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Strengthening of structures with Steel Reinforced Polymers: A state-of-the-art review

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ABSTRACT

Steel Reinforced Polymer (SRP) is an innovative system for the external strengthening of structures, which comprises unidirectional textiles of High Tensile Strength Steel applied with polymeric resin. The first applications of SRP in civil engineering date back to 2004, and, since then, a number of studies have been carried out on both mechanical characterization and structural applications. Nevertheless, the existing knowledge has mostly remained a fragmented skillset of the scientific community and specific guidelines for qualification and design have not been developed yet. This paper reviews the experimental works on SRP to establish its advantages and drawbacks and promote a proper knowledge transfer from academia to engineering design practice. With respect to the already well-established Fibre Reinforced Polymers (FRPs) with carbon or glass textiles, SRP exhibits comparable, or even better, tensile and bond behaviour, and, when applied for bending reinforcement or for confinement, provides equivalent or higher improvement of structural performance in terms of load bearing and displacement capacity. Even if long-term durability, shear strengthening of reinforced concrete beams and applications to masonry would still deserve more investigations, the research performed so far has already demonstrated that SRP is an effective and cost efficient solution for the rehabilitation of structures and that it can be reliably designed with the same relationships developed for FRPs.

1. Introduction

The use of Fibre Reinforced Polymer (FRP) composites for the external strengthening and repair of reinforced concrete (RC), masonry and timber structures has met over the last twenty years an increasing consensus at both the academic and industrial levels. In civil engineering, the application of these composites, mainly employing carbon or glass fibres and exploitable as adhesively bonded or mechanically fastened systems, has emerged as a competitive alternative to traditional techniques [1,2], as it is witnessed by the adoption of specific design guidelines [3–5].

The growing interest towards the development of new effective and cost efficient solutions has recently led to the introduction of innovative techniques that make use of other materials in lieu of carbon and glass. Among them, the composites with steel textiles have emerged as one of the most promising ones. These systems consist of High Tensile Strength Steel (HTSS) micro wires, twisted in cords or ropes that are then assembled parallel to each other to form unidirectional fabrics. HTSS cords were originally developed for the automotive industry as internal reinforcement of tyres. Their first application in civil engineering was proposed in 2004 to strengthen RC beams in bending [6–10], with promising results that promoted both scientific research and industrial development oriented to the use of HTSS for structural rehabilitation and upgrade.

Like FRPs, steel textiles can be externally bonded to the substrate via wet lay-up, by using either epoxy or polyester resin, obtaining a composite known as Steel Reinforced Polymer (SRP). Resins allow for relatively easy and fast installation and provide high adhesion to the substrate. On the other hand, they cannot be applied to wet substrates, have a brittle behaviour, their effectiveness is limited by the glass transition temperature (typically in the order of 50–60 °C), above which they tend to soften, and have no fire resistance, such that an outer protection layer is necessary. Furthermore, when exposed to humidity or moisture, resins tend to

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List of symbols

A_{cord}	Area of steel cord
A_f	Cross section area of dry steel textile
A_s	Area of steel rebars in tension
A_s'	Area of steel rebars in compression
D	Diameter of circular concrete member
E_f	Young's modulus of steel textile
E_t	Young's modulus of SRP
F_b^{exp}	Experimental bond strength (load)
F_b^{*exp}	Experimental bond strength (load per unit width)
F_b^{th}	Theoretical bond strength (load)
F_{max}^{exp}	Experimental maximum force in tests on structural members
F_{max}^{th}	Theoretical maximum force in bending tests
FM^{exp}	Experimental failure mode
FM^{th}	Theoretical failure mode
I_{Fmax}	Experimental percentage increase of maximum force in tests on structural members (reinforced versus unreinforced)
L_b	Bond length of SRP
L_c	Clear length of beam
L_f	Length of SRP laminate
L_s	Shear span of beam
MAPE	Mean absolute percentage error between experimental result and theoretical estimate
N	Number of homogenous tests (nominally identical for materials and geometry)
b	Width of beam’s cross section
b_f	Width of SRP
b_s	Width of substrate
d'	Concrete cover depth
f_c	Average value of cylinder compressive strength of concrete in tests on structural members
f_{cc}	Compressive strength of confined concrete member
$\bar{f}_{cc}$	Normalized compressive strength of confined concrete member ($=f_{cc}/f_{c0}$)
f_{cm}^{exp}	Experimental compressive strength of confined masonry member
f_{cm}^{th}	Theoretical compressive strength of confined masonry member
f_{cs}	Compressive strength of substrate
f_{c0}	Compressive strength of unconfined concrete member
f_d	SRP stress at debonding failure in bending tests
f_l	Effective confining pressure exerted by external jacket
$\bar{f}_1$	Normalized effective confining pressure exerted by external jacket ($= f_l/f_{c0}$)
f_y	Yield strength of steel rebars in tension
f_y'	Yield strength of steel rebars in compression
f_f	Tensile strength of steel textile
f_t	Tensile strength of SRP
f_{ts}	Tensile strength of substrate
h	Height of beam’s cross section
k_b	Geometrical corrective coefficient
k_{conf}	Axial stiffness of external jacket
k_G	Corrective factor calibrated on experimental basis for SRP end debonding
k_{Gk}	Characteristic value (5% fractile) of k_G
k_{Gm}	Average value of k_G
$k_{G,2}$	Corrective factor calibrated on experimental basis for SRP intermediate debonding
k_q	Coefficient accounting for load distribution in bending tests
k_ε	Strain efficiency factor of external confinement
p	Number of plies
s	Spacing between SRP strips for shear strengthening
t_f	Equivalent (or design) thickness of steel textile
Δ^{exp}	Experimental displacement corresponding to maximum force in tests on structural members
α_1, α_2	Coefficients for prediction of normalized compressive strength of confined concrete
β_1, β_2	Coefficients for prediction of normalized ultimate strain of confined concrete
δ	Experimental to theoretical bond strength ratio
ε_d	SRP strain at debonding failure in bending tests
ε_f	Ultimate strain of steel textile
ε_{max}	Maximum SRP tensile strain in bending tests
ε_{ccu}	Ultimate axial strain of confined concrete member
$\bar{\varepsilon}_{ccu}$	Normalized ultimate axial strain of confined concrete member ($= \varepsilon_{ccu}/\varepsilon_{c0}$)
ε_{cu}	Ultimate concrete compressive strain in bending tests
ε_{c0}	Axial strain of unconfined concrete member at ultimate load
ε_t	Ultimate strain of SRP
η	Exploitation ratio of tensile strength
ξ	Density of textile
ρ_{eq}	Equivalent reinforcement ratio
ρ_f	Reinforcement ratio of SRP
ρ_s	Reinforcement ratio of steel rebars in tension
σ_b	Experimental bond strength (stress in textile)

absorb water, which causes hydrolysis, plasticization, and saponification, modifying the polymer structure and causing deterioration of the mechanical properties and of the fiber-to-matrix bond strength. To overcome these drawbacks, alternative strengthening systems with steel textiles and inorganic matrix, named SRG (Steel Reinforced Grout), were proposed at the same time of the first studies on SRP [7]. The use of mortars in place of resins provides a better fire resistance and allows for installation on wet substrates, but may lead to a lower bond strength and, more generally, to a different structural behaviour of the strengthening system. For this reason, according to the current state of knowledge, the approaches developed for FRPs cannot be directly extended to mortar-based composites, including SRG.

A number of research studies have been carried out on Steel Reinforced Polymers since 2004. Fundamental mechanical properties (tensile behaviour), durability and shear bond performance on both concrete and masonry substrates have been widely investigated through tests on small-scale specimens. Different steel cord layouts have been examined to identify (or develop) the most suitable ones for structural applications. At the same time, a number of medium/large-scale tests have been performed on structural members to study the effectiveness of SRP for strengthening RC beams and masonry panels in bending and shear, for confining RC columns, beam-to-column joints and brickwork pillars, and for retrofitting masonry arches. Finally, applications to timber beams and floors, and to glass members have been lately proposed. These studies indicated that the tensile properties and the adhesion to the substrate of SRP are comparable to FRPs with