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EXPERIMENTAL INVESTIGATION ON THE SHEAR PERFORMANCE OF HYBRID STRUCTURES COMPRISING TEXTILE-REINFORCED CONCRETE STAY-IN-PLACE FORMWORK AND REINFORCED CONCRETE

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Abstract. Recently, the application of textile-reinforced concrete (TRC) in thin-walled precast structures has gained significant attention. Among these innovations, the combination of TRC and reinforced concrete (RC) has emerged as an effective method for creating hybrid structural systems. This paper presents the experimental results analyzing the shear behavior of a hybrid deck slab structure consisting of TRC stay-in-place (SiP) formwork and RC components. Shear performance was evaluated using 3-point bending tests on four large-scale specimens with aspect ratios (a/d) varying from 1.6 to 2.3. The average load carried by the TRC SiP formwork prior to failure—due to textile reinforcement rupture—was approximately 26.3 kN, with compressive strains at the top edge ranging from 2.8 to 3.4 ‰, just below the concrete's ultimate strain. The findings demonstrate the versatility of TRC SiP-formwork, highlighting its adaptable cross-section and substantial load-bearing capabilities, making it particularly suitable for composite bridge deck applications. The specimens experienced both shear compression and diagonal shear failures. Moreover, the TRC SiP-formwork effectively mitigated transverse cracking at the interface, enhancing bond strength and improving overall structural performance.

Keywords: shear behavior, hybrid structure; TRC, glass textile, SiP-formwork.

1. INTRODUCTION

Reinforced concrete decks are commonly constructed by pouring concrete in situ on formwork that is either stay-in-place (SiP) or removed, depending on the specific project requirements. Among these, stay-in-place RC formwork is frequently used due to its ease of fabrication and cost-effectiveness. However, this type of formwork has the disadvantage of requiring a larger thickness to meet load-bearing and stiffness demands. It is typically not considered as a composite load-bearing component with the reinforced concrete deck above. This leads to increased static loads and unnecessary material consumption. To address these challenges, recent research has focused on utilizing new materials, such as high-strength and ultra-high-strength concrete, along with non-metallic alternatives, to reduce thickness and optimize structural efficiency. Previous studies explored materials like fiber-reinforced polymers (FRP) in SiP formworks [1], but real-world implementation revealed challenges, including high initial costs, low modulus of elasticity, and limited ductility. Researchers have addressed these issues by integrating FRP with concrete in hybrid sections, resulting in cost-effective FRP-concrete hybrid sections that offer structural efficiency and economic viability.

Over the past two decades, textile-reinforced concrete (TRC) has emerged as a leading innovative material in construction. TRC combines fine-grained concrete with textile reinforcements made from basalt, carbon, or glass fibers, creating a material that is strong, lightweight, and durable [2]. TRC has been widely adopted in Europe, particularly for the repair and strengthening of existing structures, as well as in new construction. This material allows for the creation of thin-walled components, resulting in significant material and cost savings by replacing traditional steel reinforcement with corrosion-resistant textile reinforcement [3]. TRC is also recognized as an advanced material that supports sustainable development principles in modern construction practices. TRC-SiP formworks offer flexibility and significant time and cost reductions. Furthermore, TRC demonstrates exceptional resistance to cracking and durability, positioning it as a compelling option for bridge projects. TRC is a promising and adaptable solution, particularly in integrated formwork for bridges, effectively addressing challenges and delivering manifold advantages. However, the complexity of these hybrid sections highlights the need for a comprehensive database, emphasizing the challenges in their development.

Recent advancements in SiP formwork research have explored various systems, including prestressed RC formwork, thin-walled steel sheet formwork, FRP formwork, and ultra-high-performance concrete (UHPC) formwork. While much research has focused on the mechanical properties of textile-reinforced concrete (TRC) for reinforcement, its application as permanent formwork requires further investigation. Studies on TRC as permanent formwork for composite slabs ([3- 4]), beams ([5-6]), and columns ([3], [7]) reveal its significant potential in improving bending strength, durability, and load-bearing capacity in reinforced concrete (RC) structures. Notably, Brameshuber et al. [4] were among the first to explore hybrid slab structures utilizing TRC-SiP formwork, reporting considerable reductions in structural weight and eliminating the need for demolding and curing processes. Papantoniou et al. [3], [8], [9] contributed to the development of cost-effective reinforced concrete slabs and prefabricated TRC-SiP formwork elements, underscoring TRC's role in reducing production costs. Kim et al. [10] further demonstrated that TRC panels used as SiP formwork significantly increased the flexural capacity and durability of RC components. Verbruggen et al. [11] investigated composite girder systems employing TRC-SiP formwork, emphasizing its potential as a viable replacement for traditional steel stirrup reinforcement. Yin et al. [6] studied U-shaped TRC permanent formwork and its effectiveness in enhancing the overall performance of reinforced concrete elements. Li's work on composite columns with TRC permanent formwork introduced a formula for ultimate bearing capacity, showcasing superior structural properties [12]. In addition, Kim's innovative design of TRC-SiP formwork aimed at improving seismic resilience, reducing disaster-related damages, and minimizing associated social costs [7].

Despite these advancements, research has yet to explore the application of TRC-SiP formwork in bridge deck structures, warranting further investigation. Current TRC research has primarily focused on civil buildings, leaving a significant gap in its use for bridges. Bridges require higher load capacity, necessitating a dedicated exploration of TRC's potential. Urgent experimental tests are needed to assess the mechanical behavior of hybrid deck slab structures, incorporating TRC- SiP formwork and reinforced concrete. The limited duration of research on TRC formwork applications highlights the need for comprehensive studies investigating the shear performances of hybrid decks. In this research, we delve into the shear behavior of TRC-RC hybrid decks through the utilization of 3-point bending tests. The study encompasses four specimens with varying aspect ratios (*a/d*) spanning from 1.6 to 2.3. This investigation aims to provide a detailed examination of the performance and characteristics of these hybrid decks under shear loading conditions, contributing to a deeper understanding of their structural behavior.

2. TEST PROGRAM

2.1. Description of Specimens

The SiP formwork specimens a standardized width of 400mm, with lengths of 1800 mm, featuring a 25mm thick flange and two 75mm thick ribs. The ribs are inclined at approximately 82 degrees to enhance the interlocking mechanism between the precast formwork and the poured concrete. Two layers of textile reinforcement are embedded within the flange. This chosen cross-section design effectively accommodates high bending moments in both directions, with the flanges slightly sloped negatively to ensure a strong physical bond with the site-cast concrete.

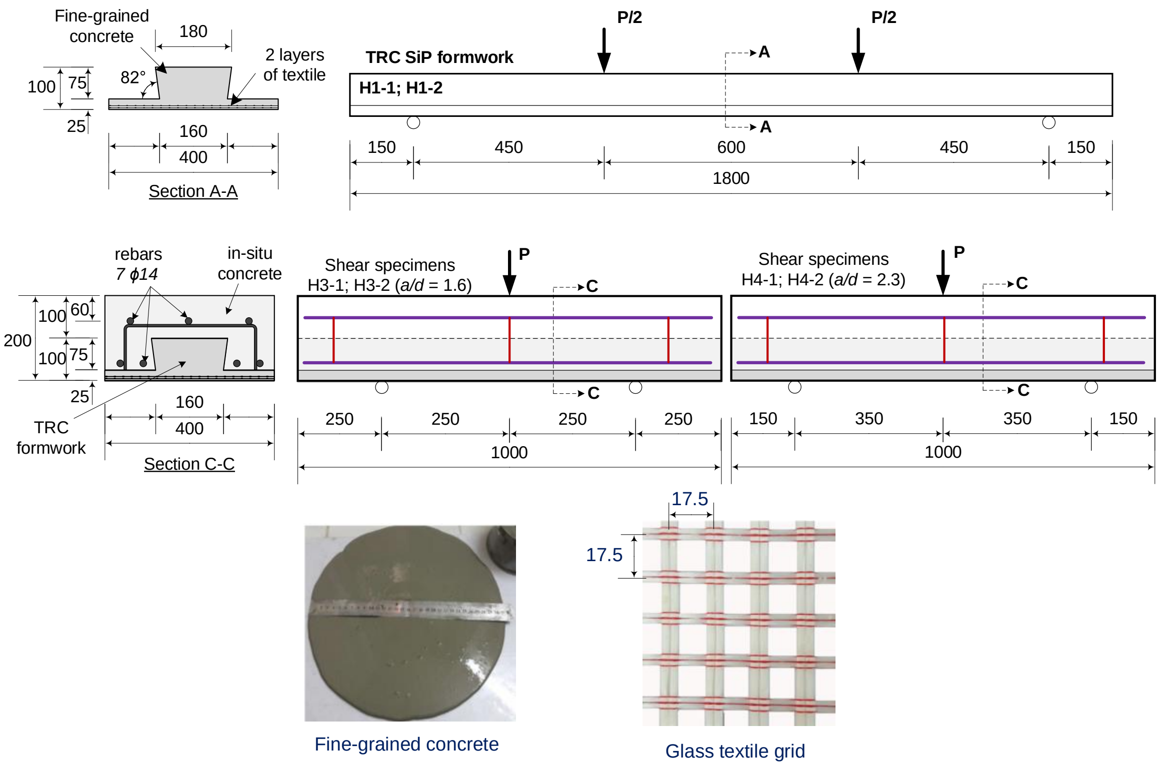

Figure 1. Details of test specimens.

To assess the shear capacity of TRC-RC hybrid decks, a 3-point bending test was conducted on this specific hybrid deck type. A total of 6 specimens were analyzed in three distinct series, varying the aspect ratio (*a/d*) from 1.6 to 2.3 for hybrid specimens. Table 1 outlines the description and properties of the test specimens. For efficiency, the experimental specimens were grouped based on length and aspect ratio, with the first group (H1) consisting of TRC formwork specimens, each 1800 mm in length. The remaining two groups, H3 and H4, had a length of 1000 mm. Experimental beam spans were adjusted by modifying the distance between supports for each series, as detailed in Figure 1.

At first, a four-point bending test will be conducted on two SiP formworks, denoted as H1-1 and H1-2, each with a clear span of 1.5 m, to assess the flexural behavior of the precast formwork. After the formwork resistance evaluation, testing will proceed on hybrid deck specimens to scrutinize their shear behaviors. Four remaining specimens with identical cross-sectional dimensions (width: 400 mm, height: 200 mm) will be utilized. The research approach employed in groups H2 and H3 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 and four D14 bars in the lower area. No extra shear reinforcement was employed in the beams.

2.2. Materials properties

The formwork component used alkali-resistant glass filaments combined into rovings to form the glass textile structure. The textile grid had a well-maintained spacing of about 17.5 mm, a 647g/m^2 surface weight, and an equal 50-50% weight distribution in both directions (Figure 1). With a fine fineness of 2400 tex, the textile featured a styrene-butadiene rubber (SBR) impregnation. The cross-sectional area of the textile in each direction along its length was 105.67 mm^2/m. The rovings exhibited a tensile strength of 1580 MPa, and the elastic modulus was approximately 107 GPa.

The textile reinforcement's characteristics required adjustments to the concrete mix for optimal performance. Formwork elements were made with fine-grained concrete featuring a maximum grain size of 0.6 mm, using high-quality Portland cement and fly ash as the binder. Concrete prisms (40 x 40 x 160 mm) were employed for strength assessment, resulting in a compressive strength of 64.2 MPa and a flexural tensile strength of 6.8 MPa. All hybrid specimens were constructed using in-situ concrete, exhibiting an average compressive strength of 42.5 MPa at 28 days. Longitudinal reinforcement bars with a diameter of 14 mm and a yield strength of 435 MPa were utilized.

2.3. Fabrication of test specimens

The construction of the TRC formwork begins by pouring a 5 mm layer of fine-grained concrete into the mold. Textile reinforcement is then tensioned and fixed to the mold, creating a smooth surface (Figure 2). Additional layers of textile and fine-grained concrete are added sequentially until the flange reaches the required thickness of 25 mm. The web formwork is then positioned, securely fastened, and filled with fine-grained concrete, which is compacted using a handheld vibrator. A curing film is applied to the structure for 28 days after casting. After the curing process, a steel wire brush is used to clean the interface by removing dust, and the reinforcement cage is inserted directly into the TRC formwork, eliminating the need for concrete spacer blocks. During the concrete pouring process, casting and vibration co-occur to ensure proper consolidation. The specimens are covered with a curing film for an additional 28 days to maintain structural integrity.

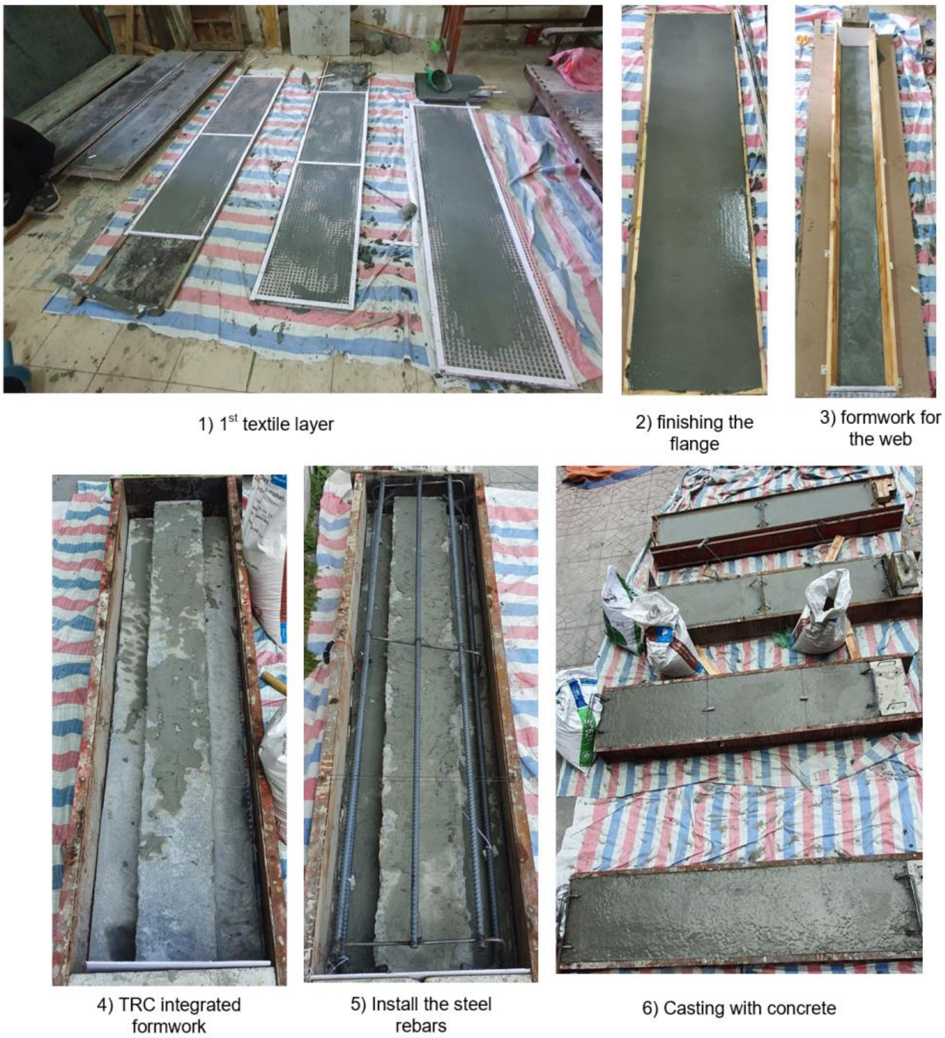

Figure 2. Fabricating the steel reinforcement cages and casting the RC column specimens.

2.4. Mechanical testing

All specimens underwent testing at the University of Transport and Communications structural laboratory. Formwork specimens (H1-1 and H1-2) were initially subjected to a four-point bending test with a clear span of 1500mm. The second set included four specimens tested under three-point symmetrical loading using a 3000-kN hydraulic actuator at a 0.2 mm/min rate. Load transfer, deflections, and strain measurements were recorded during the experiments using a load cell, and strain gauges were placed on longitudinal rebars and concrete surfaces. Preloading of 5kN was applied before actual loading to eliminate gaps between specimens and support. The beam testing setup, including strain gauge locations, is depicted in Figure 3.

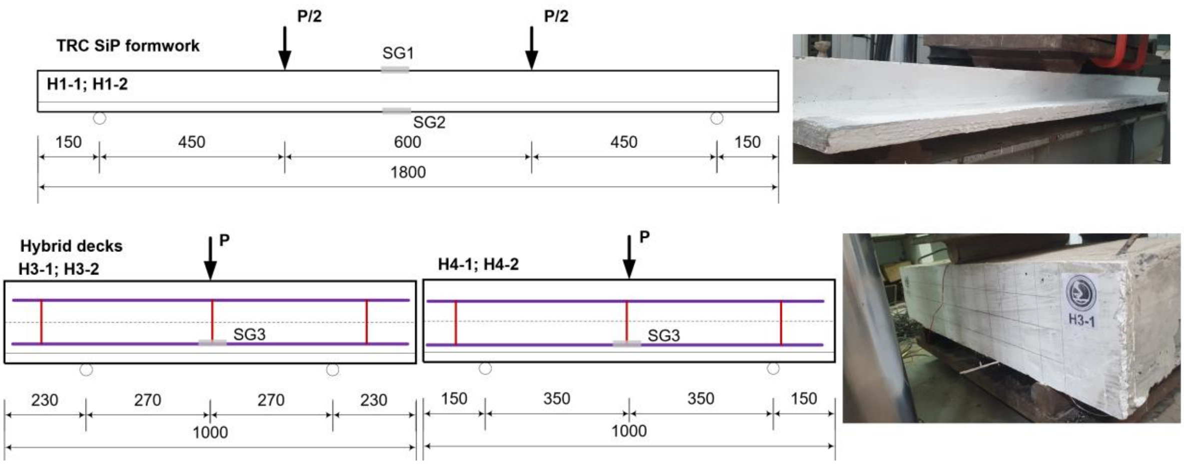

Figure 3. Test Configuration.

3. EXPERIMENTAL RESULTS

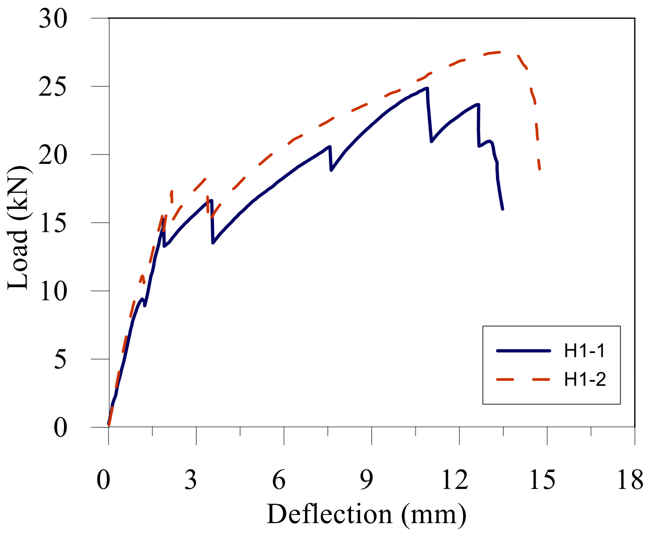

Figure 4. Load-deflection relationship of TRC formwork.

Figure 4 depicts the load-deflection relationship for TRC formwork H1–1 and H1–2, while Figure 5 shows their corresponding cracking patterns. The load-deflection behavior of TRC formwork H1–1 and H1–2 is divided into four stages: pre-cracking, crack formation, crack stabilization, and failure. In Stage I, the stiffness of the fine-grained concrete governs the pre-cracking state, with initial flexural cracks appearing around 17 kN, causing load redistribution to the textile reinforcement. The cracking load slightly exceeds construction requirements, factoring in self-weight, steel reinforcement, and freshly poured concrete. In Stage II, vertical cracks form in the pure bending zone due to principal tensile stress. Stage III sees the formation of multiple cracks, with load stabilization attributed to the textile reinforcement's tension-stiffening effect. The failure occurred in Stage IV, where ultimate loads of 24.8 kN and 27.8 kN were recorded for H1–1 and H1–2, respectively, due to the tensile rupture of the textile. Compressive strains at failure ranged from 2.8 to 3.4 ‰, just below the ultimate strain of the fine-grained concrete.

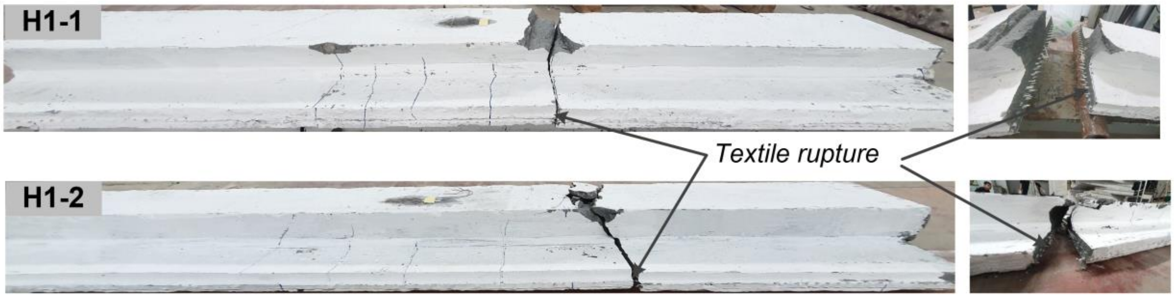

Figure 5. The failure mode of TRC formwork specimens H1-1 and H1-2.

Figure 6 depicts applied loads against vertical displacements for aspect ratios of 1.6 and 2.3. Additionally, Figure 7 illustrates crack formation, while Figure 11 provides strain gauge readings from transverse and longitudinal reinforcements in hybrid decks. Notably, the load-deflection curves in Figure 7 exhibit a consistent failure behavior across all G2 specimens, characterized by shear cracks prevailing over flexural cracks. Shear failure, attributed to concrete strut crushing or diagonal tension, was uniformly observed in all specimens, with no instances of flexural failure.

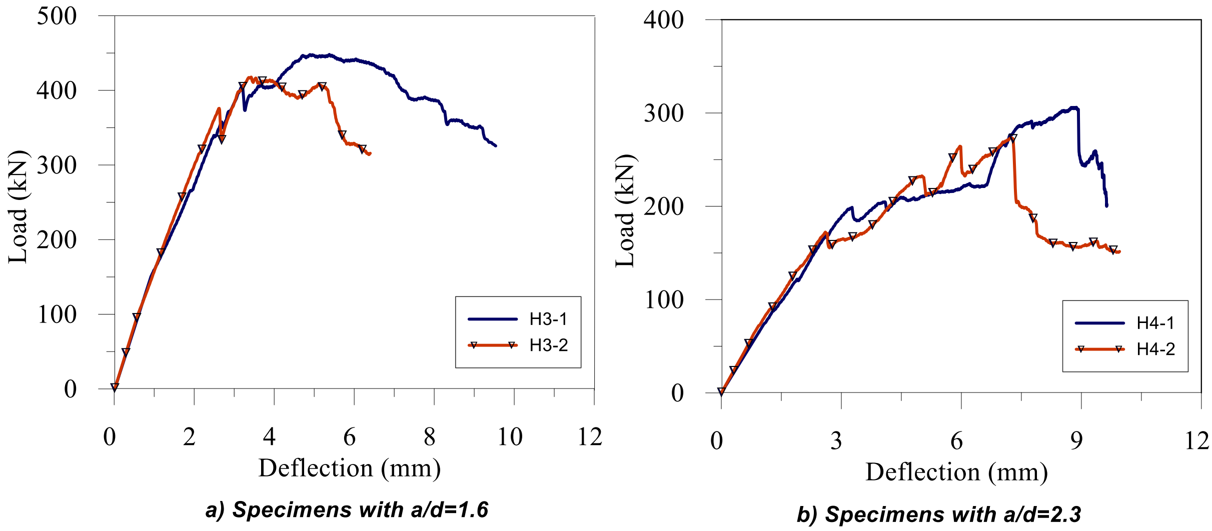

Figure 6. Load-deflection curves of specimens with different aspect ratios.

Shear failure in beams with an aspect ratio (*a/d*) of 1.6, as shown in Figure 8-a, began with the formation of mid-span flexural cracks that stopped progressing toward the neutral axis when the bond between the steel rebars and surrounding concrete at the supports weakened. Additional shear cracks developed, connecting with the flexural cracks and facilitating load redistribution. This was followed by the rapid development of inclined cracks propagating toward the neutral axis, leading to sudden failure as these cracks converged in the crushed concrete strut without any delamination between the formwork surface and the in-situ concrete. Figure 7 displays the load-deflection relationships for specimens H3-1 and H4-1, illustrating the brittle shear behavior of deep beams. Both specimens showed nearly linear stiffness until maximum shear forces, with flexural cracks forming at 175 kN and 185 kN for H3-1 and H3-2, respectively. As the load increased, flexural cracks expanded, and shear cracks emerged at approximately 280 kN, extending along the shear spans. At failure, crushing occurred along critical shear cracks and nodal zones. Shear strengths recorded were

447.99 kN for H3-1 and 417.79 kN for H3-2.

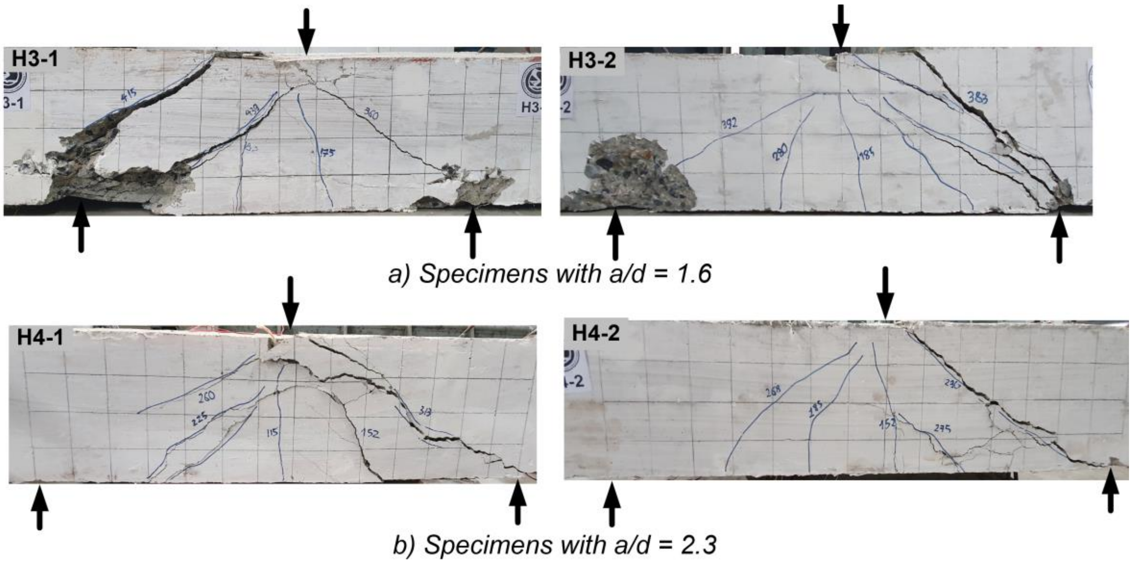

Figure 7. Shear failure of hybrid specimens.

Longitudinal cracks in the tension zone of slab segments arose from two mechanisms. First, splitting forces generated by the bond between concrete and steel longitudinal reinforcement caused cracks to form early at mid-span and extend through the shear span, leading to a loss of bond between concrete and reinforcement. Second, dowel cracks initiated from flexural shear cracks caused the separation of the concrete cover. These two mechanisms interact within the shear span, making it difficult to distinguish between them based solely on the ultimate crack pattern. Beams H4-1 and H4-2 exhibited displacements of 3.41 mm and 5.36 mm, respectively, as shown in Figure 6.

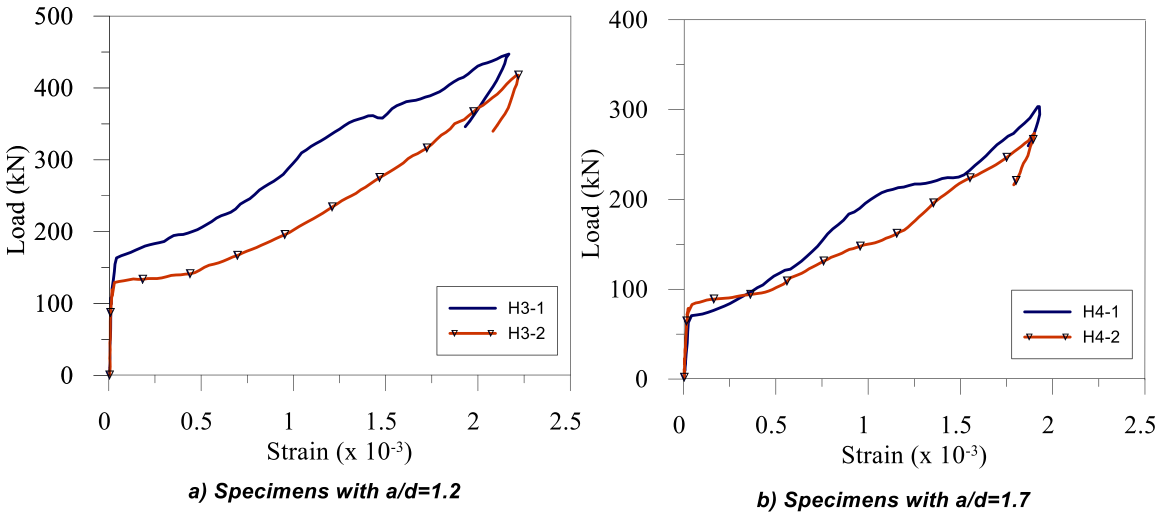

Figure 8. Load vs tensile strain in longitudinal steel reinforcement.

Strain gauge readings (Figure 8) revealed that tensile stresses in the longitudinal steel bars at failure were below the yielding strain of the steel. Both beams experienced diagonal shear failure, with the initial shear crack developing from a steep flexural crack in the tensile zone and curving toward the compression zone, forming a dowel crack along the tensile reinforcement—the primary shear crack allowed for load redistribution, enabling the formation of secondary flexural shear cracks. Ultimately, the critical shear crack, formed by the connection of horizontal branches of multiple shear cracks, led to a diagonal tension failure mode, distinct from flexural-shear or shear compression failures.

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 6-b). Both specimens showed nearly linear relationships up to the first shear cracks at applied loads of approximately 225 kN. Subsequently, shear force increased gradually with the emergence of secondary or tertiary flexural shear cracks, leading to complete failure. In specimens H4-1 and H4-2, visible load drops coincided with unstable shear crack propagation through the compression zone toward the supports. The appearance of a new inclined branch in the shear crack above the topmost reinforcement layer marked the load drop, indicating its independence from the reinforcement's position. This crack resulted from combined shear loads transferred through dowel action and interlocking faces between TRC-SiP formwork and in-situ concrete, disrupting local stress transfer through aggregate interlock, particularly below the crack. Beams H4-1 and H4-2 exhibited lower shear strength than those with an aspect ratio of 1.6, reaching a maximum strength of 306.11 kN and 273.71 kN, respectively. This disparity may account for lower strains in longitudinal steel bars compared to specimens H3-1 and H3-2 (Figure 8). Displacements for H4-1 and H4-2 were 8.87 and 7.24 mm, respectively, significantly higher than those with an aspect ratio of 1.6.

4. CONCLUSION

This study examined the shear behavior of TRC-RC hybrid decks on six specimens across three series with varying aspect ratios. The TRC-SiP formwork's cross-section can be adapted to specific applications, offering significant load-bearing capacity making it ideal for composite bridge deck structures. The cracking load of the formwork slightly exceeded construction requirements, accounting for TRC elements, steel reinforcement, and freshly poured concrete. Ultimate loads were recorded at 24.8 kN and 27.8 kN, with failure due to tensile rupture of textile reinforcement. Compressive strains at failure ranged from 2.8 to 3.4 ‰, just below the ultimate strain of the concrete. The inclined rib design improved interlocking between the formwork and concrete. Shear strengths for specimens H3-1 and H3-2 averaged 432.89 kN, while beams H4-1 and H4-2 demonstrated lower shear strength, averaging 289.91 kN. The study highlighted two mechanisms for longitudinal cracking in the tension zone, and shear failures were categorized as shear-compressive and diagonal shear failures, depending on the aspect ratio. TRC formwork also prevented transverse cracks at the interface, enhancing interfacial bond strength and overall structural integrity.

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