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OVERVIEW OF THE MECHANICAL PROPERTIES OF STEEL REINFORCED GROUT SYSTEMS FOR STRUCTURAL RETROFITTING

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Abstract. *Steel Reinforced Grout (SRG) is a mortar-based composite recently developed for structural retrofitting, which provides high tensile strength with limited increase in mass and in stiffness, and whose effectiveness relies on the good interaction between steel cords and inorganic matrices. Many companies already supply SRG systems for rehabilitation activities and the scientific community has been working intensively on experimental and numerical investigations to demonstrate their effectiveness for structural applications, which also led to the inclusion of SRG in national and international standards for product qualification and design. However, a clear view of the mechanical properties of these systems is still lacking, due to their variability, which, in turn, strongly depends upon cord layout, textile architecture, and characteristics of the matrix. This paper provides an overview of the mechanical properties of SRG composites on the basis of the tests carried out at Roma Tre University and of the other experimental evidences available in the literature. The results of tensile tests on bare textiles and SRG coupons with different inorganic matrices, and of bond tests on masonry and reinforced concrete substrates are collected and the performances of the different SRG systems are compared. The influence of the mortar matrix on crack spacing, ultimate strain and tension stiffening in tensile tests is analysed. The capacity of the steel cords to ensure a proper shear transfer through interlocking within the matrix and the effect of cord density on failure mechanisms in bond tests are also discussed.*

1 INTRODUCTION

Steel Reinforced Grout (SRG) is a class of innovative mortar-based composites, named as Fabric Reinforced Cementitious Matrix (FRCM), developed for structural rehabilitation, as externally bonded reinforcements of existing reinforced concrete and masonry constructions. They can enhance structural capacity without alterations of geometry, mass and stiffness. Similarly to other FRCM systems, SRG may represent a valid solution to traditional techniques, such as the installation of steel tie-bars, the construction of crowning beams or the laying of

reinforced concrete plater overlays, which may be invasive, non-reversible, more expensive and inappropriate for applications to historical buildings. Therefore, they actually are an effective strengthening system first at all for cultural heritage thanks to their high compatibility between mortar matrix and masonry substrate.
SRG specific benefits have been demonstrated by a number of investigations carried out in different application fields. More specifically, experiments showed that the use of steel as reinforcement in FRCM composites provides an improvement of mechanical properties thanks to the ductility [1, 2] and the high tensile strength [3] of the textile. The layout of the cords also ensures a particularly efficient interlocking with mortar matrices, improving the bond at their interface [4, 5, 6, 7]. Finally, connection and anchorage systems can be effectively added to SRG overlays [8, 9, 10], allowing their installation on various structural members [11, 12, 13, 14] and ensuring particularly high gains in load carrying capacity as well [17,18]. On the basis of such investigations, SRG composites are currently included in the testing [19], acceptance [20] and design [21, 22] guides.
This paper collects the most recent research studies on SRG carried out in Roma Tre University according to EAD certification procedure [23], which followed those performed within the RILEM TC-250 CSM (Composites for the Sustainable Strengthening of Masonry) [22]. The most significant mechanical characteristics are compared to discuss the effect of the following parameters: architecture of the single cord, density of the textile, characteristics of the matrix and the substrate materials (concrete, clay bricks and tuff units).

2 MECHANICAL PROPERTIES OF STEEL TEXTILE AND SRG COMPOSITE UNDER DIRECT TENSILE TEST

In this paragraph, results of direct tensile test on bare steel textile and on SRG coupons are collected from Roma Tre University tests and others experimental investigations.

Figure 1.1: Experimental set up for tensile tests on dry textile

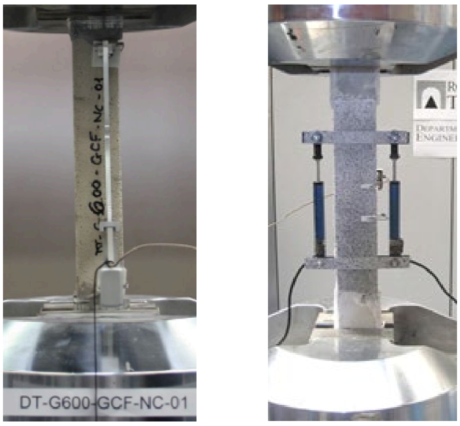


Figure 2.2: Experimental setup for tensile tests on SRG coupons


Figure 3.3: Experimental setup for shear bond tests

2.1 Tensile behaviour of steel textile

Direct tensile tests (Figure 1.1) on steel textiles are carried out to obtain peak stress, corresponding strain, and Young's modulus. In particular, in this case are collected properties and results from Roma Tre University(†)[24] and RILEM TC 250-CSM(*) [25, 26, 27] experimental studies on four typologies of steel textiles:

S1) Galvanized Steel textile, consisting in Ultra High Tensile Strength Steel (UHTSS) cords with 6.35mm spacing, 0.084mm design thickness and 670g/m^2 surface mass density (low density). Each cord (Area=0.538mm^2) is obtained by twisting 2 wires around 3 rectilinear ones, having 0.108mm^2 cross section area.

S2) Galvanized Steel textile, consisting in Ultra High Tensile Strength Steel (UHTSS) cords with 3.18mm spacing, 0.169mm design thickness and 1340g/m^2 surface mass density (low-medium density).

S3) Steel textile, characterized by AISI 304 stainless steel made of cords, with 3.18 mm spacing. Each cord (cross section area=0.595mm^2) is obtained by twisting 5 wires having 0.119 mm^2 cross section area; 0.188mm design thickness and 1500g/m^2 surface mass density.

S4) Steel textile, characterized by AISI 316 stainless steel made of ropes, obtained by twisting several small wires; ropes have a cross section area of 0.69mm^2 each and are spaced 5mm.

Table 1: Geometrical properties and mechanical characteristics of steel textile under direct tensile test

Specimen label	c [cords/mm]	i [mm]	γ [g/m^2]	t [mm]	f_s [N/mm^2]	E_s [kN/mm^2]	ε_s [%]
S1*	0.157	6.35	670	0.084	3191	186	2.19
S2†	0.314	3.18	1340	0.169	3005	184	1.90
S3*	0.315	3.18	1500	0.188	2084	130	2.29
S4*	0.200	5.00	1057	0.138	1150	147	1.18

c = cord density; i = spacing; γ = surface mass density; t = equivalent (design) thickness
f_s= peak stress; E_s= secant Young's modulus ; ε_s =strain corresponding to peak stress;
*= RRT by RILEM TC-250 CSM experimental tests [25, 26, 27]
†= experimental tests recently carried out in Roma Tre University according to EAD [24]

Table 1 reports the main results of direct tensile tests on bare textiles: galvanized steel achieves the maximum tensile stress (around 3000N/mm^2). Stainless steel tensile behaviour assumes Young's modulus lower than galvanized one, which could depend not only on the steel treatment (galvanized vs stainless) but also on the different cord architecture, causing a limited easy handling as well.

2.2 Tensile behaviour of SRG coupons

Direct tensile test provides also the constitutive behaviour of SRG (Figure 1.2). The main mechanical parameters in the un-cracked, cracking, fully cracked stages are collected in this paragraph [22, 23]. In order to make SRG coupons for direct tensile tests, the four abovementioned textiles are combined with the following mortars:

ML) Lime based mortar with geopolymeric binders.

MG) Geopolymeric mortar.

MP) Lime and pozzolana based mortar.

MR) Fibre-reinforced cement mortar with polymeric additives.

Table 2 summarizes and compares the experimental results and failure modes (Figure 2.1), of six SRG systems, from Roma Tre University $^{(\dagger)}$ [24] and Rilem TC 250-CSM $^{(*)}$ experimental investigations [25, 26, 27].

Table 2: Properties of mortars and mechanical characteristics of SRG coupons under direct tensile test

Steel textile	Inorganic mortar				SRG direct tensile results				
Label	Label	f_{cm} [N/mm^2]	E_{cm} [kN/mm^2]	f_{tm} [N/mm^2]	f_t [N/mm^2]	ε_t [%]	E_{1m} [kN/mm^2]	E_{3m} [kN/mm^2]	Failure mode
S1*	ML	20.6	11.42	5.42	3461	2.03	914	184	A-AB
S2†					2918	1.82	1063	187	A
S1*	MG	56.3	22.01	10.31	3365	1.90	1718	186	A-AB
S2†					2964	1.92	1352	195	A
S3*	MP	6.4	6.31	1.24	2448	1.75	547	178	A-AB
S4*	MR	22.7	10.0	11.2	1045	1.23	892	102	B

f_{cm} = compressive strength; E_{cm} = Young's modulus from tests on cubic specimens; f_{tm} = tensile strength from three-point bending tests; f_t= peak stress ε_t =strain corresponding to peak stress; E_{1m}= Young's modulus in un-cracked stage; E_{3m}= Young's modulus in cracked stage.
*= RRT by RILEM TC-250 CSM experimental tests [25, 26, 27]
†= experimental tests recently carried out in Roma Tre University according to EAD [23, 24]

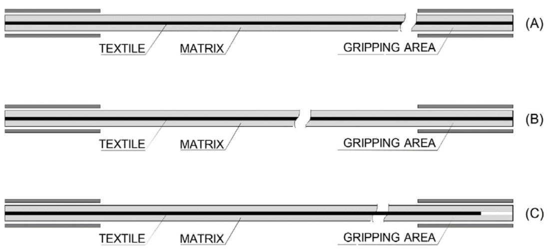


Figure 2.1: Failure mode in direct tensile tests (Rilem procedure)

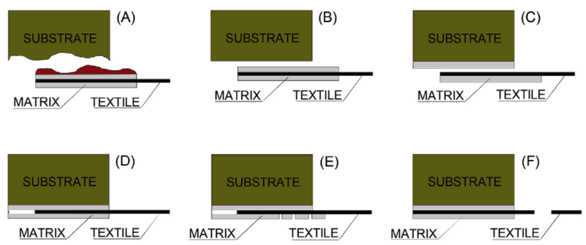


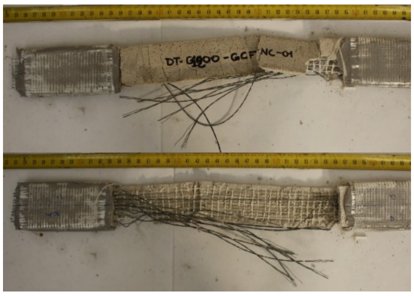
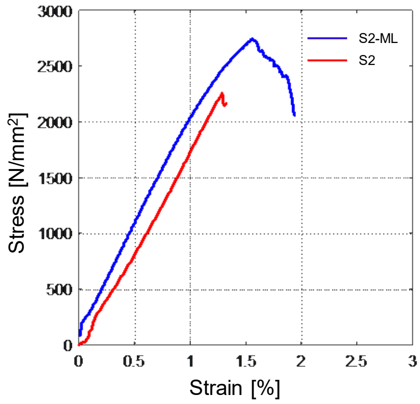
Figure 2.2: Failure mode in shear bond tests (Rilem procedure)

Experimental data collected in Table 2 show that peak stress values (f_t) and Young's modulus at third stage (E_{3m}) are generally very similar to those of bare textiles (f_s , E_s – Table 1). For instance, in SRG systems made by "S1" steel textile, the mortar contribution is calculated up to 8%, definitely more than ones made by "S2".

This phenomenon can be attributed to the fact that the low density of cords well-establishes a stress transfer among mortar layers, promoting the mechanical interlocking between cords surface and mortar. At the same time, the maximum contribution of mortar is detected for "S3-MP" system, in which the SRG peak stress value increases by 18% with respect to the dry steel textile. In this case, mortar improves the loading distribution between steel cords. For each test on SRG carried out under direct tensile, the ultimate strain corresponding to peak stress value is very close to that calculated for bare textiles, with the only exception of "S3-MP".

Concerning the failure modes (Figure 2.1), in general the main failures occur near the gripping areas (Failure mode "A") because of local stress concentration, anticipated by a progressive cracking development along the entire length of the coupon. Ruptures took place in the middle (Failure mode "B") of the coupon only for "S4-MR" system. Failure "C", characterized by cracking in the length of the specimen and fibers slippage, in any case is not observed.

From this test type, tension stiffening could be also clearly observed thanks to the distributed crack pattern. For both systems made by "S2" steel textile, crack spacing (Figure 3) is similar and as a result, the failure mode does not depend on the type of the mortar.

<table>
<tr><th>Specimen label</th><th>Failure mode</th><th>Stress-strain average curve
Tensile behaviour</th></tr>
<tr><td>S2-ML†</td><td></td><td>
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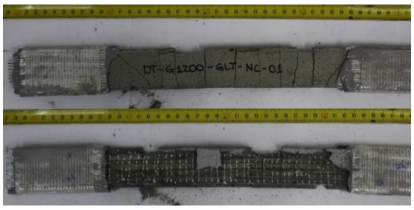
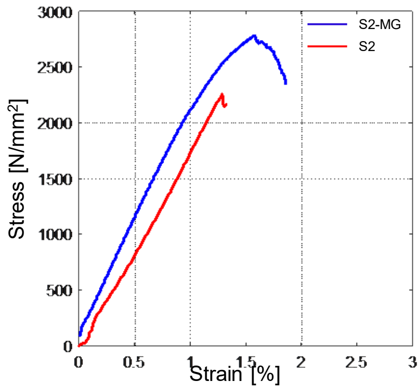
<tr><td>S2-MG†</td><td></td><td>
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Figure 3: Failure mode in systems with "S2" steel textile (low-medium density). †= experimental tests recently carried out in Roma Tre University according to EAD [23, 24]

3 SRG-TO SUBSTRATE BOND BEHAVIOUR

Single-lap shear bond test (Figure 1.3) allows studying the SRG-to-substrate stress transfer behaviour, which is represented by the following properties: stress at peak load (f_b), exploitation ratios (η_{dry}= f_b/f_s, the amount of dry textile tensile strength that is exploited at bond failure; η_{comp}= f_b/f_t, the amount of SRG tensile strength that is exploited at bond failure). Failure modes are also recognized (Figure 2.2): failure mode "A" corresponds to debonding with cohesive failure of the substrate; failure mode "B" happens when debonding occurs at the matrix-to-substrate interface. For debonding at the textile-to-matrix interface, failure mode is named "C". Failure mode "D" identifies the textile slippage within the mortar matrix. Failure mode "E" occurs when textile slippage within the matrix and cracking of the outer layer of mortar are observed. Tensile rupture of the textile (out of bonded area) is classified in failure mode "F". In the following paragraphs shear bond performances of SRG composites bonded to different substrates (concrete, clay brick masonry and tuff blocks) are discussed. The following sections collect the experimental data provided by Ascione and co-authors [30] for concrete substrate, Round Robin Test RILEM TC 250-CSM procedures [25] for brick masonry, and finally others research documents for tuff substrate [31, 32].

3.1 SRG-to-concrete bond behaviour

The analysis of SRG-to-concrete substrate bond behaviour is illustrated in a recent research available in literature [30], in which different parameters have been investigated. Herein, tests with manufacturing and curing characteristics of SRG similar to Round Robin Test TC 250-CSM procedures are selected. Regarding geometrical dimensions of strengthening strip, the bonded interface length is 300mm, the width dimension is 100mm and the number of layer is chosen equal to 1. The SRG curing is carried out in room temperature for 28 days and then wet clothes are placed on the top of composite surface each day for two weeks. Inorganic mortar assumes these properties: >50MPa is the strength in compression, the tensile strength in bending is evaluated >8 MPa (28days in curing) and the elastic modulus in compression is comprised in a range from 20 to 22GPa. In addition, the properties of concrete prisms are comparable to reinforced concrete in existing buildings (concrete cylindrical strength after 28 days in the range of 13-25MPa). The surface finish (bush hammered and sandblasted) and the density of steel reinforcement ("S1" an "S2") are the only variable parameters.

Table 3: Shear bond tests results for SRG-to-concrete substrate

Specimen label	Substrate – surface finish	f_b [N/mm^2]	η_{dry} [%]	η_{comp} [%]	Failure mode
S1-ML	Concrete – bush hammered	2705	85	78	C or F
S2-ML	Concrete –bush hammered	1035	34	31	C
S1-ML	Concrete – sandblasted	2847	89	82	C or F
S2-ML	Concrete – sandblasted	899	30	28	C

In Table 3, shear bond test results on concrete substrate are collected: stress values at peak load depend on the steel density and not on the surface finish. Indeed, the global response of SRG made of low-density steel textile ("S1") is mainly provided by steel reinforcement and the subsequent failure mode corresponds to steel cords tensile failure. On the other hand, steel textiles with higher density fail at a peak load value which is the half of that achieved by lower density textiles, thus not exploiting all the strength properties of the SRG composite. This is the reason why, in "S2" systems, failure occurs by matrix debonding ("C") within the system, at the steel-mortar interface. For systems made by "S1" steel textile, failure mode "C" is associated to steel cords rupture in the unbonded region ("F" mode).

3.2 SRG-to-masonry bond behaviour

Steel Reinforced Grout-to-masonry substrate bond behaviour was deeply studied in the Round Robin Test initiative organized by the Rilem TC 250-CSM, with laboratories of several research centres from all Europe involved [25].

The maximum value of stress at peak load was recorded for SRG strengthening made by "S1" galvanized steel and lime mortar (Table 4). Failure occurred in the unbonded textile ("F" mode), therefore both exploitation ratios are very close to 100%. S4-MR system also exhibited a good bond performance, as shown by the high values of the exploitation ratio. In this case, textile slippage within the matrix took place (Failure mode "D").

Table 4: Shear bond tests results for SRG-to-masonry substrate

Specimen label	Substrate	f_b [N/mm^2]	η_{dry} [%]	η_{comp} [%]	Failure mode
S1-ML*	Clay brick masonry	3023	95	87	F
S1-MG*	Clay brick masonry	2457	77	71	B or C
S3-MP*	Clay brick masonry	1169	56	48	D
S4-MR*	Clay brick masonry	939	82	89	D

3.3 SRG-to-tuff bond behaviour

In order to investigate the SRG-to-tuff bond behaviour, test data from De Santis and de Felice [31] and Bilotta and co-autohors [32] are analysed in this paragraph. From the first document published in 2015, shear bond test performances regarding tuff unit strengthened with two systems ("S1-ML" and "S1-MG") are reported in this study. At the same time, other two cases are provided by the second research: in particular, two typologies of SRG systems applied to tuff units are analysed. Both the systems are made of the same mortar, named "MH", which is a bi-component premixed pozzolan-based grout also including hydraulic natural lime, sand, polymeric additives and short glass fibers spread in the matrix, having 12.4N/mm^2 compressive strength and 6.2N/mm^2 flexural strength. Two galvanized steels are used: three specimens are manufactured with "S5" steel textile and other three with "S6" steel type. Their properties are reported in Table 5.

Table 5: Geometrical properties and mechanical characteristics of steel textile

Specimen label	c [cords/mm]	t [mm]	φ [mm]	$f_f^{(s)}$ [N/mm^2]	$E_f^{(s)}$ [kN/mm^2]	$\varepsilon_f^{(s)}$ [%]
S5	0.100	0.149	1.38	1570	200	1.10
S6	0.200	0.138	0.93			

c = cord density; t = equivalent (design) thickness; φ = cord diameter; f_f= nominal tensile stress of dry fibers; E_f= Young's modulus ; ε_f = ultimate strain; $^{(s)}$ = data provided by supplier

Table 6: Shear bond tests results for SRG-to-tuff substrate

Specimen label	Substrate	f_b [N/mm^2]	η_{dry} [%]	η_{comp} [%]	Failure mode
S1-ML	Single tuff block	1676	52.6		C
S1-MG	Single tuff block	1876	58.9	-	A-C
S5-MH-1	Single tuff block	183	12	-	B
S5-MH-2	Single tuff block	414	28	-	D
S5-MH-3	Single tuff block	414	24	-	D
S6-MH-1	Single tuff block	1118	71	110	F
S6-MH-2	Single tuff block	1159	74	114	F
S6-MH-3	Single tuff block	476	30	47	B
S6-MH-4	Single tuff block	421	27	41	B

From Table 6, experimental data show the high variability of single-lap shear bond tests carried out on tuff substrate. SRG systems made by "S1" galvanized steel textile achieve the maximum bond value: in particular, "S1-MG" exhibited a higher value of the bond strength with respect to "S1-ML", because geopolymer mortar is stronger than lime one. On the other hand, the maximum exploitation was achieved only for two tests (η_{dry}=71-74% η_{comp}=110-114%). Generally, in the other tests, a relatively lower bond capacity was observed, because of the weakness of the substrate and inappropriate surface preparation (debonding at tuff-matrix interface, failure mode "B").

3 CONCLUSIONS

The critical review of existing experimental evidences leads to the following observations on the tensile and bond behaviour of SRG composites:

- The rough surface of the steel cords provides an effective load transfer capacity with the mortar, as demonstrated by the distributed cracks developing under tensile loading; on the basis of available results, this is independent from the type of mortar matrix;
- The good interaction between steel cords and mortar matrix contributes to the efficiency of the SRG-to-substrate shear transfer capacity, as demonstrated by the high values of the exploitation ratios (about η=80%) detected in shear bond tests, with failure occurring by either detachment at the textile-to-matrix interface or tensile rupture of the cords.
- On the other hand, the smoother surface of steel ropes may lead to the slippage of the textile associated with a lower bond capacity (about η=50%);
- The development of adequate interlocking between textile and mortar matrix highly relies on the spacing between the steel cords.

The following issues still deserve further research efforts:

- influence on textile-to-matrix bond capacity of diameter and surface of steel cord;
- influence on substrate-to-SRG bond behaviour of substrate preparation, especially on irregular masonry surfaces and on weak substrate materials;
- long-term durability, in terms of both test protocols and results, to be developed in parallel with the research on other mortar-based composites [32, 33, 34, 35, 36].

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