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SHEAR BOND BEHAVIOUR OF MULTI-PLY STEEL REINFORCED GROUT COMPOSITES FOR THE STRENGTHENING OF CONCRETE STRUCTURES

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Abstract: *Steel Reinforced Grout (SRG) composites, comprising Ultra High Tensile Strength Steel (UHTSS) textiles embedded in inorganic matrices, have experimentally proved effective for a number of structural retrofitting applications. Nevertheless, existing knowledge is mainly based on the behaviour of SRG systems with a single textile layer, whereas the use of more plies may be required when strengthening large structural members. This paper presents the preliminary results of an experimental study on SRG composites comprising multiple layers of galvanised UHTSS textiles within a geopolymer mortar. Single-lap bond tests were carried out to investigate the effect of number of plies (one, two or three) and fabric density (4 or 8 cords/in) on the SRG-to-concrete bond performance, which is crucial for the effectiveness of the retrofitting work.*

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Introduction

Fiber Reinforced Polymers (FRPs) are used extensively in retrofitting applications worldwide. However, several disadvantages, mainly related to the use of resins, such as the poor behaviour to fire conditions, the relatively high cost of epoxy resins and the lack of vapour permeability with adverse effects on reinforced concrete structures, render them less appealing with high environmental cost (Thermou et al. 2015). The last few years, a new generation of mortar-based systems, named Fabric Reinforced Cementitious Matrix (FRCM) composites, has been developed. Recent studies have demonstrated the efficiency of these systems in providing excellent application on wet surfaces, good performance at high temperatures, and excellent durability. The Steel-Reinforced Grout system is a relatively new system that consists of Ultra High Tensile Strength Steel (UHTSS) unidirectional textiles embedded in cement, lime or geo-polymer matrices. The cords are spaced at different distances (i.e. different density textiles are available) and fixed to a non-structural glass fibre mesh.

The response of the FRCM systems relies on the bond quality at the textile-to-matrix and substrate-to-matrix interfaces. Understanding the shear transfer mechanisms in mortar-based composite system is fundamental for their further development and use in structural applications. In general, mortar-based systems may exhibit different failure modes, differently from FRPs, which generally fail within the substrate (de Felice et al. 2018).

De Santis et al (2017) carried out a large round-robin test campaign to investigate the bond behaviour in SRG system on masonry substrates. They tested four SRG systems made of a combination of three different textiles and four mortar matrices. SRG systems were comprised of only one layer of reinforcement and were applied for a length of 260 mm upon the substrates. They found that the bond performance is dependent on a set of parameters including the mechanical characteristics of the steel textile and the matrix, the bond between the cords and the matrix, surface preparation, curing conditions, and test setup. Six modes of failure were identified including debonding of SRG composite with and without fragments of the substrate, detachment of the steel textile and the top layer of the matrix, slippage of steel textile with and without cracking of the loaded end of the composite, and rupture of cords.

The bond behaviour of SRG system on concrete substrate was studied by Sneed et al (2016) and Bencardino et al (2017). Sneed et al (2016) used a single-layer SRG composite with a 4 cords/in textile embedded in a thixotropic mineral mortar. The external layer of the matrix was omitted for half of the specimens in order to assess its role in the stress transfer mechanism. All the tested specimens, including the ones without external layers, failed due to debonding at textile-matrix interface. Load-slip behaviour for specimens with and without external layer of matrix was almost similar and was represented by a linear stage followed by a slight reduction in stiffness. Bencardino et al (2017) also investigated the bond characteristics of SRG composites on concrete substrates. SRG composite was made of stainless steel textile embedded in an inorganic fireproof matrix. Four bond lengths were examined including 100 mm, 150 mm, 200 mm, 250 mm, 300 mm, and 400 mm. It was found that the load-global slip of the tested specimens is comparable to that of FRP system. It was also reported that failure occurred at the textile-to-matrix interface, which implies that the bond behavior of SRG system is not dependent on the mechanical properties of the substrate. By examining different bond lengths, it was concluded that the effective transfer length for this system is roughly 200 mm.

The SRG composite system has been used effectively as externally bonded reinforcement for the flexural strengthening of RC beams and the use of multiple layers of fabric was investigated in some recent works on reinforced concrete members reinforced in flexure (Napoli and Realfonzo 2015). Nevertheless, the shear transfer mechanism developed along the multiple layers of the steel fabric and the overall mechanical behaviour of multi-ply SRG composites has not been studied in detail yet. A first attempt to develop a deeper understanding on the mechanical performance of multi-ply SRG composites has been made by lap-tensile tests in (Thermou et al. 2018). The objective of this study is to investigate the bond behaviour of multi-ply SRG composites applied to concrete substrates. For this purpose, a total of 18 single-lap shear bond tests were carried out on SRG composites made of one, two, and three layers of galvanised UHTSS textiles within a geopolymer mortar applied to concrete prisms.

Experimental programme

A total of 18 direct single-lap shear bond tests were carried out on plain concrete specimens. Specimens were labelled following the notation SB-MXY where SB stands for shear bond tests, M denotes medium compressive strength substrate, X indicates the density of the steel textile (X=4 for textiles of 4 cords/in and X=8 for textiles of 8 cords/in), and finally Y is for the number of steel textile piles (Y=1, 2, 3 for one, two and three layers, respectively). A total of six series of specimens were tested including SB-M41, SB-M42, SB-M43, SB-M81, SB-M82, SB-M83. Each series had three nominally identical specimens.

Materials

Two types of steel textiles were used for this investigation with the same mechanical characteristics but different density textiles (4 cords/in and 8 cords/in). The textile is made by unidirectional Ultra High Tensile Strength Steel (UHTSS) cords fixed to a non-structural glass fibre mesh. Each cord is made by twisting 2 galvanised steel filaments on three rectilinear ones at a high torque angle. The equivalent thicknesses of the two textiles are 0.084 mm and 0.168 mm. The cords have a breaking load of 1.6 kN at a strain of 2%. The tensile strength and the modulus of elasticity of the textile are 23200 MPa and 186 GPa respectively (De Santis et al. 2017). The grout used to make SRG composite was made by mixing geopolymer mortar with water at a mixing ratio of 0.20. The 28-day compressive strength of concrete specimens was 27 MPa.

Specimens preparation

The bonded area of the SRG reinforcement had a length of 300 mm, a width of 100 mm, and a thickness of 6 mm, 9 mm, and 12 mm for 1, 2 and 3 layers of steel textiles, respectively. To enhance the bond between the substrate and the composite, substrate was grinded using an electrical grinder. Prior to the application of SRG composite, the substrate was cleaned from dust and moisten with water. A first layer of grout was applied and the thickness was controlled by means of a specially-designed acrylic mould. Immediately after applying the first layer of grout, steel textile was placed and gently impregnated and another layer of grout is applied. This process was repeated for the specimens provided with 2 and 3 layers of textile. Following the recommendation developed by RILEM TC 250-CSM (de Felice et al. 2018), the SRG strip was applied 50 mm off the edge of the concrete specimen to avoid edge effect. The dry part of the steel textile (outside the composite) was 400 mm long. To grip the steel textile, its end was impregnated in a two-part epoxy and placed between two aluminium plates.

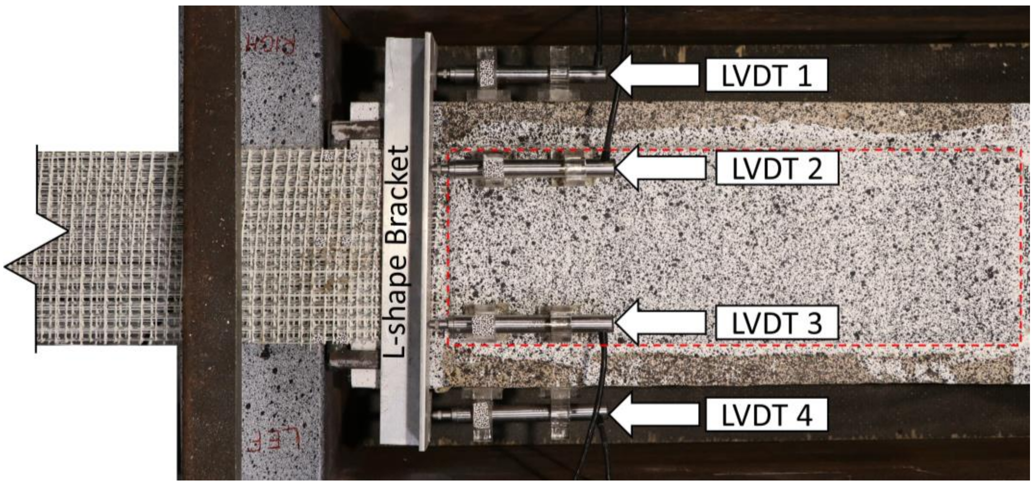

Figure 1 Instrumentation of the shear bond test

Test setup

A 50-kN hydraulic actuator was used to apply a horizontal force. The specimen was placed inside a reaction frame with its back edge being secured to the frame to avoid back uplifting. Slip was measured using 4 LVDTs reacting against a plate fixed to the steel textile such that two LVDTs were attached to the composite and the other two were attached to the substrate [Figure 1]. Load was acquired from the integrated load cell connected to data acquisition system.

Results and discussion

Shear bond tests results are provided in Table 1 including average load at failure, corresponding average axial stress in the textile, slip at failure, and finally mode of failure for each series. Average stress was calculated by dividing the failure load by the total cross-sectional area of steel cords for each series. Slip refers to the relative slip between the upper layer of SRG composite and the substrate.

Series	**Steel textile density** (cords/in)	**Number of layers**	**Number of cords**	**Average load at failure** (kN)	**Average axial stress** (N/mm^2)	**Slip at failure** (mm)	**Mode of failure**
SB-M41	4	1	15	21 [27%][1]	2399	2.05 [5%]	a[2]
SB-M42		2	30	21.7 [15%]	1341	1.40 [11%]	b[3]
SB-M43		3	45	22.4 [9%]	925	0.89 [53%]	b
SB-M81	8	1	30	15.8 [6%]	977	1.22 [14%]	c[4]
SB-M82		2	60	26 [8%]	804	1.05 [34%]	b, c
SB-M83		3	90	26.2 [8%]	541	0.99 [44%]	b

1. Coefficient of variation
2. a= mixed mode of failure comprising cords rupture and bond failure at substrate-composite interface
3. b= cohesive bond failure at substrate-composite interface
4. c= interlaminar shearing at textile-grout interface

Table 1. Shear bond test results

The difference in the average failure load between all specimens comprising low-density steel textiles (i.e. series SB-M4) was almost negligible. On the other hand, for their counterparts (i.e. series SB-M8), there was an increase of approximately 65 % in the average failure load for specimens strengthened with two layers of steel textile (SB-M82) compared to that of the specimens strengthened with only one layer of textile (SB-M81). However, the average load at failure for series SB-M83 was almost the same as series SB-M82.

In terms of average axial stress, there is a reduction of approximately 44% and 61% for series SB-M42 and SB-M43, respectively, compared to series SB-M41, whereas the reduction for their counterparts was 18% and 45% for series SB-82 and SB-M83, respectively, compared to series SB-M81. Although series SB-M42 and SB-M81 had the same number of cords (i.e. 30 cords), the stress for SB-M42 was 27% higher than that of SB-M81 as this latter failed earlier at the textile-to-matrix interface.

In terms of slip, series SB-M41 developed the largest slip among all tested series. In general, there is a decreasing trend for slip as the number of steel textile layers is increased with this trend being more notable for the series utilising low-density textile. However, apart from series SB-M41, slip was comparable and ranged from 1.4 mm to 0.89 mm.

In Figure 2, stress-slip envelopes are presented for each series. All series showed a first stage characterized by a linear branch associated with the elastic behaviour of the system. The stiffness of the linear stage is higher for the series comprising only one layer of steel textile. As the number of textile layer was increased the slope of the linear segment decreased. This linear stage is followed by a nonlinear stage as a result of local damage at both substrate-to-matrix and textile-to-matrix interfaces. Some series showed a third stage where the slip was increasing at almost constant load (e.g. series SB-M81 in Figure 2b).

Figure 3 provides a comparison in terms of stress-slip response for series comprising low-density and medium-density steel textiles separately.

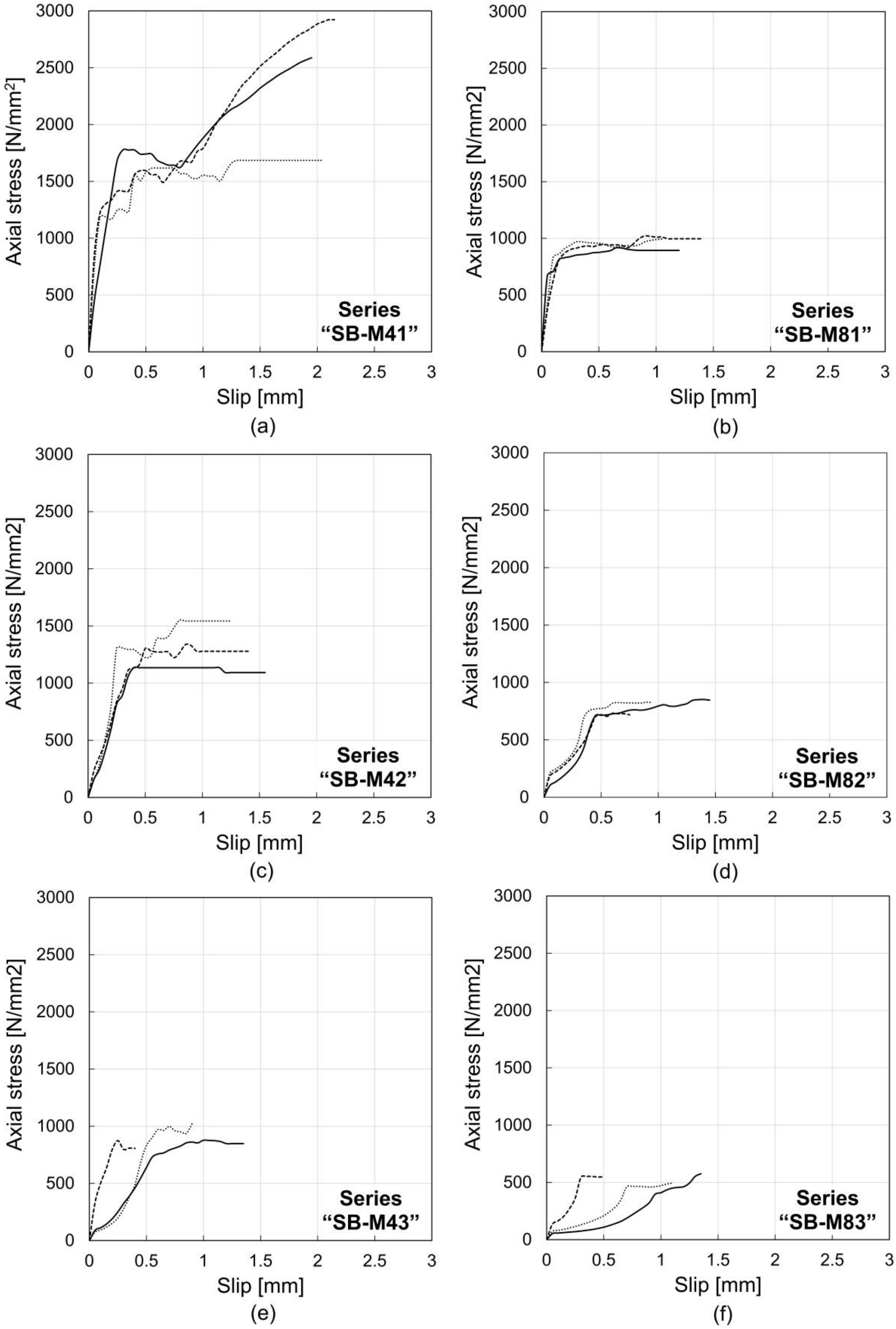

Figure 2 Stress-slip envelope curves for (a) Series SB-M41, (b) Series SB-M81, (c) Series SB-M42, (d) Series SB-M82, (e) Series SB-M43, and (f) Series SB-M83

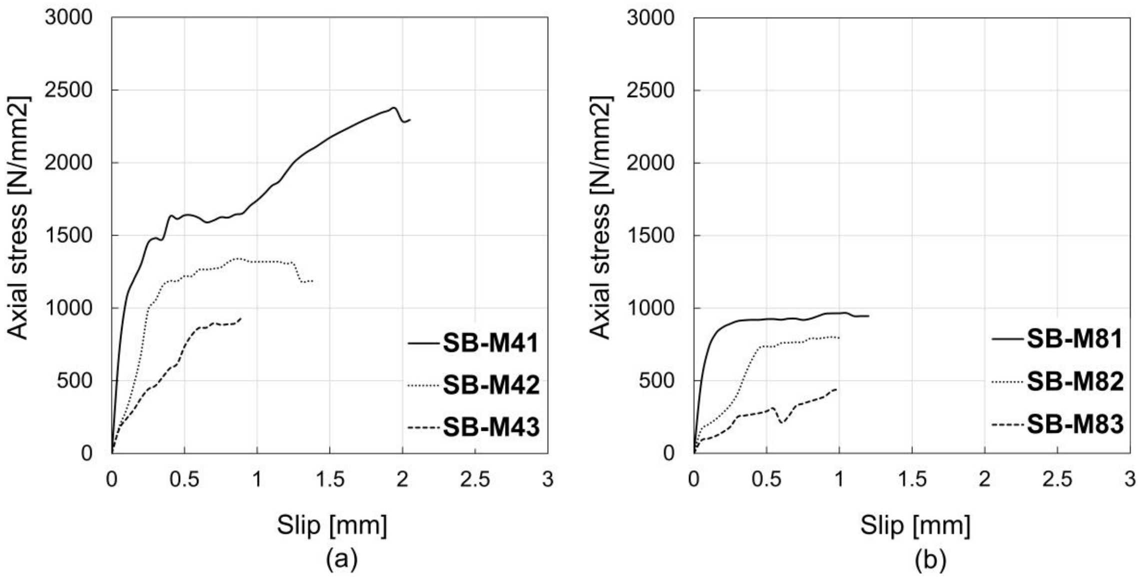

Figure 3 Stress-slip curves for one, two, and three layers of (a) Low-density steel textile (4 cords/in) and (b) Medium-density steel textile (8 cords/in)

Figures 4(a)-(f) present the specimens at the end of the tests for each series. Three different modes of failure were observed including failure by tensile rupture in steel cords followed by a cohesive failure at substrate-composite interface (mode a), pure cohesive failure in bond between the SRG composite and the substrate with a higher involvement of the latter (mode b), and interlaminar shearing between the steel textile and the grout (mode c). The first mode of failure was observed for series SB-M41 where some cords reached their maximum stress suggesting a non-uniform stress distribution, which may be due to possible misalignment or manufacturing imperfections. This local tensile rupture was immediately followed by a cohesive debonding at the substrate-to-matrix interface.

Almost all specimens strengthened with two and three layers of steel textiles characterised a pure cohesive debonding at the substrate-to-matrix interface with fragments of the substrate and the SRG composite was almost intact after detachment. Series SB-M81 and two specimens of series SB-M82 developed an interlaminar shear failure at textile-to-matrix interface such that the upper layer of grout and steel textile detached from the bottom layer of grout. The relatively denser structure of steel textiles of 8 cords/in proved responsible for triggering bond failure at the interface between the steel textile and the grout. Indeed, none of the series that have low-density textile failed at textile-to-matrix interface as both layers of grout developed a better bond compared to that of the composites with medium-density textiles.

All specimens strengthened with two and three layers of both steel textiles almost experienced a cohesive debonding failure at substrate-to-matrix interface. The debonding load was on average 22 kN and 26 kN for series comprising low-density and medium-density steel textiles, respectively. This can be attributed to the improved stress transfer mechanism in composites utilising medium-density textiles as the stress is better dissipated over a larger area of the matrix thanks to the larger number of cords (60 and 90 cords for series SB-M82 and SB-M83, respectively, and 30 and 45 cords for series SB-M42 and SB-M43, respectively).

Conclusions

The bond behaviour of SRG systems comprising steel textiles of two different densities applied to a medium compressive strength substrate was investigated in this paper. To this end, a total of 18 single-lap shear bond tests were carried out on concrete prisms strengthened with SRG system of one, two, and three layers of textile. It was concluded that the increase of the number of textile layers resulted in a reduction of average axial stress in the textile and average slip. Stress-slip response showed a stage of linear branch followed by nonlinear behaviour and for some series a third stage where the slip increased with a constant load. Three different mode of failure were observed including rupture of cords followed by a cohesive debondong at substrate-to-matrix interface, pure cohesive debondong at substrate-to-matrix interface involving the substrate, and an interlaminar shear failure at textile-to-matrix interface. It was, also, found that composites made of multi-ply textile of medium density steel textiles tend to have a better dissipation of stresses within the composite and hence increasing the interfacial debonding load.

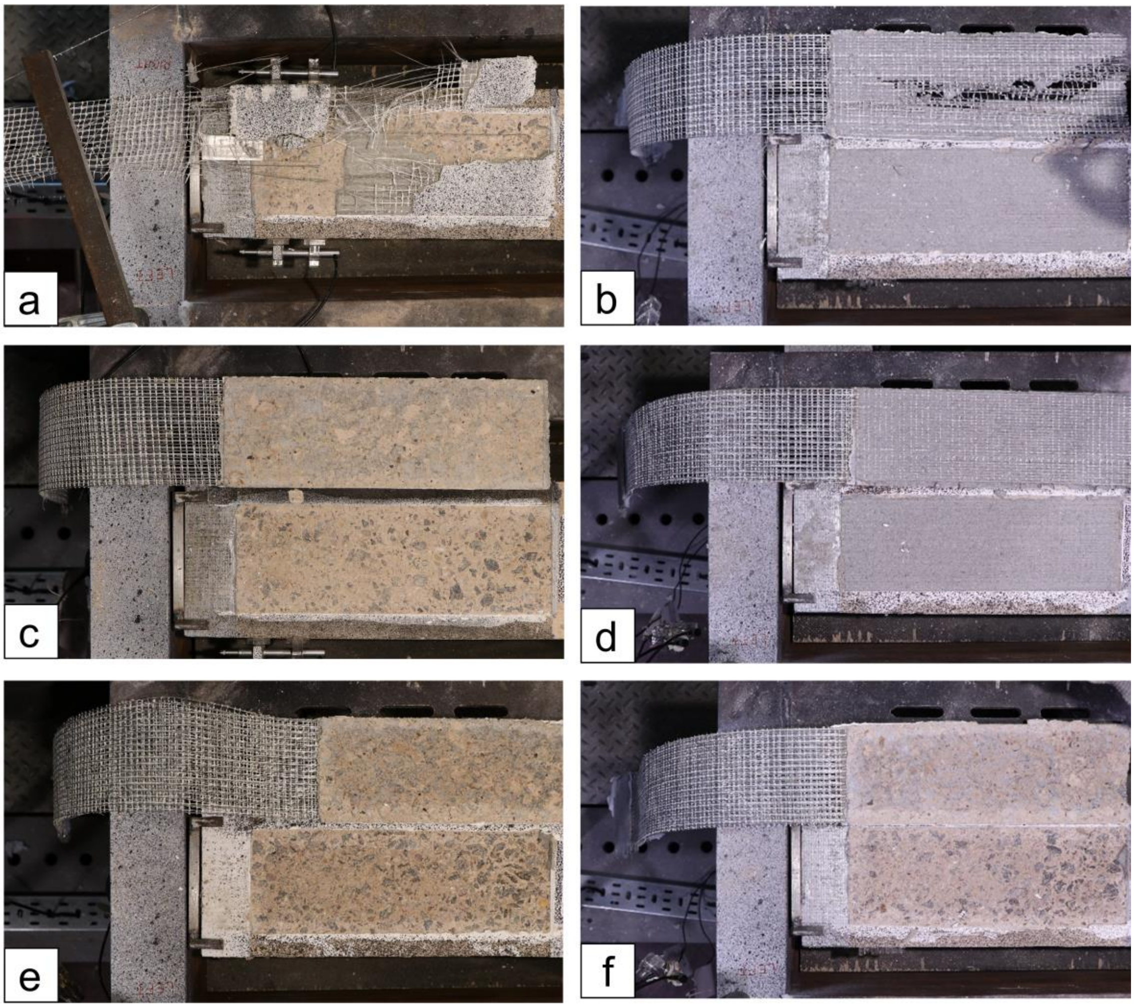

Figure 4 Mode of failure of different specimens from (a) Series SB-M41, (b) Series SB-M81, (c) Series SB-M42, (d) Series SB-M82, (e) Series SB-M43, and (f) Series SB-M83

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