Experimental Study on the Flexural Behavior of Steel-Textile-Reinforced Concrete: Various Textile Reinforcement Details

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Abstract: In this study, one reinforced concrete specimen and six textile reinforced concrete (TRC) specimens were produced to analyze the flexural behavior of steel-textile-reinforced concrete. The TRC specimen was manufactured using a total of four variables: textile reinforcement amount, textile reinforcement hook, textile mesh type, textile lay out form. Flexural performance increases with textile reinforcement amount, textile reinforcement hook type and textile reinforcement mesh type. The flexural performance was improved when physical hooks were used. Furthermore, textile reinforcement was verified as being effective at controlling the deflection.

Keywords: steel textile reinforced concrete; textile reinforced concrete; reinforced concrete; prestressed textile; flexural behavior; AR-glass textile; hook; steel textile reinforced concrete

1. Introduction

Textile-reinforced concrete (TRC) is a composite member made by combining the mesh-type reinforcement fiber from carbon, alkali-resistant (AR) glass, aramid, and similar materials with concrete [1]. Unlike steel reinforcement, the main advantage of reinforced concrete (RC) is that the textile does not develop corrosion, and thus it emerges as an alternative for new reinforcement. It does not require a thick cover over the concrete to prevent rebar corrosion, thereby offering the advantages of high durability and weight loss [2–4]. Thus, TRC has been used in sandwich panels and in small-scale overpasses, together with FRP bars. Further, TRC has high levels of strength, ductility, and free formability, allowing it to be applied in various areas ranging from building exterior materials, roofs, pedestrian bridges, and other structural members, as well as highway sound barriers, waterproof barriers, etc. [1,5–8]; it also has wider applications compared to fiber-reinforced concrete (FRC) [5,9–12]. Brameshuber [1] reported various structural behaviors from uniaxial tensile and flexural tests with thin TRC members. The behavior of TRC specimens were analyzed under various conditions and a sufficient structural capacity was obtained. Williams Portal et al. [4] reported on flexural tests on thin TRC slabs, and non-linear finite element method (FEM) analysis was performed. Volkova et al. [5] reported on a three-point bending test with TRC that was made using glass and carbon. All TRC specimens displayed a higher strength than RC. These studies analyzed the structural behavior of TRC specimens in small specimens, but it is difficult to use them as the main member that resists most loads in the structure.

The form of the fibers constituting the textile does not provide a perfect concrete–fiber bond [2,13]. The roving or yarn consists of hundreds or tens of thousands of filaments, and the spacing between
the filaments is too small to allow for concrete penetration, thereby leading to a concrete–textile bond occurring only with the exterior fibers, and no bond with the interior fibers. Concrete–fiber models have been presented to explain the bond behavior of textiles, and studies have been conducted to increase the bond performance, such as epoxy’s penetration of textiles and the attachment of sand to textiles [14–16]. Yin et al. [15] reported on a four-point bending test with thin TRC specimens. This study used 10 × 10 mm and 20 × 20 mm sized mesh textiles. The results of the experiment for a narrow mesh spacing were better than for a wide mesh spacing. U-shape iron hooks can not only improve the bonding performance of textiles and concrete, but also improve the shear ability of concrete. Yin et al. [16] reported a four-point bending test with steel-textile reinforced concrete. The specimens used were a hybrid textile that was made of E-glass and carbon. TRC specimens had the effect of reducing the crack width and spacing. It also had satisfactory flexural ductility. These post-processing courses, however, weaken the free formability, an advantageous feature of textiles, and give rise to an unnecessary process when applying it to the field. Even though post-processing increases the flexural and bond performance, it is difficult to apply on site. Therefore, in this study, the flexural performance structure test was conducted based on the pure textile, and the feasibility of various textile layout methods was verified to solve the textile–concrete bond problems. The TRC specimens, which are composite specimens of steel reinforcement and textiles, were fabricated and were examined in terms of their applicability in civil structures that need to support high loads.

2. Experiment Program

In this paper, one RC specimen and six TRC specimens were manufactured. Multiple layers of textile were used to increase the load [17]. In this case, the textile–mortar bond problems developed, therefore the specimens were manufactured in such a way that it would increase the textile efficiency by using the variables of textile reinforcement amount, textile hook type, textile mesh type, and textile layout method [18].

2.1. Textile

The textile that was used in the experiment in this study was woven from AR glass fiber and was coated with 16.5% zircon to resist the alkali component of the concrete. The textile properties provided by the manufacturer are shown in Table 1. Figure 1a shows an 8 × 8 mm mesh spacing, and Figure 1b shows that the spacing was adjusted to 24 mm vertically and 40 mm horizontally because of mortar penetrated the textile reinforcement well. The tensile strength of the filament was 1789 MPa and its modulus of elasticity was 68 GPa.

| Properties and Geometric Parameters | AR Glass |
|------------------------------------|----------|
| Number of filaments per yarn (or roving) | 1600 |
| Tensile strength of the warp (N/50 mm *) | 2142 |
| Tensile strength of the weft (N/50 mm) | 1833 |
| Rupture elongation ratio of the warp (%) | 2.85 |
| Rupture elongation ratio of the weft (%) | 2.36 |
| Tex of the yarn (g/km) | 640 |
| Area of the yarn (or roving) (mm²) | 0.246 |

* GB/T 7689.5 idt ISO 4606.
2.2. Fine Concrete

The concrete used in the manufacture of a TRC member should be carefully selected by considering the type of aggregate according to the type of textile. The use of aggregates larger than the textile mesh spacing prevents the aggregates from penetrating through the grids, reducing the bond between the textile and the concrete, as well as causing damage to the textile due to the aggregate and deforming its shape. Therefore, most TRC products use fine concrete with fine aggregates. In this study, sand with a maximum diameter of 0.42 mm was used. Table 2 shows the mixing proportion of the fine concrete that was used in the experiment and the design reference compressive strength (35 MPa).

Table 2. Mix proportion of fine concrete with W/B 0.45.

| Component          | Unit  | Content |
|--------------------|-------|---------|
| Water              | kg/m³ | 315     |
| Cement             |       | 490     |
| Fly ash            |       | 175     |
| Silica fume        |       | 35      |
| Sand No. 6 (0.42–0.22 mm) |       | 500     |
| Sand No. 7 (0.22–0.15 mm) |       | 713.75  |
| Superplasticizer   | %     | 0.7     |

2.3. Specimens

Both the RC and TRC specimens had a 1500 mm length, a 150 mm height, and a 120 mm width, with support located 100 mm from the end. The detailed specifications of the specimens are shown in Figure 2. D6 (6.35-mm diameter) rebars, which were the smallest, were used for both tensile and shear reinforcement and to clearly identify the textile’s performance. The yield strength was 400 MPa, and the modulus of elasticity was 200 GPa. To prevent shear failure, five shear reinforcements were placed from each end to 400 mm. Two and three steel reinforcements were placed at the top and at the bottom, respectively, in the RC specimen, and two steel reinforcements were placed at the top and bottom each in the TRC specimens. Textiles corresponding to one steel reinforcement were reinforced in T1 such that the RC specimen and T1 specimen had the same reinforcement with the same tensile capacity. The textile was placed directly on top of the steel reinforcement, as shown in Figure 2c.

2.4. Manufacture of the Specimens

The experimental variables and the experimental comparison group of the TRC specimens were as follows: (1) textile reinforcement amount (T1, T1.5, T2.2); (2) textile hook type (T1, T1_H); (3) textile mesh type (T1, T1_M); and (4) textile layout (T2_1, T2_2). The detailed specifications of each specimen are shown in Table 3.
The manufacture process of the TRC specimens is shown in Figure 3. It was the bundle of 8 × 8 mm textiles in one layer that made it difficult for the mortar to penetrate the textiles. Thus, the textiles of the specimens (except T1_M) were fabricated with a grid size of 24 mm vertically and 40 mm horizontally. In the case of the textiles made with a larger grid size, the general aggregate was made of mortar. This also enabled mortar’s better penetration of the textile. The textile reinforcement could have the same axial capacity. At this time, the TRC tensile strength for textile and mortar bond was defined as 40% of the textile tensile strength [19]. Textile reinforcements were placed over the tensile steel reinforcement because of the sufficient cover thickness of concrete. T1.5 used 1.5 times more textiles than the T1 series, and the T2 series used 2.2 times more than T1 series.

In the T1 series, textiles corresponding to the tensile force of one steel reinforcement were placed on top of the steel reinforcement to have the same axial capacity. At this time, the TRC tensile strength for textile and mortar bond was defined as 40% of the textile tensile strength [19]. Textile reinforcements were placed over the tensile steel reinforcement because of the sufficient cover thickness of concrete. T1.5 used 1.5 times more textiles than the T1 series, and the T2 series used 2.2 times more than T1 series.

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resist the loads in the same location. Textile reinforcement was placed on top of the steel reinforcement and was assembled before it was stretched manually from both ends to maintain the linearity when placing concrete [20].

![Manufacture procedure of the TRC specimens.](image1)

The RC, T1, T1_M, T1.5, and T2_1 specimens were fabricated using bundles of textile reinforcements, as shown in Figure 4a, and T1_H was fabricated as shown in Figure 4b. T2_2 was produced as shown in Figure 4c. T1_H fixed both ends of the specimen to the upper steel reinforcement.

![Various textile reinforcement methods: (a) normal TRC; (b) textile hook of T1_H; and (c) two layers of T2_2.](image2)

2.5. Test Setup

The support was 100 mm from the end of the specimen, and the span section was 1300 mm. The loading was applied at a rate of 0.1 mm/s until the specimen was destroyed. The loading point was 200 mm away from the center of the specimen such that the maximum moment was generated in the 400 mm section at the center of the specimen. The deflection was measured by installing a linear variable differential transformer (LVDT) at the center and at the loading point. Four concrete strain gauges were installed at the top and sides of the concrete, and two reinforcement strain gauges were installed at the center of the steel reinforcement. The extended Pi-shaped gauges (PI gauge) were attached to the surface of the specimen where the textile was placed to measure the strain of the beam in the net bending section. The extended PI gauges were installed to indirectly obtain the behavior of the textile in the cracking. The measured data included various factors, such as the strain and crack widths of the textile and concrete. The test setup and gauge attachment location are shown in Figure 5.
3. Experiment Results

3.1. Crack and Failure

The progress of cracking was confirmed via visual inspection. Similar flexural cracks were observed in all the specimens, and the number of cracks is shown in Table 4. All TRC specimens produced more cracks than that of the RC specimens [19]. Therefore, textile reinforcement was considered advantageous for the uniform distribution of cracks [15,21]. In all the specimens, a crack occurred at the tension side of the center, and flexural cracks with the same shape as that of the RC beam displayed cracks that progressed from the center to the support due to the loading, as shown in Figure 6. In addition, it was confirmed that the cracks were more evenly distributed in the T1_M and T2 series, which had a small mesh spacing or a large amount of reinforcement. In other words, when the mesh spacing was narrow, the crack control at more vertical and horizontal intersections was effective, and when the mesh spacing was widened to 24 × 40 mm, more than twice the textile amount was required.

Figure 5. Test setup of the specimens.

Figure 6. Crack development of the RC and TRC series specimens: (a) RC, (b) T1, (c) T1_H, (d) T1_M, (e) T1.5, (f) T2_1, and (g) T2_2.
Figure 7a shows the flexural performance of the RC, T1, T1.5, and T2_1 specimens according to the textile reinforcement amount. The ultimate load was 22.93 kN for the RC specimen, 20.22 kN for T1; 22.81 kN for T1.5, and 23.43 kN for T2_1. Compared to the RC specimen, the ultimate loads of the TRC specimens were as follows: T1—88%, T1.5—99%, and T2_1—102%. When the textile reinforcement amount was increased 1.5 times from T1 to T1.5, the flexural performance increased 11%. Furthermore, from T1.5 to T2_1, the flexural performance increased 3%. As the textile reinforcement amount increased, the increase rate of the flexural strength decreased because the inner fiber of the roving decreased the area of the bond with fine concrete, which is known as an internal slip and fracture, as shown Figure 8 [22].
Figure 7. Load and deflection curves: (a) textile reinforcement amount, (b) textile mesh type, (c) textile hook type, (d) textile layout, and (e) load–deflection graph.

Figure 8. Slip and fracture inside the textile: (a) slip and (b) fracture.

Figure 7b shows the flexural performance of the RC, T1, and T1_M specimens according to the textile mesh type. T1 was fabricated with 18 textiles composed of 24 × 40 mm meshes, and T1_M was made with 9 textiles composed of 8 × 8 mm meshes to make the warp fiber area the same as that of T1. Therefore, the amounts of textile reinforcement of the two specimens were the same, and thus a difference in the textile mesh type, and thus a difference in the amount of textile reinforcement. T1_M had a 23.18 kN ultimate load, which was 101% of the RC specimen, and a 13% ultimate load performance improvement compared to T1. In the case of T1_M, the number of weft rovings of T1_M was greater than that of the textiles arranged in T1, which partially served as a physical stud with warp rovings. That is, as the load increased, more force was required to generate the slippage of warp roving due to the cross-point of the weft and warp rovings [15].

Figure 7c shows the flexural performance of the RC, T1, and T1_H specimens according to the textile hook type. T1 was a specimen made only using the bond of concrete and textile, and T1_H adopted physical hooks (hooks or anchorages) at both ends of the specimen. The textile reinforcement amount of the two specimens was the same. T1_H had a 26.14 kN ultimate load, which
was 113% of the performance compared with the RC specimen, and showed a 29% ultimate load performance improvement compared to T1. Due to the low elastic modulus and cross-sectional area of the textiles, T1 had a smaller flexural stiffness compared to the RC specimen, thereby giving it a greater deflection increase rate according to the increasing load. T1_H, despite having one-third of the textile reinforcement amount of the other specimens, had an excellent initial flexural stiffness and displayed cracks later compared to the RC and T1 specimens.

Figure 7d shows the flexural performance of the RC, T2_1, and T2_2 specimens according to the textile layout form. T2_1 had 40 textiles in one layer, and T2_2 had two layers of 20 textiles in two layers to improve the textile-concrete bond area. T2_1 had a 23.43 kN ultimate-load, which was 102% and 116% of the ultimate load performances compared to the RC and T1 specimens, respectively. T2_2 had a 24.29 kN ultimate load, which was 106% and 120% of the ultimate-load performances compared to the RC and T1 specimens, respectively.

T2_2 had double the textile bond area compared to T2_1, thereby slightly improving the flexural performance by 4% in terms of the ultimate load. T2_2 was higher than T2_1 in terms of deflection under the yield load, where the division of layers in the same textile reinforcement amount can be said to have had a minimal impact on the performance improvement of specimen.

Figure 7e shows the flexural performance of the all specimens. All TRC specimens were similar to the RC specimen. In particular, the flexural performance of T1_H was the best. In other words, hook type greatly affects flexural performance.

Ductility

To evaluate the ductility, the ultimate load deflection–yield load deflection ratio was defined, and the yield load was selected based on the yield point of the steel reinforcement. The minimum ductility index for safety in flexural members was approximately 2–3 or higher [23], and the ductility of all the TRC specimens was 2 or higher. Furthermore, all TRC specimens were higher than the RC specimen, which had a ductility index of approximately 2–5. In particular, the ductility increased for specimens with an appropriate textile reinforcement amount, narrow mesh type, and hook type because of the high strain rate and slippage of textile reinforcement.

3.3. Strain

Figure 9 shows the strain according to the height of the specimen cross-section. The strain of the 140-mm and 120-mm points was measured using a concrete strain gauge, and the strain of the lowest level (at a 20-mm height) was measured using the extended PI gauge.

Figure 9a,b compares the strain values according to the textile hook type. Figure 9b shows that the strain before 20 kN was smaller than the strain in the same portion in Figure 9a. This was because the textile was perfectly fixed using both ends of the textile reinforcement hook.

All specimens (except T1_H) showed that the strain increased after the yield point, while the strain constantly increased even after the yield point. In other words, the textile reinforcement for having the same performance as the RC specimen was disadvantageous for a stable flexural behavior.

Figure 10 shows the load–strain graph of all specimens. The T1 series specimens showed similar trends to the RC specimens. In the case of the T1 specimen, the strain rapidly increased at about 20 kN but could not be measured accurately. At the same load, the T1_H specimen showed the smallest strain and showed the closest behavior to that of the RC specimen.
Figure 9. Strain distributions for different load levels: (a) T1, (b) T1_H, (c) T1_M, (d) T1.5, (e) T2_1, and (f) T2_2.
3.4. Serviceability

To verify the serviceability of the specimens according to their textile reinforcement amount, the loads against the maximum allowable deflection of the specimens were compared. In this study, $l/360$ was selected by considering the instantaneous deflection and the floor structure and excluding the long-term deflection effect [24,25]. The maximum allowable deflection for the 1300 mm span was 3.61 mm. Table 6 shows the load at the maximum allowable deflection of each specimen.

| Name | Load at the Max. Permissible Deflection (kN) | $\delta_{p,RC}/\delta_{p,TRC}$ |
|------|------------------------------------------|--------------------------------|
| RC   | 14.13                                     | 1                              |
| T1   | 11.59                                     | 0.82                           |
| T1_H | 18.40                                     | 1.30                           |
| T1_M | 13.26                                     | 0.94                           |
| T1.5 | 11.04                                     | 0.78                           |
| T2.2 | 11.78                                     | 0.83                           |
| T2.2_L | 10.48                                    | 0.74                           |

4. Conclusions

In this paper, the flexural performance of the flexural members of steel-textile-reinforced concrete and appropriate textile reinforcement methods were verified. Toward this end, the reinforced concrete (RC) specimens and the six steel-textile-reinforced concrete (TRC) specimens were compared.

1. The textile was placed over the steel reinforcement, which had a remarkable reinforcement effect on the flexural behavior of the TRC specimens, resulting in the same type of flexural cracking in all specimens. It was found that TRC was more advantageous for distributing cracking evenly because cracking occurred more frequently overall in TRC than in RC.

2. The flexural performance of the specimen increased with increasing the textile reinforcement amount. However, the results of comparing the T1–T1.5 and T1.5–T2_1 textile results showed that the performance of the test did not increase proportionally with the increase of the textile reinforcement amount. This was because as the textile reinforcement amount increased, slippage occurred because the bond of concrete to inner textile reinforcement was not perfect.

3. When the mesh of the textile was made smaller, the number of contacts in the warp and weft rovings of the textile increased, which prevented slippage between the textiles. In addition, when reinforcing the same textile reinforcement amount, the area of fiber that was unbonded from concrete was reduced, thereby securing a flexural performance close to the design value.
The adoption of the textile reinforcement hook for textiles significantly improved the flexural performance and was proven to be effective at controlling the deflection of the beams despite the low rigidity of the used textile.

In most of the TRC specimens in this study, ductility similar to that of the RC specimen was found; therefore TRC can be expected to have a sufficient ductility for beam stability. The load comparison at the same maximum allowable deflection for the TRC usability verification proved that TRC was disadvantageous compared to RC. Regarding the textile reinforcement hook, the TRC specimens showed better performance than the RC specimen. The experiment in this study, however, considered the flexural performance of the flexural members of steel-textile-reinforced concrete in special cases; therefore further research is needed to generalize the experimental results.

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