EXPERIMENTAL STUDY ON STRUCTURAL PERFORMANCE OF TEXTILE REINFORCED CONCRETE BOX BEAMS

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Abstract: *Textile Reinforced Concrete (TRC) is an innovative building material specially suited for lightweight precast members. High strength textile reinforced combined with fine-grained concrete allows casting thin-walled members with thicknesses ranging from 15 ÷ 30 mm. Geometric and structural modifications are necessary to improve the performance of thin-walled building components in TRC. This paper presents the experimental results of structural responses of box beams using TRC. Ten specimens in two groups are designed with different longitudinal and transverse textile reinforcement ratios. All the specimens are loaded under a four-point bending test, in order to investigate both flexural and shear behaviour of TRC box beams.*

Keywords: *TRC, textile reinforced concrete, box beam, flexure, shear, carbon textile.*

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I. INTRODUCTION

Textile Reinforced Concrete (TRC) combines multi-axial textile reinforcement with fine-grained concrete to enhance each component's advantages. TRC is the new alternative building material and is applicable for both building strengthening and new structures. For structural applications, TRC presents numerous benefits. The textile reinforcement is commonly made of a high-strength and light-weight material (carbon and alkali-resistant glass fibres) that is generally lighter and stronger when compared to ordinary reinforcement steel [1]. The concrete cover can be reduced significantly compared to ordinary steel-reinforcements resulting in thin-walled, slender and light-weight concrete structures. Textile reinforcement typically consists of a bidirectional (orthotropic) grid of rovings that can be easily aligned with stresses' principal direction. This allows for both flexural and shear resistances in complex geometry structures.

The possible application field of TRC ranges from façade panels, sandwich elements, fabricated structures, slender pedestrian bridges to thin-walled shell structures. A U-shaped bridge in Albstadt-Ebingen (Germany) is the first bridge made out of pure carbon concrete (see Figure 1). To avoid high costs of restoration and enable a slender and durable bridge, TRC was chosen as a building material. This means that the bridge completely dispenses with reinforcing steel reinforcements and steel prestressing. Adapted from a U-shaped structural system, the resulting slim TRC bridge has dimensions with a length of 15.55 m, a width of 2.8m and thicknesses of only 70 mm [2]. The bridge used carbon textile as the reinforcement and was tested in full-scale before practical applied on site. Compared to an ordinary solution with steel-reinforced concrete, this TRC bridge used 50% less consumption of primary energy, with a simultaneous reduction in CO^2 emissions of 30%.

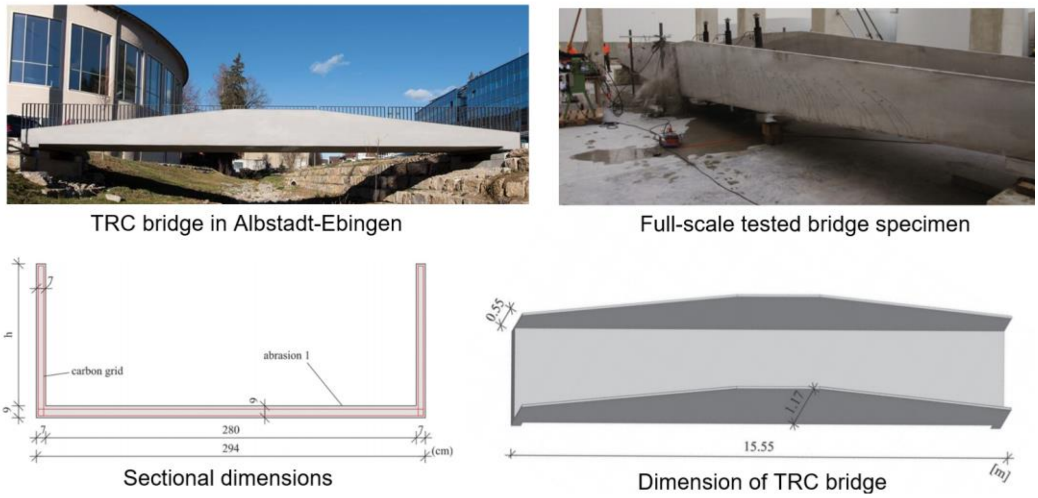


***Figure 1**. The first bridge made out of pure carbon concrete in Albstadt-Ebingen (Germany) [2]*

Despite those advantages, the number of practical applications using TRC is still negligible in the current state. One explanation for this situation is the available design codes and guides do not provide any recommendations for TRC since fundamental studies and relevant applications are still limited. A few amounts of research has been dedicated to find a suitable dimensioning and assessment of TRC structures. Some studies have already investigated the use of TRC as an exterior cladding system and façade [3]. Fundamental work on sandwich panels with thin-walled TRC facings has been done [5]. In this work, different configurations of TRC sandwich panels were produced, tested and analytically assessed. Thin-walled TRC elements are most suited to be realised within a prefabrication facility, including parking slabs [7], precast formworks [8], and thin-walled shell structures [9]. However, the studies on slender beams' behaviour using TRC have been minimal. Valeri [10] investigated the flexural and shear behaviour of TRC beams with an I-shaped cross-section utilizing three-point bending tests. In this work, because of the thin-walled sectional property and relatively low stiffness to strength ratio of glass textile reinforcement, beams lose their stability before reaching their material strength limit states. Besides, the shapes of thin-walled elements should also be considered by achieving sufficient anchorage of the textile fabrics and avoiding splitting failure. Using a very high tensile strength reinforcement (up to 3500 MPa), relatively long anchoring lengths are needed for carbon textile reinforcement. The difficulity in design slender U-shaped TRC components rests with the anchoring needed for transverse reinforcement. According to the usual strut-and-tie-model, the internal forces' equilibrium can only be guaranteed if the ties of the reinforcement are anchored in the compression zone, however, inaccessible with U-beams.

To provide sufficient stability, another solution in the form of a box beam should be used.

The shear and torsional properties of the closed section also offer more advantages than the I section. In contrast to U-beam, the designed box beams allow for a necessary anchorage length of the transverse textile reinforcement, which will need to avoid the pull-out effect. However, currently, there is no publication available that dealt with fabricated TRC box beam. Therefore, investigations are required to characterize and understand the structural behaviour of the TRC box beam.

In this paper, the main objectives are to experimental evaluate the structural performances of TRC box beams in flexure and shear. Three main investigated parameters were: the ratio of longitudinal textile reinforcement, the presence of shear textile reinforcement, and the shear span. The experimental tests were completed in two parts. The first part was conducted on eight "short" beams to capture both flexural and shear behaviour of TRC box beams. The second part was carried out on two "long" beams to understand the flexural behaviour of this type of beam. The experimental results are introduced and discussed in terms of cracking behaviour, deflection, flexure and shear capacities, and failure modes.

II. EXPERIMENTAL TEST

II.1 Specimens configuration

Altogether ten box beams were fabricated for testing. They classified into two categories; the first group contained eight "short" beams with a length of 1 m, and the second group included two "long" beams with a length of 2 m. All the beams had a similar section with a 150 × 200 mm dimension and an opening of 90 × 140 mm. The design of the box beams was desired to achieve the most lightweight concrete beam possible. The bottom flange was set to be 30 mm (the minimum allowed thickness due to the requirement of using five textile layers). The thickness of the top flange and vertical webs also equals 30 mm (Figure 2).

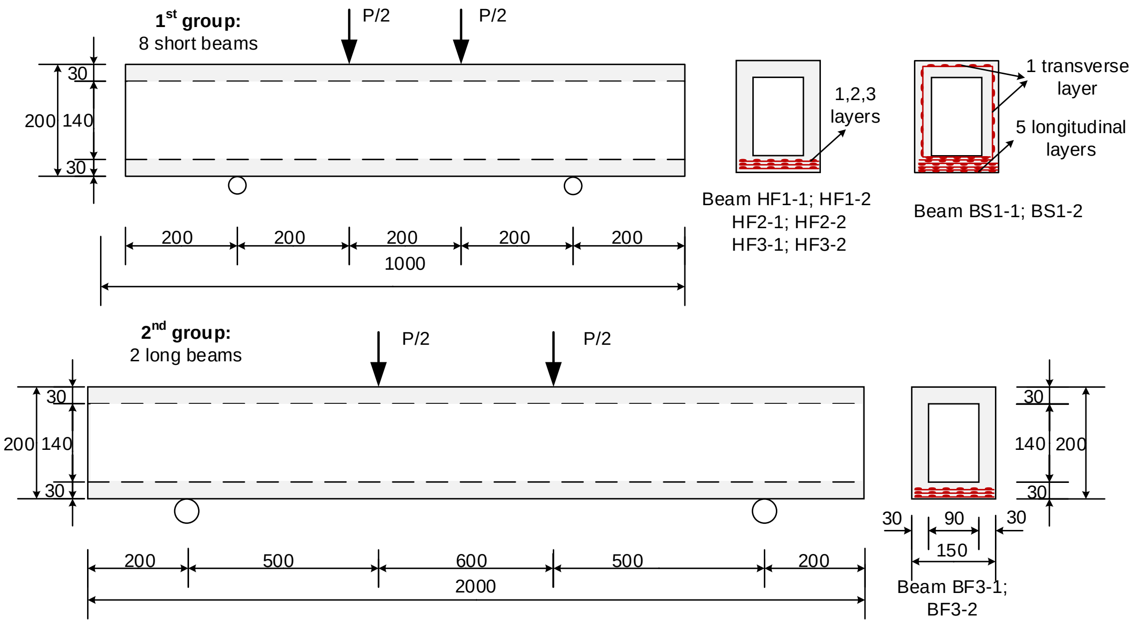


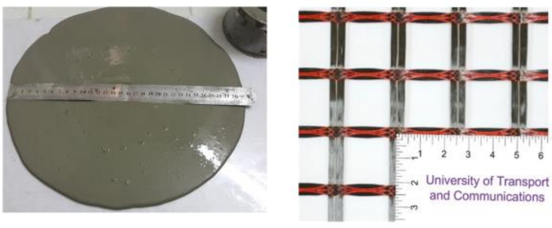
***Figure 2**. Details of test beams in two groups*

In the first group, eight beams were loaded under a four-point bending test, with a clear span of 600 mm. The overhanging spans at two ends are kept at 200 mm, in order to satisfy the anchorage length of textile reinforcement into the fine-grained concrete. The shear span is chosen as 200 mm, corresponding to the shear-span-to-depth ratio (*a/d*) almost equals 1.0. In this group, six beams reinforced with only longitudianl textile reinforcement varied from 1 layer (beams HF1-1, HF1-2), 2 layers (beams HF2-1, HF2-2) to 3 layers (beams HF3-1, HF3-2). For each case, two nominally identical specimens were manufactured. The idea was to examine both shear and flexural behaviour of box beams using only one test setup. The increase in textile reinforcement ratio allows modifying the flexural failure mode in low ratio specimens into the shear failure mode in high ratio specimens. In specific, the box beams with small percentages of textile reinforcement are designed to fail in flexure. On the other hand, the beams with a large reinforcement ratio will be failed in shear to determine the shear strength of TRC box beams without "stirrups". Besides, the two other beams (BS1-1, BS1-2) reinforced with five layers of longitudianl textile reinforcement and one transverse textile layer were tested to evaluate the absence of shear reinforcement on the shear capacity.

In the second group, to evaluate the flexural behaviour, two long beams with three layers of longitudianl textile reinforcement was tested with a simple span of 1600 mm. The shear-span-to-depth was chosen as 2.5 to obtain the flexural failure. The detailed information for each specimen is also mentioned in Table 1.

II.2 Material specification

The fine-grained binder systems with a maximum grain size of 0.63 mm were explicitly designed for carbon textile application. The high-performance plasticizer and fly ash were added to ensure the best possible bond properties between the textile reinforcement and the surrounding matrix (Figure 3-a). The fine-grained concrete (FGC) was mechanically characterized by testing six 40 mm × 40 mm × 160 mm prisms. The average flexural strength and average compressive strength at 28 days were equal to 6.85 MPa and 49.2 MPa, respectively.



a) Fine-grained concrete *b) Carbon textile*

Figure 3. *Carbon textile and fine-grained concrete*

In this study, the carbon textile reinforcement Sigratex Grid 350 was used (Figure 3-b). The carbon fibre yarns, having a count of 1600 tex, were processed in the warp and weft directions with a distance of approximately 25 mm between them. Each carbon roving has a cross-sectional area of 0.88 mm^2 (in both directions), coated with 15% styrene-butadiene. The tensile strength and elastic modulus of the textile reinforcement were 3550 MPa and 225 GPa, respectively.

The bond behaviour between the textile surface and the fine-grained concrete matrix was experimentally analyzed, following the test guideline of Zulassung Z-31.10-182 [11]. The average bond strength of carbon textile and the fine-grained concrete was 2.1 MPa. Based on the experimental results, the sufficient anchorage length of textile in fine-grained concrete can be calculated as about 160 mm.

II.3 Fabricating specimens and test setup

Altogether ten box beams were fabricated at the University of Transport and Communications. Firstly, the highly flowable fine-grained concrete (FGC) was poured into the steel formwork to create a thin layer. The textile was then pressed slightly into the FGC until the FGC protruded out of the perforations between the rovings. The second FGC layer was then applied to completely cover the textile reinforcement. After finishing the bottom flange, a foam beam with sectional dimensions of 90 × 140 mm was placed inside the formwork to create a hollow core. The FGC was continuously poured into the formwork to cast the web and the top flange. The procedure was repeated for each layer of textile (Figure 4). The concrete cover and thickness between each textile layer were kept at approximately 4 ÷ 5 mm.

Figure 4. *Fabricating ten box beams in two groups*

All the tests were conducted in the Structural Engineering Laboratory at the University of Transport and Communications, Vietnam. Specimens were monotonically loaded using displacement controlled method, with a loading rate of 1 mm/min. The schematic view and a view of the test setup are shown in Figure 5. Two linear variable differential transformer (LVDT) were installed on the beam's bottom surface to measure its deflections during the test. Moreover, strain-gauges were used to record compressive and tensile strains of concrete at upper and lower surfaces during the experiment. A computer-based data acquisition system was used to record the load from the load cell, the deflection from LVDT, and concrete strains from strain-gages.

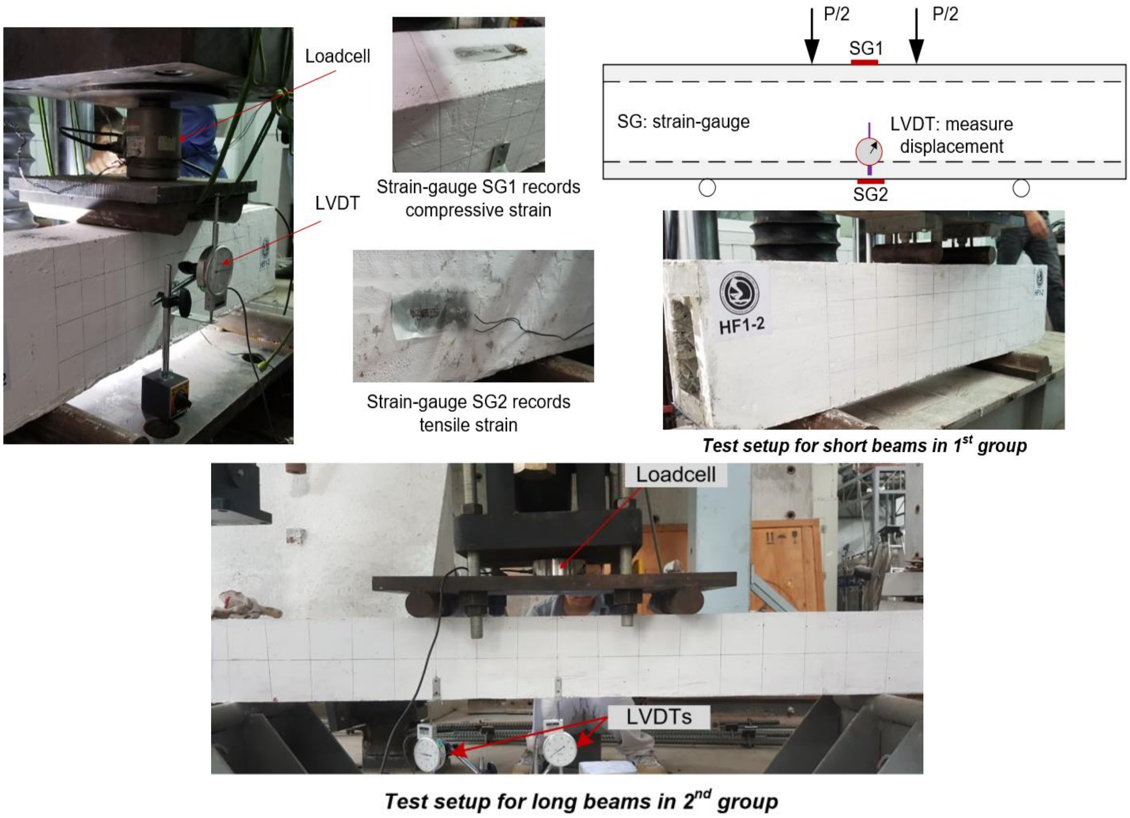


Figure 5. *Test setup for short beams and long beams*

III. RESULTS AND DISCUSSION

The test results of the eight box beams in the first group are summarised in Table 1. Load versus mid-span deflection curves are presented in Figure 6 and Figure 8 for all test beams. Besides, final modes of failure and crack patterns are illustrated in Figure 7 and Figure 9. In the beams HF1-1 and HF1-2 using one textile layer, the first crack was found to develop on the pure bending zone's tension fibre. These cracks were formed at a load of about 25 kN. Both beams were characterised by a sudden and brittle loss of their bearing capacity after reaching the ultimate load of approximately 42 kN. These two beams failed in bending due to the rupture of the longitudinal reinforcement in the tension flange. Rupture of the textile occurred for a vertical crack located at mid-span (see Figure 7). Small crack openings were observed at failure, and failure occurred without warning signs (absence of plastic deformation, large deflections or cracks).

Table 1. *Summary of test results for eight box beams in 1st group*

Group	Beam	Number of textile layers		Longitudinal reinforcement		Ultimate load (kN)	Failure mode
		Longi-tudinal	Trans-verse	Area (mm^2)	Ratio (%)		
1	HF1-1	1	0	5.28	0.045	42.6	Flexure/ rupture of textile
	HF1-2					40.8	
	HF2-1	2	0	10.56	0.091	60.7	Shear / large diagonal cracks
	HF2-2					54.6	Flexure/ rupture of textile
	HF3-1	3	0	15.84	0.138	81.4	Shear / large diagonal cracks
	HF3-2					83.6	
	BS1-1	5	1	26.4	0.234	117.7	Shear / large diagonal cracks
	BS1-2					110.6	
2	BF3-1	3	0	15.84	0.138	54.9	Flexure/ rupture of textile
	BF3-2	3	0			57.5	

Similarly, the flexural failure of beam HF2-2 (using 2 layers of textile) can also be described as brittle since no visible plastic deformations announcing failure could be observed. The highest load at this specimen was 54.6 kN. It should be noted that the most extensive flexural crack appeared next to the bending zone. However, for the beam HF2-1 with the same configuration, the shear failure was obtained with the large shear crack. The first two visual cracks appeared in the pure bending area at a 36 ÷ 38 kN load range. The shear crack became larger and larger with increased deflection and the beams failed by plate-end shear at about 60.7 kN. However, the failure occurred right after the presence of inclined cracks, representing the weak contribution of aggregating interlocking effect in shear resistance due to the fine aggregate in fine-grained concrete.

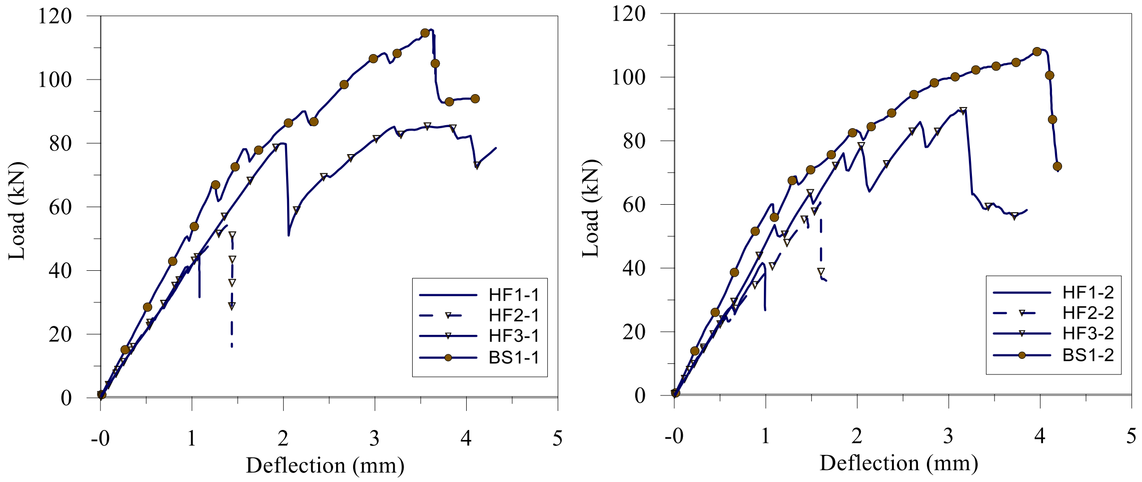


Figure 6. *Load-deflection curves of eight short beams in 1st group*

Both beams HF3-1 and HF3-2, using three layers of textile reinforcement in the bottom flange, failed in shear with the large diagonal cracks. The first flexural crack values of the beams produced with 3 textile layers were significantly higher than others made with 1, and 2 layers. More vertical cracks in the middle span were also found due to the better bonding between textile reinforcement and fine-grained concrete. Then, the first small visual shear crack appeared in a load range of 60 ÷ 65 kN. These beams did not develop new diagonal cracks, the existing shear cracks widened further and propagated towards the loading point. After reaching the ultimate load (at a load level of 81 kN), the diagonal cracks extended, and the beam failed gradually. Compared to the shear failure in beam HF2-1, in the same load level, beams with more longitudinal reinforcement exhibited smaller web diagonal crack width due to the dowel action of reinforcement across the cracks.

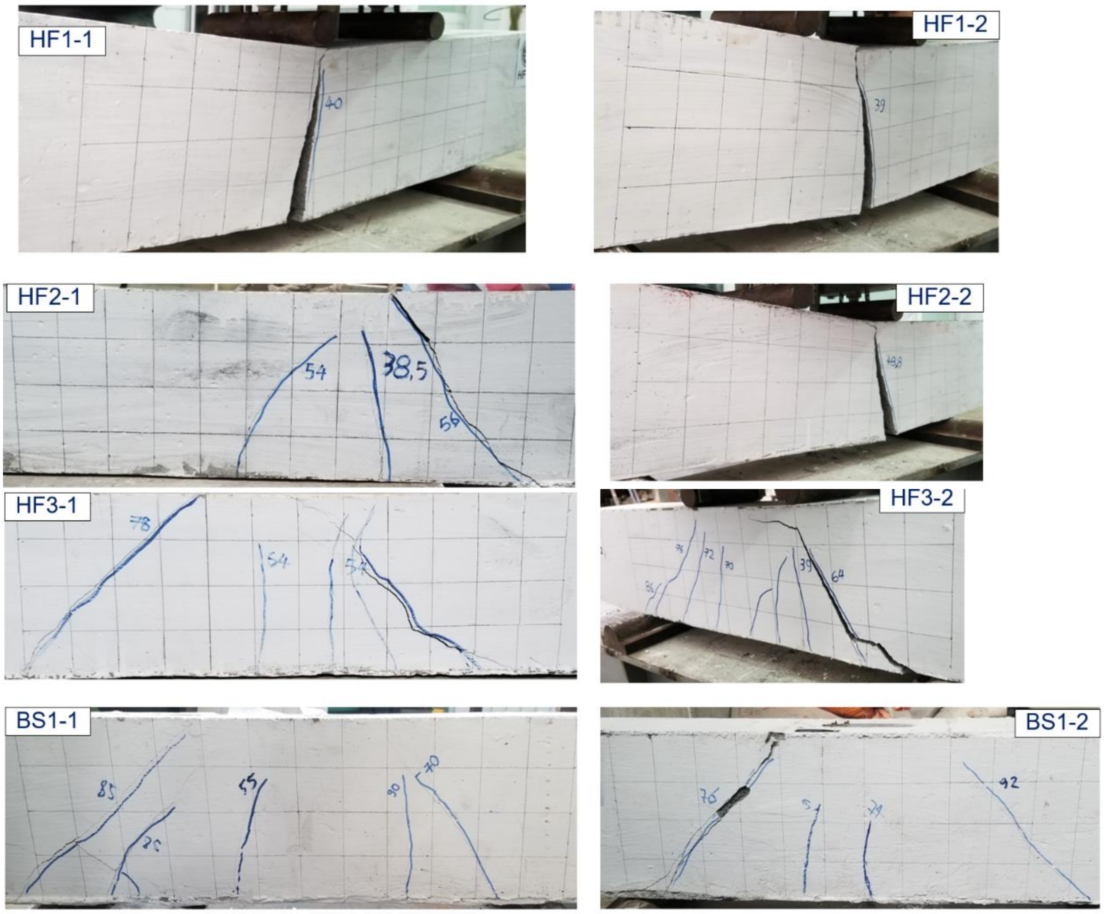


Figure 7. *Crack patterns of short beams in 1st group*

Beams BS1-1 and BS1-2 consisted of five longitudinal textile layers in the bottom flange and one transverse layer in the shear webs. In both beams, the cracking loads were approximately 35% higher than beam HF3-1 due to the higher longitudinal reinforcement ratio. The crack development was similar for both beams. As the load is increased after the formation of the first flexural crack, more cracks begin to appear and propagated diagonally towards the corners of the applied load (i.e. under the position of applied load). These cracks became wider and visible to the naked eye as the load increased. Unlike the beams HF3-1 and HF3-2 reinforced without transerver reinforcement, more shear cracks appeared in beams BS1-1 and BS1-2. At higher load levels, shear cracks developed in an inclined and smeared manner (see Figure 7). These inclined cracks merged at the gussets level, leading to longitudinal delamination cracks at the bottom flange. After cracking, the load still increased with the smaller stiffness due to the aggregate interlocking effect and the longitudinal rebars' dowel action. The failure occurred due to the extension of the large diagonal shear crack and the tensile break of transverse textile rovings at the load level of 117 kN. The ultimate loads were approximately 42 % higher than other beams without shear reinforcement. At the maximum load, the shear crack widths were approximately 0.5 mm, while the maximum flexural cracks width were controlled within 0.3 mm.

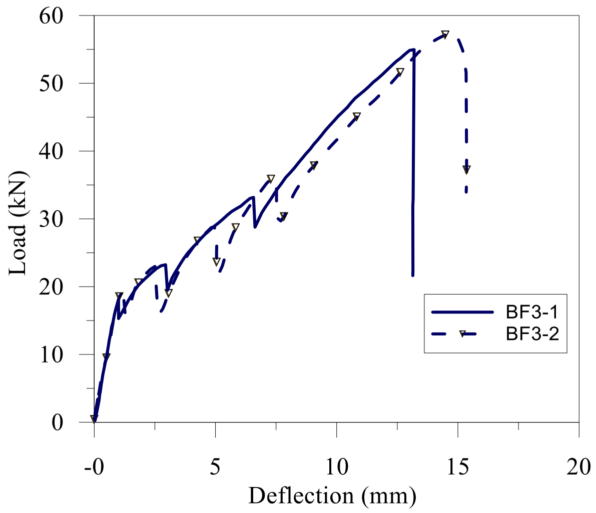


Figure 8. *Load-deflection curves of two long beams in 2nd group*

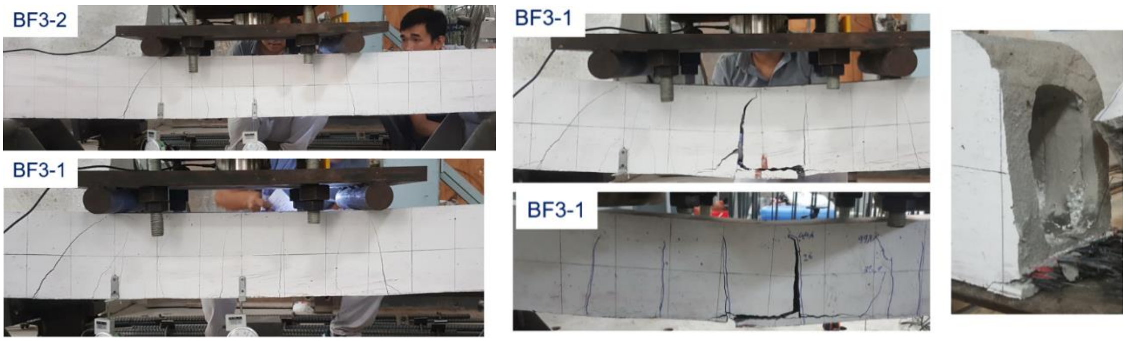


Figure 9. *Crack patterns of long beams with 3 textile layers*

In the 2nd group, two box beams (BF3-1 and BF3-2) consisted of 3 layers of textile reinforcement in the bottom flange was bent with a clear span of 1600 mm, corresponding to a shear-span-to-depth ratio equals 2.5. According to Figure 8, it is evident that the relationship obtained is linear up until the first crack appears at a loading of about 20 kN. The cracks in the pure bending zone continuously appeared, resulting in a decrease in the beams' stiffness. That was followed by a nonlinear load-deflection response when further increments of load were applied until the beams failed. Cracks are reflected in the graphs as instantaneous drops in applied load during this stage. The average ultimate load and mid-span deflection of the two beams were 56 kN and 14 mm, respectively. After reaching the maximum load, the load suddenly drops to zero. The two "long" beams failed in flexure due to the tensile rupture of textile reinforcement in the bottom flange. The formation of wide flexural cracks at the mid-span was presented in Figure 9.

IV. CONCLUSION

The study's primary purpose was to determine the structural performances of TRC box beams in both shear and flexure. The design of the box beams was desired to achieve the most lightweight concrete beam possible. The three main investigated parameters were the longitudinal textile reinforcement ratio, the presence of shear textile reinforcement, and the shear span.

In the first group, eight short box beams with different longitudinal and transverse reinforcement ratios were tested to determine the flexural and shear strength. For the beams with 1 and 2 textile layers in the bottom flange, flexural failure was obtained due to textile reinforcements' tensile rupture. By increasing the amount of carbon fiber along the load-carrying direction, the ultimate loads were significantly increased up to 38.9%. The other four beams in this group had large diagonal cracks in the final stage, representing the shear failure. In the box beam with 3 textile layers in the bottom flange, the failure occurred right after the presence of inclined cracks. It means the contribution of aggregating interlocking effect in shear resistance was weak due to the presence of fine aggregate in fine-grained concrete. For the box beams with a transverse textile layer in the web, failure occurred due to the extension of the large diagonal shear crack and the tensile break of transverse textile rovings. Compare to the beams without shear reinforcement, an increase of the shear capacity up to 42% could be reached in these two beams. In the second group, two long beams were tested with a shear-span-to-depth ratio equals 2.5. Both beams were failed in flexure due to the tensile break of textile reinforcement in the bottom flange.

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