Textile Reinforced Concrete (TRC) for precast Stay-in-Place formwork elements

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ABSTRACT: The main goal of the present study is to experimentally investigate the response of structural elements cast against thin-walled stay-in-place formwork elements made of Textile Reinforced Concrete (TRC). TRC comprises an innovative composite material consisting of fabric meshes made of long woven, knitted or even unwoven fibre yarns (e.g. carbon, glass or aramid) in at least two (typically orthogonal) directions embedded in a cementitious matrix (mortar or fine-grained concrete). The experimental investigation described in this study was carried out on two types of reinforced concrete specimens: the first one included 22 beam-type specimens incorporating flat TRC stay-in-place formworks and the second one included 11 prismatic column-type specimens cast into permanent precast TRC shafts.

1 INTRODUCTION

Construction management is always focused on the minimization of two inter-related factors: the duration of construction and the total (life-cycle) cost of a structure. The use of Stay-in-Place (SiP) – or permanent – formwork elements addresses this goal and offers additional benefits such as reduced maintenance costs and improved safety (by reducing hazards during construction). SiP formwork is a structural element that is used to contain the placed concrete, mould it to the required dimensions and remain in place for the life of the structure (Wrigley, 2001). Permanent formwork elements are distinguished into participating and non-participating ones; the former contribute to the strength of the structure through composite action with the cast-in-place parts of it, while the latter make no strength contributions. Several different SiP formwork systems have been developed incorporating a variety of materials, such as steel, timber and fiber reinforced polymers (FRP). High corrosion susceptibility, poor durability and low fire resistance are, respectively, some marked drawbacks of the aforementioned systems. The alleviation of these drawbacks may be realized by using cementitious composite materials consisting of inorganic matrices (cement-based mortars or micro-concrete) reinforced by non-corrosive fiber yarns arranged in a grid structure. The generic term for these materials is Textile Reinforced Concrete (TRC) [RILEM, 2006]. In this case, composite behavior is achieved mainly through mechanical interlock between the matrix and the grid openings; furthermore, the fibers’ properties may be fully exploited since the quantity and the orientation of the yarns can be selected according to the design requirements (contrary to the fiber reinforced concrete, in which fibers are randomly distributed and oriented). The flexibility of the textile meshes allows for the design of thin SiP formwork elements with complex geometry. This study presents the results of an experimental investigation conducted on concrete elements cast against thin-walled TRC SiP formwork.

2 EXPERIMENTAL PROGRAM

2.1 Beam-type specimens

Beam-type specimens measuring 1500 mm in length, 150 mm in width and 100 mm in total height, were subjected to four-point bending. The following parameters were examined in order to investigate their influence on the flexural behavior of the composite elements:

- Fiber reinforcement ratio (corresponding to 1 and 2 layers);
- Fiber rovings’ coating (polymeric and none);
- Treatment of the TRC/cast-in-situ concrete interface (smooth and rough);
- Spacing of the textile reinforcement layers (1 mm and 6 mm);
- Filaments’ material (e-glass and carbon).
The construction of the specimens was divided into two stages. Initially, a thin-walled flat TRC element (measuring 1500 mm × 150 mm × 12 mm, as in length × width × height) was produced by application of two 6 mm thick mortar layers, within which the textile reinforcement (either in 1 or 2 layers) was placed. In the case of double-layer textile reinforcement, a thin mortar layer (1 mm in thickness) was used to separate the textiles and to ensure that an adequate quantity of matrix material would protrude through the grid openings in order to provide better bond conditions. In most specimens, the exposed surface of the TRC element was roughened while in a fresh state by the formation of longitudinal grooves using a hand tool. In order to investigate the influence of the formwork’s surface treatment two TRC elements received smoothing. Following a 24-hour curing period the specimen’s main part (88 mm in thickness) was cast on top of the TRC and the completed beam was stored in a curing chamber (20°C, 98%RH) for 28 days (until testing). For 15 specimens the main part consisted of plain concrete, while for the remaining specimens reinforced concrete was used. Steel reinforcement comprised two longitudinal bars (with a diameter of 8 mm), positioned at an effective depth of 75 mm (resulting in a reinforcement ratio equal to approx. 9‰). No transverse reinforcement was used. The specimen geometry is shown in Figure 1.

For the TRC matrix material a commercial inorganic binder was used consisting of a blend of cementitious powders and a low fraction of polymers. The water to cementitious materials ratio was equal to 0.23; the compressive and flexural strength (measured at 28 days) were equal to 24 MPa and 6.3 MPa, respectively. The mean 28-day compressive strength of the concrete was equal to 21.2 MPa. The average yield stress of the steel reinforcement was equal to 571.6 MPa.

Two basic types of commercial textiles with equal quantity of fiber rovings in two orthogonal directions (0°/90°) were used. The first type comprised high-strength carbon fiber rovings and the second one e-glass fiber rovings. In either textile the width of each roving was equal to 3 mm and the clear spacing between rovings was 7 mm. The weight of fibers in the textiles was 348 g/m² and 480 g/m² for carbon fibers and e-glass fibers, respectively. The nominal thickness of each layer (based on the equivalent smeared distribution of fibers) was 0.095 mm and 0.092 mm for the carbon fiber textile and the e-glass fiber textile, respectively. The resulting volumetric ratio of fibers in the TRC element (fiber volume per TRC unit volume) was approximately equal for both carbon (7.9‰) and e-glass fibers (7.6‰). The geometric fiber reinforcement ratio for either type of fibers was approximately equal to 1‰ per textile layer. The guaranteed tensile strength of the fibers (as well as of the textile, when the nominal thickness is used) in each direction was taken from data sheets of the producer equal to 3350 MPa (carbon) and 1600 MPa (e-glass). The elastic modulus of the fibers was 225 GPa (carbon) and 70 GPa (e-glass). The fiber rovings in most of the textiles were uncoated, but in a small number of textiles they were polymer-coated. The textile structure is shown in Figure 2. Figure 3 illustrates stages of the specimens’ construction.

A total of 22 specimens were constructed: 12 specimens comprised plain concrete main parts, 7 specimens comprised reinforced concrete main parts and 3 were used as control specimens. The specimens designated as “Con” and “Conm” consisted of plain concrete and were cast against a retrievable and a SiP TRC formwork, respectively. Specimen “ConS” was also cast against a retrievable formwork.
and consisted of reinforced concrete. Specimens are
given the general notation $X_F$, where $X$ denotes the
number of textile layers of the TRC element (1 or
2) and $F$ denotes the type of fibers of the textiles
(C for carbon and G for e-glass). Indices “c” and
“s”, where applicable, denote polymer-coated textiles
and smooth TRC/concrete interface, respectively. The
following specimens with plain concrete main parts
were constructed: 1C, 2C, 1Cc, 1CcS, 1G, 2G,
1Gc, 2Gc and 1Gcs. The notation of specimens with
reinforced concrete main parts is complemented with
the letter “S”. These specimens are the following: 1CS,
2CS, 1CcS, 1GS, 2GS and 1GcS.

Three additional specimens with plain concrete
main parts were constructed in order to investigate the
effect of the textile inter-layer spacing along with the
combined use of carbon and e-glass fiber textiles and
the combined use of coated and uncoated e-glass fiber
textiles. More specifically, specimens CGI and CGp
were both cast on top of TRC elements each contain-
ing one layer of carbon and one layer of e-glass
fiber textiles, the only differences being the spacing
of the two layers (6 mm for CGI and 1 mm for CGp)
and the resulting TRC thickness (18 mm for CGI and
12 mm for CGp). Specimen GcG was cast on top of
a TRC element reinforced with two layers of e-glass
fiber textile, one coated (closest to the bottom of the
specimen) and one uncoated.

All specimens were tested under monotonic four-
point bending at a total span of 1400 mm using a
stiff steel frame. The displacement-controlled load-
ing protocol was applied using a vertically positioned
500 kN MTS actuator. The load application points
were 50 mm distant from the mid-span. The displace-
ment application rate was equal to 0.016 mm/sec.
Displacements were measured at mid-span using an
external rectilinear displacement transducer (of 50 mm
stroke capacity) mounted on one side of the specimen
(Fig. 4).

2.2 Column-type specimens

Prismatic column-type specimens with square cross
section ($224 \times 224$ mm) and 500 mm height were
tested under concentric monotonic compressive load-
ing. The construction procedure of these specimens
resembled the one of the beam-type specimens. First, a
thin-walled TRC SiP shaft was constructed measuring
500 mm in height and 12 mm in thickness. Following a
curing period of 28 days the main part of the specimen
was cast in the TRC formwork consisting of rein-
forced concrete. The reinforcement was of the same
grade as the one used for the beam-type specimens
and comprised a 460 mm high steel cage formed by
4 longitudinal bars (12 mm diameter) and square ties
(8 mm diameter) with a spacing of 100 mm (Fig. 5).

The parameters under investigation were:
- Filaments’ material (e-glass and carbon);
- Fiber rovings’ coating (polymeric and none);
- Matrix material;
- Fiber rovings’ orientation.

The TRC column-type formwork elements were
cast in a custom-made modular metallic mould mea-
suring 500 mm in height. Two sets (each of four steel
plates) formed a 12 mm gap in which the cement based
mortar was hand-pumped through a plug at the bottom
of the mould. The plates’ edges were chamfered at a
curvature radius of 15 mm. Prior to fixing the plates
together a single-layer textile was put in place (in the
middle of the space between the inner and the outer
parts of the mould) allowing for a 200 mm overlap.

Four different textiles were used in the TRC shafts.
The first two were identical to the ones used for
the production of the flat TRC SiP formwork elements,
while the other two comprised polymer-coated fiber
rovings (carbon for one of the textiles and e-glass for
the other) oriented at $+45^\circ/ -45^\circ$. Apart from roving
orientation the textiles differed in no other aspect.

Two types of inorganic mortars were used: the first
one (mortar I) was identical to the mortar used for
the flat SiP formwork elements (measured 28-day com-
pressive and flexural strength were equal to 23.1 MPa
and 6.88 MPa, respectively); the second mortar (mor-
tar B) was of higher compressive strength (51.7 MPa)
Figure 6. Load versus mid-span deflection curves.

and of lower flexural strength (2.5 MPa) than mortar I. Both mortars included a moderate quantity of superplasticizer so that high fluidity and pumpability could be achieved.

A total of 11 specimens were constructed. One specimen (designated as “Con”) was cast in a retrievable formwork and was used as the control specimen. The remaining specimens were cast in the TRC moulds. The mean 28-days compressive strength of the concrete used in this specimen series was equal to 21 MPa. Mortar I was used for the production of half of the TRC shafts, whereas mortar B was used for the remaining ones. The specimens receive the general notation MFO, where M denotes the mortar type (I or B), F denotes the type of fibers in the textile (C for carbon and G for e-glass) and O denotes the roving orientation (90 for 0/90° and 45 for +45°/−45°). Index “c” is used to distinguish the polymer-coated textiles. According to the following hybrid (composite) specimens were produced: BC90, BCc45, IC90, ICc45, BG90, BGc90, BGc45, IG90, IGe90, IGe45. All specimens were stored in a curing chamber (20°C, 98% RH) for a time span of 28 days (i.e. until testing). Axial concentric monotonic compression was exerted on all specimens in a displacement control mode at a rate of 0.035 mm/sec using a 4000 kN capacity loading machine. Axial deformations were measured by an external lvdt (with a gauge length of 250 mm) positioned at mid-height.

3 RESULTS AND DISCUSSION

3.1 Beam-type specimens

The load versus mid-span deflection curves for all specimens are given in Figure 6. Higher load and deflection at failure was recorded for all composite specimens in comparison to the control ones. Specimens Con and Conm responded in an almost identical manner (failing at the same load and deflection) due to a single crack that formed in the mid-span. Failure of plain concrete specimens cast on top of uncoated carbon TRCs was attributed to progressive pull-out of fiber rovings from the inorganic matrix. Failure of their e-glass counterparts was the result of the sleeve filaments’ damage (i.e. of the fracture of individual fibers found on the perimeter of the rovings) caused by stress concentrations in the cracks’ edges. For the same type of specimens (i.e. comprising plain concrete main parts) the use of polymer-coated textiles and the increase of the textile reinforcement ratio led to a denser cracking pattern with smaller
crack widths (Fig. 7). This fact is indicative of homoge-
neous stress distribution in the TRC element and of high stress transfer capacity between the mortar
and the textile. Shear failure of specimen 2Cc con-
irms this observation. Coating of the rovings seems
to improve textile/mortar bond conditions and fiber
alignment by stabilizing the fiber bundles at the textile
joints and by preventing their relative slippage in these
areas. Furthermore, the coating procedure results into
partial impregnation of the fiber bundles, providing
strain compatibility between the inner and the outer
filaments.

According to the experimental results the effect of
the TRC/concrete interface roughness is rather small
but deserves more experimental attention since it is
strongly dependent on: the roughness scheme (i.e. the
magnitude of surface undulations); the mechanical
properties and the maximum aggregate size of cast-
in-place concrete; and the elapsed time between TRC
and concrete casting (i.e. the effect of chemical bond).
Regardless of the surface treatment that the SiP form-
works received in this investigation all TRC/concrete
interfaces remained intact during testing.

By comparison of the response of specimens CGp
and CGI it is concluded that the increase of the matrix
thickness between the textile layers (and the con-
sequent increase of the TRC thickness) has small
influence in regard to ultimate load-bearing capac-
ity and deformability. The observed differences are
clearly attributed to the change of effective depth.

Crashing of concrete in the compression zone for
specimens with steel reinforced main parts was the
cause for load-bearing capacity reduction. The steel
reinforcement (acting as crack arrestor) led to dense
crack patterns with small crack widths. The effect
of polymer coating of the textiles in this case was
also beneficial but less pronounced. The quantified
influence of the rovings’ polymer coating and the tex-
tile reinforcement ratio is given in Tables 1 and 2,
respectively.

Table 1. Influence of polymer-coated textiles (coated vs
uncoated).

<table>
<thead>
<tr>
<th>Specimens</th>
<th>% increase at maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main parts made of plain concrete</td>
<td></td>
</tr>
<tr>
<td>Single layer carbon TRC 1C ↔ 1Cc</td>
<td>112.9</td>
</tr>
<tr>
<td>Double layer carbon TRC 2C ↔ 2Cc</td>
<td>26.0</td>
</tr>
<tr>
<td>Single layer e-glass TRC 1G ↔ 1Gc</td>
<td>13.1</td>
</tr>
<tr>
<td>Double layer e-glass TRC 2G ↔ 2Gc</td>
<td>147.5</td>
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<tr>
<td>Main parts made of reinforced concrete</td>
<td></td>
</tr>
<tr>
<td>Single layer carbon TRC 1CS ↔ 1CcS</td>
<td>10.7</td>
</tr>
<tr>
<td>Single layer e-glass TRC 1GS ↔ 1GcS</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* Shear failure

Table 2. Fiber reinforcement ratio effect (higher vs lower
reinforcement ratio).

<table>
<thead>
<tr>
<th>Specimens</th>
<th>% increase at maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main parts made of plain concrete</td>
<td></td>
</tr>
<tr>
<td>Uncoated carbon TRCs 1C ↔ 2C</td>
<td>129.9</td>
</tr>
<tr>
<td>Coated carbon TRCs 1Cc ↔ 2Cc</td>
<td>36.0</td>
</tr>
<tr>
<td>Uncoated e-glass TRCs 1G ↔ 2G</td>
<td>42.9</td>
</tr>
<tr>
<td>Coated e-glass TRCs 2Gc ↔ 2Gc</td>
<td>212.6</td>
</tr>
<tr>
<td>Main parts made of reinforced concrete</td>
<td></td>
</tr>
<tr>
<td>Uncoated carbon TRCs 1CS ↔ 2CS</td>
<td>22.7</td>
</tr>
<tr>
<td>Uncoated e-glass TRCs 1GS ↔ 2GS</td>
<td>8.3</td>
</tr>
</tbody>
</table>

* Shear failure

The theoretical value of flexural capacity was cal-
culated by a cross section analysis based on idealized
material constitutive laws for concrete in compression
and carbon or e-glass fiber textile (and steel where
applicable) in tension and on the classical assumptions
of plane cross sections and negligible contribution of
the concrete below the neutral axis. Uniform stress
distribution across each roving’s cross section and per-
fec TRC to concrete bond was assumed. Possible
failure modes included textile fracture (prior or after
steel yielding, if applicable) and concrete compressive
crushing.

For all specimens except those comprising plain
concrete main parts cast on top uncoated TRC form-
work elements the calculated values of flexural capac-
ity were in good agreement to the experimental ones.
Specimens incorporating uncoated TRCs exhibited
lower experimental moment capacity in comparison
to the theoretical value. Lack of full exploitation of
the textile properties in these specimens is attributed
to the inability of the matrix material to penetrate and
impregnate the fiber yarns. This fact leads to the inhomogeneous stress distribution between the outer and the inner filaments and thus the former carry larger tensile stresses in comparison to the latter [this has also been reported by Voss and Hegger (2006)]. As a result, the well-bonded e-glass outer filaments fail in tension and rapid crack width opening occurs until the dry core filaments are fully stressed. For the case of carbon rovings, differential stress distribution results in telescopic sliding of the filaments. The ratio of experimental to theoretical value of the flexural moment capacity can be considered as a coefficient of effectiveness ($\text{CEF}$) of the textile reinforcement. Based on the above discussion this ratio was found to be close to unit for specimens comprising reinforced concrete main parts and for plain concrete specimens with polymer-coated TRCs. For uncoated TRCs supporting plain concrete toppings the coefficient of effectiveness depends on the fiber volume ratio and on the type of fibers (e.g. $\text{CEF}$ equals to 0.32 and 0.56 for specimens 1C and 2C, respectively). The influence of polymer-coated textiles becomes clearer in Figure 8, where $\text{CEF}$ is plotted against the polymer-coated textile content for specimens 2G, 2Gc and GcG.

3.2 Column-type specimens

All specimens exhibited similar response under concentric monotonic compressive loading. The normalized axial stress versus axial strain curves are shown in Figure 9. Normalized stress is defined as the ratio of the compressive stress $f_{cc}$ over the specimen’s concrete compressive strength $f_c$ (specimens were cast with concrete of slightly different compressive strength, with a mean value equal to 21 MPa). Mortar B TRC shafts were cracked prior to testing due to shrinkage. These specimens failed under lower maximum load (by 10–18%) compared to the control specimen. Better response was observed for specimens cast in mortar I TRC shafts. Yet, these specimens (but one) also failed under lower maximum load (by 6% on average) compared to the control specimen. This was due to early local buckling of the TRC element, as explained hereafter. From the early stages of loading vertical cracking and flaking of the matrix material was evident on the TRC elements, resulting in the low contribution of the thin-walled TRC elements to the load-bearing capacity of the specimens. Until the peak load was reached, growing of the vertical cracks width was observed (especially at the specimens’ corners where stress concentration was present) and local buckling of the formwork occurred at the vicinity of the load application areas (top and bottom parts of the columns); this was accompanied by mortar spalling. The confining action of the TRC formwork was activated after maximum load was reached, resulting into the increase of post-peak deformability. Buckling of the vertical steel bars was observed in a later stage of the test (at 50% load carrying capacity reduction) causing textile rupture total failure of the specimens.

High compressive strength/low shrinkage matrices (e.g. fiber reinforced mortars) are recommended in order to avoid the premature failure of TRC element. Additionally, the installation or the formation of shear connectors on the inner side of the TRC elements is expected to improve composite action between the SiP formwork and the core concrete. It is pointed out that the main purpose of use of these innovative composite elements is not augmenting the load carrying capacity of axially loaded structural
members. The main structural advantage of these systems, if used as participating formwork, lies in the increase of deformability. In this study (using low textile reinforcement ratios), the experimental results indicate an increase in deformability by 25% to 75% (corresponding to the axial strain at a post-peak axial stress equal to 80% of the specimen’s compressive strength) compared to the monolithic specimen.

4 CONCLUSIONS

The experimental investigation presented in this study provides useful information on the behavior of composite TRC/concrete structural elements which can be used for the conduction of large scale tests. Further research is needed in order to establish a design methodology for TRC SiP formwork elements that is based on realistic structural behaviors.

REFERENCES
