the maximum load. In specific, a first ascending linear branch with high axial stiffness is followed by a second ascending non-linear branch with progressively decreasing stiffness due to mortar cracking. The post-peak behaviour was different depending on the failure mode which in turn was different depending on the amount of TRM reinforcement. For one and two TRM layers, the post-peak behaviour was generally characterized by a progressive load-drop to a residual strength (Fig. 7a and b). In contrast, when three and four TRM layers were applied the load-drop was sudden without any residual strength provided (Fig. 7c and d).

The failure modes observed in LX_N specimens can be classified in two types: (a) slippage of the fibers within the mortar (Fig. 8a and b), and (b) debonding of TRM from the concrete substrate with peeling off part of the concrete cover (Fig. 8c–e). The first failure mode occurred in all specimens with one or two TRM layers, whereas the second occurred in all specimens with three or four layers.

For the specimens strengthened with one or two TRM layers, the failure mechanism was controlled by slippage and partial rupture of the longitudinal fibers through the mortar at the loaded end, where a single crack was developed (at an early loading stage) and further opened at the end of the test (Fig. 8a and b). After failure, a residual strength was recorded which was attributed both to the contribution of friction between the inner filaments themselves and the outer filaments with the surrounding matrix.

When TRM debonding from the concrete substrate occurred, it was accompanied by removal of a thin concrete cover layer (Fig. 8c–e). Failure was initiated by the formation of a longitudinal crack at the loaded end; this crack was continuously propagating towards the free end as the load was increasing. At peak load, propagation of the crack up to free end caused full detachment (debonding) of the TRM composite from the concrete surface and the load dropped to zero. A noticeable difference between the specimens failed due to fibers slippage and those specimens failed due to TRM debonding is that in the latter case several transversal cracks developed on the TRM face as shown in Fig. 9. Hence, a better distribution of stresses along the bond length was achieved in these cases. After debonding occurred, a rotation of the specimen with respect to the longitudinal axes was observed (Fig. 9). This is because the failure was control by one of the two monitored sides of the concrete prism. However, this rotation had no effect on the behaviour up to the ultimate load.

Specimens LX_N_S, with different concrete surface preparation (sandblasting instead of grinding), attained maximum loads of 31.2, 33.9 and 40.4 kN for three layers, and 36.1, 37.2 and 41.9 kN for four layers, for bond lengths equal 100, 150 and 200 mm, respectively. As illustrated in Fig. 10a, the global behaviour of these specimens (in terms of force-displacement curves) is nearly identical to their counterparts from the LX_N group, indicating that the concrete

Table 2
Summary of test results.

Specimen	(1) Maximum load, $P_{max.}$ (kN)		(2) Displacement at maximum load δ_{max} (mm)		(3) Average maximum load, $P_{av.}$ (kN)	(4) Average displacement at maximum load δ_{av} (mm)	(5) Axial stress in textile fibers σ_t (MPa)	(6) Failure mode[b]
	S1[a]	S2[a]	S1[a]	S2[a]				
L50_1	7.15	8.29	0.25	0.23	7.7	0.24	507	A
L50_2	19.12	17.76	0.79	0.70	18.4	0.75	605	A
L50_3	23.95	21.16	0.72	0.66	22.6	0.69	496	b
L50_4	26.46	29.31	0.46	0.62	27.9	0.54	459	b
L100_1	12.28	10.96	0.53	0.50	11.6	0.52	763	a
L100_2	22.82	24.14	1.01	1.00	23.5	1.01	773	a
L100_3	29.62	32.82	0.85	1.04	31.2	0.95	684	b
L100_4	32.77	37.27	0.83	0.92	35.0	0.88	576	b
L150_1	11.74	12.58	1.32	1.21	12.2	1.27	803	a
L150_2	25.25	25.34	1.10	1.11	25.3	1.11	832	a
L150_3	34.49	35.62	1.05	1.07	35.1	1.06	770	b
L150_4	38.55	37.2	1.4	1.51	37.9	1.46	623	b
L200_1	13.51	14.25	1.23	1.24	13.9	1.24	915	a
L200_2	27.65	28.59	1.35	0.81	28.1	1.08	924	a
L200_3	37.44	34.55	1.56	1.9	36.0	1.73	790	b
L200_4	41.26	41.74	1.31	1.57	41.5	1.44	683	b
L250_1	14.92	17.32	2.29	2.55	16.1	2.42	1059	a
L250_2	30.25	28.63	1.2	1.6	29.4	1.40	967	a
L250_3	38.55	37.51	1.56	1.55	38.03	1.56	834	b
L250_4	42.79	40.89	1.22	1.35	41.8	1.29	688	b
L450-1	17.54	17.2	2.51	2.15	17.4	2.33	1145	a
L450-2	32.8	30.4	3.51	3.62	31.6	3.57	1040	
L100_3_S	30.64	31.77	1.27	1.46	31.2	1.37	684	b
L150_3_S	34.99	32.74	0.99	1.05	33.9	1.02	743	
L200_3_S	40.18	40.57	1.85	1.19	40.4	1.52	886	
L100_4_S	35.63	36.58	1.24	0.75	36.1	1.00	594	
L150_4_S	37.64	36.74	1.19	0.80	37.2	1.00	612	
L200_4_S	41.45	42.35	1.35	1.19	41.9	1.27	689	
L100_3_Ls	29.9	29.84	1.04	1.12	29.9	1.08	656	b
L150_3_Ls	30.67	30.79	1.36	1.29	30.7	1.33	673	
L200_3_Ls	33.68	36.17	1.81	1.99	34.9	1.90	765	
L100_4_Ls	32.67	31.76	0.92	0.85	32.2	0.89	530	
L150_4_Ls	34.7	35.54	1.13	1.45	35.1	1.29	577	
L200_4_Ls	36.81	38.63	1.48	1.39	37.7	1.44	620	
L150_1_C	22.7	21.08	1.45	1.64	21.9	1.55	1441	c
L200_1_C	23.21	24.6	1.44	1.54	23.9	1.49	1572	
L150_2_C	29.1	29.89	0.8	0.89	29.5	0.85	970	
L200_2_C	32.94	30.77	0.95	1.05	31.9	1.00	1049	
L100_3_W	38.43	41.47	1.21	1.29	40.0	1.25	877	a
L100_4_W	49.19	52.31	1.17	1.25	50.75	1.21	835	

[a] Specimen number.
[b] a: Slippage and partial rupture of textile fibers through the mortar; b: Debonding of TRM from the concrete substrate including part of the concrete cover; c: Debonding at the textile/mortar interface (interlaminar shearing).

surface preparation did not affect the bond behaviour. Also the failure mode remained unchanged, comprising TRM debonded from the concrete substrate at the mortar-concrete interface with a thin layer of the concrete cover being peeled-off (Fig. 11a).

As shown in Table 2, supported by Fig. 10b, specimens with low concrete strength (LX_N_Ls) reached an ultimate load of 29.9, 30.7 and 34.9 kN for three layers, and 32.2, 35.1 and 37.7 kN for four layers, for bond lengths of 100, 150 and 200 mm, respectively. As illustrated in Fig. 10b, the global behaviour of this group of specimens was very similar to their counterparts with higher concrete strength in terms of force-displacement curves. Debonding of TRM from the concrete substrate was accompanied with removal of concrete particles which remained attached to the debonded TRM strip (Fig. 11b).

The force-displacement curves of the specimens retrofitted with coated textiles (LX_N_C) are presented in Fig. 10c. The ultimate load for one TRM layer was 21.9 kN and 23.9 kN for 150 and 200 mm bond length, respectively, which is substantially higher with respect to their counterparts. The corresponding ultimate load for two TRM layers was 29.5 and 31.9 kN for 150 and 200 mm bond length, respectively. As shown in Fig. 10c the post-peak behaviour of LX_N_C specimens was different from their counterparts from group LX_N, owing to the different failure mode observed. In particular, all specimens with coated textiles failed due to debonding of TRM at the textile/mortar interface (Fig. 11c), whereas their counterparts failed due to slippage of the textile fibers through the mortar (Fig. 8a and b). Failure in this case was within the TRM thickness, and is associated to the stiff behaviour of the coated textiles. This type of failure mode can also be described as inter-laminar shearing. A denser crack pattern was observed in all specimens with the coated textiles, indicating a better activation of the textile fibers in tension.

Finally, the load-displacement curves for specimens LX_N_W, which were wrapped with two TRM layers in order to provide better anchorage, are shown in Fig. 12a; Specimens L100_3_W and L100_4_W, reached an ultimate load of 40 and 50.8 kN for three and four layers, respectively (for 100 mm bond length). In terms of ultimate load they performed better than their counterparts (Table 2), whereas a change on the failure mode was also observed. Wrapping of the prism did not allow for debonding of the TRM

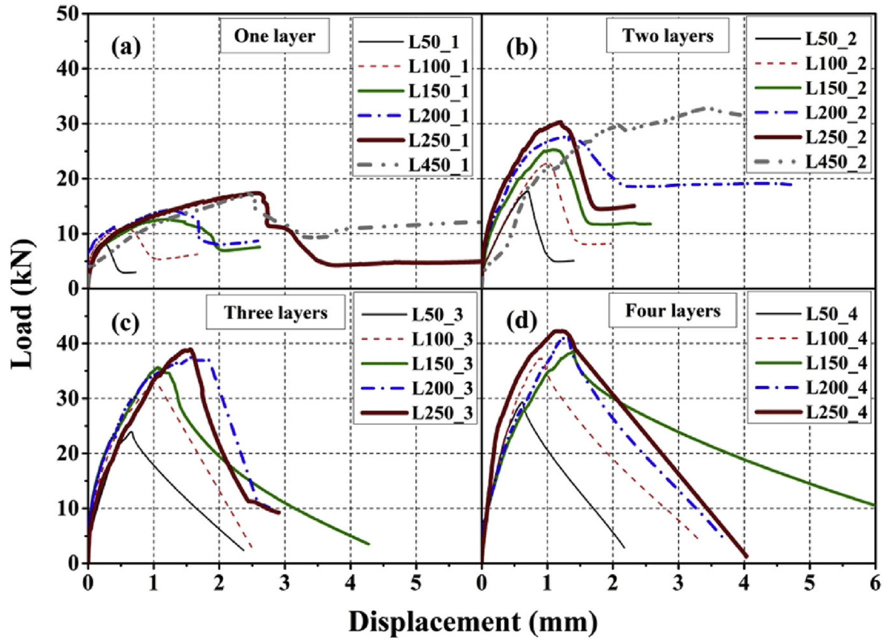

Fig. 7. Load-displacement curves of LX_N group specimens.

strips and damage was localized in the loaded-end, where a single transversal crack appeared Fig. 12b. Ultimately, the textile fibers slipped through the mortar resulting in a residual capacity as shown in Fig. 12a.

4. Discussion

In terms of the various parameters investigated in this experimental programme, an examination of the results in terms of ultimate loads and failure modes revealed the following information.

4.1. Influence of the bond length and the number of layers

The effect of the bond length and the number of layers on the load-carrying capacity is depicted in Fig. 13. The curves in Fig. 13 clearly demonstrate that by increasing either the bond length or the number of layers, the bond capacity increases in a non-proportional way. Similar to the bond behaviour of FRP strips [31], after a certain bond length the anchorage force tends to reach a constant value which is considered as the maximum anchorage force. This length is called “effective bond length” (L_{eff}) and according to the curves provided in Fig. 13 is in the range of 200 and 300 mm for the number of layers (one to four) investigated. This in agreement with the conclusions of previous studies [20,22–23]. Even in cases with one and two TRM layers, where there is significant friction between the inner and outer filaments when slippage occurs, by providing a large bond length (450 mm) the load capacity was marginally increased.

For the same bond length, increasing the number of layers resulted in an increase in the load-carrying capacity. This effect was more pronounced for the transition from one to two layers, whereas for more layers it was gradually becoming less significant. Almost the same trend was followed for all examined bond lengths between 50 and 250 mm. The most important effect of increasing

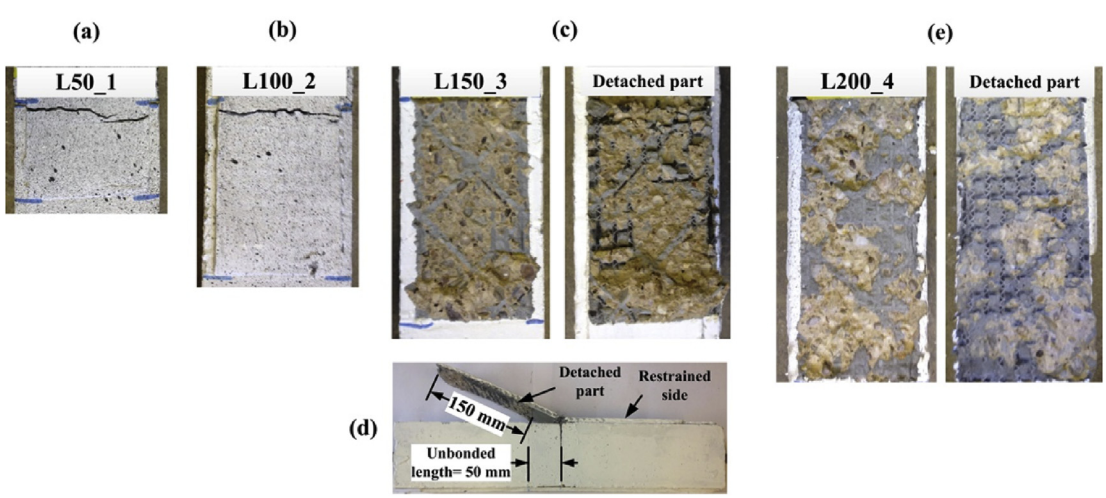

Fig. 8. Failure mode of specimens in group LX_N: (a),(b) single crack formation and slippage of the fibers through the mortar for specimens with one and two TRM layers, respectively; (c),(d),(e) TRM debonding at concrete/matrix interface including a thin layer of concrete cover, for specimens with three and four layer.

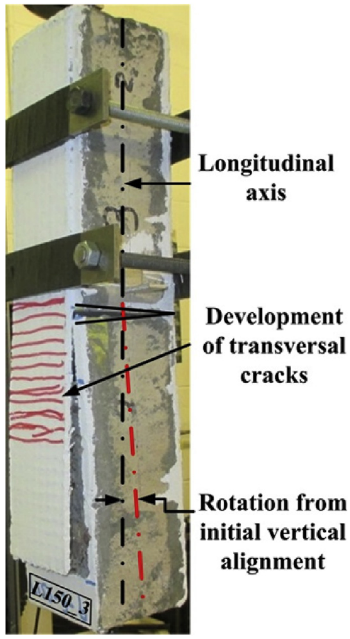

Fig. 9. Development of transversal cracks and the rotation of the specimen relative to initial alignment after ultimate load.

the number of layers though, is related to the change in the failure mode. In particular, as explained in the results section, specimens of LX_N group strengthened with one or two layers failed due to slippage of the textile fibers through the mortar, whereas specimens with three or four layers failed due to TRM debonding from the concrete substrate with peeling off of a part of the concrete cover.

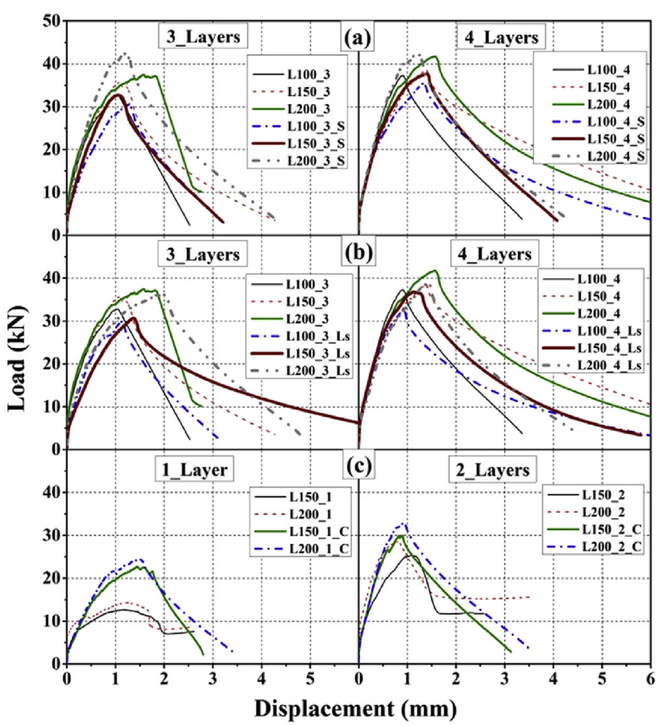

Fig. 10. Load-displacement curves for specimens having as a parameter; (a) the concrete surface preparation, (b) the concrete compressive strength and (c) the textile coating.

The above finding adds new information to the existing knowledge, because in all previous studies on bond between TRM and concrete (where the maximum number of layers examined was two), failure occurred either at the interface between fibers and mortar or at the interface between concrete and mortar without involving the concrete cover. It is noted that failure of TRM involving peeling off of the concrete cover has also been reported in the study of Tetta et al., 2015 [10], where RC beams were retrofitted in shear with TRM U-jackets, and has also been observed by the authors in flexural strengthening of RC beams with TRM [30]. This type of failure is very common in case of FRP bonded to concrete [31], indicating that TRMs can behave similar to FRPs.

The bond length had also an effect on the residual strength of the specimens failed due to slippage of the fibers, which is related to the friction developed between the inner and the outer filaments of each individual fiber roving. Table 3 shows the percentage of residual load compared to the maximum load recorded for specimens one and two TRM layers. It is generally concluded that the larger the bond length, the higher the slipping surfaces become, so the residual strength do.

Fig. 14 shows the variation of the normal stress in the textile fibers [calculated by Eq. (1)] with the bond length for different number of TRM layers. It is generally observed that by increasing the number of layers the normal stress decreases, which is consistent with the behaviour of FRP bonded plates to concrete [31]. Only for the transition from one to two layers, the stress in the fibers marginally increases for bond length between 50 and 200 mm. This is possibly connected to the complex mechanism of fibers slippage occurring in specimens with one and two TRM layers.

4.2. Influence of surface preparation

Fig. 15a and b shows a comparison between the ultimate loads of specimens having the same bond length but different concrete surface preparation, for three (Fig. 15a) and four (Fig. 15b) TRM layers. In the majority of the cases, grinding the concrete surface and creating of a grid of grooves is as effective as sandblasting in transferring shear stresses from TRM to concrete. Moreover, the shape of the force-displacement curves in Fig. 10 is the same for both surface preparation methods. Hence, it can be concluded that both ways of surface preparation are suitable, something that needs further investigation for other textile geometries and other types of mortar. This is in agreement with the study of D' Antino et al., 2015 [25] where no differences were observed between specimens with untreated and sandblasted concrete surfaces, strengthened with one PBO-fibers TRM layer.

4.3. Influence of concrete compressive strength

The concrete compressive strength was selected to be investigated only for three and four TRM layers, because of the failure mechanism observed in LX_N specimens. In particular, TRM debonding from the concrete substrate involving part of the concrete cover (a failure mechanism which is associated to the concrete strength) occurred only in the case of three and four TRM layers. When one or two TRM layers were used, the failure was attributed to the concentration of the damage in one single crack. For this reason it is believed by the authors that the concrete strength would not influence the results of specimens with one and two TRM layers.

A comparison of the ultimate loads between the LX_N_Ls specimens (lower compressive strength – approximately 15 MPa) and the LX_N specimens (higher compressive strength – approximately 30 MPa) is made in Fig. 15c, d. In all cases, the use of a lower compressive strength concrete had a negative impact on the load-

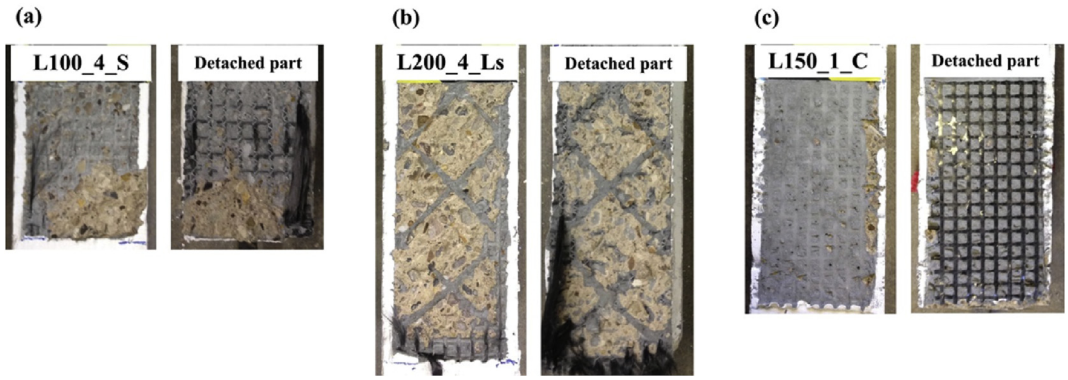

Fig. 11. Typical failure mode of specimens with: (a) sandblasted concrete surface, (b) low concrete compressive strength, and (c) coated textiles.

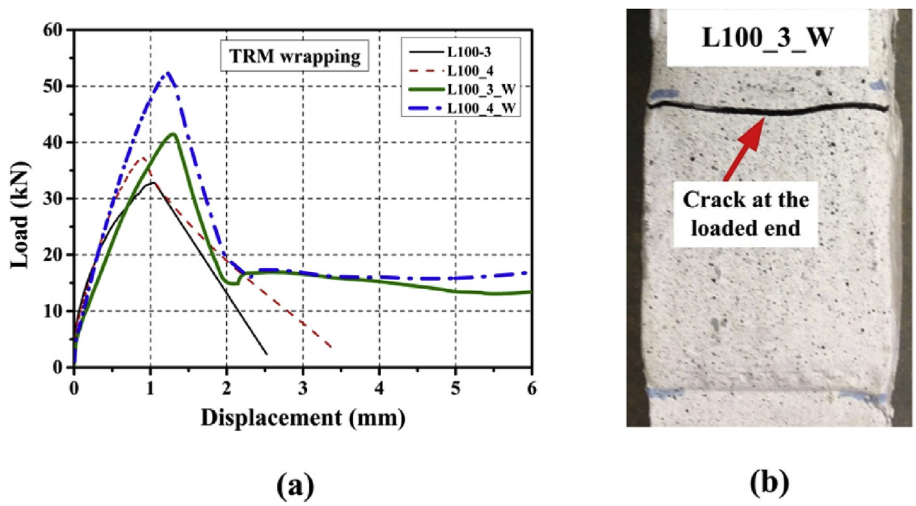

Fig. 12. (a) Load-displacement curves of specimens with anchorage through wrapping and comparison with counterpart specimens without anchorage; (b) typical failure of specimens with anchorage through wrapping with TRM jackets.

carrying capacity of the specimens. For specimens with lower concrete strength, the reduction in the ultimate bond capacity was 4.1%, 12.5% and 3.1% for three TRM layers and 8%, 7.4% and 9.2% four TRM layers, and for bond lengths equal to 100, 150, and 200 mm, respectively. As expected, the lower (by 50%) compressive strength resulted in a decrease in the ultimate load which on average was equal to approximately 7.5%. This reduction, though, cannot be considered as significant as it may be in the range of the statistical error. It is noted that the insignificant effect of the concrete strength on the load capacity has also been reported by D'Antino et al., 2015 [25]. However, in their study the concrete was not directly involved

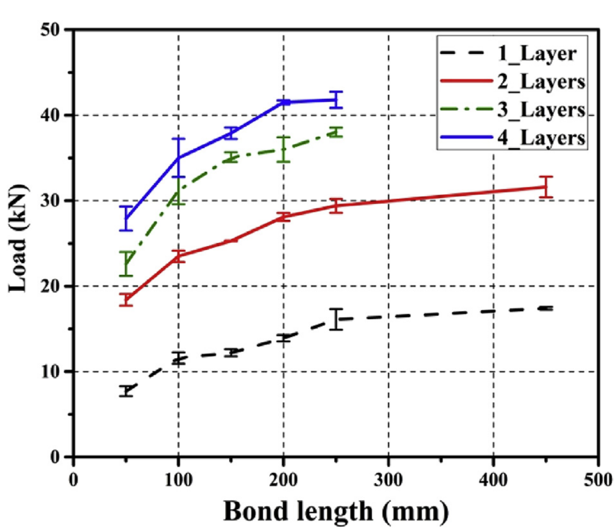

Fig. 13. Variation of ultimate load with the number of layers and bond length.

Table 3
Percentage of the residual load due to friction with respect to maximum recorded load for specimens with one and two layers of TRM.

Name	Percentage of residual load (%)	
	S1[a]	S2[a]
L50_1	36.4	36.2
L50_2	33.5	28.5
L100_1	46.9	57.8
L100_2	33.3	34.0
L150_1	60.7	60.1
L150_2	46.6	43.4
L200_1	57.0	61.1
L200_2	56.8	65.8
L250_1	42.2	61.2
L250_2	52.2	52.4
L450-1	71.3	70.3
L450-2	75.0	81.6

[a] Specimen number.

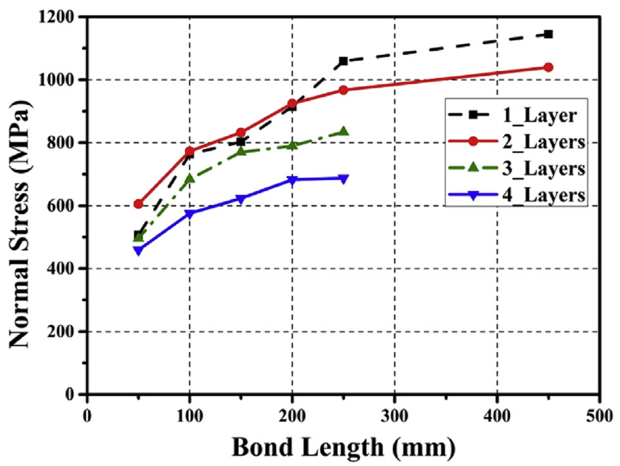

Fig. 14. Variation of normal stress with the number of layers and bond length.

in the failure mode which was at the interface between the matrix and the fibers.

4.4. Influence of coating

Coating the textile fabric with epoxy resin was investigated only for specimens with one and two TRM layers, to improve the failure mode (slippage of the fibers through the mortar) observed in these specimens with uncoated textiles. According to the results, the effect of coating was twofold: (a) change in the failure mode, and (b) significant increase of the load-carrying capacity. The failure mode changed from slippage of the fibers through the surrounding matrix to debonding of TRM at the textile/mortar interface (interlaminar shearing). Comparison of the ultimate loads of specimens with one and two layers of coated textiles and of specimens with uncoated textiles is shown in Fig. 15e for different bond lengths. The ultimate load was increased by 79.5% and 71.9% for specimens with one layer and 16.6% and 13.5% for specimens with two layers, for bond lengths equal to 150 and 200 mm, respectively.

Coating the textile with epoxy resin makes the textile more stable and easy-to-apply, while at the same time it increases its rigidity. When a good level of impregnation of the fibers with resin is achieved, the inner filaments of the rovings are better bound to the outer filaments. As a result, the mechanism of transferring stresses from the fibers to the matrix is improved providing better mechanical interlock conditions. Ultimately, the textile fibers are better utilized in carrying tensile forces and the load capacity increases. A more uniform distribution of stresses is also achieved (something that is indicated by the formation of several transversal cracks) and the failure mode changes from local slippage of the fibers to global debonding of the TRM strips with the failure surface though being within the TRM thickness (textile/mortar interface).

4.5. Influence of anchorage through wrapping

The influence of anchorage through confinement (full wrapping) was investigated for a short bond length (100 mm) and for 3 and 4 TRM layers. The idea behind this was to improve the bond conditions when a short bond length (less than the effective bond length) is provided, by preventing early TRM debonding. As shown in Fig. 15f, the load capacity was increased by 28% and 45% when three and four TRM layers, respectively were anchored through wrapping with TRM jackets; note that the bond length was equal to 100 mm whereas two TRM layers were used for wrapping. As expected, the failure mode changed from TRM debonding to partial rupture and slippage of the fibers across a single crack developed at the loaded end (Fig. 12b).

A conclusion that must be highlighted is that the anchored TRM strips with a short bond length (100 mm) not only reached, but

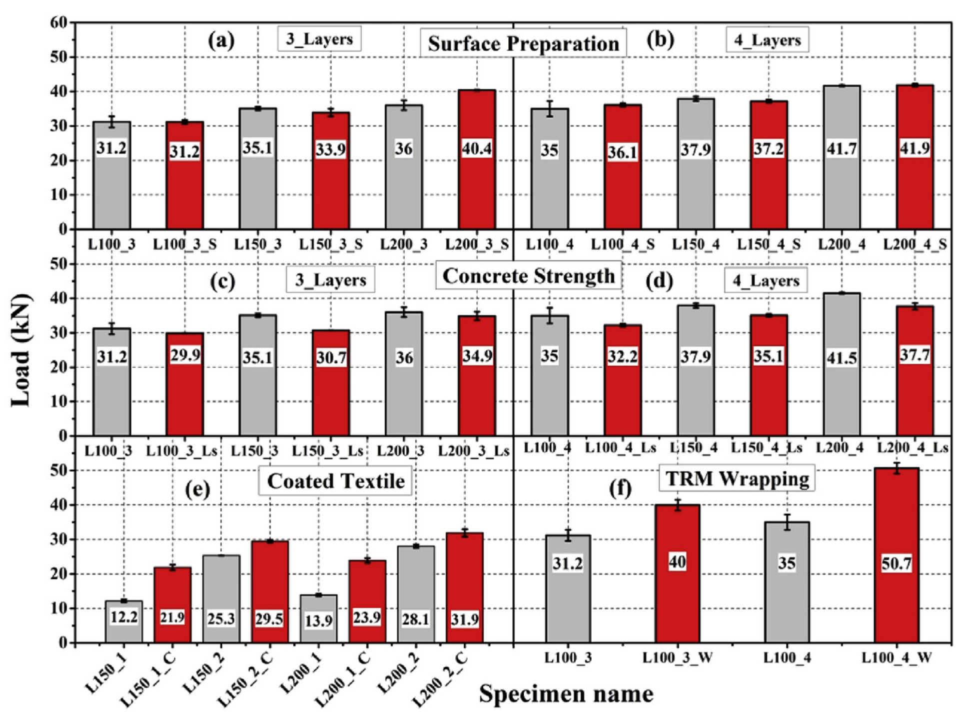

Fig. 15. Effect of different parameters on the bond capacity of the specimens: (a), (b) surface preparation; (c),(d) concrete compressive strength; (e) textile coating; (f) anchorage through wrapping with TRM jackets.

exceeded the load capacity of non-anchored strips with much higher bond length. Particularly, by comparing specimen L100_3_W with specimens L200_3 and L250_3, an increase of the maximum load of 11.1% and 5.2%, respectively, is observed. Similarly, by comparing specimen L100_4_W with specimens L200_4 and L250_4, the increase in the maximum load reaches 22.3% and 21.4%, respectively. Therefore, wrapping with TRM jackets is recommended to improve the bond conditions when the available length for anchorage of TRM reinforcement is limited.

5. Conclusions

The present paper builds on the results of a comprehensive experimental programme for the investigation of the bond between textile-reinforced mortar (TRM) and concrete. Eighty specimens were fabricated and tested under double-lap shear. This poly-parametric study included the investigation of: (a) the TRM bond length, (b) the number of TRM layers, (c) the concrete surface preparation, (d) the concrete compressive strength, (e) the coating of the textile, and (f) the anchorage through wrapping. The main conclusions drawn are summarized below:

- By increasing the bond length, the bond capacity increases in a non-proportional way for all the number of TRM layers examined (1–4). After a certain bond length, the so-called effective bond length, the bond capacity marginally increases. It was found that this length is in the range of 200–300 mm for the examined number of layers and for the materials used in this study.
- By increasing the number of TRM layers for the same bond length, the bond capacity increases in a non-proportional way. The increase was more pronounced for the transition from one to two layers, whereas for more layers it was gradually becoming less significant.
- The number of layers has a significant effect on the failure mode. For one and two TRM layers the failure was due to slippage of the textile fibers through the mortar at a single crack close to the loaded end. For three and four TRM layers the failure was attributed to debonding at the mortar/concrete interface including detachment of a thin concrete layer, similarly to EB FRP systems.
- Different concrete surface preparation methods (grinding and formation of a grid of grooves versus sandblasting) did not influence the bond characteristic between TRM and concrete, suggesting that both methods are suitable.
- The use lower concrete compressive strength marginally affected the bond strength of the TRM to concrete. A 50% reduction in concrete's compressive strength resulted in an average decrease of the ultimate bond capacity of 7.5%, without affecting the failure mode.
- Coating the textile with an epoxy adhesive has a twofold effect: (a) change in the failure mode from slippage through the mortar to TRM debonding at textile/mortar interface, and (b) bond strength increase.
- The anchorage of TRM strips through wrapping with TRM jackets results in substantial increase of the bond strength (up to 45% for 4 TRM layers), by preventing debonding from the concrete substrate.

It is important to note that the above conclusions are based only on the materials used in this study (specific carbon-fiber textile, and specific type of mortar). Therefore future research could be directed towards investigating different types of materials, and deriving analytical expressions for the calculation of the bond length and the bond strength of TRM composites bonded to concrete surfaces.

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References

[1] Triantafillou TC, Papanicolaou CG, Zissimopoulos P, Laourdekis T. Concrete confinement with textile-reinforced mortar jackets. ACI Struct J 2006;103(1):28–37.
[2] Bournas DA, Lontou PV, Papanicolaou CG, Triantafillou TC. Textile-reinforced mortar versus fiber-reinforced polymer confinement in reinforced concrete columns. ACI Struct J 2007;104(6).
[3] Carloni C, Bournas DA, Carozzi FG, D'Antino T, Fava G, Focacci F, et al. “Fiber reinforced composites with cementitious (inorganic) matrix”, Chapter 9. In: Pellegrino C, Sena-Cruz J, editors. Design procedures for the use of composites in strengthening of reinforced concrete structures – State of the art report of the RILEM TC 234-DUC. Springer, RILEM STAR Book Series; 2015. p. 349–91.
[4] Brückner A, Ortlepp R, Curbach M. Textile reinforced concrete for strengthening in bending and shear. Mater Struct 2006;39(8):741–8.
[5] D' Ambrisi A, Focacci F. Flexural strengthening of RC beams with cement-based composites. J Comp Constr 2011;15(5):707–20.
[6] Loreto G, Leardini L, Arboleda D, Nanni A. Performance of RC slab-type elements strengthened with fabric-reinforced cementitious-matrix composites. J Comp Constr 2013;18(3):A4013003. http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000415. 2014.
[7] Koutas LN, Bournas DA. Flexural strengthening of two-way RC slabs with textile-reinforced mortar: experimental investigation and design equations. J Compos Constr 2016. http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000713.
[8] Azam R, Soudki K. FRCM strengthening of shear-critical RC beams. J Comp Constr 2014;18(5):04014012. http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000464.
[9] Tzoura E, Triantafillou TC. Shear strengthening of reinforced concrete T-beams under cyclic loading with TRM or FRP jackets. Mater Struct 2014. http://dx.doi.org/10.1617/s11527-014-0470-9.
[10] Tetta ZC, Koutas LN, Bournas DA. Textile-reinforced mortar (TRM) versus fiber-reinforced polymers (FRP) in shear strengthening of concrete beams. Comps Part B 2015;77:338–48.
[11] Tetta ZC, Koutas LN, Bournas DA. Shear strengthening of full-scale RC T-beams using textile-reinforced mortar and textile-based anchors. Comps Part B 2016;95:225–39.
[12] Ombres L, Verre S. Structural behaviour of fabric-reinforced cementitious matrix (FRCM) strengthened concrete columns under eccentric loading. Compos Part B 2015;75:235–49.
[13] Bournas DA, Triantafillou TC, Zygouris K, Stavropoulos F. Textile-reinforced mortar versus FRP jacketing in seismic retrofitting of RC columns with continuous or lap-spliced deformed bars. J Compos Constr 2009;13(5):360–71.
[14] Bournas DA, Triantafillou TC. Bond strength of lap-spliced bars in concrete confined with composite jackets. J Comp Constr 2011;15(2):156–67.
[15] Bournas DA, Triantafillou TC. Bar buckling in RC columns confined with composite materials. ASCE J Compos Constr 2011;15(3):393–403.
[16] Bournas DA, Triantafillou TC. Biaxial bending of RC columns strengthened with externally applied reinforcement combined with confinement. ACI Struct J 2013;110(2):193–204.
[17] Koutas L, Bousias SN, Triantafillou TC. Seismic strengthening of masonry-infilled RC frames with TRM: experimental study. J Comp Constr 2015;19(2):04014048. http://dx.doi.org/10.1061/(ASCE)CC.1943-5614.0000507.
[18] Papanicolaou CG, Triantafillou TC, Karlos K, Papathanasiou M. Textile reinforced mortar (TRM) versus FRP as strengthening material of URM walls: out-of-plane cyclic loading. Mater Struct 2007;41(1):143–57.
[19] Faella C, Martinelli E, Nigro E, Paciello S. Shear capacity of masonry walls externally strengthened by a cement-based composite material: an experimental campaign. Constr Build Mater 2010;24(1):84–93.
[20] D'Ambrisi A, Feo L, Focacci F. Experimental analysis on bond between PBO-FRCM strengthening materials and concrete. Compos Part B 2013;44(1):524–32.
[21] D'Antino T, Pellegrino C, Carloni C, Sneed LH, Giacomin G. Experimental analysis of the bond behavior of glass, carbon, and steel FRCM composites. Key

Eng Mat 2014;624:371–8.
[22] Sneed LH, D'Antino T, Carloni C. Investigation of bond behavior of PBO fiber-reinforced cementitious matrix composite-concrete interface. ACI Mater J 2014;111(1–6).
[23] Tran CT, Stitmannaithum B, Ueda T. Investigation of the bond behaviour between PBO-FRCM strengthening material and concrete. J Adv Conc Tech 2014;12(12):545–57.
[24] Awani O, El Refai A, El-Maaddawy T. Bond characteristics of carbon fabric-reinforced cementitious matrix in double shear tests. Constr Build Mater 2015;101:39–49.
[25] D'Antino T, Sneed LH, Carloni C, Pellegrino C. Influence of the substrate characteristics on the bond behavior of PBO FRCM-concrete joints. Constr Build Mater 2015;30(101):838–50.
[26] Ombres L. Analysis of the bond between fabric reinforced cementitious mortar (FRCM) strengthening systems and concrete. Compos Part B 2015;28(69):418–26.
[27] Sneed LH, D'Antino T, Carloni C, Pellegrino C. A comparison of the bond behavior of PBO-FRCM composites determined by double-lap and single-lap shear tests. Cem Conc Compos 2015;64:37–48.
[28] EN 1015-11. Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar. Brussels: Comité Européen de Normalisation; 1993.
[29] Serbescu A, Guadagnini M, Pilakoutas K. Standardised double-shear test for determining bond of FRP to concrete and corresponding model development. Compos Part B 2013;55:277–97.
[30] Raoof SM. Flexural strengthening of reinforced concrete beams with textile reinforced mortar (TRM). Department of Civil Engineering, The University of Nottingham; 2015. PhD annual report (2nd year).
[31] Yao J, Teng J, Chen J. Experimental study on FRP-to-concrete bonded joints. Compos Part B 2005;36(2):99–113.