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Durability of steel reinforced polyurethane-to-substrate bond

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ABSTRACT

Steel reinforced polyurethane (SRPU) is an innovative composite material which comprises a unidirectional steel textile and a polyurethane matrix. By the virtue of the high flexibility of the polyurethane, which redistributes the shear stresses between reinforcement and substrate, SRPU has recently proved effective for specific externally bonded strengthening applications. The long-term SRPU bond performances, however, have not been sufficiently investigated to date. Nevertheless, they are of the utmost importance for mitigating the risks and the costs associated to damage and repair/substitution in the long-term. This is crucial for the sustainability of the building stock and of the rehabilitation measures developed for its lasting safeguarding. In this work, the durability of the bond of SRPU applied to masonry substrates was investigated. Single-lap shear bond tests were carried after drying, immersion in alkaline or substitute ocean water solutions, exposure to high humidity, and freeze-thaw cycles. Bond tests and SEM and EDS analyses showed that artificial aging did not generally affect the SRPU bond performance. The zinc coating, however, proved sensitive to the prolonged attack of alkali, which modified the interface between steel cords and polyurethane, suggesting the need of protecting the fabric by a complete covering with the matrix.

1. Introduction

Steel reinforced polyurethane (SRPU) is a composite material developed for the externally bonded reinforcement of structural members, which comprises a unidirectional textile of ultra-high tensile strength steel cords and a highly deformable polyurethane matrix [1]. The use of steel fabrics in polymeric composites for civil engineering applications has recently emerged as a valuable alternative to that of other textiles, such as carbon and glass fibre sheets. Steel reinforced polymers (SRPs) proved effective for the strengthening of reinforced concrete and masonry structures under bending, shear and axial loading (see Ref. [2] and the references therein). In SRPU, the epoxy resins used in the more widely established fibre/steel reinforced polymers (FRP/SRP) is replaced by polyurethane, whose tensile modulus of elasticity is two orders of magnitude lower than that of epoxy resins ($10 \div 20\,\mathrm{N/mm^2}$ versus $1000 \div 5000\,\mathrm{N/mm^2}$), whereas the ultimate strain is at least ten times higher ($10 \div 45\%$ versus $0.8 \div 4\%$) [1]. By the virtue of its high deformability, polyurethane efficiently redistributes the shear stresses over the composite-to-substrate interface [3], preventing local stress concentrations from triggering cohesive debonding in brittle substrates (e.g., masonry). As a result, the bond strength of SRPU experimentally resulted higher than that of SRPs [1]. This technology has also been proposed for re-bonding SRP strips detached from the substrate [4] as a quick repair solution for the protection of damaged structures, with possible applications in post-disaster emergency works [5,6].

Nevertheless, the investigations carried out so far have mainly focussed on the bond strength of SRPU [1,4,7] and on the enhancement of ultimate strength provided by SRPU strips applied to structural members [5], whereas long-term performance has not been properly tackled yet. The durability of the steel fabrics against salt attack [2] and of the polyurethane under thermal cycles [8] and combined ultraviolet radiation, moisture and heat [9] has been investigated, but no studies have been devoted to the durability of the substrate-to-SRPU load transfer capacity so far. And instead, it is of the utmost importance for the long-term effectiveness of the strengthening work and, therefore, for the safety of the strengthened member, which relies on the load transfer capacity between substrate and composite reinforcement. Adequate durability performances mitigate the risks and the costs

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Table 1
Experimental plan.

	Series	Substrate	Textile side	L_b [mm]	Days at testing	Aging	N
Unaged specimens	B-M	Clay brick	M	200	50–61	None	4
	M-M	Brick masonry	M	200	61–74	None	6
	M-280 M	Brick masonry	M	280	61–74	None	6
	B-C-1	Clay brick	C	200	1	None	5
	B-C-28	Clay brick	C	200	28	None	5
	B-C-140	Clay brick	C	200	140–237	None	6
Aged specimens	B-M-HU1	Clay brick	M	200	98	High humidity 1000 h	4
	B-M-HU3	Clay brick	M	200	369–375	High humidity 3000 h	4
	B-M-FT	Clay brick	M	200	370–376	Freeze-thaw	4
	B-C-DR	Clay brick	C	200	28–29	Drying	5
	B-C-OW1	Clay brick	C	200	141–144	Substitute ocean water 1000 h	5
	B-C-OW3	Clay brick	C	200	211	Substitute ocean water 3000 h	5
	B-C-OWC	Clay brick	C	200	214	Substitute ocean water 1000 h (cyclic)	5
	B-C-AL1	Clay brick	C	200	141	Alkaline 1000 h	5
	B-C-AL3	Clay brick	C	200	210–211	Alkaline 3000 h	5
	B-C-ALC	Clay brick	C	200	214	Alkaline 1000 h (cyclic)	5

associated to damage and repair/substitution, contributing to the sustainability of the building stock and of the rehabilitation measures developed for its lasting safeguarding [10,11].

Some lessons can be learned from the research carried out on FRPs, which indicated that humidity/moisture is particularly aggressive for polymeric matrices [12–18], whereas, due to the impermeability of the resins, freeze-thaw cycles [19–22] or combined temperature/humidity cycles [23–26] may damage the substrate and reduce the bond strength. Finally, ACI 440.2R-17 [27] considers alkalinity, salt water, chemicals, ultraviolet light, high temperatures, high humidity, and freeze-thaw cycles amongst the causes of environmental deterioration of FRPs.

This paper presents an experimental study on the durability of the bond of SRPU composites. Single-lap shear bond tests were performed on brick and masonry substrates. First, the influence of the roughness of the substrate, the bond length, the net area of matrix at the interface with the textile (where failure typically occurred), and the curing time were investigated on unaged specimens. Then, the durability of bond performance was investigated after different artificial aging processes, such as drying, constant or cyclic immersion in alkaline or substitute ocean water solutions, exposure to high humidity, and freeze-thaw cycles. The results of shear bond tests provided information on the long-term performances of the SRPU-to-substrate load transfer capacity, which rules the effectiveness of the externally bonded SRPU reinforcements, contributing to filling the existing knowledge gap. Scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) analyses were carried out after the shear bond tests to develop a deeper understanding on the deterioration produced by artificial aging, identify possible protection measures for SRPU reinforcements in structural applications, and contribute to the development of accelerated artificial aging protocols.

2. Experimental plan and setup

2.1. Materials and specimen manufacturing

In this study, a unidirectional textile of Ultra High Tensile Strength Steel (UHTSS) cords was used, having 2000 g/m^2 surface mass density and 0.254 mm design thickness. Each cord is made of five galvanized (zinc-coated) wires, with 0.1076 mm^2 cross sectional area each. The cords are placed at 2.12 mm spacing parallel to each other on a supporting glass mesh, which eases storage and installation. The textile has 3201 N/mm^2 tensile strength, 2.24% ultimate strain and 186.1 kN/mm^2 tensile modulus of elasticity [28].

The steel textile was bonded to brick and brickwork substrates using a two-component highly deformable polyurethane. Among the various types of polyurethane matrices that have been developed for externally bonded reinforcements, flexible joints and protective coatings, which differ in terms of mechanical properties (tensile strength, ultimate elongation, elastic modulus) [7], the polyurethane of PS type was used in this study. It has 2.87 N/mm^2 tensile strength, 45% ultimate strain and 14.8 N/mm^2 Young's modulus and exhibits a hyperelastic tensile stress versus tensile strain behaviour [4]. Its water vapour resistance factor, measured in accordance with [29], is $\mu = 1200 \div 1300$.

The solid bricks used as substrates were provided by SanMarco-Terreal (Italy) and had 120 mm × 250 mm × 55 mm size, 14.8 N/mm^2 compressive strength, 2.5 N/mm^2 tensile strength and 5.76 kN/mm^2 Young's modulus [30]. Brick masonry prisms were manufactured with the same clay bricks and a commercial ready-mix M5 class hydraulic lime mortar (according to [31]) and were made of five half bricks and four 10 mm thick bed joints.

The steel textiles were bonded to the substrates after 6 months from the manufacturing of the prisms. One strip of steel textile comprising 24 cords, corresponding to an effective width of 50.8 mm and a cross-sectional area of 12.9 mm^2, and 600 mm long, was bonded for either 200 mm or 280 mm to one side of the substrate. The bonded area was 50 mm wide and its loaded end (its edge on the side where the load was applied) was 30 mm far from the edge of the substrate to avoid edge effects. A standard wet lay-up procedure was followed [32,33]. First, dust was removed with compressed air and a primer (one component polyurethane) was applied to improve the SRPU-to-substrate adhesion. Then, the textile was bonded to the substrate using a roller to ensure proper impregnation of the matrix both in the substrate and through the steel cords.

2.2. Experimental plan

The study included shear bond tests on both unaged and aged specimens (Table 1). In the former set (unaged specimens), the following parameters were investigated:

- Type of substrate: both brick (Fig. 1a) and brickwork prisms (Fig. 1b and c) were used to study the influence of the roughness of the substrate. In the label of the specimens, brick substrates are identified by letter B, whereas letter M identifies masonry prisms.
- Bond length (L_b): SRPU strips were bonded for a bond length of 200 mm on brick substrates (Fig. 1a) and for either 200 mm (Fig. 1b) or 280 mm (Fig. 1c) on brickwork prisms.
- Position of the glass mesh in the installed SRPU strip, either above the cords or below the cords, to investigate the influence of the amount of matrix that passes through the voids between the steel cords. The former layout is labelled as C (the textile is placed with the cords toward the substrate, Fig. 2a), whereas the latter one is labelled as M (the textile is placed with the glass mesh toward the substrate, Fig. 2b). The index of voids (i.e., the empty space through