ORIGINAL ARTICLE

Latin American Journal of Solids and Structures
www.lajss.org

Flexural and Shear Behavior of Hybrid Deck Structures Composed of Textile Reinforced Concrete Integrated Formwork and Reinforced Concrete

Huy-Cuong Nguyen[a], **Thi-Thanh-Thuy Pham**[a]*

[a] University of Transport and Communications, No.3 Cau Giay street, Hanoi, Vietnam. Email: nguyenhuycuong@utc.edu.vn, thuyptt1@utc.edu.vn

* Corresponding author

https://doi.org/10.1590/1679-78257980

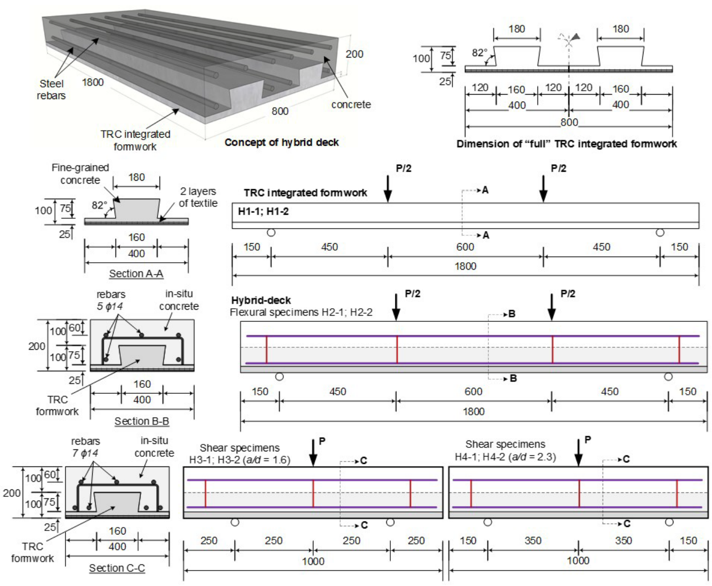
Abstract

The integration of textile-reinforced concrete (TRC) and reinforced concrete (RC) has recently emerged as a promising strategy for developing hybrid structures. This study examines the flexural and shear behavior of a hybrid deck combining TRC-integrated formwork and RC through 3-point and 4-point bending tests on eight specimens with aspect ratios (a/d) ranging from 1.6 to 2.9. The test results show that the TRC integrated formwork, with its customizable cross-section and strong load-bearing capacity, is ideal for bridge deck structures. Its cracking load exceeds the required construction strength. Furthermore, the TRC formwork enhances load-carrying capacity, stiffness, and ductility, serving as an effective shear connector between concrete layers. The hybrid deck specimens display minimal, fine cracks, indicating enhanced crack resistance, improved serviceability, and reduced crack occurrence. Shear compressive and diagonal shear failures were noted in specimens, but the TRC formwork successfully averted transverse cracks at the interface, ensuring enhanced interfacial bond strength and structural integrity.

Keywords

flexure, shear, hybrid-deck; textile reinforced concrete, integrated formwork.

Graphical Abstract



Received: January 03, 2024. In revised form: May 03, 2024. Accepted: May 24, 2024. Available online: May 24, 2024.
https://doi.org/10.1590/1679-78257980

1 INTRODUCTION

The increasing use of precast concrete formwork panels in building construction has driven a search for innovative materials to enhance efficiency, sustainability, and cost-effectiveness. While traditional concrete structures benefit from cost-saving precast panels, they face challenges such as cracking and durability, especially in challenging environments. Nelson et al.'s (2014) examination delved into the utilization of materials such as fiber-reinforced polymers (FRP) in integrated formwork. However, the practical application has unveiled ongoing difficulties and challenges. Despite FRP's potential to mitigate steel corrosion in bridges, it has limitations, including high initial costs, low modulus of elasticity, and limited ductility. To address these issues, researchers have explored integrating FRP with concrete in hybrid sections, resulting in cost-effective FRP-concrete hybrid sections that offer structural efficiency and economic viability.

Textile-reinforced concrete (TRC) emerges as a promising solution, blending concrete's mechanical properties with the ultra-high tensile strength of textile materials. TRC builds upon the numerous benefits of FRP material while addressing and enhancing certain drawbacks. As Naaman (2016) notes, TRC's lightweight characteristics make it conducive for the effortless handling and installation of thin-wall structures. This minimizes reliance on cumbersome lifting equipment, leading to enhanced overall efficiency. Its high strength-to-weight ratio ensures resilience to heavy loads and external forces. Textile reinforcement's flexibility allows easy shaping and moulding, ideal for crafting complex thin-wall structures with intricate designs. According to Papantoniou and Papanicolaou (2008), formworks integrated with TRC are acknowledged for their ability to construct intricate shapes, providing flexibility and substantial reductions in both time and cost. Furthermore, TRC demonstrates exceptional resistance to cracking and durability (Huy and Dang 2020), essential qualities for withstanding harsh environmental conditions, positioning it as a compelling option for bridge projects. TRC proves to be a promising and adaptable solution, particularly in integrated formwork for bridge projects, effectively tackling inherent challenges and delivering manifold advantages. Nonetheless, the complexity of these hybrid sections highlights the need to establish a comprehensive database, emphasizing the challenges in their development.

Contemporary investigations into stay-in-place (SIP) formwork encompass various types, such as prestressed RC formwork, thin-walled steel sheet formwork, FRP formwork, and ultra-high-performance concrete (UHPC) formwork [3]. While extensive research has been conducted on the mechanical performance and application of textile-reinforced concrete (TRC) in reinforcement, limited attention has been given to its role as a permanent formwork. Recent research conducted by Brameshuber and Markus (2004), Papantoniou and Papanicolaou (2008, 2010), Papanicolaou and Papantoniou (2016), Kim et al. (2020), and Yin et al. (2021) has conducted experiments on TRC permanent formwork composite slabs, beams, and columns. These studies illustrate the effectiveness of TRC in improving the bending characteristics, durability, and load-bearing capacity of reinforced concrete structures.

Brameshuber and Markus (2004) pioneered studies on hybrid slab structures using TRC integrated formwork with a 10mm wall thickness, offering significant weight reduction. The cross-section flexibility allows tailored applications with high load-bearing capacity, and the elements, remaining in place during construction, eliminate the need for demolding and curing. Notably, TRC-integrated formwork elements feature a high-quality surface appearance. Papantoniou and Papanicolaou (2008, 2010) and Papanicolaou and Papantoniou (2016) conducted a series of studies investigating the use of TRC-integrated formwork in structural elements. The first study evaluated the response of beam and column-type specimens cast using TRC stay-in-place formwork. The second study proposed an optimal design methodology for cost-effective one-way reinforced concrete slabs cast on TRC stay-in-place formwork. The third study introduced an optimum design procedure for prefabricated TRC stay-in-place formwork elements, demonstrating TRC's effectiveness in reducing production costs and meeting design criteria for various applications.

In a comprehensive exploration of TRC applications, Kim et al. (2020) delved into using TRC panels as SIP formwork and protective layers for RC elements. The research demonstrated a substantial increase in flexural capacity and durability, with an ultimate load capacity of 136% greater than RC slabs without TRC panels. Moreover, the investigation highlighted the positive impact of PVA short fibres on TRC's mechanical properties, enhancing initial cracking strength and crack resistance. Verbruggen et al. (2013) focused on composite girder structures employing TRC integrated formwork, revealing that TRC formwork used as shear reinforcement improved concrete beam load-bearing capacity and cracking moment, offering a promising alternative to traditional steel stirrup reinforcement. Yin et al. (2021)examined U-shaped TRC permanent formwork, showcasing its ability to enhance the performance of reinforced concrete members by improving bonding, restraining core concrete, increasing load capacity, seismic deformation capacity, and limiting crack development. Li and Yin (2021) and Kim's et al. (2019) innovative proposal also concentrated on TRC-integrated formwork in composite column structures. Li's research 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 presented a rectangular cross-section and modularisation method, anticipating enhanced seismic performance, reduced disaster damage, and lowered social costs for post-disaster recovery. These studies underscore TRC's versatility and efficacy in improving various aspects of structural performance.

No research has been published on applying TRC-integrated formwork in bridge deck structures, with current studies primarily concentrating on using FRP or UHPC for permanent formwork in hybrid decks. Nelson's et al. (2014) review on FRP-SIP form systems for bridge decks calls for more research in design guidelines, durability, economics, moisture, frost, and fire concerns. Kolísko et al. (2017) explore UHPC boards as lost formwork, identifying the lighter UHPC board as optimal. Numerical analysis confirms compliance with limit states, emphasising construction height and weight optimisation advantages. The research also notes economic benefits in the natural bond between precast form panels and cast-in-place decks, especially in hybrid decks.

The existing body of research on TRC has predominantly focused on its application in civil buildings, leaving a substantial gap in its utilisation in bridge structures. Unlike other structures, bridges demand much higher load capacity, necessitating a dedicated exploration of TRC's potential in this domain. Experimental tests are urgently required to assess hybrid deck slab structures' flexural and shear behaviour, incorporating TRC integrated formwork and reinforced concrete for bridge construction. Ensuring that the formwork system can withstand construction loads and endure the lifespan of bridge decks is critical for creating more resilient and durable structures. This gap in research represents an opportunity to enhance our understanding of TRC's performance in bridge applications, contributing to the development of sustainable and resilient building practices amid the challenges posed by climate change. While TRC has demonstrated commendable mechanical and structural performance, its full potential remains to be substantiated, particularly in addressing the drawbacks of conventional reinforced concrete deck slabs in bridge construction. The limited duration of research on TRC formwork applications highlights the need for comprehensive studies investigating both flexural and shear performances of hybrid decks. This paper explores the flexural and shear behaviour of TRC-RC hybrid decks using 3-point and 4-point bending tests tailored to this specific deck type. Eight specimens were studied across four different series, featuring aspect ratios (*a/d*) ranging from 1.6 to 2.9.

2 EXPERIMENTAL PROGRAM

2.1 Specimens description

In bridge deck applications, integrated formworks with more extended elements are deemed more practical, leading to the selection of formwork with a span width of 1.5m. A pre-calculation was conducted to determine the necessary cross-section. The design of TRC formwork components follows a two-state categorisation: the construction stage and the service stage. During the construction stage, which occurs after formwork construction, considerations include potential loading conditions from handling, storage, transportation, and on-site assembly. The critical design load in this state is the uniform load, encompassing the self-weights of TRC elements, steel reinforcement, and freshly poured concrete. Other load cases, such as impact and highly concentrated loads, must also be considered to prevent cracking. Design considerations include limiting crack width, ensuring significant inertia and static moments for high load capacity with minimal deflection, maintaining a low cross-sectional height for easy placement of tensile steel reinforcements, securing a connection with the concrete surface to prevent detachment during a fire, and achieving a lightweight design for easy manual handling or lifting. Subsequently, the service state examines the hybrid deck, which is composed of TRC and in-situ concrete topping, resulting in a specific cross-sectional configuration illustrated in Figure 1 that comprehensively addresses both construction and service stages.

The designed integrated formwork has dimensions of 800mm in width and 1800mm in length, incorporating a 25mm thick flange and two 75mm thick ribs. The rib is angled at approximately 82 degrees, enhancing the interlocking connection between the precast formwork and the concrete component. The formwork will be reinforced by embedding two layers of textile in the flange. This chosen cross-section offers the benefit of effectively supporting high bending moments in two directions, with flanges featuring a slight negative slope to establish a strong physical bond with the site concrete. Due to the symmetry of this structure, the test specimens are only 400 mm wide, which is half the width of the designed formwork sample.

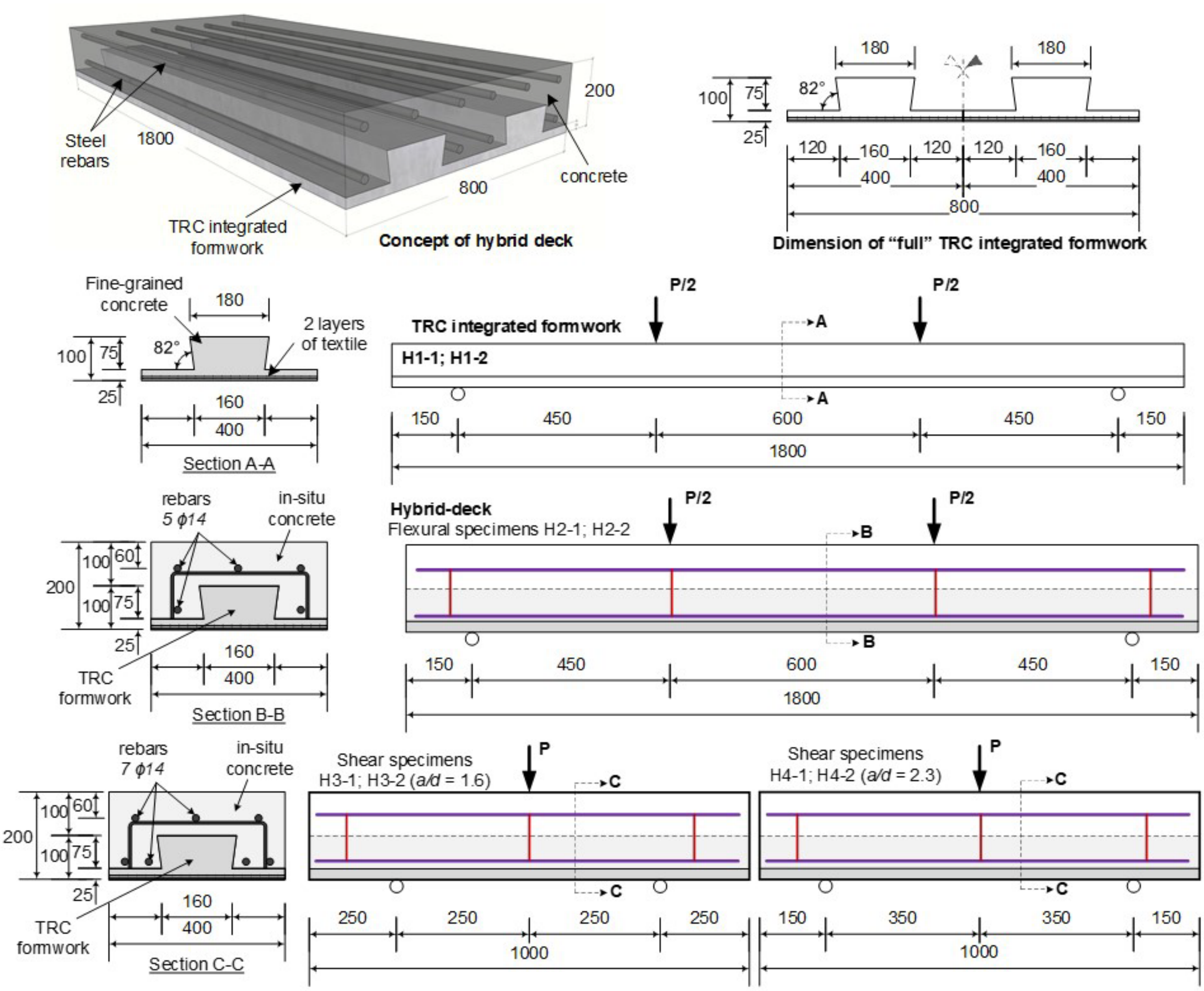


Figure 1: Details of test specimens

To investigate the load capacity of TRC-RC hybrid decks, 3-point and 4-point bending tests were conducted on this specific hybrid deck type. A total of 8 specimens were examined across four distinct series, with variations in the aspect ratio (*a/d*) ranging from 1.6 to 2.9 (for hybrid specimens). Table 1 provides an overview of the description and properties of the test specimens. For efficiency, the experimental specimens were divided into two groups based on the length of the samples. The first group (G1) included series H1 and H2, each having a length of 1800 mm. The second group (G2), comprising series H3 and H4, had a length of 1000 mm. The spans of the experimental beams were adjusted by modifying the distance between the supports for each series. A detailed illustration of the experimental setup is provided in Figure 1.

Table 1: Summary of test specimens

Group	Test mechanism	Specimens	Specimen's dimension			Number of steel rebars	Test Configuration		
			Width (mm)	Height (mm)	Length (mm)		Shear span (mm)	Pure bending zone (mm)	Aspect ratio
G1	4-point bending	H1-1, H1-2 (TRC formwork)	400	80	1800	-	450	600	6.1
		H2-1, H2-2	400	200	1800	5	450	600	2.9
G2	3-point bending	H3-1, H3-2	400	200	1000	7	250	-	1.6
		H4-1, H4-2	400	200	1000	7	350	-	2.3

In group G1, a four-point bending test will be conducted on two integrated formworks, denoted as H1-1 and H1-2, each with a clear span of 1.5 m, to assess the flexural behaviour of the precast formwork. After the formwork resistance evaluation, testing will proceed on hybrid deck specimens to scrutinise their flexural and shear behaviours. Six remaining specimens with identical cross-sectional dimensions (width: 400 mm, height: 200 mm) will be utilized. Among these, two bending specimens (H2-1 and H2-2) will have a length of 1800 mm, while the remaining four shear specimens (in group G2) will have a length of 1000 mm. To assess the effectiveness of TRC formwork in reducing concrete cracks in a bridge deck under bending conditions, the flexural specimens (H2-1 and H2-2) will undergo testing via a 4-point bending test. The research approach employed in group G2 for shear specimens was devised to induce shear failure mechanisms resembling those observed in full slabs through destructive testing. A meticulous selection of longitudinal reinforcement ratio, strength, shear slenderness, and projecting length at the supports was undertaken to prevent premature flexural or anchorage failure. As a result, specimens H3 and H4 exhibit shear lengths of 250 mm and 350 mm, respectively, corresponding to aspect ratios of 1.6 and 2.3.

The hybrid specimen contains three D14 bars in the upper section, two D14 bars (for H2 flexural specimens) and four D14 bars (for H3 and H4 shear specimens) in the lower section. No extra shear reinforcement was employed in the beams.

2.2 Materials specification

The formwork component employed glass textile for reinforcement, combining numerous alkali-resistant glass filaments into rovings to establish the textile structure. The textile grid had a well-maintained spacing of approximately 17.5 mm, a 647g/m^2 surface weight, and an even 50-50% weight distribution in both directions. The textile exhibited a fine fineness of 2400 tex and had a styrene-butadiene rubber (SBR) impregnation. The cross-sectional area of the fibre grid along its length in each direction is 105.67 mm^2/m. The rovings had a tensile strength of 1580 MPa, and the elastic modulus was determined to be approximately 107 GPa.

The characteristics of the textile reinforcement necessitated specific requirements for the concrete mix. To facilitate concrete penetration through the fabric mesh, adjustments were made to the maximum grain size to align with the openings in the textiles. Moreover, a high level of flowability was crucial to achieve the desired workability. The formwork elements were made with fine-grained concrete, featuring a maximum grain size of 0.6 mm. A blend of high-quality Portland cement and fly ash served as the binder. Concrete prisms measuring 40 x 40 x 160 mm were used to determine the bending tensile and uniaxial compressive strength. The concrete demonstrated a compressive strength of 64.2 MPa and a flexural tensile strength of 6.8 MPa. All hybrid specimens were built using in-situ concrete, exhibiting an average compressive strength of 42.5 MPa as measured by a cylinder at 28 days. Longitudinal reinforcement bars with a diameter of 14 mm and a yield strength of 435 MPa were utilized.

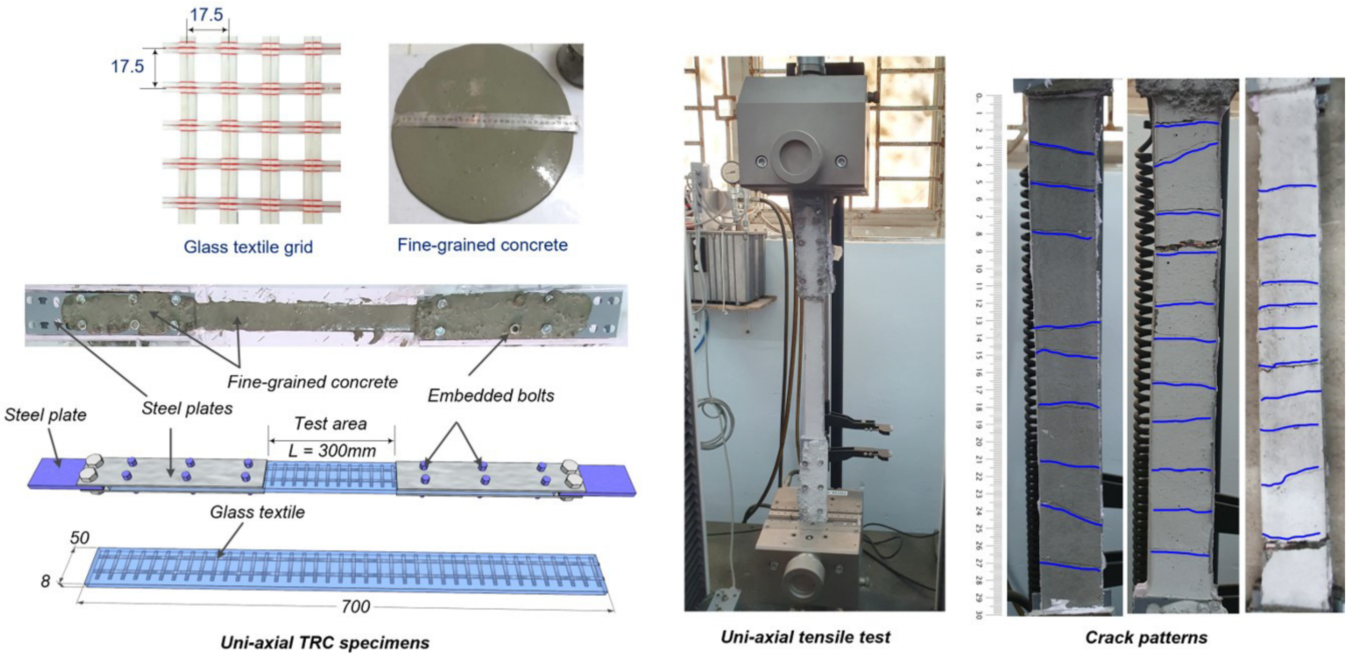


Figure 2: Uni-axial tensile test for TRC plate

The mechanical performance of textile-reinforced concrete (i.e., textile roving embedded into fine-grained concrete) was validated through a uniaxial tensile test following the Recommendation of RILEM TC 232-TDT (RILEM Technical Committee, 2016). Figure 2 illustrates the test configuration and specimen geometry. The measured tensile strength of the rovings reached 1460 MPa, slightly smaller than the tensile strength of bare roving. Additionally, Figure 2 illustrates cracked patterns featuring cracks spaced approximately 25-40 mm apart. This emphasises the effective bonding properties observed between glass textiles and fine-grained concrete.

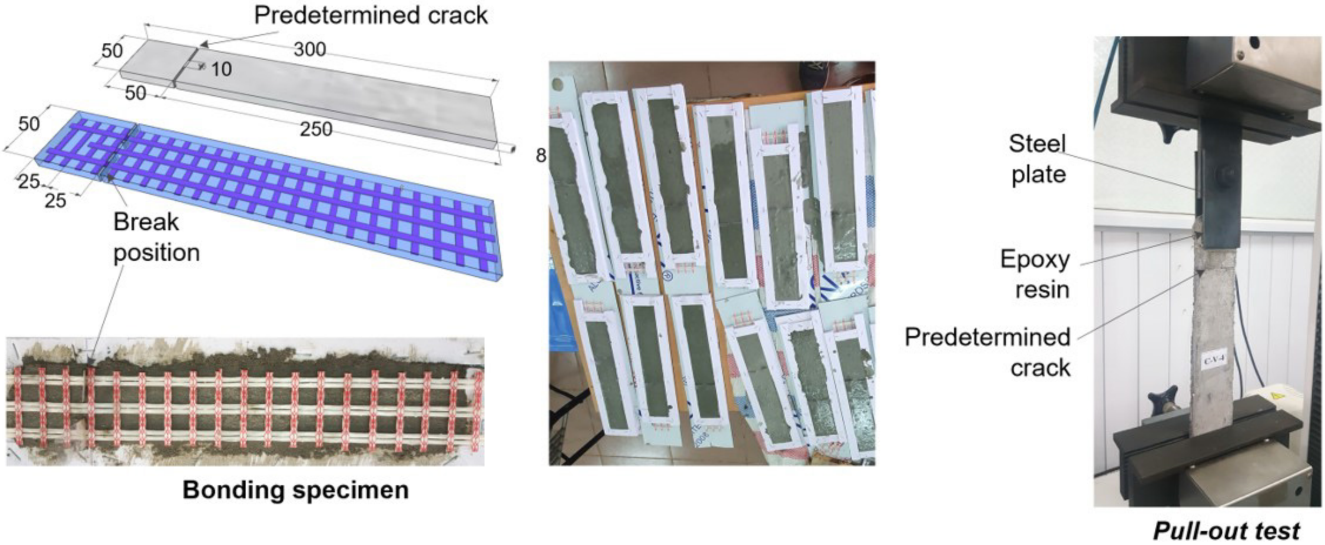


Figure 3: Pull-out test

The bond between the glass textile grid and fine-grained concrete was evaluated using the single-sided pull-out test following the German Guide Zulassung Z-31.10-182 (Zulassung, 2015). The specimens with dimensions measuring 300 mm × 50 mm × 8 mm consist of only one textile layer (Figure 3). Before testing, the samples are symmetrically notched from both sides. Consequently, only the centrally positioned yarn with an embedding length of 25 mm is subjected to the pull-out. This yarn is drilled or sawed through at a distance from the notches to establish the available anchorage length. The outcome of this test provides the force that can be transmitted at this specific anchorage length. The experimental results demonstrate a sturdy bond between glass textile and fine-grained concrete, showcasing an average bonding strength of 23.2 N/mm and an anchor length of approximately 110 mm.

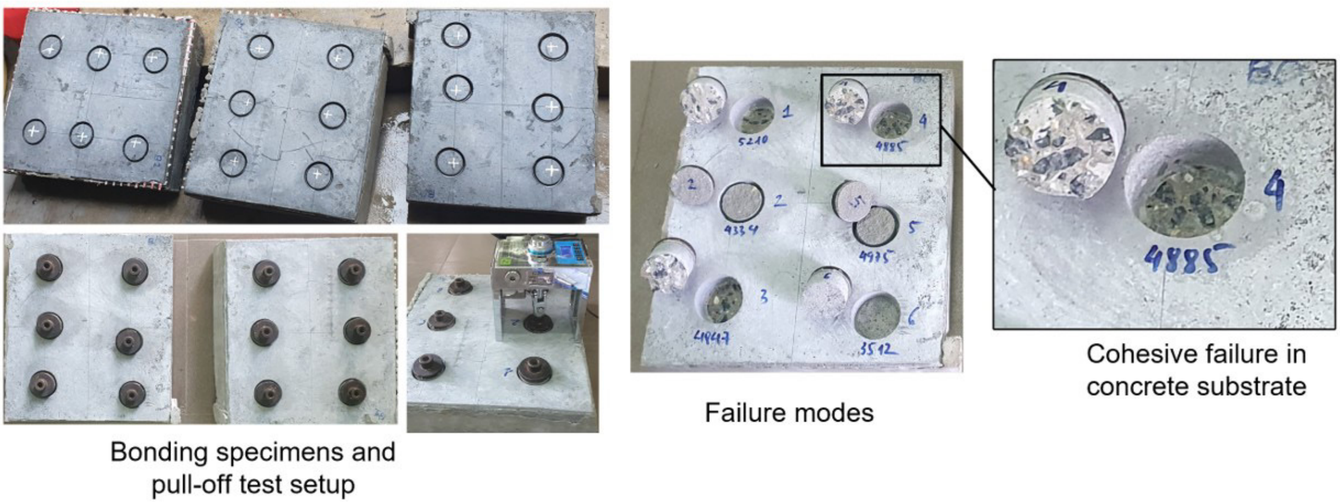


Figure 4: Pull-off test for evaluating interfacial bonding strength

The study employed a pull-off test to investigate interfacial behaviour by applying a fine-grained concrete layer onto the substrate according to AC434 guideline procedures (ACI Committee, 2016). These tests not only evaluate chemical and mechanical damage but also reveal the composite system's weakest layer by examining the fracture surface's position. A circular cut of 50 mm diameter was made on the fine-grained concrete layer and into the concrete substrate. Subsequently, a steel plate was attached to the fine-grained concrete surface, and the pull-off test was conducted (see Figure 4). The test identified two failure types: cohesive failure and adhesion failure. The predominant failure mode was cohesive, occurring when the fracture surface was within the concrete substrate. Some specimens displayed adhesive loss, where the fracture surface was within the interfaces between the concrete substrate and the fine-grained concrete layer. Based on the maximum indicated load, the average pull-off strength was computed at approximately 2.45 MPa.

2.3 Fabrication of Specimens

In the TRC formwork procedure, fine-grained concrete is initially poured into the formwork at a 5 mm thickness. The textile is then cut to the required dimensions affixed to the mould with specific tension, and the process is iteratively continued, resulting in a meticulously smoothed surface. Subsequently, an additional fine-grained concrete layer is applied with a thickness of 5 mm, and this process is repeated with successive layers of textile (Figure 5). Subsequently, the concrete is skillfully applied with a trowel until the desired flange thickness of 25 mm is achieved. Upon completing the concreting of the slab, the web formwork is positioned on the panel formwork and securely fastened. At last, the fine-grained concrete is poured into the wooden mould for the web, and a handheld vibrator is applied to achieve thorough compaction of the concrete. Following casting, a film is used for maintenance for an additional 28 days.

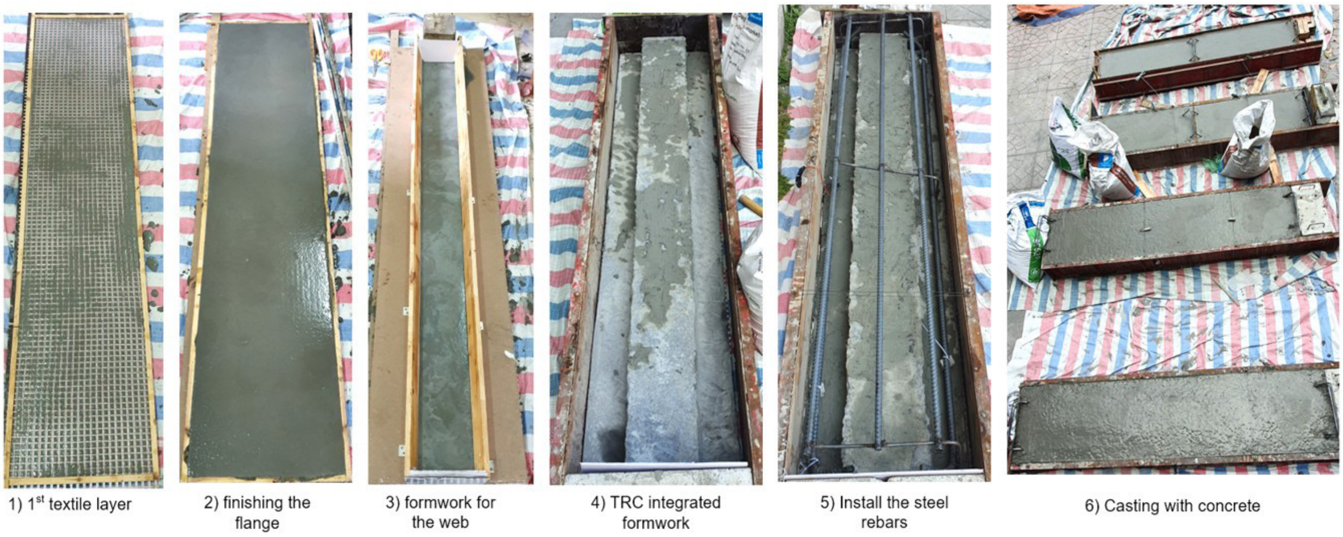


Figure 5: Fabricating the steel reinforcement cages and casting the RC column specimens.

After casting the TRC formwork, use a steel wire brush to sweep the interface bristles, removing any dust. Following this, insert the reinforcement cage into the TRC formwork. In contrast to conventional methods, no concrete cushion block is included in the TRC formwork; instead, the TRC formwork serves as the covering for the hybrid specimens. The pouring process involves simultaneous casting and vibration of the in-place concrete. The cast specimens are then covered with a film and undergo 28 days of curing to ensure structural integrity.

2.4 Mechanical tests

All specimens were subjected to testing at the structural laboratory of the University of Transport and Communications. The formwork specimens (H1-1 and H1-2) and the flexural hybrid samples (H2-1 and H2-2) underwent an initial four-point bending test. These specimens were structured as simply supported slabs with a clear span of 1500mm. To apply a line load to the steel frame, a 3000-kN hydraulic actuator was employed. The actuator transmitted the load to a steel beam, which transferred the load to the slab. Deflections were measured at the centre of the specimen, and the loads during the experiments were recorded by a load cell on the head of the hydraulic actuator. Strain gauges were installed to record the strain of the longitudinal rebars and the concrete on the top and bottom surfaces. Before the actual loading, a preloading of 5kN was performed to eliminate any gap between the specimens and the support, followed by unloading. The arrangement for the beam testing, including strain gauge locations, is presented in Figure 6. Similarly, the second set (G2) comprised the four specimens tested under three-point symmetrical loading. The centralised load was administered at a rate of 0.2 mm/min.

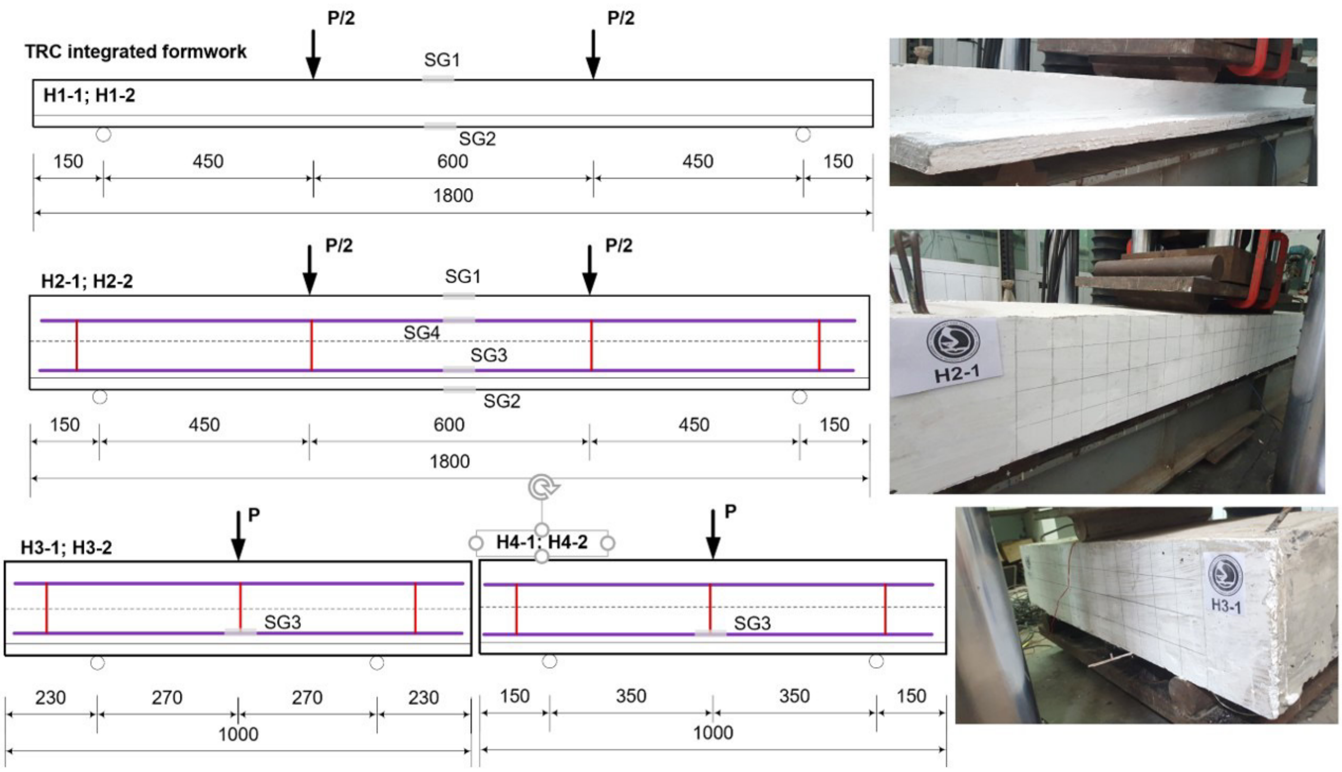


Figure 6: Test configuration

3 RESULTS AND DISCUSSION

3.1 Flexural behavior

Figure 7 illustrates the load-deflection relationship for TRC formwork H1–1 and H1–2, while Figure 8 depicts the corresponding cracking patterns observed in these panels. For a thorough comprehension of the flexural properties of TRC formwork, a conventional framework categorizes it into four stages: Stage I (pre-cracking), stage II (formation of cracks), Stage III (stabilization of cracks), and Stage IV (failure).

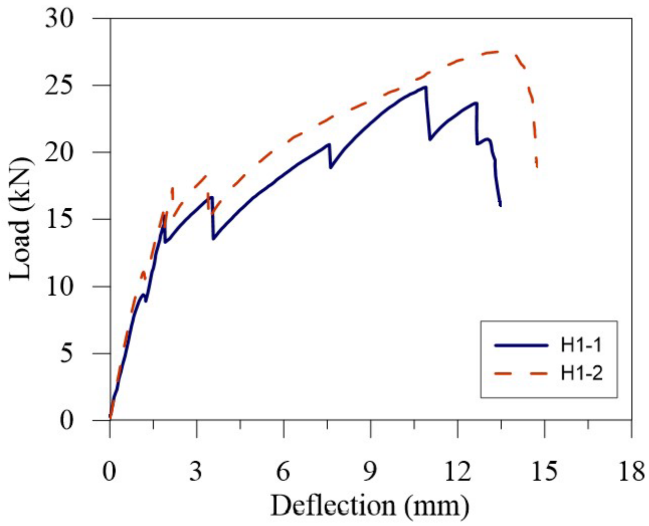


Figure 7: Load-deflection relationship of TRC formwork

In Stage I, identified as the initial elastic pre-cracking state, the stiffness of the fine-grained concrete primarily determines the behaviour. Around 17 kN, the first flexural cracks emerge, leading to abrupt unloading due to the brittle load redistribution to the textile reinforcement. The cracking load slightly surpasses the required strength during construction, calculated considering the self-weights of TRC elements, steel reinforcement, freshly poured concrete, and additional considerations for impact and highly concentrated loads. Vertical cracks in the pure bending zone of the formwork are likely at Stage II, attributed to the principal tensile stress before cracking, arising from minor shear stress and prevailing flexural stress. In Stage III, multiple cracks are evident, marked by noticeable load jumps despite minimal load increases. The ongoing formation of cracks eventually reaches a stabilization point in Stage III, demonstrating an increase in stiffness attributed to the properties of the textile reinforcement. This effect is commonly referred to as tension stiffening. Upon reaching failure in Stage III, the ultimate loads for H1–1 and H1–2 were recorded as 24.8 kN and 27.8 kN, respectively. The failure was ascribed to the tensile rupture of textile reinforcement in both layers, as depicted in Figure 8. Compressive strains at the top edge varied between approximately 2.8 to 3.4 ‰ at the point of failure, slightly below the ultimate strain of fine-grained concrete.

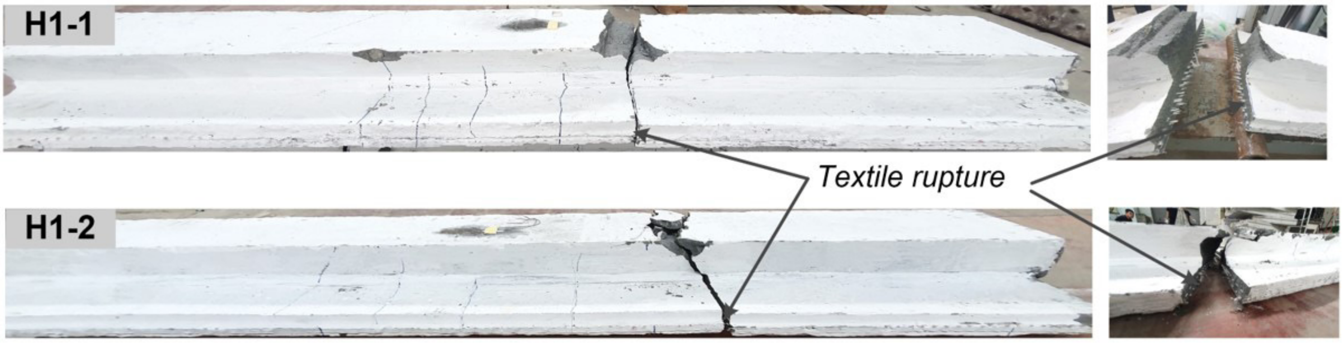


Figure 8: The failure mode of TRC formwork specimens H1-1 and H1-2

Figure 9 depicts the relationship between load and deflection for the flexural specimens H2-1 and H2-2. The ultimate states of these two hybrid-deck specimens are also displayed in Figure 10, showcasing concrete cracking and structural deformation. Numerous flexural cracks emerged around the pure bending region as the load increased. These cracks deepened, reaching over 90% of the deck height as the load approached its maximum. Ultimately, a typical flexural failure occurred, marked by the rupture of glass textile reinforcement in TRC formwork, combined with the yielding of the bottom-layer steel reinforcement.

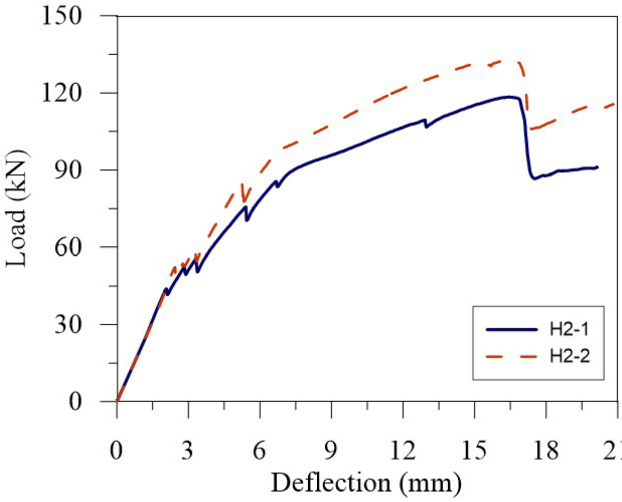


Figure 9: Load-deflection relationship of TRC-RC hybrid deck specimens H2-1 and H2-2

It should be noted that the initial flexural cracking load was determined by observing alterations in the slope of the load-strain curves and verified through visual examination. Generally, the load recorded by the strain gauges was less than the cracking load observed visually when the initial flexural crack manifested, approximately at 52 kN. All initial cracks were localized within the pure bending zone of the hybrid specimens. Upon scrutinizing the cracks during damage, the TRC-RC hybrid deck exhibited fewer cracks in the pure bending section, with smaller height and larger spacing. This suggests that the TRC integrated formwork hybrid specimens have more irregular finer cracks, displaying a slower extension to the upper section of the beam. Typically, these cracks appear straight, with inclined cracks exhibiting a narrower profile. TRC formwork works well in preventing cracks in two main ways: first, it makes components stronger, delaying the start of cracks, and second, if cracks do happen, the TRC material slows down their growth and reduces how often cracks occur in the beam. During the last phase, a few inclined cracks emerge at the shear span but are relatively narrow in width.

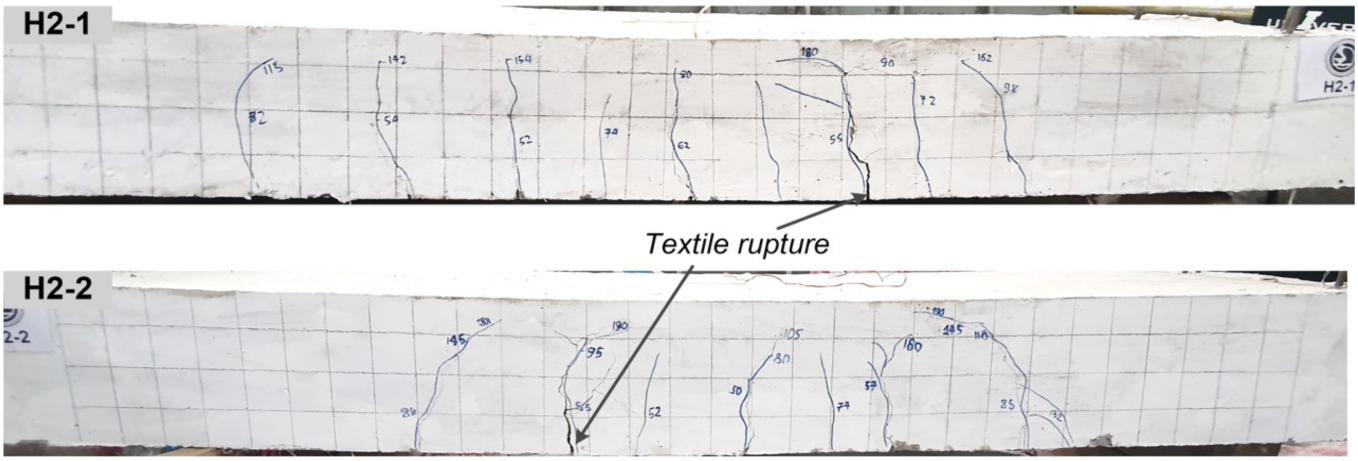


Figure 10: Crack patterns of flexural hybrid specimens

Both flexural specimens displayed similar behaviour, categorized into three main stages. In the initial stages, before flexural cracking occurred, the specimens showed a linear load–deflection pattern until concrete cracking. After cracking, there was a slight decrease in stiffness. Compared to conventional RC decks, including TRC formwork and textile reinforcement could significantly reduce the stiffness loss. The yielding loads for H2-1 and H2-2 were approximately 79 kN, estimated from the load-strain relationship in Figure 13. Following the yielding of the reinforcing bars, a significant increase in tension force was transferred to the glass textile. The post-yielding segment of the load-deflection diagram extends 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, closely aligning with that of the control beams. The load level stabilized at approximately 87 kN after descending from the peak value of 120.4 kN.

Notably, at both ends of the deck, there was no evidence of a slip between the TRC formwork and the concrete. Figure 10 highlights the absence of longitudinal and transverse cracks at the interface between the TRC formwork and post-cast concrete. In the absence of a horizontal crack at the interface, shear stress emerges, directly linked to the midspan bending moment and influenced by the elastic modulus ratio between the precast formwork and post-cast concrete. The TRC formwork effectively prevents potential transverse cracks and separation by ensuring a larger contact area with the post-cast concrete, resulting in significantly greater interfacial bond strength. Consequently, the shear stress on the interface remains below the interfacial bond strength, ensuring the structural integrity of the composite system.

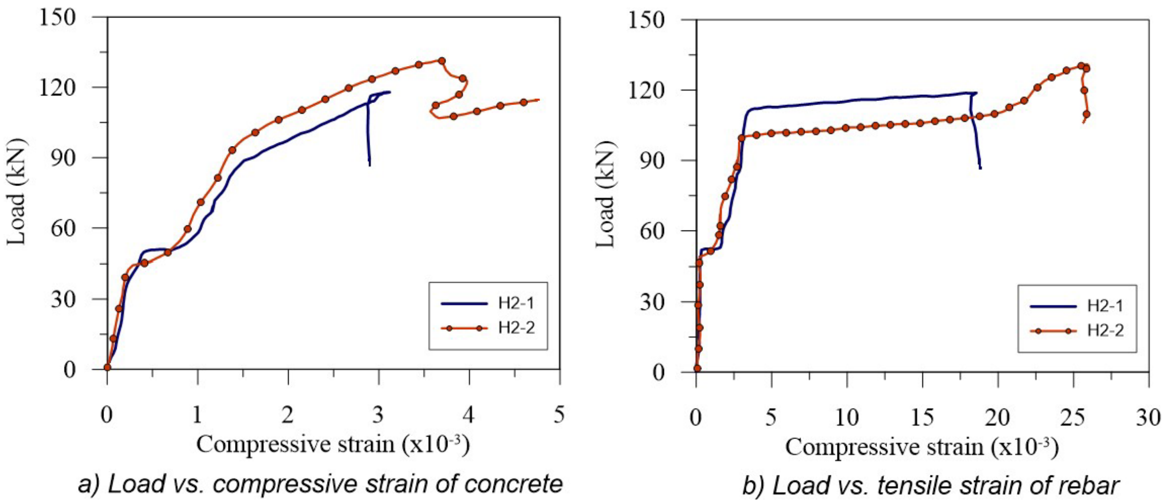


Figure 11: Load-deflection relationships of TRC-RC hybrid deck flexural specimens

Notably, there is no evidence of slip between the TRC formwork and concrete at both deck ends. Figure 10 illustrates the absence of cracks at the TRC-concrete interface. Without horizontal cracks, shear stress arises, linked to the midspan bending moment and influenced by the elastic modulus ratio. The TRC formwork prevents transverse cracks and separation by ensuring a larger contact area, resulting in stronger bond strength. This ensures that shear stress remains below the bond strength, preserving the structural integrity of the composite system. This also illustrates the impact of the inclined rib design, intended to improve the interlocking connection between the integrated formwork and the in-situ concrete.

During failure, the tensile strain of the steel reinforcement reaches a range of 18 to 26‰, surpassing the yield limit significantly and satisfying plastic failure criteria compared to conventional RC structures (Figure 11-b). Simultaneously, the concrete in the compression zone stretches by about 3 to 4.3‰, getting close to its ultimate compressive strain (Figure 11-a).

3.2 Shear behavior

This section presents the outcomes of shear tests conducted on four hybrid-deck specimens. Figure 12 plots applied loads against vertical displacements, considering aspect ratios of 1.6 and 2.3. Meanwhile, Figure 13 visualizes crack formation, and Figure 14 presents strain gauge readings from transverse and longitudinal reinforcements in hybrid decks. Notably, load-deflection curves in Figure 10 reveal a consistent failure behaviour across all specimens in group G2, characterized by shear cracks dominating over flexural cracks. Shear failure, resulting from concrete strut crushing or diagonal tension, was consistently observed in all specimens, and there were no occurrences of flexural failure.

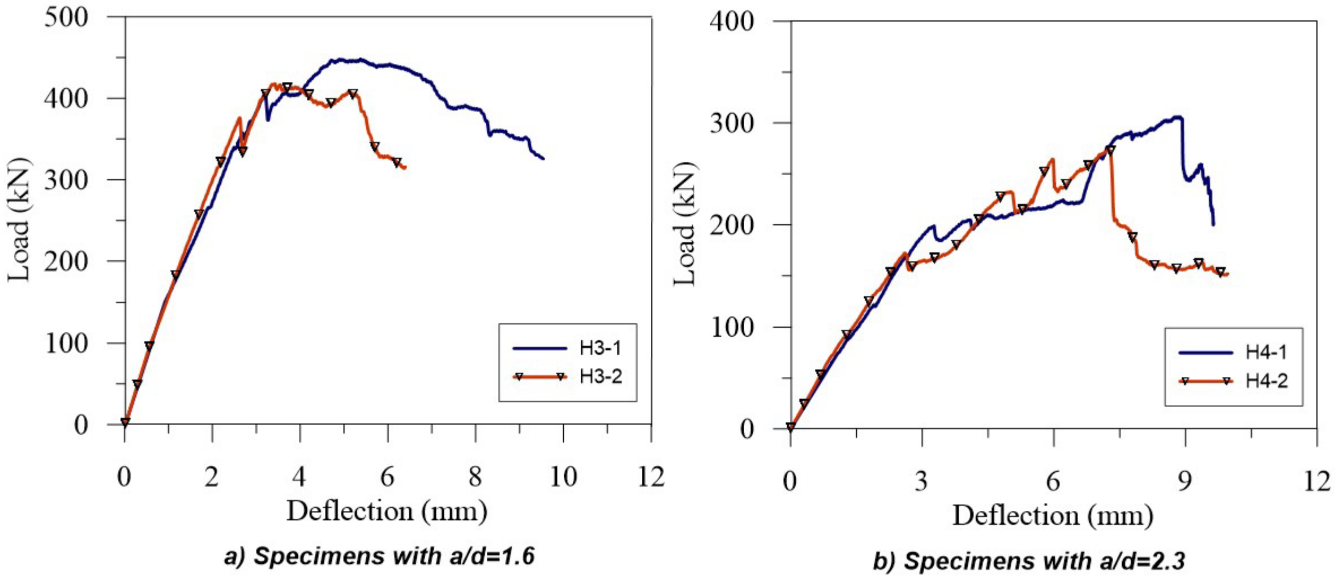


Figure 12: Load-deflection curves of specimens with different aspect ratios

Shear compressive failure was observed in beams with an aspect ratio (a/d) equal to 1.6, as depicted in Figure 13-a. The initiation of cracking begins with developing a few flexural cracks at mid-span. The progression of these cracks towards a neutral axis halts when the adhesive between the steel rebars and the adjacent concrete at the support is weakened. Additional shear cracks emerged, linking flexural cracks and facilitating the redistribution of loads. Subsequently, a sudden development of an inclined crack occurs, propagating towards the neutral axis. The failure occurs abruptly as these inclined cracks converge in the crushed concrete strut. No indications of delamination exist between the integral formwork surface and the in-situ concrete.

In Figure 12,, the load-deflection relationships for specimens H3-1 and H4-1 illustrate the shear behaviour of deep beams. They reveal a brittle failure in short-span concrete beams, characterized by nearly linear relationships up to the maximum shear forces. Both specimens exhibit identical stiffness in the linear range leading to the failure stages. The initial cracks observed in the tested beams were flexural, appearing at the centre of the beams under applied loads of 175 kN and 185 kN for specimens H3-1 and H3-2, respectively. As the applied loads increased, these flexural cracks extended towards the top sections of the beams. Shear cracks started to emerge at approximately 280 kN for both specimens, spreading extensively along the shear spans with further shear loading. At the failure stage, crushing occurred along both specimens' critical shear cracks and nodal zones at the loading points. The shear strengths recorded during the tests were 447.99 kN for specimen H3-1 and 417.79 kN for specimen H3-2.

Noticeable longitudinal cracks in the tension zone were observed on both sides of the slab segments. These cracks originated from two mechanisms. Firstly, splitting forces were generated due to the bond between concrete and steel longitudinal reinforcement. Such cracks manifested early at mid-span, where the moment is maximal and extended throughout the rest of the shear span, resulting in the loss of longitudinal reinforcement bond. Secondly, dowel cracks, initiated from flexural shear cracks, separated the concrete cover. The ultimate crack pattern alone does not suffice to distinguish between the two mechanisms, as both mechanisms interact and superimpose within the shear span.

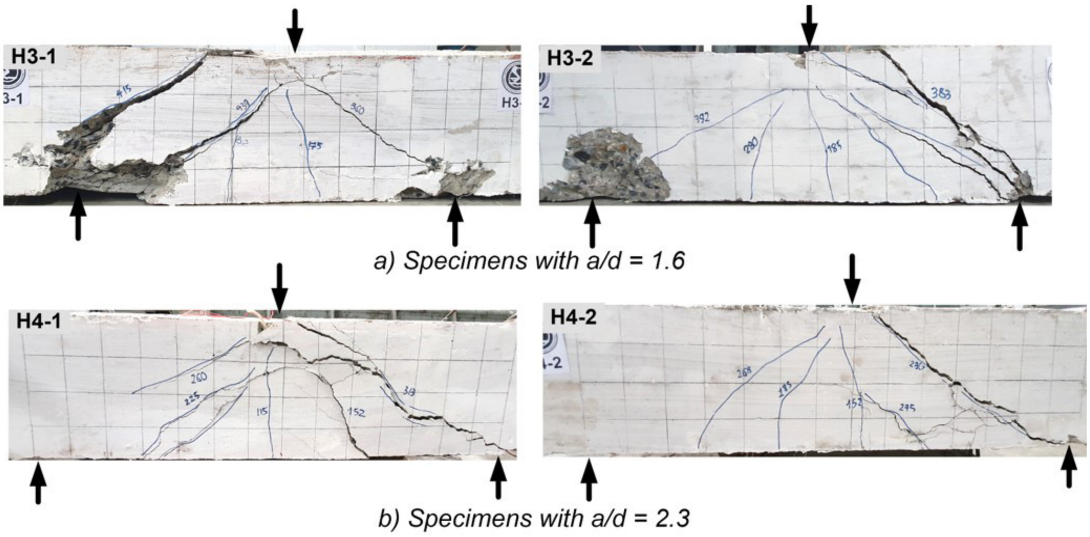


Figure 13: Shear failure of hybrid specimens

Observations from Figure 12 indicate that the displacements of tested beams H4-1 and H4-2 are 3.41 and 5.36 mm, respectively. Figure 14 displays strain gauge readings obtained from longitudinal steel bars and indicates that tensile strains at failure were smaller than the yielding strain of steel rebars. Diagonal shear failure occurred in beams H4-1 and H4-2 (longer aspect ratio), emphasizing the influence of aspect ratios on failure modes. Similar to the 1.6 aspect ratio, the initial shear crack originated from a steep flexural crack in the tensile zone, moving towards the compression zone with a curved shape and a flattening inclination. Additionally, a dowel crack formed along the tensile reinforcement. However, this primary shear crack did not immediately fail, allowing for load redistribution. This redistribution led to the development of secondary flexural shear cracks with a shallower inclination. The ultimate straight shape of the critical shear crack at the point of failure emerged from the connection of the horizontal branches of all shear cracks and the last, flatter flexural shear crack. The straight crack appeared suddenly in these tests and did not gradually develop from a flexural crack. Therefore, this failure can be identified as diagonal tension failure, distinct from flexural-shear failure or shear compression failure.

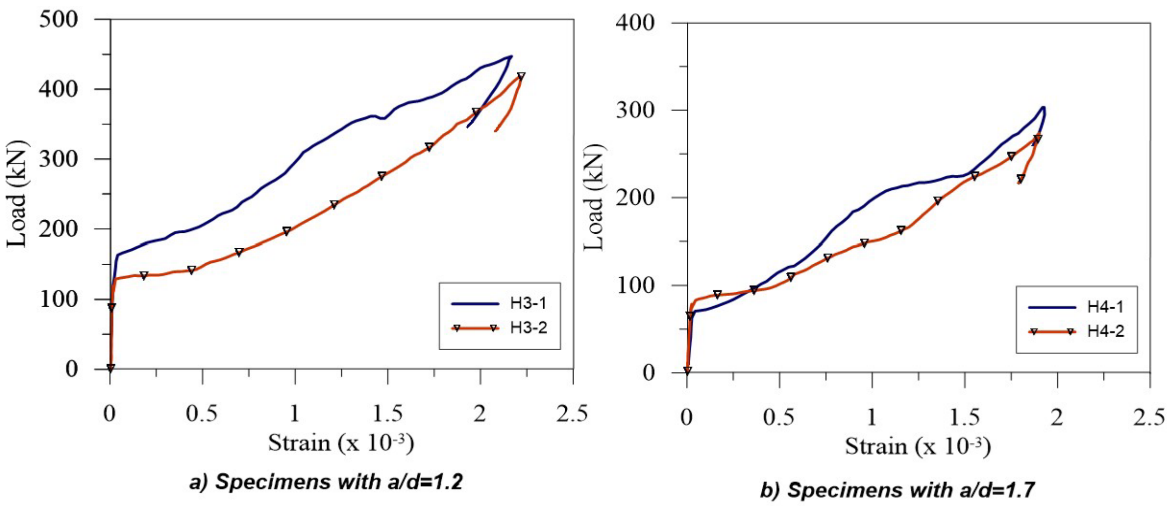


Figure 14: Load vs tensile strain in longitudinal steel reinforcement

The load-deflection relationship in specimens with an aspect ratio of 2.3 closely resembled that of specimens with an aspect ratio of 1.6. Figure 12-b illustrates nearly linear relationships in both specimens up to the first shear cracks, which were initiated at applied loads of approximately 225 kN. After this juncture, the shear force gradually rises, accompanied by the emergence of secondary or tertiary flexural shear cracks. The second shear crack emerges and ultimately results in complete failure. This pattern is evident in specimens H4-1 and H4-2, where noticeable load drops coincide with unstable shear crack propagation through the compression zone towards the supports. The appearance of a new inclined branch in the shear crack above the topmost reinforcement layer signifies the load drop shown in Figure 12-b. As a result, this crack is not directly impacted by the reinforcement's position. The vertical stresses needed to form this crack result from the combined shear loads transferred through dowel action and the interlocking of faces between TRC-integrated formwork and in-situ concrete. This crack disrupts the local stress transfer through aggregate interlock, particularly in the section below the crack.

Beams H4-1 and H4-2 exhibited lower shear strength than those without an aspect ratio of 1.6, with a maximum strength of 306.11 kN and 273.71 kN, respectively. This discrepancy may explain the lower strains in longitudinal steel bars compared to those in specimens H3-1 and H3-2 (Figure 14). Displacements for H4-1 and H4-2 were 8.87 and 7.24 mm, respectively. These displacements are significantly higher when compared to those with an aspect ratio of 1.6.

4 CONCLUSION

This study delved into the flexural and shear behaviour of TRC-RC hybrid decks utilizing 3-point and 4-point bending tests on a dedicated hybrid deck type. The investigation involved the analysis of eight specimens across four distinct series, encompassing various aspect ratios. The findings lead to the following conclusions:

The TRC integrated formwork's cross-section can be customized for specific applications, offering substantial load-bearing capacity. Its suitable size, material properties, and structure make it viable for bridge deck composite structures. The cracking load of the proposed integrated formwork slightly surpasses the required strength during construction, considering TRC elements, steel reinforcement, and freshly poured concrete, with enhanced interlocking connection due to the inclined rib design.

The TRC formwork improved load-carrying capacity, stiffness, and ductility, serving as a beneficial shear connector between concrete layers. The hybrid deck specimens exhibited minimal, fine cracks, demonstrating enhanced crack resistance, increased serviceability, and reduced crack occurrence. When properly designed and constructed, the integrated TRC formwork has the capability to improve both the flexural capacity and durability of RC structures.

The shear behaviour analysis observed shear compressive and diagonal shear failures in specimens with different aspect ratios. The TRC formwork effectively prevented transverse cracks at the interface, ensuring greater interfacial bond strength and structural integrity.

Acknowledgments

The authors extend our sincere gratitude to the technical engineers at the Structural Laboratory of the University of Transport and Communication for their support. Huy-Cuong Nguyen was funded by the Postdoctoral Scholarship Program of Vingroup Innovation Foundation (VINIF), code VINIF.2023.STS.16. This research is funded by the University of Transport and Communications (UTC) under the project code T2022-XD-012TD.

Author’s Contribuitions: Conceptualization, HC Nguyen; Methodology, TTT Pham; Investigation, TTT Pham and HC Nguyen; Writing - original draft, TTT Pham and HC Nguyen; Writing - review & editing, TTT Pham and HC Nguyen; Funding acquisition, TTT Pham.

Editor: Marco L. Bittencourt

References

ACI Committee 434, (2016) Acceptance criteria for masonry and concrete strengthening using fabric-reinforced cementitious matrix (FRCM) and steel reinforced grout (SRG) composite system, no. 800, 2017.

Brameshuber, W. & Markus, K. (2004). Textile Reinforced Concrete (TRC) For Integrated Formworks. ACI Symposium Publication, 224. doi: 10.14359/13407

Huy, C. N., & Dang, Q. N. (2020). Experimental study on flexural behavior of prestressed and non-prestressed textile reinforced concrete plates. Transport and Communications Science Journal. 71(1), p 37-45. https://doi.org/10.25073/tcsj.71.1.5.

Kim, H.-Y., Koh, K.-T., You, Y.-J., Ryu, G.-S., Seo, D.-W., Jin, S.-S., . . . Nam, J.-H. (2020). Load-deflection behaviour of concrete slab-type elements casted on stay-in-place TRC formwork. Composite Structures, 244, 112310. doi: https://doi.org/10.1016/j.compstruct.2020.112310.

Kim, W., S. Kim, and S. Kim, (2019) Innovative Stay-in-Place Formwork Method for Reinforced Concrete Columns, Conference: Creative Construction Conference 2019. p117-123, https://doi.org/10.3311/CCC2019-018.

Kolísko, J., Čech, J., Tej, P., & Kněž, P. (2017). UHPC panels utilized as permanent formwork of in-situ cast reinforced concrete deck bridges. IOP Conference Series: Materials Science and Engineering, 246(1), 012043. doi: 10.1088/1757-899x/246/1/012043.

Li, S., & Yin, S. (2021). Research on the mechanical properties of assembled TRC permanent formwork composite columns. Engineering Structures, 247, 113105. doi: https://doi.org/10.1016/j.engstruct.2021.113105.

Naaman, A. E. (2016). 18 - Thin TRC products: Status, outlook, and future directions. In T. Triantafillou (Ed.), Textile Fibre Composites in Civil Engineering (pp. 413-439): Woodhead Publishing.

Nelson, M., Fam, A., Busel, J., Bakis, C., Nanni, A., Bank, L., Hanus, J. (2014). FRP Stay-in-Place Structural Forms for Concrete Bridge Decks: A State-of-the-Art Review. ACI Structural Journal, 111, 1069-1080. doi: 10.14359/51686810.

Papanicolaou, C. G., & Papantoniou, I. C. (2016). 11 - Optimum design of textile-reinforced concrete as integrated formwork in slabs. In T. Triantafillou (Ed.), Textile Fibre Composites in Civil Engineering (pp. 245-274): Woodhead Publishing.

Papantoniou, I.C and Papanicolaou, C.G. (2008). Textile Reinforced Concrete (TRC) for precast Stay-in-Place formwork elements. in Tailor Made Concrete Structures, pp.475–481, Taylor& Francis, London, UK, 2008.

Papantoniou, I.C and Papanicolaou, C.G., (2010) Minimum Cost Design of one-Way TRC/RC composite slabs, International RILEM Conference on Material Science conference, RILEM Publications SARL, p165 – 175.

RILEM Technical Committee 232-TDT (2016), Recommendation of RILEM TC 232-TDT: test methods and design of textile reinforced concrete.

Verbruggen, S., Remy, O., Wastiels, J., & Tysmans, T. (2013). Stay-in-Place Formwork of TRC Designed as Shear Reinforcement for Concrete Beams. Advances in Materials Science and Engineering, 2013, 648943. doi: 10.1155/2013/648943.

Yin, S., Cong, X., Wang, C., & Wang, C. (2021). Research on flexural performance of composited RC beams with different forms of TRC permanent formwork. Structures, 29, 1424-1434. doi: https://doi.org/10.1016/j.istruc.2020.12.034.

Zulassung Z-31.10-182 (2015), Gegenstand: Verfahren zur Verstärkung von Stahlbeton mit TUDALIT (Textilbewehrter Beton), Prüfstelle: DIBt, Antragsteller: TUDAG TU Dresden Aktiengesellschaft.