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Experimental and analytical study of reinforced concrete beams shear strengthened with different types of textile-reinforced mortar

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HIGHLIGHTS

- Experimental campaign of RC beams strengthened with different types of TRM.
- Comparative analysis of the mechanical behaviour developed by the tested specimens.
- Evaluation of the bonding behaviour and flexural toughness provided by TRM.
- Analysis of the shear strength provided by TRM according FRP and TRM models.
- Analytical method to accurately predict the shear strength provided by TRM.

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ABSTRACT

Textile-reinforced mortar (TRM) is a composite material that overcomes some drawbacks of other RC (reinforced concrete) shear strengthening solutions. In this work, four different types of TRM are used as a shear strengthening system on RC beams tested until failure. A comparative study of their mechanical performance shows that the different TRM combinations used were able to increase the load bearing capacity and change their failure mode. Moreover, new methodologies that permit evaluating the bonding behaviour of TRM and the increment in flexural toughness are presented. The experimental results are compared with previous FRP and TRM analytical formulations. Finally, new formulae for calculating the shear contribution of TRM based on experimental results are proposed.

1. Introduction

Today, a sustainable construction strategy requires the enlargement of infrastructure life cycle or changing the use of existing facilities. Ageing and damages reduce the load bearing capacity of the existing infrastructure [1]. Therefore, strengthening structures is a crucial issue for a green economy. In particular, the restoration and repair of reinforced concrete (RC) structures usually requires strengthening activities.

The need for higher capacity of shear stirrups is a case of special concern because shear failure is sudden and the corresponding collapse is difficult to foresee. Traditional shear reinforcements of concrete structures include additional stirrups and increasing the size of the cross section [2]. Another technique uses the external post tensioning of the structure. On the other hand, external steel plates can be attached by adhesives or anchors to both sides of the beam [3,4]. Improvements in composite technologies and reduction of manufacturing costs have created a new generation of solutions that spread in construction 30 years ago. FRP (fibre-reinforced polymer), a family of materials that was born in the aerospace industry, is commonly used in repair work [5]. In general, these materials can have a higher strength to weight ratio than traditional strengthening materials such as concrete and steel. They are easier to transport, cut and cast-in-place, allowing for shorter construction time.

Nevertheless, the use of organic resins classifies this latest reinforcement technique as an environmentally unfriendly solution, which also implies technical issues as noted in the work by Triantafillou and Papanicolaou [6]. Early FRP developments focused on substituting polymeric matrices for cement-based

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inorganic matrices. A promising alternative came from TRM (textile-reinforced mortar), a new composite material consisting of a fabric as a tensile withstanding material, where the fibres are grouped in tows and arranged as a mesh, which is embedded in a cementitious matrix. Mortar plays two roles as a matrix and an adhesive to the existing structural surface. Although TRM was intended as part of prefabricated structures [7] (it is also known as textile-reinforced concrete, TRC), a significant part of their development focused on the external reinforcement of masonry structures. Studies on masonry walls subjected to in-plane loads [8], out-of-plane loads [9], eccentric compression [10], and applications on masonry arches [11] showed that TRM performs properly as a reinforcement material for masonry structures. This fact has stimulated many manufacturers to develop products (mortars and textiles) specifically designed for the reinforcement of masonry elements.

TRM was also used as a shear strengthening system of RC structures, and it was compared with FRP solutions. Triantafillou and Papanicolaou [12] studied the structural response of RC beams reinforced with carbon textiles using organic and cement matrices. Blanksvärd et al. [13] analysed the behaviour of different fabrics of carbon fibres combined with various types of mortars and resins. Al-Salloum et al. [14] compared the behaviour of beam-column joints reinforced with FRP and TRM and subjected to cyclic loads.

Moreover, Brückner et al. [15] found the relationship between the number of layers of glass textiles and the increase in the shear capacity of structural elements. They also studied the relationship between the bonding performance of TRM and the lengths of fibre anchorage and different layouts of mechanical anchors [16]. Similarly, Al-Salloum et al. [17] investigated the performance of basalt textiles for TRM and analysed the influence of the number of layers and the orientation of fabrics on the shear capacity of reinforced beams. Recent studies [18,19] confirmed the feasibility of shear strengthening RC beams with TRM under static and cyclic loads.

Finally, Si Larbi et al. [20] studied the feasibility of strengthening RC beams with different shapes of TRM precast plates bonded to the concrete surface with epoxies. Related with this application method, Contamine et al. [21] identified the failure mechanisms in concrete beams by comparing precast TRM reinforcing plates and in situ applied TRM.

At the end of 2013, the first version of a design guide was published for TRM external reinforcements, ACI 549.4R-13 [22], with a proposal for TRM shear strengthening. Previously, other authors proposed analytical models [12,13,20] based on reference FRP standards: fib-Bulletin 14 [23] and ACI 440.2R-08 [24].

Preceding works carried out on RC beams strengthened with TRM against flexural failure showed that the use of different combinations of textiles and mortars directly affects their load bearing capacity [25,26]. However, it is not known if this comparison can also be extrapolated to shear reinforcement because stress states are completely different. Thus, this paper presents a comparative analysis of the mechanical behaviour of RC beams strengthened in shear with different types of TRM. With this aim, an experimental program was carried out, where 9 RC full-scale beams were tested using four different TRM solutions for shear strengthening. Furthermore, two new methodologies are proposed to evaluate (1) the bonding behaviour of TRM and (2) the increment in flexural toughness that these materials provided. This paper includes a critical study about the applicability of various existing analytical models: TRM shear strengthening from ACI code [22] and formulations from FRP adapted to a cement matrix [23,24]. Finally, this work proposes an analytical method for determining the contribution of the TRM to the shear resistance of RC beams, which is based on a novel formulation of the effective strain of the TRM ($\varepsilon_{fe,TRM}$).

2. Materials and specimen preparation

2.1. Reinforced concrete beams

For the experimental campaign, 9 beams were designed and built with a lack of shear reinforcement in two particular areas, as shown in Fig. 1. Beams had a length of 1.70 m and a cross-section of 300 mm × 300 mm. Three longitudinal reinforcement bars of Ø16 mm were installed on the top and the bottom; 5 transverse reinforcement stirrups of Ø8 mm were also installed. All reinforcement bars were B500S. Three different batches of concrete were used. The mechanical properties of the concrete and steel are summarized in Table 1 and were obtained according to the specifications of EN 12390-1 [27], EN 12390-3 [28] and EN ISO 15630-1 [29]. One of the specimens was a control beam, and the other 8 were strengthened with different TRM combinations. All specimens were cured in ambient conditions for more than 30 days.

2.2. TRM components

2.2.1. Mortars

Mechanical properties of the TRM mortar matrices are included in Table 2 Tests to determine the compressive and flexural strength were carried out according to EN 1015-11 [30]. Moreover, tensile strength values calculated from the flexural strength according to Bernat [31] are also included. Bonding strength values were provided by the manufacturers, who used double-shear push tests to determine the values. Four types of mortar were used:

- Bicomponent mortar (designated as PHDM) with high strength cement, glass fibres, selected aggregates and synthetic polymers in aqueous dispersion. It is a material specially designed for masonry, and it can also be used as a restoration mortar.
- Hydraulic mortar (designated as XM750) with high bonding capacity, fibres and special additives. It is a mortar designed for application in concrete structure repairing.
- Hydraulic pozzolanic mortar (designated as XM25) with additives. This mortar is perfectly compatible in terms of chemical, physical and mechanical properties with masonry structures.
- Hydraulic mortar modified with polymeric additions (designated as R3). This is a mortar designed for structural repairing.

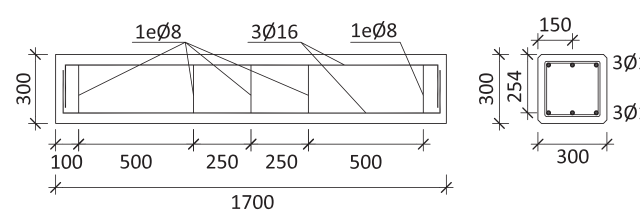

Fig. 1. Geometry and steel reinforcement of the tested beams (all dimensions in mm).

Table 1
Mechanical properties of the concrete and steel bars.

Concrete			Steel		
Cast batch	f_{cm} [MPa]	E_c [GPa]	f_y [MPa]	f_u [MPa]	E_s [GPa]
Batch-1	34.07	32.92	517.20	633.63	198.48
Batch-2	33.78	32.83			
Batch-3	40.85	34.82			

Table 2
Mechanical properties of the mortars used as TRM matrices.

Mortar	Compression strength (MPa)	Flexural strength (MPa)	Tensile strength (MPa)	Bonding strength* (MPa)
PHDM	35.40 (2.53)	8.63 (0.57)	3.81 (0.57)	2.0
XM750	30.02 (2.21)	10.65 (0.80)	4.70 (0.80)	–
XM25	24.95 (1.64)	7.87 (0.78)	3.47 (0.78)	0.8
R3	24.65 (1.43)	8.13 (0.99)	3.59 (0.99)	–

Values in brackets indicate coefficient of variance.
* Values provided by manufacturer.