FLEXURAL BEHAVIOR OF ONE-WAY TEXTILE REINFORCED CONCRETE (TRC) / REINFORCED CONCRETE (RC) COMPOSITE SLABS

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Abstract
This study illustrates the results of an experimental campaign aiming at the investigation of the flexural behavior of composite concrete slabs comprising participating Stay-in-Place (SiP) formwork elements made of a cementitious composite material, namely Textile Reinforced Concrete (TRC), and conventional steel reinforced concrete toppings. Four-point bending monotonic tests were conducted on three different specimen types: (i) single-module corrugated TRC formwork elements, (ii) single-module TRC/RC slabs and (iii) multi-module TRC/RC slabs. The influence of the following design parameters on the flexural behavior was investigated: textile and steel reinforcement ratios, cementitious matrix type (coarse or finely grained polymer-modified mortar) and textile coating (polymer impregnation or none). The obtained results indicate that TRC/RC composite slabs comprise a promising alternative to conventional composite slab systems.

1 Introduction
The use of Stay-In-Place (SiP) formwork elements for the production of composite concrete slabs satisfies a combination of favourable performance criteria, such as economy (e.g. reduced construction time and site ergonomy), aesthetics (ready-to-use finished surfaces), improved mechanical performance (through rigorous quality control) and relatively small environmental impact. The main distinction of SiP (a.k.a. permanent or integrated) formwork elements is between participating and non-participating ones; the former contribute to the bearing capacity of the structural member through composite action with the cast-in-place parts, while the latter make no strength contributions. A wide range of materials has been utilized for the production of SiP formwork elements including steel, steel-reinforced or fiber-reinforced concrete and fiber-reinforced polymers. The use of Textile Reinforced Concrete (TRC) for the production of such formwork can be advantageous compared with SiP structural systems comprising other materials, owing to the use of non-corroding reinforcement embedded in a thin-walled cementitious product of high load-bearing capacity.

Experimental studies in the field of composite structural members incorporating participating SiP formwork elements of cementitious composition are very scarce ([1], [2], [3]). This study presents selected results deriving from an extensive experimental campaign that aimed to investigate the flexural behaviour of one-way TRC/RC composite slabs. In this context, three types of specimens were constructed: SiP formwork beam-like specimens tested as standalone elements (Type A specimens), single-module TRC/RC composite slabs (beam-like specimens – Type B specimens) and multi-module TRC/RC composite slabs (Type C specimens).

2 Experimental program

2.1 Specimens and materials

Specimen geometry for all types is given in Figure 1. Corrugated (Delta-shaped) TRC formwork elements measuring 2750 mm × 333 mm × 78 mm (length × width × height, respectively) comprised Type A specimens. The top and bottom flange and the web of all formwork elements had a uniform thickness equal to 25 mm. In Type A specimens the textile reinforcement ratio and the fibrous material type comprised the parameters under investigation. Type B specimens were formed by casting a RC topping on top of TRC formwork elements identical to those used as Type A specimens; these beam-like specimens measured 2750 mm × 333 mm × 150 mm (length × width × height, respectively). The investigated design parameters for Type B specimens included steel and textile reinforcement ratios and fiber type of the textile reinforcement. Type C specimens (TRC/RC composite slabs) incorporated channel-shaped formwork elements and measured 2750 mm × 1000 mm × 160 mm (length × width × height, respectively). The parameters under investigation for Type C specimens included the type of treatment the textiles' rovings received (i.e. polymer coating or no coating) and the granularity of the polymer-modified mortar used for TRC formwork construction (i.e. finely grained or coarser sand).

Figure 2 illustrates all textiles used in this work and summarizes their properties (filament's tensile strength, σ_{fil}, is provided by the producer). Steel reinforcement of the in-situ concrete topping was of B500C class (520 MPa and 621 MPa, yield point and tensile strength, respectively). A welded wire mesh (B500A ∅4.2/150 mm with 634 MPa and 658 MPa, yield point and tensile strength, respectively) was positioned in the compression zone of Type B and Type C specimens. All TRC SiP formwork elements were produced using a custom-designed polymer-modified mortar (with the addition of a water-soluble polymer powder at 3% per cement weight) with a maximum sand particle size of either 2 or 4 mm and the following composition: 450 kg/m^3 and 480 kg/m^3 cement (CEMII 42.5N); 1200 kg/m^3 and 1100 kg/m^3 sand; 260 kg/m^3 and 350 kg/m^3 limestone filler; 1.3% and 2.1% superplasticizer per cement weight for the mixture containing coarse and fine sand, respectively. The mean compressive and flexural strengths and modulus of elasticity for both mortar mixtures at an age of 90 days (when the majority of tests was performed) were equal to 12 MPa, 60 MPa and 23 GPa, respectively. The mean compressive and splitting tensile strength and modulus of elasticity of the in-situ concrete at an age of 28 days (in-situ concreting took place 28 days prior to testing) was equal to 28 MPa, 2.6 MPa and 24 GPa, respectively.

In order to ensure full composite action between the integrated formwork element and the concrete topping, shallow shear keys (indentations) with 100 mm length, 46 mm width and 6 mm depth were formed on the upper surface of the bottom TRC formwork flange with 110 mm spacing (center to center). For the formwork elements used in Type B specimens the shear keys were formed only in the shear span region. For formworks integrated in Type C specimens the indentations were formed across the entire length of the element. Additionally, the top flange of the Delta-shaped formwork elements was ended at 240 mm before the ends of the element in order to create an opening and allow for the formation of a full in-situ concrete end-zone. The latter aimed at the enhancement of both horizontal and vertical shear resistance in the support region.

All specimen construction parameters are given in Table 1. Specimens receive the following notation: T_M_S_L(c), where T stands for the specimen Type (A, B or C); M stands for the textile fibrous material [GI, GII, CI, CII and CIII, as per Figure 2 – superscript ^{FS} (for Type C specimens only) denotes the use of finely graded sand]; S stands for the steel reinforcement scheme (where applicable, as in X∅Y, X being the number of bars and Y their diameter); and L stands for the number of textile layers in the TRC formwork (1, 2, 3 or 4). The indication “c” (where is applicable) which follows the number of textile layers notation, denotes that the textile reinforcement is polymer-coated by hand. In Table 1 the volumetric fiber ratio (V_f) corresponds to the cross sectional area of the fibers in the textile running along the specimen’s span over the cross section of the bottom TRC flange. Finally, the steel reinforcement ratio (ρ_s) corresponds to the cross section of the rebars over that of the composite member.

2.2 Test setup and instrumentation

For all specimens the clear measured 2550 mm and the shear span was equal to 850 mm. The tests (monotonic four-point bending until failure) were performed in a strong frame using a 500 kN capacity actuator at a displacement-control mode (at a rate of 0.016 mm/sec). The deflection profiles during testing were measured using five displacement transducers, as shown in Figure 1. In order to monitor slip along the TRC/RC interface, a series of digital displacement transducers was positioned along the interface. All sensors were connected to a data acquisition system.

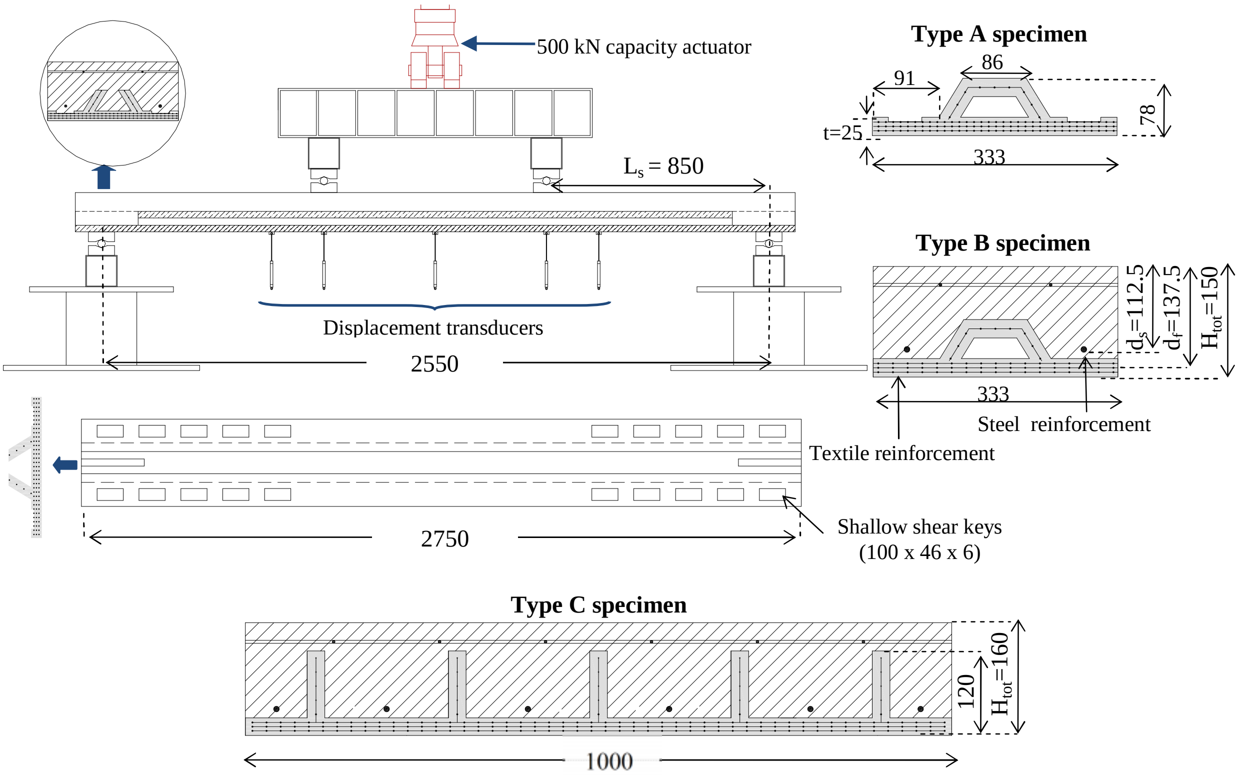
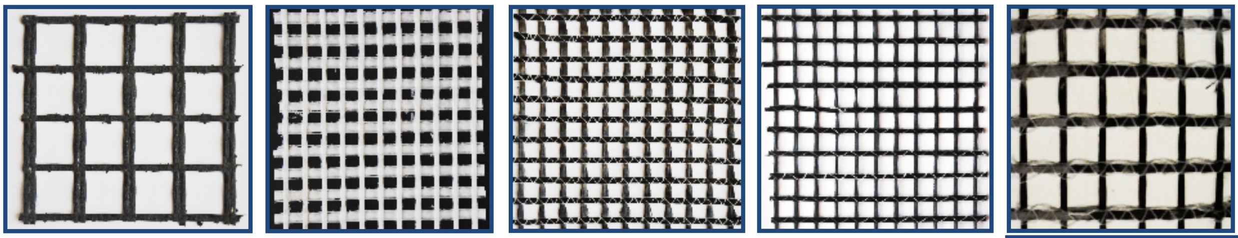


Figure 1. Test setup configuration and specimen types (all dimensions in mm)



GI	GII	CI	CII	CIII
E_f = 70 GPa	E_f = 70 GPa	E_f = 225 GPa	E_f = 225 GPa	E_f = 225 GPa
t_f = 0.062 mm	t_f = 0.092 mm	t_f = 0.096 mm	t_f = 0.048 mm,	t_f = 0.048 mm
Mesh size: 25 mm	Mesh size: 10 mm	Mesh size: 10 mm	Mesh size: 10 mm	Mesh size: 20 mm
σ_{fil} = 1600 MPa	σ_{fil} = 1600 MPa	σ_{fil} = 3800 MPa	σ_{fil} =3800 MPa	σ_{fil} =3800 MPa
Industrial coating	Industrial coating	No industrial coating	No industrial coating	No industrial coating

Figure 2. Textile reinforcement as received by the industry

Specimen	Textile reinforcement					Steel reinforcement
	Fibrous material	**Coating type**	**No of Layers**	**V_f (‰)**	**E_fA_f (kN)**	**ρ_s (‰)**
A_GI_2L	E-Glass	Coating A	2	4.96	2890	N.A.
A_GI_3L	E-Glass	Coating A	3	7.45	4335	N.A.
A_GI_4L	E-Glass	Coating A	4	9.92	5780	N.A.
A_GII_2L	E-Glass	Coating B	2	7.36	4289	N.A.
A_GII_3L	E-Glass	Coating B	3	11.04	6433	N.A.
A_CI_2L	Carbon	Uncoated	2	7.68	14385	N.A.
A_CII_2L	Carbon	Coating C	2	3.84	7192	N.A.
A_CII_4L	Carbon	Coating C	4	7.68	14385	N.A.
B_GI_4∅4.2_2L	E-Glass	Coating A	2	4.96	2890	1.10
B_GI_2∅8_2L	E-Glass	Coating A	2	4.96	2890	2.01
B_GI_2∅10_2L	E-Glass	Coating A	2	4.96	2890	3.14
B_GI_4∅4.2_3L	E-Glass	Coating A	3	7.44	4335	1.10
B_GI_2∅8_3L	E-Glass	Coating A	3	7.44	4335	2.01
B_GI_2∅10_3L	E-Glass	Coating A	3	7.44	4335	3.14
B_GII_2∅8_3L	E-Glass	Coating B	3	11.04	6433	2.01
B_CII_2∅8_2L	Carbon	Uncoated	2	7.68	14385	2.01
B_CII_2∅8_2Lc	Carbon	Coating C	2	3.84	7192	2.01
C_CIII^{FS}_6∅8_3Lc	Carbon	Coating C	3	5.76	32400	1.88
C_CIII^{FS}_6∅8_3L	Carbon	Uncoated	3	5.76	32400	1.88
C_CIII_6∅8_3L	Carbon	Uncoated	3	5.76	32400	1.88
Control	N.A.	N.A.	N.A.	N.A.	N.A.	1.88

Coating A: Industrially applied bitumen; Coating B: Industrially applied polymer resin; Coating C: Polymer resin applied by hand

Table 1. Notation and construction parameters for all specimens

2.3 TRC behavior under pure tension

For the characterization of the formwork elements monotonic direct tensile tests were conducted using dumbbell TRC specimens, measuring 19 mm in thickness 120 mm in width and 613 mm in length. Test setup and specimen geometry are depicted in Figure 3. Specimens receive the same notation as previously discussed lacking the designation T as non-relevant. Figure 4 illustrates the stress-strain curves obtained from the tests. All specimens failed due to textile reinforcement rupture. For specimens with polymer-coated carbon reinforcement, extensive spalling of the cementitious matrix was observed prior to fiber fracture. The spalling mechanism initiated from a longitudinal crack which started from a tensile crack tip and spread between the reinforcement layers. For all specimens, increase of the textile reinforcement layers resulted in the increase of the failure stress. For specimens with GI textile reinforcement the increase of fiber volume ratio by 50% and 100% resulted in an increase of the failure stress equal to 30% and 60%, respectively. For specimens, reinforced with type GII textile the increase of fiber volume ratio by 50% resulted in 56% increase of the failure stress. Although specimen GI_3L shares the same axial rigidity with specimen GII_2L its failure stress was by 33% lower than the one of specimen GII_2L. This fact reveals the influence of textile grid structure (denser transverse reinforcement) in specimen's load bearing behavior. Hand-applied polymer coating of CII and CIII textiles resulted in the full exploitation of the fibers as failure stress of specimen CI_2L is equal to the one of specimens CII_2Lc and CIII_2Lc.

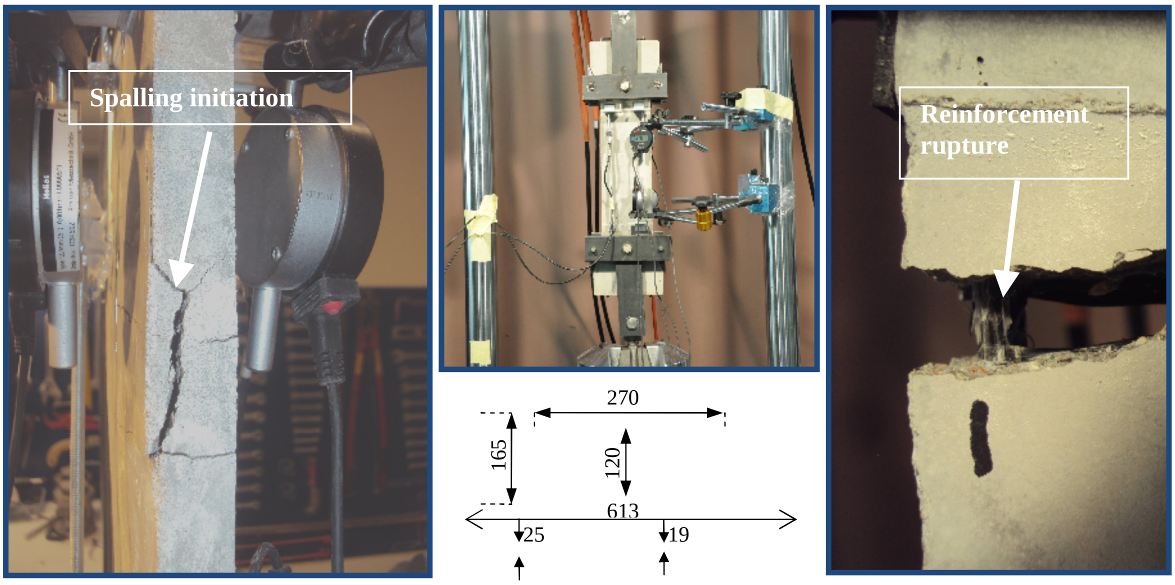


Figure 3. Test setup and failure modes for the tensile tests

3 Experimental results and discussion

3.1 Type A specimens

In Figure 5 the load-midspan deflection curves for Type A specimens are presented. A flexural behavior with a dense crack pattern was observed. The dense crack pattern spread outside of the displacement induction zone leading to textile reinforcement rupture for all specimens. After the first crack an extended multiple cracking behavior was observed (similar to the one noticed during direct tensile testing) which is attributed to the matrix contribution in tensile stress undertaking. After the end of the crack formation stage, the textile reinforcement acted as the only tensile stresses carrier. Specimens with textiles comprising GII and carbon fibers exhibited a higher first crack load compared to specimens reinforced with GI textiles. For specimens reinforced with GI textile reinforcement the increase of fiber volume ratio by 50% and 100% resulted in an increase of failure load equal to 85% and 195%, respectively. For specimens, reinforced with GII reinforcement the increase of fiber volume ratio by 50% resulted in an increase of ultimate load by 82%. Bending action in combination with the exhibited dense crack pattern led to the increase of the effectiveness of textile reinforcement. The failure load comparison of specimens A_CI_2L and A_CII_2Lc enhance this outcome.

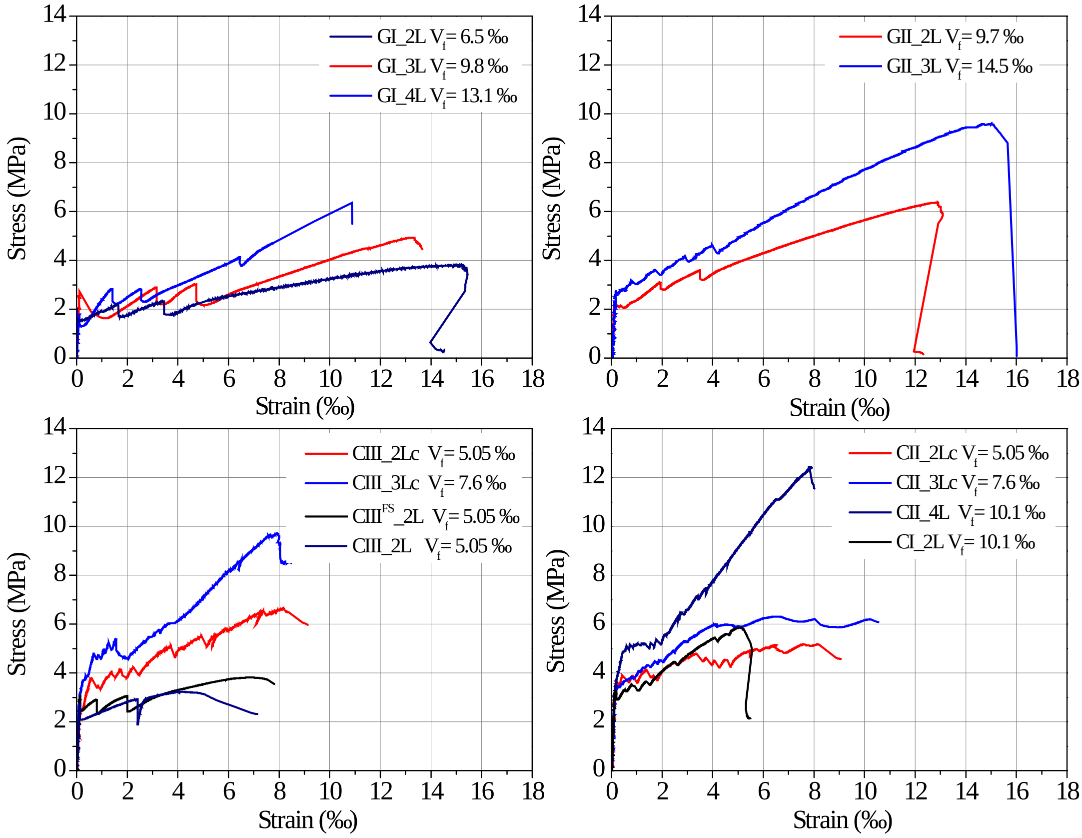


Figure 4. Stress-strain curves derived from dumbbell TRC specimens subjected to direct tension

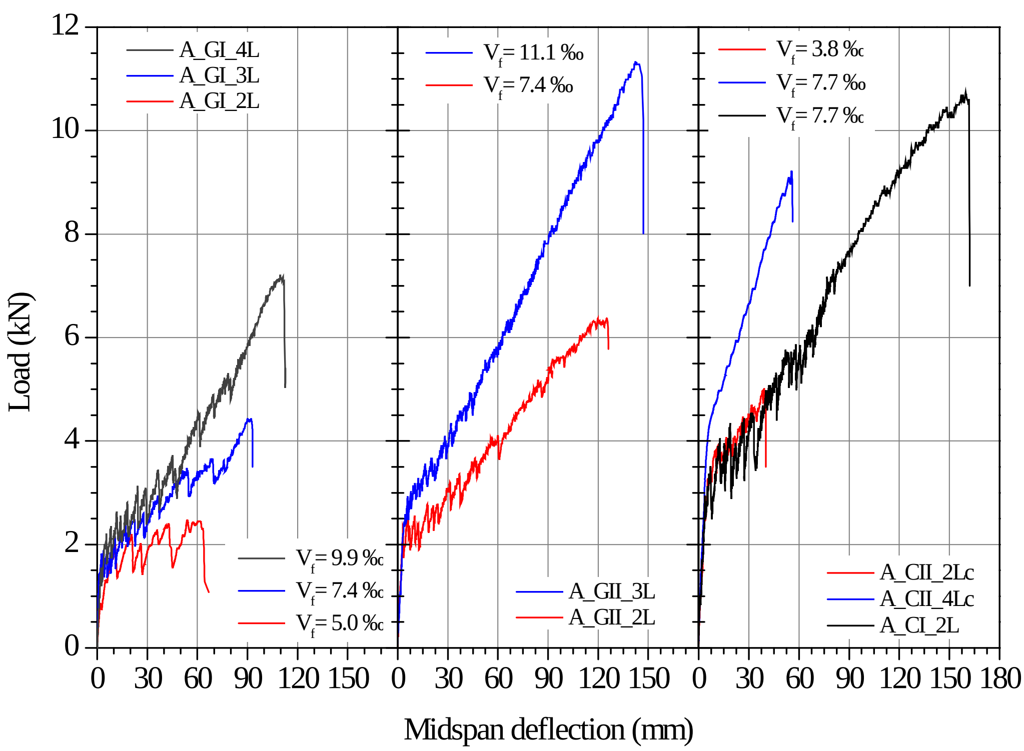


Figure 5. Load- Midspan deflection curves for Type A specimens

3.2 Type B specimens

Figure 6 illustrates the load-midspan deflection curves for Type B specimens. All specimens with Glass fiber TRC formworks failed due to textile reinforcement rupture that followed the yielding of steel reinforcement exception being the specimens receiving ∅4.2 rebars, which failed due to steel bar rupture. A trilinear curve fits well with the load-midspan deflection curve. The characteristic points of this curve are the cracking load (denoted as CL in Figure 6), the steel yielding load (YL) and the textile reinforcement rupture load (FL). After steel yielding a linear ascending branch with reduced stiffness compared to the stiffness before yielding is observed. The lower failure load of specimen B_CII_2Lc (by 6%) compared to the failure load of B_CI_2L indicates that the use of polymer coating allows for the full exploitation of the reinforcement's mechanical properties. According to the test results, specimens B_CI_2L, B_CII_2Lc and B_GII_2L exhibited the same behavior. For specimens reinforced with GI textiles the increase of fiber volume ratio by 50% resulted in an increase of the failure load by approximately 35% (except of specimens with 4.2 mm diameter bars). Finally, specimens reinforced with GII and carbon textiles exhibited higher first cracking load compared to specimens reinforced with GI textiles. For all specimens a dense crack pattern was observed. All cracks formed in the formwork element crossed the TRC/RC interface vertically and continued in the RC part of the composite slab. The crack pattern reveals a strong composite behavior. Interface slip measurements (not shown here) support this outcome. Maximum slip readings in the order of 0.2 mm for all specimens were observed in the ¾ of the shear span.

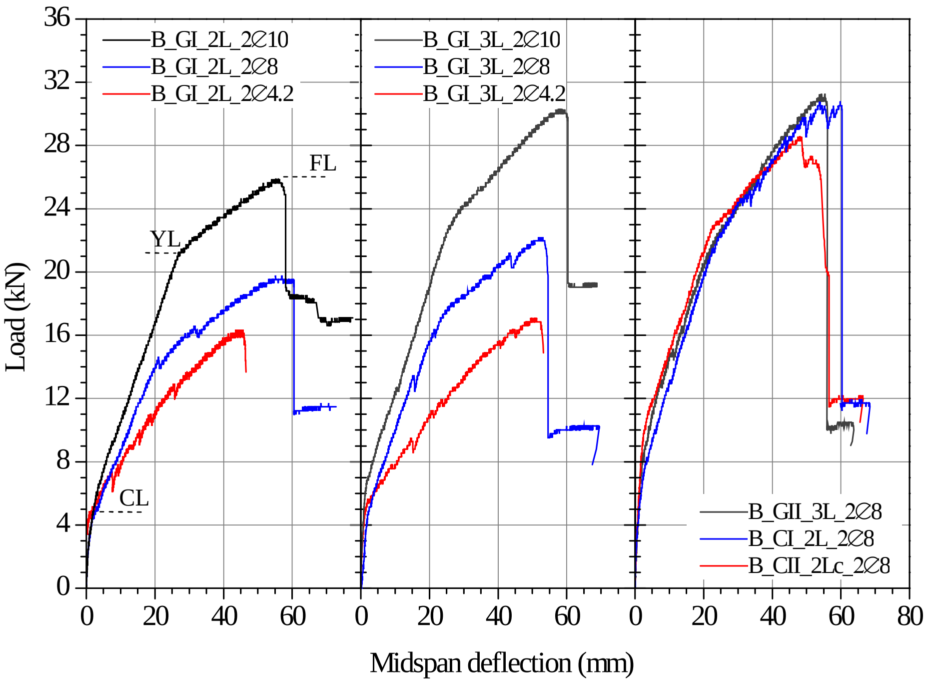


Figure 6. Load- Midspan deflection curves for Type B specimens

3.3 Type C specimens

In Figure 7 the load-midspan deflection curves for Type C specimens are given. All specimens failed due to textile reinforcement rupture following steel reinforcement yielding. Textile reinforcement rupture for specimen $C\_III^{FS}\_6∅8\_3Lc$ was accompanied by spalling of matrix cover. $C\_III^{FS}\_6∅8\_3Lc$ specimen exhibited higher failure load compared to its uncoated counterpart by 45%. Also for type C specimens, a full composite behavior was observed. The failure load of all type C specimens was higher than the one of the control specimen. The contribution of the textile reinforcement in the load bearing capacity ranged between 70% to 145%.

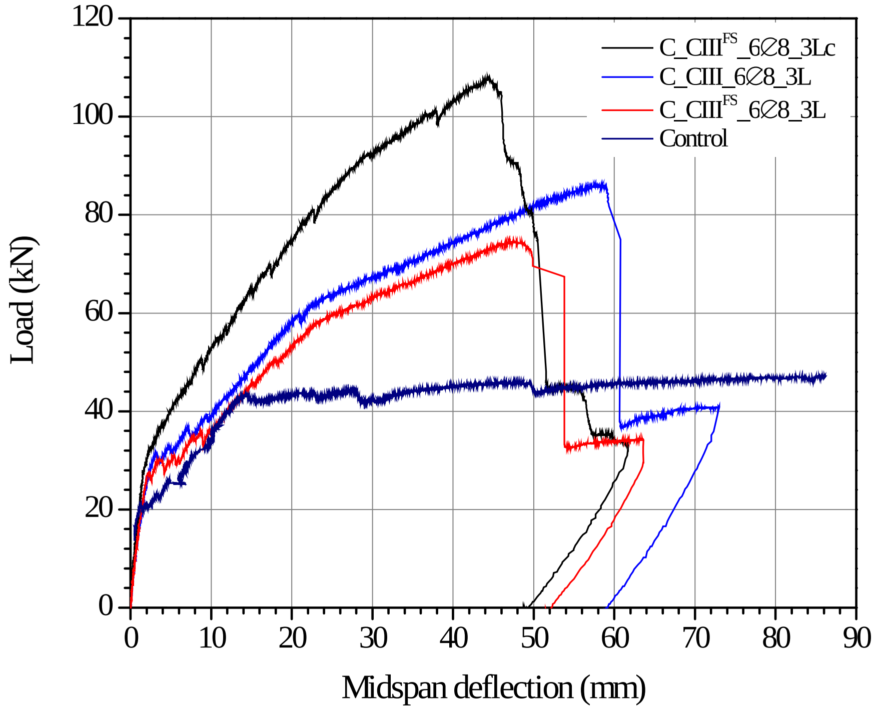


Figure 7. Load- Midspan deflection curves for Type C specimens

4 Conclusions

Study of the experimental results concludes that TRC elements can be used as a SiP participating formwork element. The use of polymer-coated textile reinforcement allows for the full utilization of reinforcement's mechanical properties. Equivalent stiffness design solutions result in a similar response. Attributed to the stickiness of the mortar with the finely grained sand, weak bond regions were observed and led to a reduced failure load (compared to the coarse grained counterpart). The use of the coarse grained matrix did not act negatively on the textile reinforcement-matrix bond quality and resulting at the same time in an economic mixture design. Full composite behavior can be achieved by the formation of the indentations at the top surface of the formwork element. The composite behavior is enhanced with the formation of the full in-situ concrete end zone.

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