2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

A COMPARATIVE EXPERIMENTAL STUDY OF STRENGTHENED COLUMN-TYPE SPECIMENS USING STEEL REINFORCED GROUT (SRG) JACKETING

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Abstract: *This paper presents the results of a recent experimental investigation of short reinforced concrete column-type specimens, externally confined with Steel Reinforced Grout (SRG) jackets. Three groups of specimens where casted and tested under monotonic uniaxial compression. Each group comprised three different specimens, with a geometry of 200×200×380 mm, corresponding to a 2/3 scale of a 300×300 mm column. Parameters of investigation were the transverse steel reinforcement (i.e. no reinforcement, 100 mm spacing and 200 mm stirrup spacing) and the number of SRG layers (i.e. one or two). The geometry and the materials were selected to be similar to experimental setups found in literature. Thus, a comparison between SRG, Fiber Reinforced Polymer (FRP) and Textile Reinforced Mortar (TRM) jacketing for confinement was possible. Experimental evidence demonstrated that all alternative jacketing systems were able to increase both strength and deformation capacity of the specimens.*

Introduction

Over the last decades, the increased need for retrofitting existing structures worldwide led to the increased application of fiber reinforced polymers (FRP) as externally applied reinforcement, due to their favorable mechanical and geometrical properties (e.g. no change to the geometry of the retrofitted member, high strength-to-weight ratio, corrosion resistance and relatively fast and easy application) (Bakis et al. 2002, among others). However, the use of epoxy resins is related to various drawbacks; namely, high cost, poor behaviour in high temperatures, toxicity, lack of vapour permeability, inability to apply on wet surfaces and incompatibility with traditional building materials (Thermou et al. 2013, Kouris and Triantafillou 2018, Thermou and Hajirasouliha 2018b). In an attempt to limit or eliminate these disadvantages, the replacement of organic with inorganic matrix was proposed. Thus, a new generation of mortar-based composite systems was introduced. One of these materials is Textile Reinforced Mortar (TRM) which was developed by Triantafillou et al. (2006) (among others). TRM combines high-strength fibers (e.g. carbon, glass, basalt or bezobisoxazole fibers) in the form of grid textiles (with open-mesh configuration) with inorganic matrices, such as cement-based mortars (Koutas et al. 2019). These composite materials have been studied during the last two decades for confinement, flexural and shear strengthening of reinforced concrete (RC) members (Triantafillou et al. 2006, Bournas et al. 2007, Tzoura and Triantafillou 2014, Triantafillou and Papanicolaou 2006, Raoof et al. 2017 among others). Recent research studies towards the development of an innovative, cost-effective retrofitting material led to the Steel-Reinforced Grout (SRG) system, where Ultra-High Tensile Stress Steel (UHTSS) textiles are combined with inorganic binders for retrofitting of RC structures. SRG was initially developed by Thermou and Pantazopoulou (2007) and further developed (Thermou et al. 2013, 2014, 2015, 2016, 2017, 2018a, 2018b, 2018c) and has been proved to be efficient in strengthening RC members.

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Objectives, methodology and main conclusions

The main objective of the experimental program was to compare the efficiency of SRG, FRP and TRM jacketing in increasing the axial compressive capacity of concrete and reinforced concrete columns through passive confinement. For this purpose, materials and geometry were selected to be similar (i.e. same specimen geometry and internal steel reinforcement, similar concrete mix, proportional axial stiffness of the different strengthening materials) to the experimental investigation by Bournas et al. (2007), where a comparison between TRM and FRP confinement was investigated. Experimental results demonstrated that SRG jacketing managed to increase both load and deformation capacity of the specimens. Specimens with one layer of SRG jacket failed due to debonding of the jacket, whereas specimens with two layers of SRG jackets failed due to combined debonding and tensile fracture of the steel cords. These two failure modes are characterized as semi-ductile and ductile, respectively (Thermou and Hajirasouliha, 2018b). All the aforementioned jacketing methods managed to substantially improve the compressive behaviour of both plain concrete and reinforced concrete specimens.

SRG jacketing method

SRG as material

Steel-Reinforced Grout (SRG) jackets consist of Ultra-High Tensile Strength Steel (UHTSS) cords (wires) combined with a mortar (grout) that serves as the connecting matrix. Steel reinforced fabrics are made of unidirectional steel cords and a fiberglass micromesh which is perpendicular to the cords and facilitates the installation of the fabric. Cords utilized in the present study were 3×2 type (made by wrapping three straight filaments by two filaments at a high twist angle) (Figure 1, left). The aforementioned wires are galvanized in order to increase their resistance against corrosion. Several densities of the fabrics (i.e. cords per cm) are available ranging from 1.57 to 9.06 cords/cm. In the present study, the density of the UHTSS fabric was equal to 3.15 cords/cm (8 cords/in), which is considered as a medium-density fabric (Figure 1, right). It is important to mention that Thermou et al. (2015) and Thermou and Hajirasouliha (2018) observed that using the 4.72 cords/cm fabric, or denser, may impose difficulties in the penetration of the mortar through the dense fabric gaps. The UHTSS fabric is usually bonded with the external surface of the specimen using a commercial mortar. The same mortar is used to cover the final layer of the fabric and therefore, to ensure that the fabric is fully embedded.

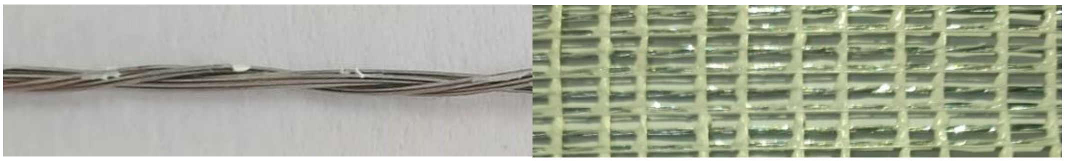

Figure 1: Type 3x2 cord (left) and UHTSS fabric with density equal to 3.15 cords/cm (right).

Concrete confinement with SRG jackets

Wrapping of concrete or reinforced concrete elements with SRG jackets aims to provide passive confinement stresses, when those elements are subjected to axial compression. Therefore, increased strength and deformation capacity of the member is expected. SRG jackets were utilized in the past as a confinement material for reinforced concrete (R/C) members subjected to axial compression (Thermou et al. 2013, 2014, 2015, 2016, 2017, 2018b, 2018c) but also for members under combined axial loading and cyclic lateral displacement reversals (Thermou and Pantazopoulou 2007, Thermou et al. 2018a). Moreover, influence of parameters such as loading rate and cross section shape were investigated (Thermou et al. 2013, 2015). The aforementioned experimental studies proved that SRG jacketing managed to increase both ultimate load and deformation capacity (curvature ductility). It was also observed that the presence of the jacket does not modify the initial stiffness but mainly affects the post-elastic behaviour of the specimen. The three observed failure modes are (a) debonding at termination of the steel fabric, (b) tensile fracture of the steel cords of the fabric and (c) partial debonding. A low tensile strength mortar, a short overlap length or a very dense fabric may promote debonding. Contrariwise, a jacket with sufficient overlap length and low-density fabric is prone to rupture of the fabric. These conclusions were made by Thermou et al. 2014 and Thermou and Hajirasouliha 2018c. In members with rectangular section, fracture may initiate at one of the corners due to stresses concentration

(Thermou et al. 2015). It is worth mentioning that similar conclusions were made for TRM-confined RC specimens (Triantafillou et al. 2006, Bournas et al. 2007, Koutas et al. 2019).

Description of the experimental program

Geometry and strengthening configuration

Three (3) concrete and six (6) reinforced concrete column-type specimens were constructed from the same concrete mix. These specimens had a 200 mm square cross section representing a 2/3 scaled model of a prototype column with a 300 mm square cross section and a height of 380 mm. The four corners of all specimens were rounded at a radius equal to 20 mm. The influence of the corner radius for SRG systems was investigated by Thermou et al. (2015). Moreover, Koutas et al. (2019) proposed rules for the corner radius of TRM-strengthened concrete columns. Radius should be, in general, equal to $b_c/10$ or 25mm (where b_c is the smallest of the two section sides) (Thermou et al. 2015, Koutas et al. 2019). The prisms were divided into three groups, with three specimens each. The first group comprised plain concrete specimens (i.e. with no internal steel reinforcement, group U). The specimens in the second and third groups were reinforced with four longitudinal 12 mm diameter steel bars, each placed at one corner of the section. The second and third group of specimens had stirrups placed every 200 mm (group S200) and 100 mm (group S100), respectively (Figure 2). Each group comprised one control specimen (i.e. without SRG jacket), one specimen with one layer of SRG jacket and one specimen with two layers of SRG jackets. The specimen details appear in Table 1.

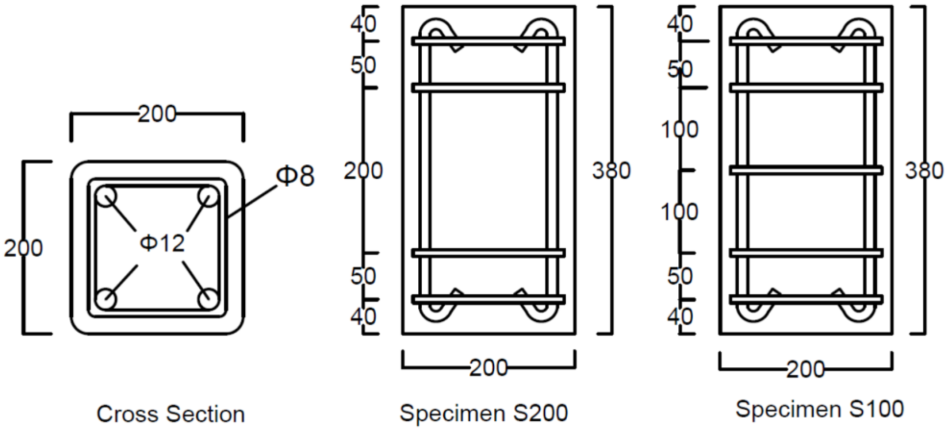

Figure 2: Internal steel reinforcement configurations of groups S200 and S100.

Group	Long. Reinf.	Trans. Reinf.	Control specimen	1 SRG jacket	2 SRG jackets
U	-	-	U_C	U_S1	U_S2
S200	4Φ12	Φ8/200	S200_C	S200_S1	S200_S2
S100	4Φ12	Φ8/100	S100_C	S100_S1	S100_S2

Table 1: Specimen details and nomenclature.

Material properties

The same concrete mix was used for all specimens. The average compressive strength of seven 150 mm-sided cubes at 28 days was equal to $f_{cm} = 24.10$ MPa, with a standard deviation equal to SD = 0.8 MPa. It is worth mentioning that, the average concrete compressive strength in the study of Bournas et al. (2007) was equal to $f_{cm} = 24.65$ MPa. The steel grade used for the reinforcement was B500C. In the experimental study of Bournas et al. (2007), the number of TRM and FRP layers was selected based on the fact that the two systems would provide equivalent confinement (i.e. equal axial stiffness). Towards this direction, the axial stiffness of each SRG jacket was calculated as proportional to the axial stiffness of each FRP layer. The axial stiffness, $K_{f,s}$, is equal to $K_{f,s} = t_s \times E_{f,s}$, where t_s is the equivalent thickness and $E_{f,s}$ is the elastic modulus. The equivalent thickness per unit width, t_s, is equal to $t_s = D_f \times A_{cord}$ where D_f is the density of the fabric (cords/cm) and A_{cord} is the area of each cord (cm^2). Due to practical restrictions and material availability, using more than two SRG layers or a denser UHTSS fabric was not possible. As mentioned formerly, the use of a dense fabric may impose handling difficulties and deficient mortar-fabric connection. Thus, the axial stiffness of each SRG jacket was equal to the 37% and 41% of its TRM and FRP counterpart respectively (Table 2). Properties of the TRM and FRP configurations were obtained by Bournas (2008).

SRG (present study)			
Elastic modulus, $E_{f,s}$ (GPa)	*Equivalent thickness, t_s(mm)*	*Number of layers*	*Axial stiffness $K_{f,s}$ (kN/m)*
190	0.172	1	31.6
		2	63.2
TRM (Bournas et al., 2007)			
Elastic modulus, $E_{f,s}$ (GPa)	*Equivalent thickness, t_s(mm)*	*Number of layers*	*Axial stiffness $K_{f,s}$ (kN/m)*
225	0.095	4	85.5
		6	128.25
FRP (Bournas et al., 2007)			
Elastic modulus, $E_{f,s}$ (GPa)	*Equivalent thickness, t_s(mm)*	*Number of layers*	*Axial stiffness $K_{f,s}$ (kN/m)*
225	0.17	2	76.5
		3	114.75

Table 2: Mechanical and geometrical characteristics of each strengthening configuration.

Each layer of the SRG jacket consisted of Ultra High Tensile Stress Steel (UHTSS) fabric and cementitious grout. The steel fabric consisted of 3×2 type cords, with a density of 3.15 cords/cm and equivalent thickness of 0.169 mm. The geometrical and mechanical properties of each cord as provided by the manufacturer appear in Table 3. A commercial one component geo-mortar was used as the connecting matrix. The mechanical properties of the mortar appear in Table 4.

Cord diameter (mm)	**Cord area (mm^2)**	**Break load (N)**	**Tensile strength, $f_{fu,s}$ (MPa)**	**Strain to failure, $\varepsilon_{fu,s}$ (mm/mm)**	**Elastic modulus, E_f (GPa)**
0.827	0.538	1506	2800	0.015	190

Table 3: Geometrical and mechanical properties of a single SRG cord, as provided by the manufacturer.

Modulus of elasticity, E_m (GPa)	**Flexural strength, f_{mf} (MPa)**	**Compressive strength, f_{mc} (MPa)**	**Adhesive bond strength, f_{mb} (MPa)**
25	10	55	2

Table 4: Mechanical properties of the utilized mortars at 28 days as provided by the manufacturer.

Fabrication of the SRG jackets

After removing the specimens from the wooden moulds, the substrate of the specimens was roughened, cleaned and then saturated. The cementitious grout was applied manually onto the surface of the specimens (Figure 3, left). The steel fabric was placed immediately after the application of the grout (Figure 3, middle). The steel fabrics were pre-bent before being applied, also considering the 20 mm corner radius of the cross section, to facilitate installation. The height of the fabric is equal to 300 mm, thus, two pieces of fabric were utilized, leaving 10 mm gap between the steel bearing plates of the loading machine and the steel fabric, both on top and bottom of the specimen. The grout was squeezed out between the gaps of the steel fabric by manually applied pressure. After the application of the fabric to one full-cycle the remaining length was lapped over the lateral surface. The lap length is equal to 2 sides of the specimen (i.e. approximately 350 mm). The bottom jacket was placed first and the upper one followed. A final coat of the cementitious grout was applied to the external surface (Figure 3, right). The grout layer including the steel reinforced jackets was less than 10 mm thick. The thickness of the grout layer was such as to guarantee that the steel fabric was fully embedded in the cementitious grout.

Figure 3: Application of the SRG jackets.

Experimental setup

A new experimental setup was constructed to measure both axial and lateral strain of the specimens, using twelve (12) Linear Variable Differential Transformers (LVDTs). Four (4) of these LVDTs were utilized to measure lateral strain and eight (8) to measure axial strain. The experimental setup appears in Figure 4. Axial strains are equal to the measurement of the top LVDT minus the measurements of the bottom LVDT of each side. The average strain of the four sides was calculated and utilized as the final axial strain. Load was applied monotonically, as prescribed displacement, at a rate of 0.01 mm/sec, using a 6000 kN compression testing machine and was measured using a load cell with maximum capacity of 2000 kN, which was placed at the top of all specimens.

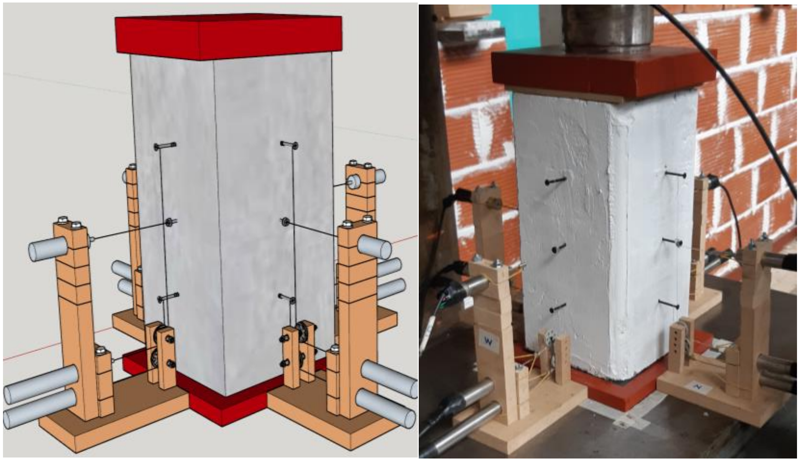

Figure 4: Experimental setup. Six out of twelve LVDTs are shown.

Test results

The aforementioned nine (9) specimens were tested under monotonic uniaxial compression. Test results appear in the following stress-strain curves (Figures 5,6,7). It is reminded that U group (U_C, U_S1, U_S2) comprised plain concrete specimens, whereas S200 (S200_C, S200_S1, S200_S2) and S100 (S100_C, S100_S1, S100_S2) groups comprised reinforced concrete specimens with stirrups placed every 200 mm and 100 mm respectively.

Stress-strain curves

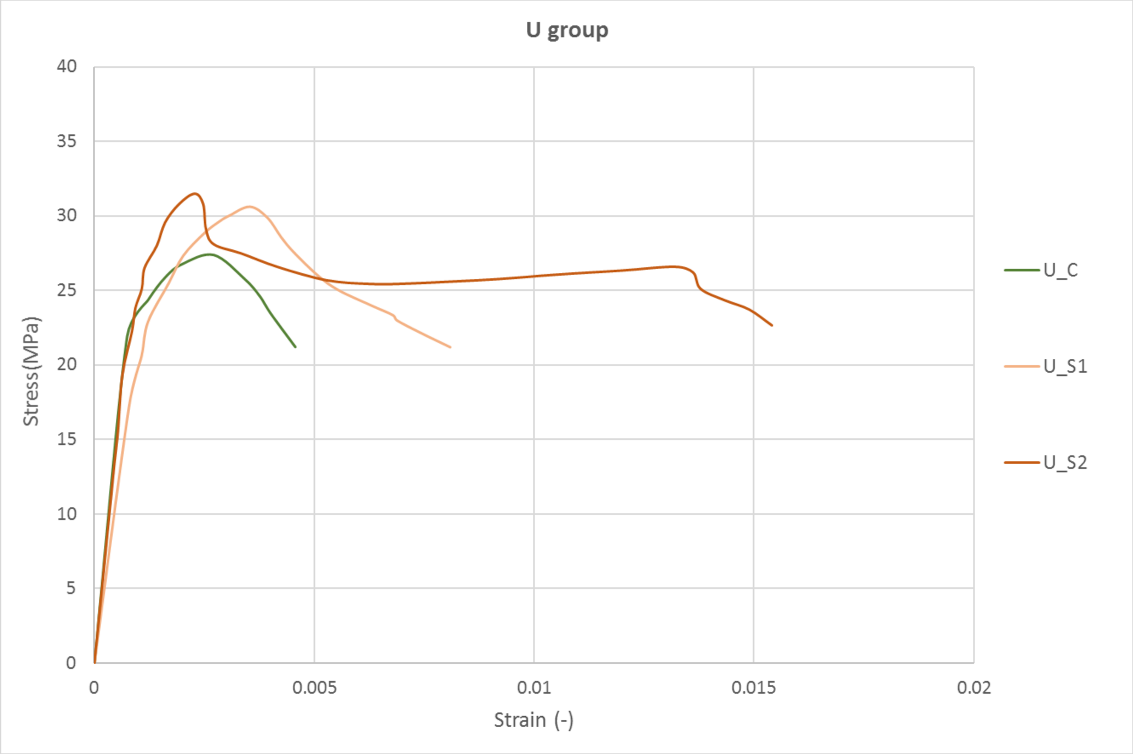

Figure 5: Axial stress-strain curves of U group specimens.

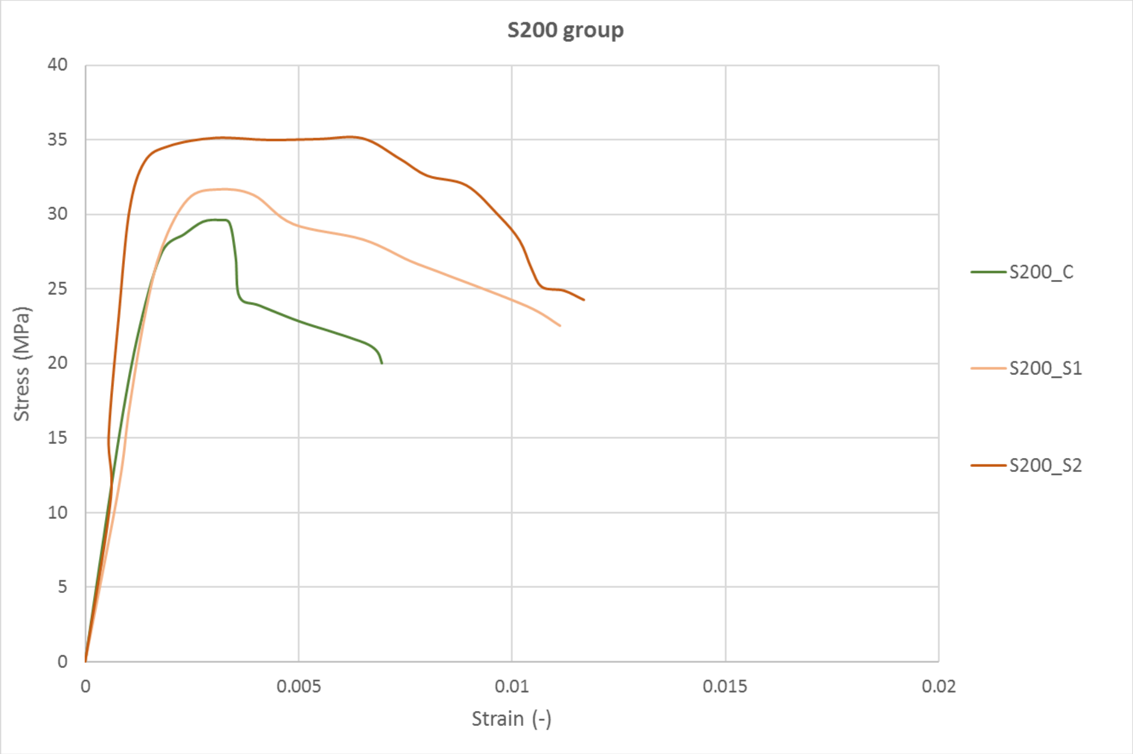

Figure 6: Axial stress-strain curves of S200 group specimens.

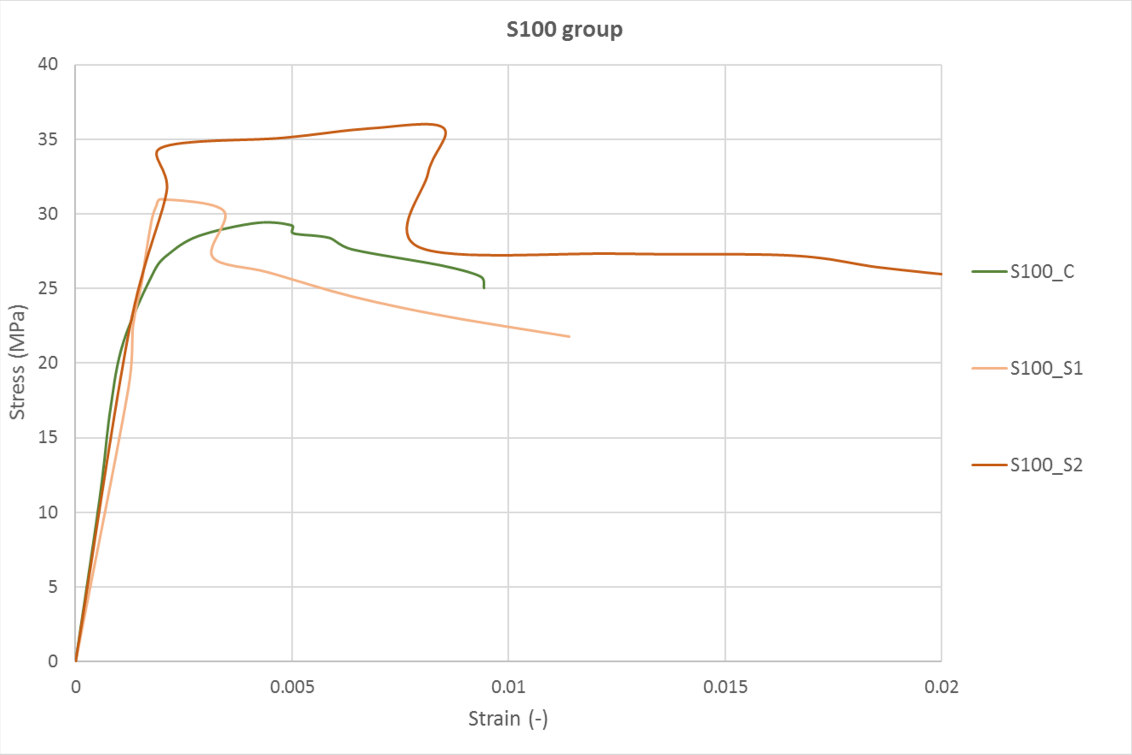

Figure 7: Axial stress-strain curves of S100 group specimens.

Failure modes

Two out of the three aforementioned failure modes were observed. Specifically, debonding of the steel fabric and mixed mode of failure (i.e. combined debonding and rupture of the steel fabric) were the appearing failure modes of the SRG-strengthened specimens. More details appear in the following table (Table 5), where *C* stands for compressive failure (which is the typical failure mode of U_C, S200_C, S100_C specimens), *D* stands for debonding and *M* stands for mixed failure.

U Group			**S200 Group**			**S100 Group**		
U_C	**U_S1**	**U_S2**	**S200_C**	**S200_S1**	**S200_S2**	**S100_C**	**S100_S1**	**S100_S2**
C	*D*	*M*	*C*	*D*	*M*	*C*	*D*	*M*

Table 5: Failure modes of the tested specimens, where C, D and M indicate compressive, debonding ang mixed failure mode respectively.

Comparison between SRG, FRP and TRM jacketing

Using the results by Bournas et al. (2007) a comparison between SRG, FRP and TRM jacketing technique is feasible. A summary of the specimens utilized by Bournas et al. (2007) appears in the following table (Table 6). The comparative results appear in the following axial stress-strain curves (Figures 8,9,10).

Group	**Control specimen**	**2 FRP jackets**	**3 FRP jackets**	**4 TRM jackets**	**6 TRM jackets**
U	U_C	U_R2	U_R3	U_M4	U_M6
S200	S200_C	S200_R2	S200_R3	S200_M4	S200_M6
S100	S100_C	S100_R2	S100_R3	S100_M4	S100_M6

Table 6: Summary of the specimens utilized by Bournas et al. (2007)

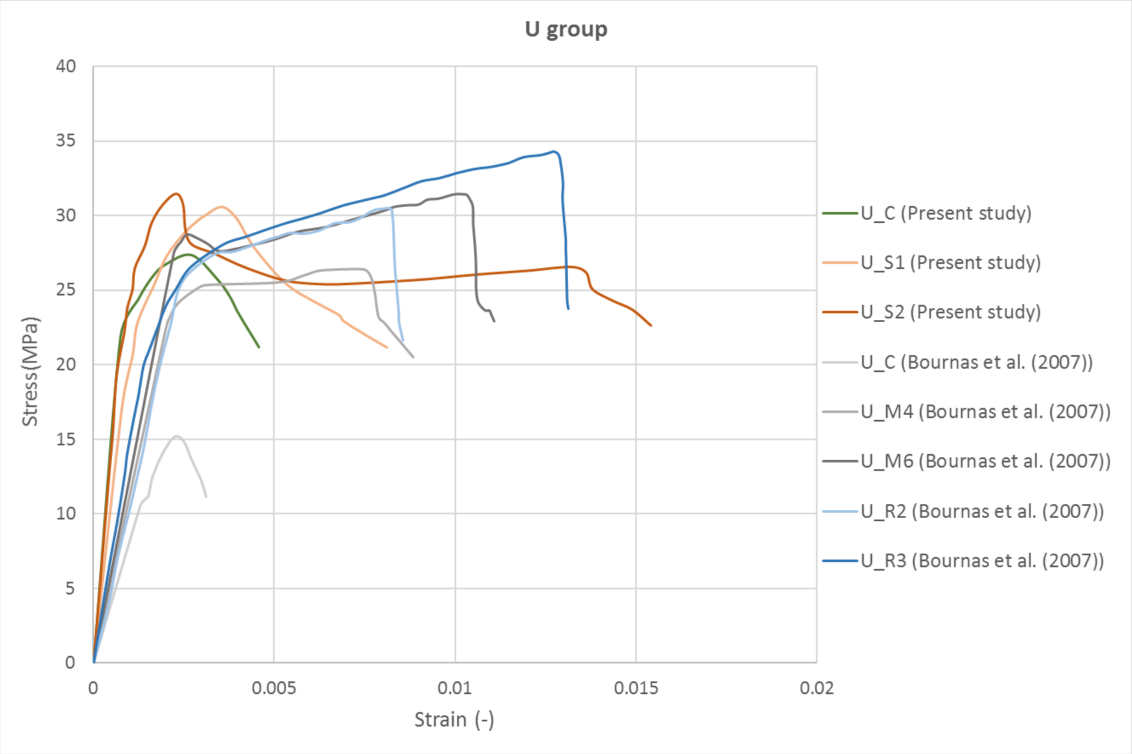

Figure 8: Comparative diagram between SRG, FRP and TRM jacketing technique for plain concrete specimens (U group).

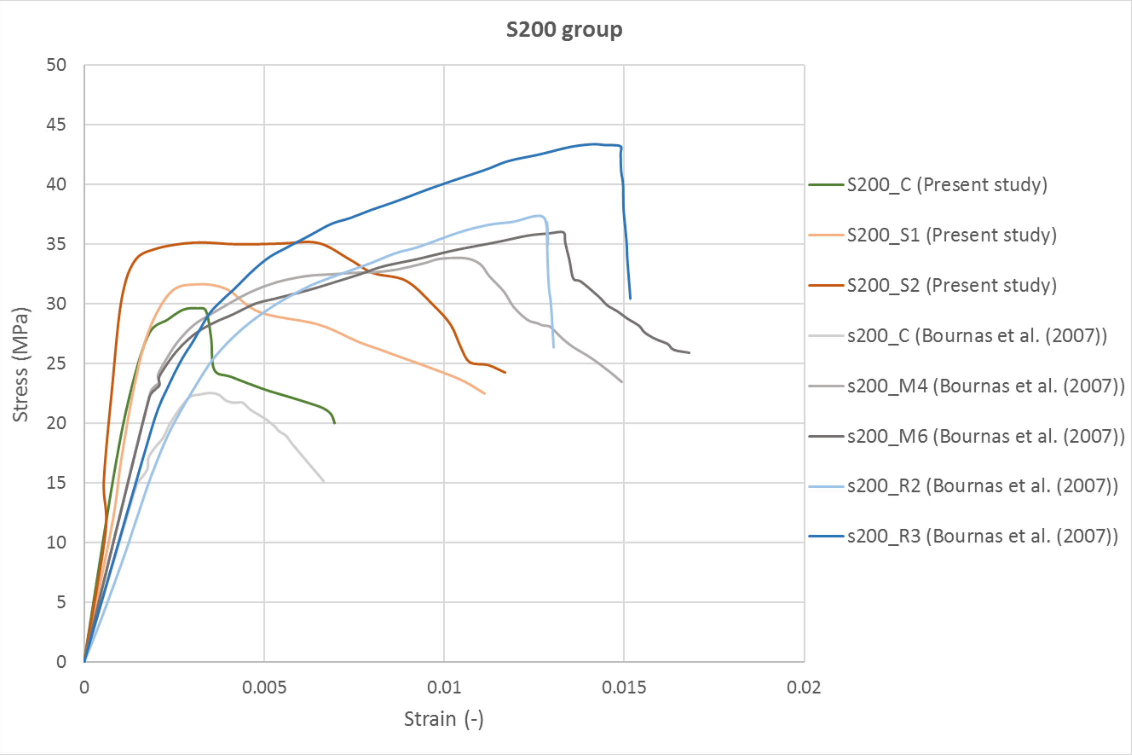

Figure 9: Comparative diagram between SRG, FRP and TRM jacketing technique for specimens with sparse stirrups (S200 group).

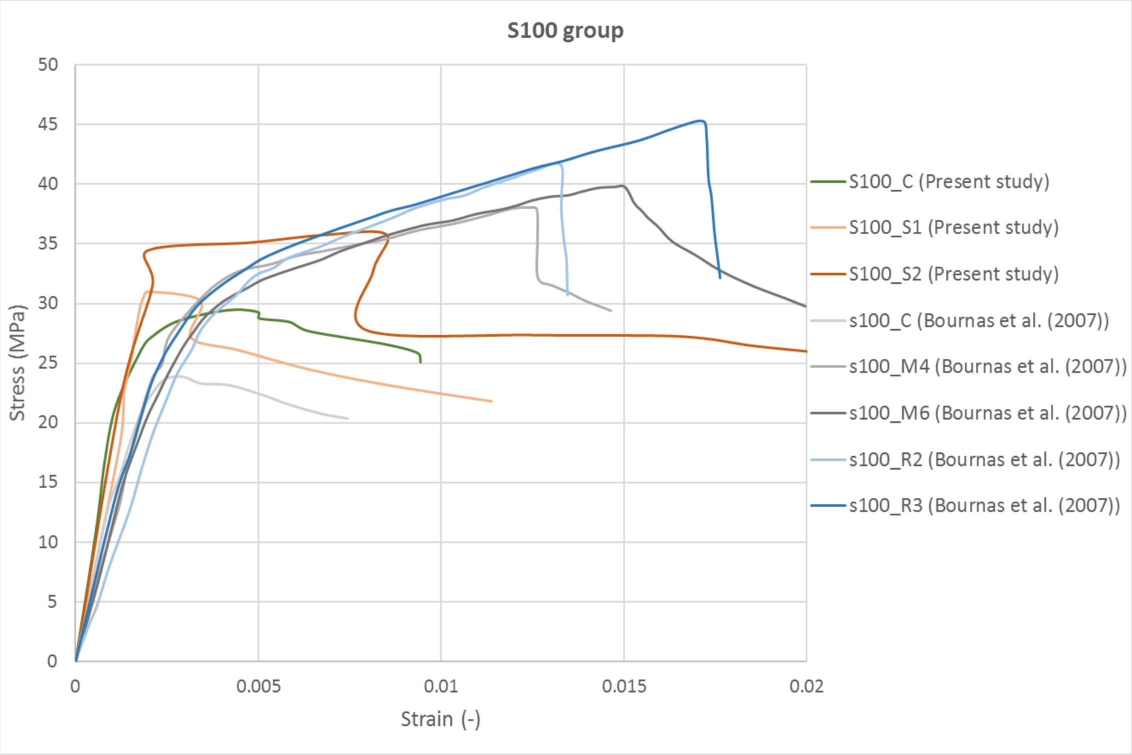

Figure 10: Comparative diagram between SRG, FRP and TRM jacketing technique for specimens with dense stirrups (S100 group).

Acknowledgements

Special thanks are attributed to Interbeton and Kerakoll S.p.A. for providing the materials.

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