

# Flexural performance of hybrid deck structures constructed using glass textile-reinforced concrete permanent formworks and reinforced concrete

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## Abstract:

The integration of textile-reinforced concrete (TRC) and reinforced concrete (RC) has recently emerged as a promising strategy for developing hybrid structures. This study investigates the flexural behaviour of a hybrid deck structure comprising a TRC-permanent formwork and RC components. The customisable cross-section of the TRC formwork allows adaptation to specific requirements, and the composite material can be tailored for high load-bearing capacity. The flexural behaviour of TRC-RC hybrid decks was investigated on four specimens through a 4-point bending test on this specific hybrid deck type. The test results highlight the adaptability of the TRC permanent formwork with its customisable cross-section and substantial load-bearing capacity, which is particularly suitable for bridge deck composite structures. The formwork cracking load surpasses the required strength during construction. Additionally, the TRC formwork improves the load-carrying capacity, stiffness, and ductility, acting as a beneficial shear connector between the concrete layers. The hybrid deck specimens displayed minimal fine cracks, indicating enhanced crack resistance, improved serviceability, and reduced crack occurrence. The TRC formwork successfully averted transverse cracks at the interface, ensuring enhanced interfacial bond strength and structural integrity.

**Keywords:** Flexure; Hybrid deck; Textile-reinforced concrete; AR-glass; Permanent formwork.

## 1. Introduction

The growing use of precast concrete formwork panels in construction has led to a quest for innovative materials with increased efficiency, sustainability, and cost-effectiveness. While traditional concrete structures benefit from cost-saving precast panels, challenges such as cracking and durability persist, especially in demanding environments. Despite attempts to use fiber-reinforced polymers (FRP) in permanent formworks, challenges such as high initial costs, low modulus of elasticity, and limited ductility persist [1]. Researchers have explored cost-effective FRP-concrete hybrid sections to overcome these issues to enhance structural efficiency and economic viability. Textile-reinforced concrete (TRC) has emerged as a promising solution that combines the

properties of concrete with the high tensile strength of textiles [2]. TRC addresses FRP drawbacks by providing ease of handling, resilience to heavy loads, and flexibility in complex structures. TRC-permanent formworks reduce time and cost, and their resistance to cracking and durability makes them a compelling choice for bridge projects [3]. Although TRC proves promising, comprehensive databases are required to address the challenges in developing these hybrid sections. Current research on stay-in-place (SIP) formworks covers several varieties, including prestressed RC formworks, thin-walled steel sheet formworks, FRP formworks, and ultra-high-performance concrete (UHPC) formworks [3]. Although much research has focused on the mechanical aspects of TRC,

limited attention has been paid to its role as a permanent formwork. Recent experiments on TRC permanent formwork composite slabs [4-5], beams [10-11], and columns [9] have shown their effectiveness in enhancing the bending, durability, and load-bearing capacity of RC structures. Brameshuber et al. [4] pioneered studies on hybrid slab structures using a TRC-permanent formwork, demonstrating significant weight reduction with a flexible cross-section for tailored applications. Papantoniou et al. [5-7] conducted a series of studies proposing optimal design methodologies for cost-effective applications of TRC-permanent formworks in structural elements, thereby reducing production costs. Kim et al. [8] explored TRC panels as SIP formwork and protective layers for RC elements, showing a substantial increase in flexural capacity and durability. Verbruggen et al. [9] focused on composite girder structures with TRC-permanent formwork, improving concrete beam load-bearing capacity and cracking moment as an alternative to traditional steel stirrup reinforcement. Yin's study [11] showcased U-shaped TRC permanent formwork, enhancing reinforced concrete members' performance. Li et al. [12] developed a formula for the ultimate bearing capacity of TRC permanent formwork composite columns, demonstrating superior mechanical properties to plain concrete columns. Kim's innovative SIP formwork design using TRC anticipated enhanced seismic performance and reduced disaster damage [9]. These studies demonstrate the versatility and efficacy of TRC in improving various aspects of structural performance.

No research has been published on the use of TRC-permanent formworks in bridge deck structures. Current studies have primarily focused on employing FRP or UHPC for permanent formworks in hybrid decks. Nelson's review [1] emphasizes the need for more research on design guidelines, durability,

economics, moisture, frost, and fire concerns in FRP-SIP form systems for bridge decks. Kolísko et al. [3] explore UHPC boards as lost formwork, highlighting the lighter UHPC board as optimal. This study also notes the economic benefits of the natural bond between precast form panels and cast-in-place decks, especially in hybrid decks.

Existing TRC research has mainly focused on civil buildings, overlooking their potential use in bridges. With higher load requirements, bridges demand dedicated exploration of TRC's suitability of TRCs. Urgent experimental tests are required to evaluate hybrid deck slab structures for bridges incorporating TRC-permanent formworks and reinforced concrete. Ensuring that the formwork can withstand construction loads is crucial for resilient and durable bridges. This research gap presents an opportunity to enhance the understanding of TRC performance in bridges, thereby contributing to sustainable building practices. Despite its commendable performance, TRC's full potential of TRC requires further substantiation, especially in addressing the disadvantages of conventional reinforced concrete deck slabs. This study explores the flexural behavior of TRC-RC hybrid decks employing four full-scale specimens using 4-point bending tests tailored to this specific deck type.

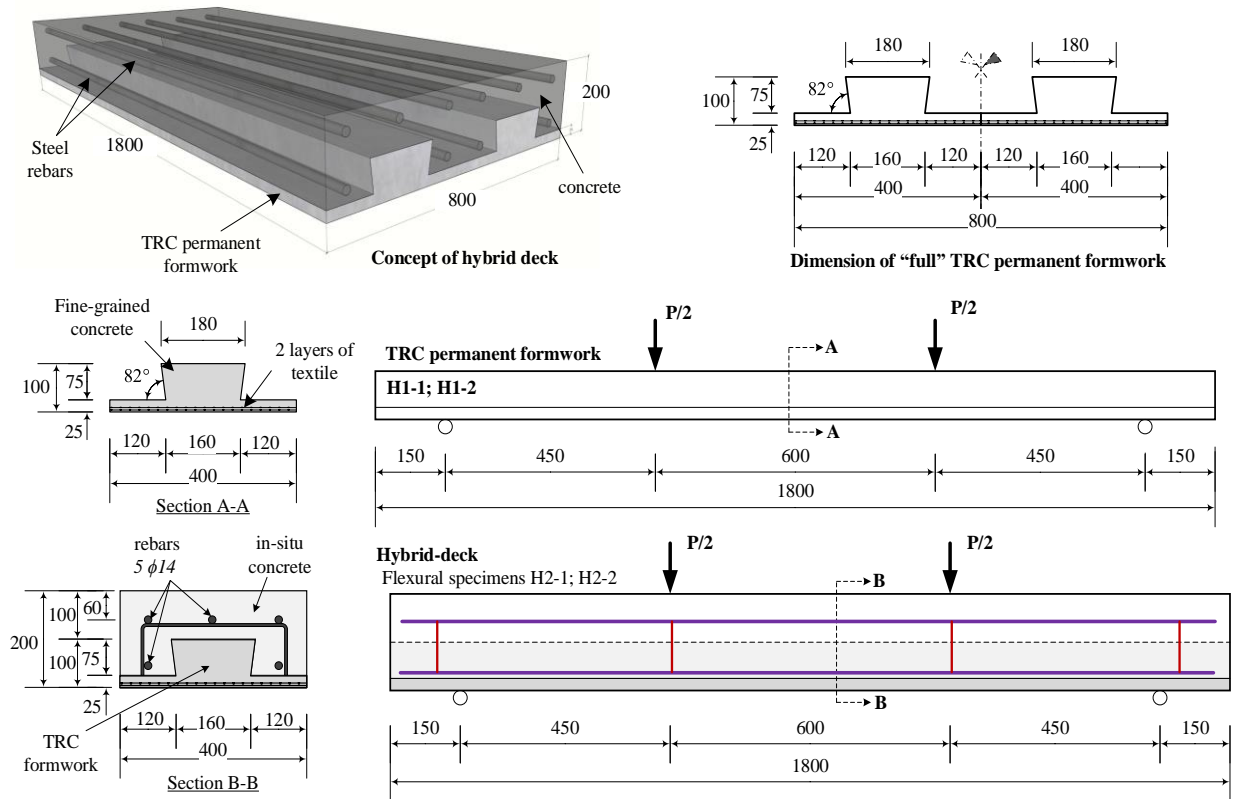
## **2. Experimental program**

### **2.1. Specimens description**

A 1.5 m span width is practical for permanent formworks in bridge deck applications. A pre-calculation determines the required cross-section. The design of TRC formwork components follows two states: construction and service. During construction, considerations include potential loading conditions, focusing on uniform loads, and other cases to prevent cracking. The design priorities include limiting the crack width, ensuring a high load capacity with minimal deflection, maintaining a low cross-sectional

height for easy reinforcement placement, securing a fire-resistant connection with the concrete surface, and achieving a lightweight design for manual handling. The service state examines the

hybrid deck, featuring a specific cross-sectional configuration that addresses the construction and service stages, as illustrated in Figure 1.



**Figure 1.** Details of the test specimens.

The first series includes two permanent formworks, H1-1 and H1-2, with a span of 1.5 m to assess flexural behavior. The second series involved hybrid deck specimens H2-1 and H2-2 with cross-sectional dimensions of 400 mm width, 200 mm height, and 1800 mm length. These specimens underwent a 4-point bending test to evaluate the effectiveness of the TRC formwork in reducing concrete cracks under bending conditions. The hybrid specimen comprised three D14 bars in the upper section and two D14 bars in the lower section without additional shear reinforcement in the beams.

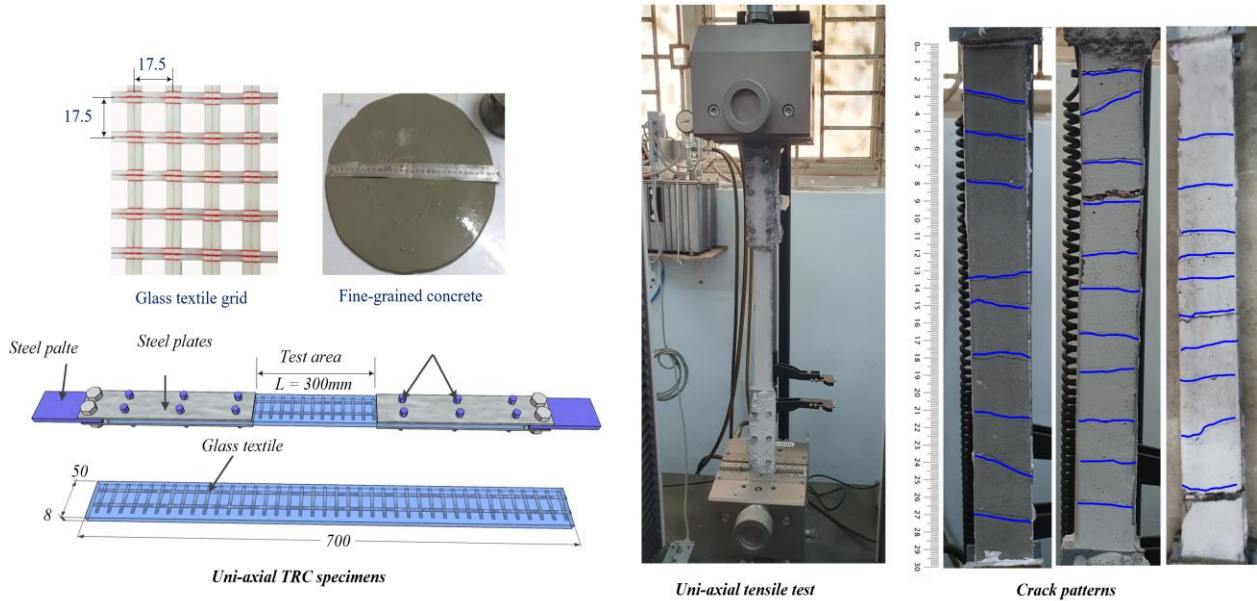
## 2.2. Materials specification

The formwork component utilized an alkali-resistant glass textile reinforcement formed by combining glass filaments into rovings to create the textile structure. The textile grid had a consistent spacing of approximately 17.5 mm,

a surface weight of 647 g/m<sup>2</sup>, and an equal 50-50% weight distribution in both directions. The textile had a fineness of 2400 tex with styrene-butadiene rubber (SBR) impregnation. The cross-sectional area of the fiber grid in each direction was 105.67 mm<sup>2</sup>/m. The rovings exhibited a tensile strength of 1580 MPa and an elastic modulus of approximately 107 GPa. Textile reinforcement characteristics require specific adjustments to the concrete mix. The maximum grain size was tailored to align the textile openings and ensure concrete penetration through the fabric mesh. High flowability was essential for the desired workability, leading to fine-grained concrete with a maximum grain size of 0.6 mm. A blend of high-quality Portland cement and fly ash was used as the binder. Concrete prisms (40 × 40 × 160 mm) were employed to determine the bending tensile and uniaxial compressive

strengths, resulting in 64.2 MPa compressive strength and 6.8 MPa flexural tensile strength. Hybrid specimens used in-situ concrete with an

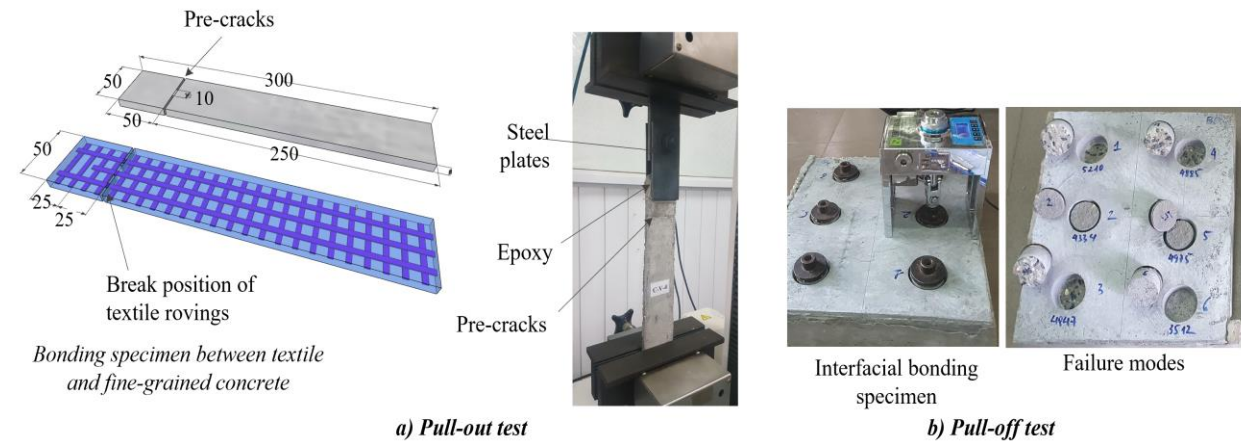
average compressive strength of 42.5 MPa at 28 days, reinforced with 14 mm diameter bars having a yield strength of 435 MPa.



**Figure 2.** Uniaxial tensile test for the TRC plate.

A uniaxial tensile test validated the mechanical performance of textile-reinforced concrete (textile roving embedded in fine-grained concrete) [14]. Figure 2 illustrates the test configuration and specimen geometry. The measured tensile strength of the rovings was

1460 MPa, slightly lower than that of the bare roving. Figure 2 also shows cracked patterns with a distance of approximately 25–40 mm, indicating excellent bonding properties between glass textiles and fine-grained concrete.



**Figure 3.** (a) Pull-out test and (b) pull-off test.

The bond between the glass textile grid and fine-grained concrete was assessed using a single-sided pull-out test [15]. Specimens with dimensions of 300 mm × 50 mm × 8 mm consisting of a single textile layer were used (Figure 3-a). Before testing, the samples were symmetrically notched from both sides, and only the centrally positioned yarn was

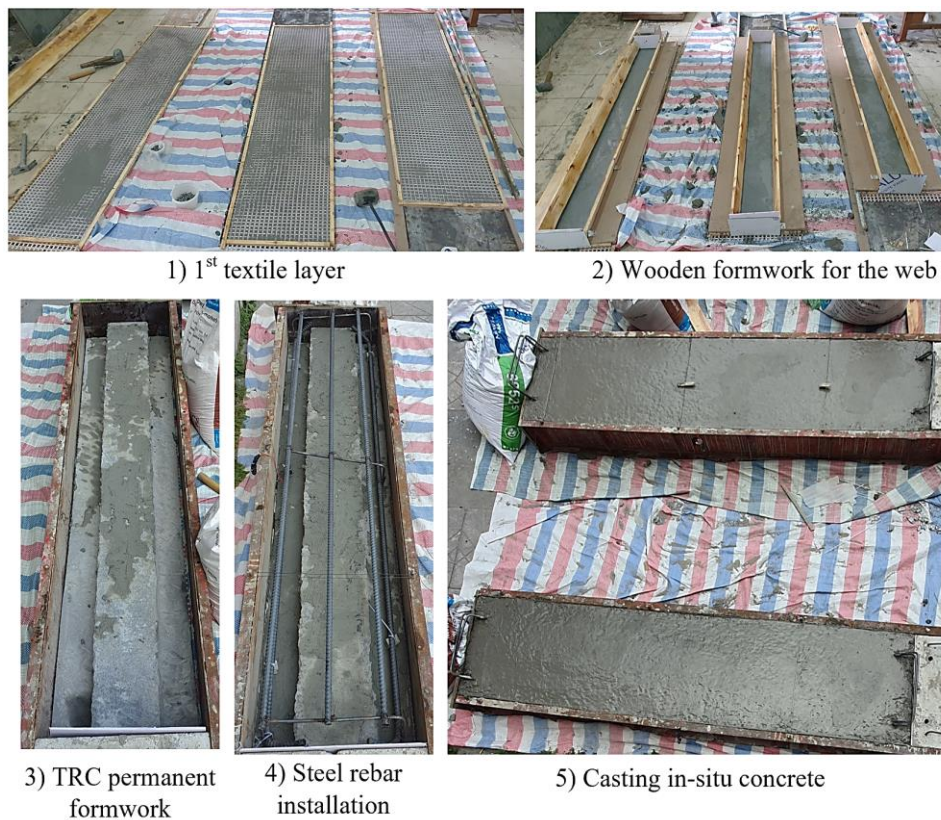
subjected to pull-out. The experimental results indicate a robust bond, with an average bonding strength of 23.2 N/mm and an anchor length of approximately 110 mm. The study utilized a pull-off test, following AC434 guidelines [13], to investigate the interfacial behaviour by applying a fine-grained concrete layer onto the substrate. These tests assess the chemical and

mechanical damage and identify the weakest layer through the position of the fracture surface. A circular cut 50 mm in diameter was made on the fine-grained concrete layer and into the substrate. A steel plate was attached to the fine-grained concrete surface for the pull-off tests (Figure 3-b). Two types of failures were identified: cohesive and adhesive. The predominant mode was cohesive failure within the concrete substrate, with some specimens displaying adhesive loss at the interfaces. Based on the maximum load, the average pull-off strength was approximately 2.45 MPa.

### 2.3. Fabrication of Specimens

During the TRC formwork procedure, fine-grained concrete was initially poured into the formwork to a thickness of 5 mm. The textile was cut to the required dimensions and affixed to a mold with a specific tension, and the process was iteratively continued to achieve a meticulously smoothed surface. Additional

layers of fine-grained concrete (5 mm each) were successively applied with layers of textiles until the desired flange thickness of 25 mm was reached (Figure 4). After completing the slab concreting, the web formwork was positioned and securely fastened on the panel formwork. Fine-grained concrete was poured into a wooden mold for the web, and a handheld vibrator was used for thorough compaction. After casting, the film was applied for maintenance for an additional 28 days. After casting the TRC formwork, a steel wire brush was used to sweep the interface bristles and remove dust. A reinforcement cage was inserted into the TRC formwork. Unlike conventional methods, no concrete cushion block was used; instead, the TRC formwork covered the hybrid specimens. Simultaneous casting and vibration of the in-place concrete occur during the pouring process. The cast specimens were covered with a film and cured for 28 days to ensure structural integrity.



**Figure 4.** Fabrication of TRC-formwork and hybrid specimens.

## 2.4. Mechanical tests



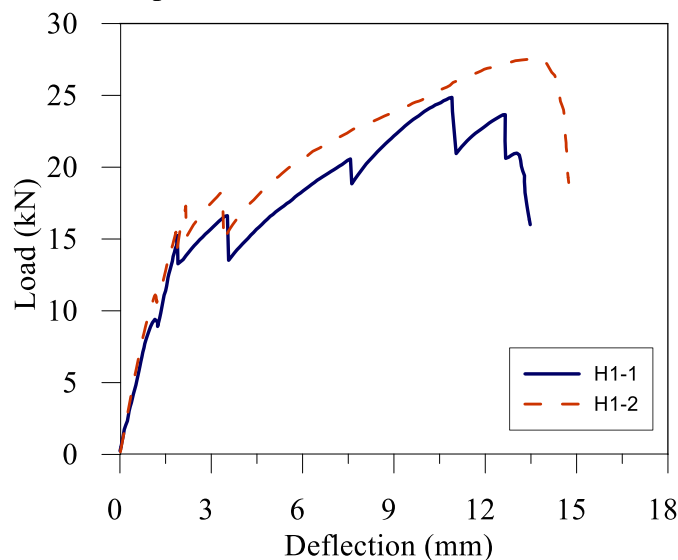
**Figure 5.** Test setup.

All specimens were tested at the University of Transport and Communications structural laboratory. The formwork specimens (H1-1 and H1-2) and flexural hybrid samples (H2-1 and H2-2) were initially subjected to a four-point bending test. These specimens were designed as simply supported beams with a 1500 mm span. A 3000-kN hydraulic actuator applied a line load to the steel frame, with deflections measured at the specimen center and loads recorded by a load cell on the actuator head. Strain gauges were installed to measure the longitudinal rebar and concrete strains on the top and bottom surfaces. 5kN preloading eliminated any gaps between the specimens and

the support before loading. The beam testing arrangement, including the strain gauge locations, is shown in Figure 5.

## 3. Results and discussion

Figure 6 shows the load-deflection relationship for TRC formworks H1-1 and H1-2, while Figure 8 illustrates the corresponding cracking patterns in these panels. To comprehensively understand the flexural properties of the TRC formwork, it was categorized into four stages: Stage I (pre-cracking), Stage II (formation of cracks), Stage III (stabilization of cracks), and Stage IV (failure).



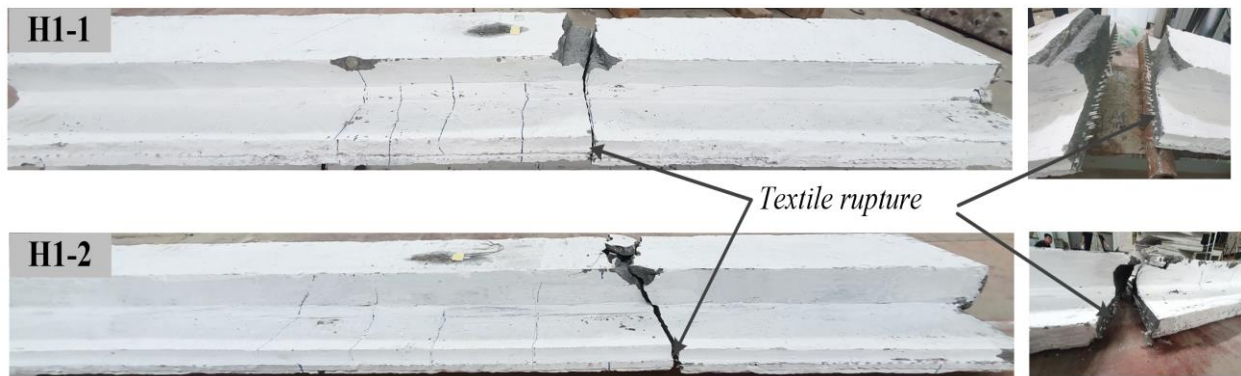
**Figure 6.** Load-deflection relationship of TRC formwork.

In Stage I, the initial elastic pre-cracking state, the behavior is primarily determined by the stiffness of the fine-grained concrete. The first flexural cracks emerged at approximately 17

kN, and the brittle load redistribution to the textile reinforcement caused sudden unloading. The cracking load slightly surpasses the required construction strength, considering the

self-weights of the TRC elements, steel reinforcement, freshly poured concrete, and additional considerations for impact and highly concentrated loads. In Stage II, vertical cracks were likely to appear in the pure tensile zone, which was attributed to the principal tensile stress before cracking. Once the bending crack initiates and expands, the tensile force exerted by the concrete is transferred to the textile reinforcement. Consequently, this phenomenon leads to several drops in the load-deflection curve. Subsequently, the stress on the textile reinforcements increased rapidly, whereas the

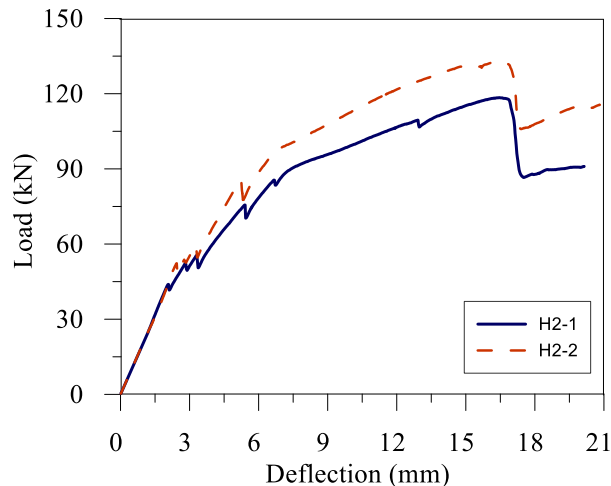
applied force continued to increase. Stage III exhibited multiple cracks with noticeable load jumps, reaching a stabilization point owing to tension stiffening from the textile reinforcement properties. The ultimate loads for H1-1 and H1-2 in Stage III were 24.8 kN and 27.8 kN, respectively, attributed to tensile rupture of textile reinforcement in both layers (Figure 7). The compressive strains at the top edge varied between approximately 2.8 and 3.4 ‰ at the point of failure, slightly below the ultimate strain of fine-grained concrete.



**Figure 7.** Failure modes of TRC formwork specimens H1-1 and H1-2.

Figure 8 shows the load-deflection relationship for flexural specimens H2-1 and H2-2, while Figure 9 displays the ultimate states of these hybrid-deck specimens, revealing concrete cracking and structural deformation. As the load increased, numerous flexural cracks emerged around the pure bending region,

deepening and reaching more than 90% of the deck height. At the maximum load, a typical flexural failure occurred, characterized by the rupture of the glass textile reinforcement in the TRC formwork and the yielding of the bottom-layer steel reinforcement.



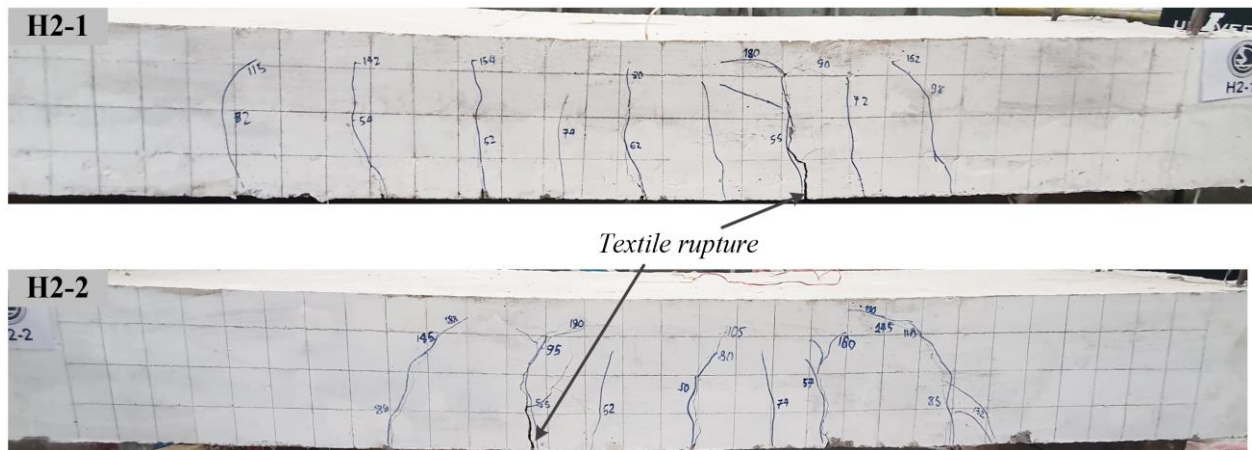
**Figure 8.** Load-deflection relationship of TRC-RC hybrid deck specimens H2-1 and H2-2.

The initial flexural cracking load, approximately 52 kN, was determined by

observing alterations in the slope of the load-strain curves and verified through visual

examination. Notably, the load recorded by the strain gauges was lower than the visually observed cracking load. The initial cracks were localized within the pure bending zone of the hybrid specimens. Upon scrutiny, the TRC-RC hybrid deck exhibited fewer and smaller cracks in the pure bending section with larger spacing, indicating irregular finer cracks extending slower to the upper section of the beam. The TRC formwork is effective in two ways: strengthening the components to delay crack initiation and slowing crack growth. A few inclined cracks that were relatively narrow appeared at the shear span during the final phase. Both flexural specimens exhibited similar behaviour, divided into three main stages. In the initial stages, before flexural cracking occurred, a linear load–deflection pattern was observed until the concrete cracked.

After cracking, there was a slight decrease in stiffness; however, the inclusion of the TRC formwork and textile reinforcement significantly reduced the stiffness loss compared with conventional RC decks. The yielding loads for H2-1 and H2-2 were approximately 79 kN, as estimated from the load–strain relationship in Figure 10. Following the yielding of the reinforcing bars, a significant increase in the tension force was transferred to the glass textiles. The post-yielding segment of the load–deflection diagram extended until the loss of strengthening action due to textile rupture. After the rupture of the textile, the load–displacement curve for the hybrid specimens decreased, aligning closely with that of the control beams. The load stabilized at approximately 87 kN after descending from the peak value of 120.4 kN.



**Figure 9.** Crack patterns of the flexural hybrid specimens.

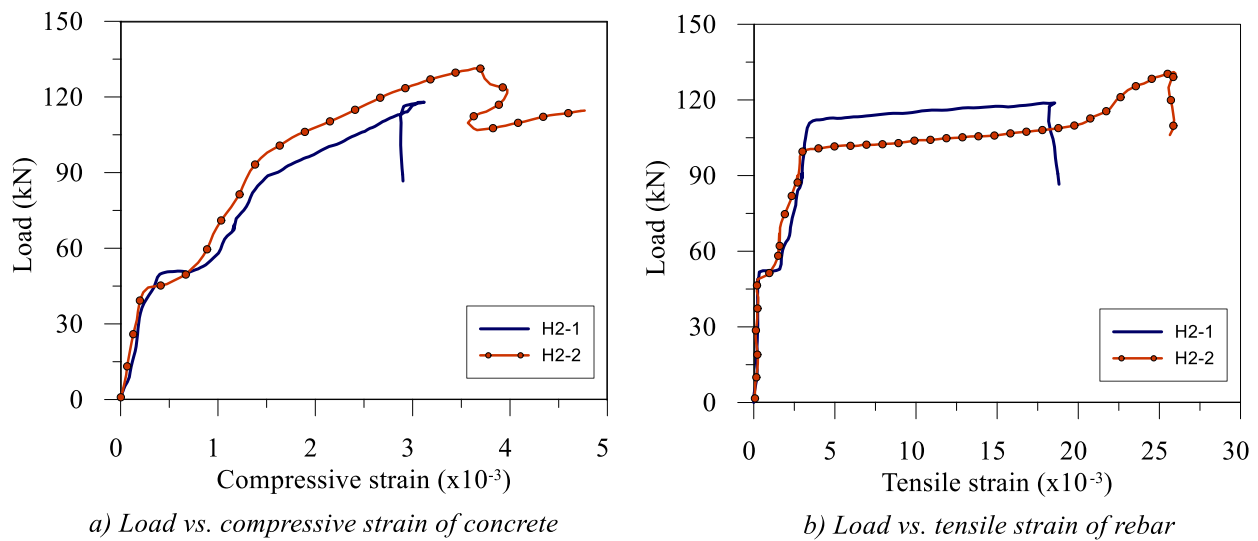
Notably, there was no evidence of slip between the TRC formwork and the concrete at either end of the deck. Figure 10 highlights the absence of longitudinal and transverse fractures at the interface between the TRC formwork and post-cast concrete. In the absence of horizontal cracks at the interface, shear stress emerged, was directly linked to the midspan bending moment, and was influenced by the elastic modulus ratio between the precast formwork and post-cast concrete. The TRC formwork effectively prevented potential transverse cracks and separation by ensuring a larger contact area with the post-cast concrete,

resulting in a significantly greater interfacial bond strength. Consequently, the shear stress on the interface remained below the interfacial bond strength, thereby ensuring the structural integrity of the composite system. This also underscored the impact of the inclined rib design, intended to enhance the interlocking connection between the permanent formwork and in situ concrete.

In the failure stage, the tensile strain of the steel reinforcement ranges from 18 to 26% (Figure 10), significantly surpassing the yield limit and satisfying the plastic failure criteria

compared to conventional RC structures. Concurrently, the concrete in the compression

zone stretched by approximately 3–4.3‰, approaching its ultimate compressive strain.



**Figure 10.** Load-deflection relationships of TRC-RC hybrid deck flexural specimens.

#### 4. Conclusion

This study investigated the flexural behaviour of TRC-RC hybrid decks through dedicated 4-point bending tests on a specific hybrid deck type. The analysis included four specimens in two series, showcasing the customizable cross-section of the TRC permanent formwork for specific applications with a substantial load-bearing capacity. The cracking load of the proposed formwork slightly exceeded the required construction strength, and the inclined rib design enhanced the interlocking connection. The TRC formwork improves the load-carrying capacity, stiffness, and ductility, thereby acting as a beneficial shear connector. Hybrid deck specimens exhibited minimal, fine cracks, indicating enhanced crack resistance, increased serviceability, and reduced crack occurrence. Properly designed and constructed permanent TRC formworks can potentially improve the flexural capacity and durability of RC structures.

#### Acknowledgments

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