

Article

Built-Up Fiber-Reinforced Polymers (FRP) Profiles with Improved Shear Performance for FRP–Concrete Hybrid Section

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Abstract: Fiber-reinforced polymer (FRP)–concrete hybrid sections, composed of FRP profiles and a concrete slab, have gathered attention in construction due to their lightweight, easy installation, and high durability. However, the low shear strength and brittle behavior of commercially available pultruded FRP profiles often leads to brittle shear failure at low load levels. To enhance the shear strength and ductility, this study proposes a novel H-shaped FRP profile that is built from two U-shaped pultruded FRP profiles and a hand lay-up sandwiched core of multi-directional fibers. Direct shear tests showed that the built-up FRP profiles failed in pseudo-ductile mode while the U-shaped pultruded FRP profiles failed in brittle mode. Built-up FRP had 1.5 times the capacity and 2.8 times the ultimate redundancy compared to pultruded FRP. Additionally, flexural tests of FRP–concrete hybrid beams revealed that the webs of the built-up FRP profiles failed in a higher shear capacity with smeared cracks.

Keywords: built-up FRP profile; FRP–concrete hybrid beam; pseudo-ductility; concrete; shear capacity



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1. Introduction

Thin-walled fiber reinforced polymers (FRP) profiles have been increasingly used as primary load-carrying elements in maintenance-free structures under harsh and corrosive environments [1–5]. Among many techniques, the process of pultrusion is gaining attention as a method for producing commercially available thin-walled FRP products at high quality and relatively low cost. Pultrusion involves the combination of reinforced fibers and liquid resin to form durable and lightweight structural shapes [6,7]. Therefore, pultruded FRP (PFRP) is characterized by its high fiber content, with fibers aligned longitudinally resulting in high strength in the fiber direction. Compared with traditional materials such as steel and concrete, PFRP has advantages including high strength-to-weight ratio, extraordinary durability under corrosion, reduced life cycle costs, and ease of transportation [6–10]. The use of pultruded FRP (PFRP) profiles in bridges, decks, girders, and space frames has significantly increased in recent years [6–14]. However, all-FRP structures has a high initial cost; thus, the combination of PFRP and concrete results in a new and cost-effective system, referred to as FRP–concrete hybrid beams/decks, where the FRP and concrete complement each other in tension and compression, respectively [15,16].

Many experimental studies on FRP–concrete hybrid decks have indicated that the FRP webs experience sudden shear fractures at relatively low load levels prior to the occurrence of flexural failures in the FRP flanges or concrete slabs [17,18]. The results of the experiments on the failure modes and ultimate loads indicate that shear failure in FRP webs can be a significant issue that limits the stress levels of the rest parts of FRP at a low level. Therefore, enhancing the shear performance has become a crucial aspect in this area of research. Zhang et al. [18] conducted a study to enhance the shear performance of FRP–UHPC hybrid beams by exploring two strategies. The first strategy involved the application of externally bonded (EB) CFRP sheets onto the GFRP webs, while the second

strategy involved increasing the number of webs in the FRP profiles. The results of the study revealed that the addition of EB CFRP sheets to GFRP webs significantly increased both the shear capacity and the rigidity of the FRP–concrete hybrid beams. Additionally, the implementation of built-up II-shaped FRP profiles resulted in nearly double the shear capacity compared to the use of I-shaped profiles in FRP–concrete hybrid beams. However, the possible debonding between the EB CFRP and PFRP profiles is a challenging problem as faced by numerous concrete/steel/timber structures strengthened by EB CFRPs [19–21].

At a micro level, the failure of FRP in shear is attributed to shear of the matrix polymer and separation at the fiber–matrix interface; thus, the strength of the matrix and the interface play a crucial role in determining the shear performance [22,23]. At the structural level, the fiber orientation also impacts the shear strength, with 0° fibers in pultruded profiles having the lowest shear strength, and 45° fibers having the highest [24,25]. Taking into account the mechanism of FRP shear failure, considerable attention has been placed on redesigning the pultrusion process and combining it with other manufacturing techniques to improve shear strength. This includes replacing uni-directional fibers with multi-directional fibers as the raw material for pultrusion [26–28], and using the pultrusion–winding manufacturing process [29–32].

The filament winding method is a process for producing FRP tubes with improved shear strength. The recent trend of combining filament winding with hollow PFRP shapes is gaining popularity as a potential solution [29,33–42]. For example, Kitane et al. [38,39] proposed a hybrid deck system consisting of filament-wound trapezoidal boxes and a confined concrete layer, which demonstrated exceptional flexural capacity and torsional stiffness. Mufti et al. [40] developed a hybrid bridge deck composed of pultruded GFRP triangular tubes and flange plates with filament winding external reinforcement. The confinement of winded fibers improved the composite action between the concrete block and the pultruded GFRP boxed structure. Deskovic et al. [41] conducted tests on 20 FRP–concrete hybrid beams, which resulted in a pseudo-ductile failure of the CFRP sheet followed by concrete crushing. The first set of beams was constructed through in-house fabrication using the filament winding technique, while the latter set was commercially available PFRP. However, the failure mode observed in the latter set was different from that in the earlier set. The later beams exhibited a mixed pattern of cracks in the GFRP box beam web, with a majority of the failures occurring due to the rupture of the flange–web joint at the support region. Liu et al. [29] proposed that utilizing filament winding reinforcement on the exterior is an effective method for enhancing the performance of FRP bridge decks. This approach can improve the transverse stiffness of the decks and curb the swelling and spreading tendencies of FRP components, thereby increasing the ultimate load and deformation capacity. However, it should be noted that filament winding can only be implemented when the section is closed and the process is complex. Recently, Zou et al. [42] proposed a new FRP grid web–concrete hybrid beam design aimed at improving the connection reliability and addressing the issue of insufficient interlaminar shear strength in GFRP profiles. The test results demonstrated that the proposed hybrid beam, despite its reduced self-weight, maintains good flexural strength, stiffness, and ductility characteristics comparable to conventional concrete beams.

In this study, a novel manufacturing method combining pultrusion and hand lay-up is proposed. The approach involves adding fiber layers through hand lay-up between two pultruded web profiles in order to enhance the overall shear behavior of the web. The proposed method is expected to produce FRP profiles with higher shear strength and more ductility under shear stresses. Direct shear tests and flexural tests of FRP–concrete hybrid beams were conducted to evaluate the shear behavior of the web with an expected higher shear strength. The experimental results are aimed at demonstrating that this method is effective in improving the shear strength and overall ductility of the FRP–concrete hybrid section.

2. Research Significance and Conception of Built-Up FRP Profiles

This study presents a new method for manufacturing built-up FRP profiles (see Figure 1) that enhances their capacity to withstand shear forces and exhibit ductile behavior under shear loads. The proposed method can combine the advantages of pultrusion and hand lay-up. This is the first time in a study that the ductility of the shear failure of FRP shapes is improved using a certain manufacture method.

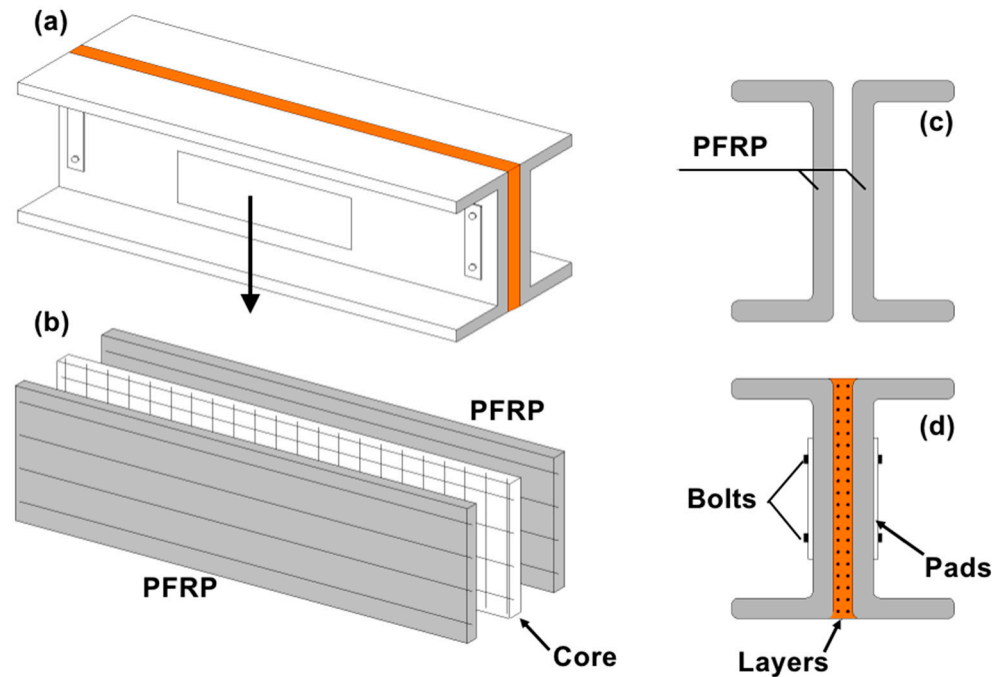
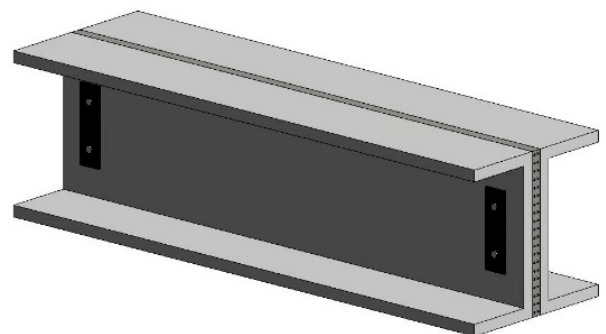


Figure 1. Illustration of construction of built-up FRP profiles: (a) built-up FRP profiles, (b) sandwiched web, (c) two C-shaped pultruded PFRP shapes, and (d) cross section of built-up FRP profiles.

The profile consists of two U-shaped PFRP plates, with a hand lay-up core in between (see Figure 2). The PFRP plates provide longitudinal stiffness and strength, behaving as formwork and providing structural support for the hand lay-up core plate. The core plate is composed of multi-directional fiber layers that can be designed to meet the required shear properties of the webs. The three parts are held together with pre-tightened steel bolts, which prevent inter-laminar delamination through the transversal prestressing effect. The PFRP plates are utilized to distribute the pre-tightened stress.



(a)



(b)

Figure 2. Products of built-up FRP profiles: (a) actual photo, and (b) 3D view illustration.

3. Construction of Built-Up FRP Profiles

The five-step manufacturing process for a built-up FRP profile is as follows: (i) drilling holes in the PFRP webs at predetermined locations for bolt tightening in step IV; (ii) grinding the backs of PFRP webs to enhance bonding between the core plate and PFRPs; (iii) using the U-shaped FRP web as a work platform to hand lay-up GFRP in layers to meet depth requirements; (iv) covering the counterpart U-shaped FRP and securing the bolts with a preset torque to assemble the three components; (v) curing for 24 h and cutting the excess material after the resin hardens.

In this study, PFRP profiles were obtained from Kangte Composite Material Co., Ltd., Nanjing, China. The PFRPs had dimensions of 152.4 mm × 228.6 mm × 11.11 mm (width × height × wall thickness) and were made of glass fiber-reinforced unsaturated resin. Glass fiber with a fiber density of 4.8 g/m and vinyl resin were used as the raw materials. Uni-directional fibers with a volume ratio of 55% were employed. To decrease the cost of PFRP, 20% of the weight of the matrix was added. It should be noted that a 10 mm radius was present in each corner of the U-shaped PFRP. The hand-layered core plates were made of glass fiber-reinforced vinyl resin with a bidirectional woven fiber fabric, having a fiber density of 4.8 g/m. Steel plates with a thickness of 5 mm and a yield strength of 460 MPa were used, with steel bolts fixed in the flanges of the FRP girders and tightened with nuts and washers. The steel bolts were tightened to a preset torque of 25 N·m using a torque wrench to provide a semi-fixed boundary condition. Steel bolts were all high-strength M8.8 grade (800 MPa ultimate strength and 640 MPa yielding strength) and all of them had a shank diameter of 12 mm. Steel washers with dimensions of 30 mm (outer diameter), 12.5 mm (inner diameter), and 1.0 mm (thickness) were used to disperse the stress caused by the steel bolts.

4. Determining the Shear Behavior of the Built-Up FRPs Using Direct Shear Test

A direct shear test (Figure 3) of PFRP and built-up FRP profiles was conducted to investigate the shear properties. Figure 3 shows that a 200 mm long segment was tested under three-point bending with a shear span of 50 mm; thus, an approximately pure shear area formed (see Figure 3). FRP profiles were loaded in the web section, supported at the two flanges. According to the layout of the web reinforcement, 16 specimens were categorized into two groups: Group_S with 12 U-shaped PFRP specimens (named as S-i), and Group_B with 4 built-up H-shaped FRP specimens with bolts (named as B-i).

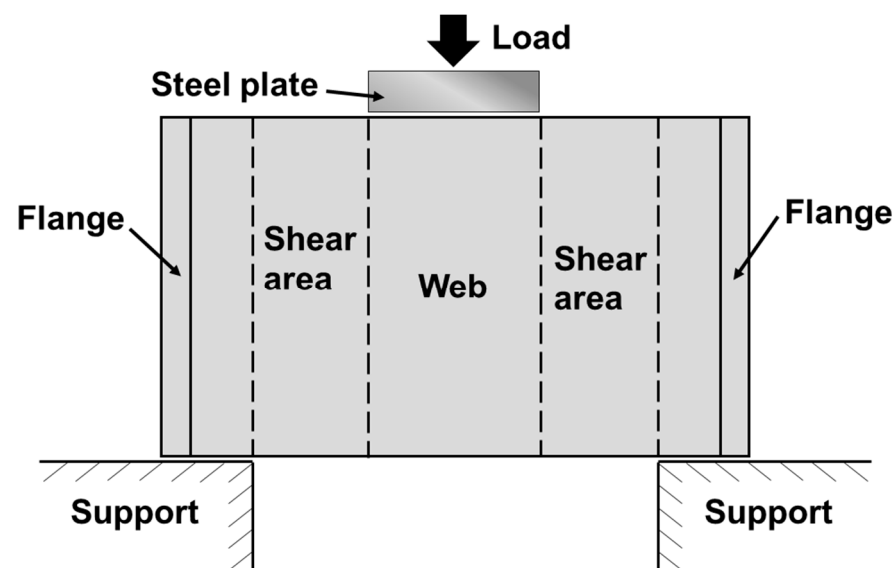


Figure 3. Illustration of direct shear testing of short FRP.

In this study, the shear properties of PFRP and built-up FRP profiles were evaluated through direct shear testing. The specimens were tested under three-point bending with a shear span of 50 mm, forming an area of pure shear (Figure 3). The FRP profiles were loaded in the web section and supported at the two flanges. The results showed that all PFRP specimens (Group_S) fractured suddenly along the fiber direction (Figure 4a). Group_B showed acoustic activities heard at approximately $0.25 P_u$, which was deduced to have been caused by interfacial debonding as some separation can be observed simultaneously. At P_u , cracks appeared along the fiber direction (Figure 4c,d). White cracks can be observed where bare glass fiber can be seen clearly. The load then decreased to about $0.65 P_u$, before slightly increasing with the consistent propagation of cracks in the fiber direction. The specimen eventually failed at about three times the displacement corresponding to the peak load. The S_{xy} – γ curves and final results are plotted in Figure 5 and Table 1, respectively. Note that P_u is the ultimate shear force, D_u is the ultimate displacement, τ_u is the ultimate shear stress, and γ_u is the ultimate shear strain.

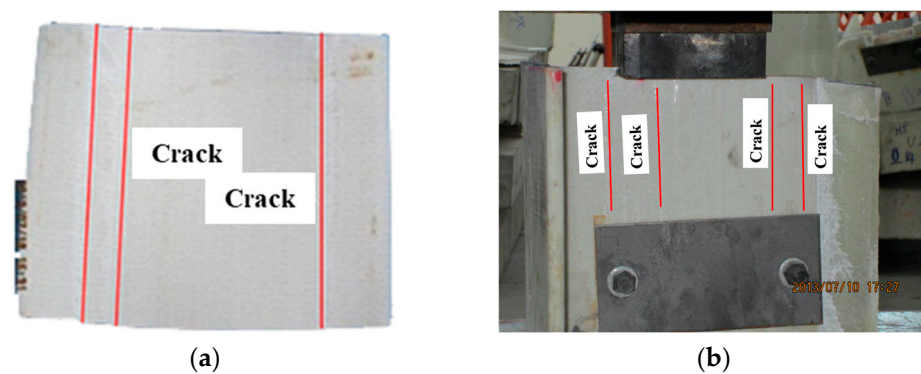


Figure 4. Typical failure modes of specimens under direct shear testing: (a) failure mode of S-1; (b) failure mode of B-1.

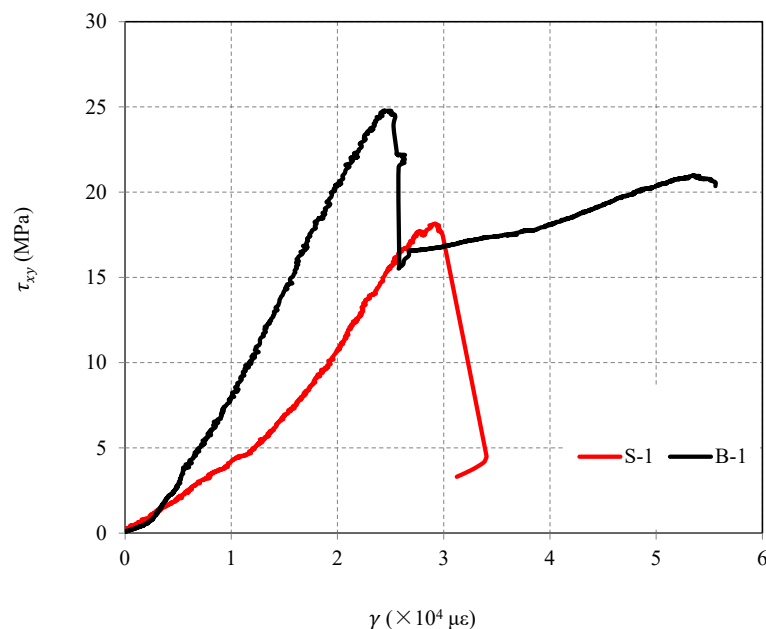
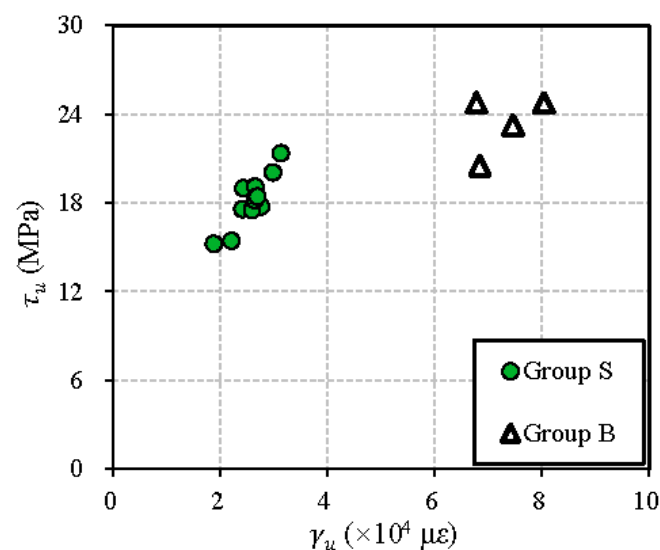


Figure 5. Shear stress–shear strain curves of specimens S-1 and B-1.

Table 1. Parameters and results of the specimens.

Specimen ID	Layout of Web Core	P_u (kN)	D_u (mm)	τ_u (MPa)	γ_u ($\times 10^4 \mu\epsilon$)	K_F	K_D	K_I
S-1	-	85.4	3.13	21.35	3.13	1.78	1.57	2.78
S-2	-	80.25	2.98	20.06	2.98	1.67	1.49	2.49
S-3	-	75.6	2.55	18.90	2.55	1.58	1.28	2.01
S-4	-	70.3	2.41	17.58	2.41	1.47	1.21	1.77
S-5	-	61.73	2.21	15.43	2.21	1.29	1.11	1.42
S-6	-	60.9	1.88	15.23	1.88	1.27	0.94	1.19
S-7	-	70.98	2.76	17.75	2.76	1.48	1.38	2.04
S-8	-	75.93	2.43	18.98	2.43	1.58	1.22	1.92
S-9	-	76.35	2.65	19.09	2.65	1.59	1.33	2.11
S-10	-	70.03	2.59	17.51	2.59	1.46	1.30	1.89
S-11	-	72.85	2.64	18.21	2.64	1.52	1.32	2.00
S-12	-	77.01	2.69	18.43	2.69	1.54	1.35	2.07
B-1	$(0^\circ/90^\circ)_6$	204.65	7.46	22.6	7.46	1.94	3.73	7.23
B-2	$(0^\circ/90^\circ)_{12}$	237.65	8.04	24.76	8.04	2.06	4.02	8.29
B-3	$(\pm 45^\circ)_{24}$	267.58	6.78	24.78	6.78	2.07	3.39	7.00
B-4	$(0^\circ/90^\circ)_{24}$	221.55	6.84	20.51	6.84	1.71	3.42	5.85

The results of the direct shear test indicate that the average shear strength of the pultruded FRP profiles was 18.21 MPa, which was 1/7.5 of the steel's 235 MPa as expected. Furthermore, the addition of bolts to the post-molded profiles in group B-1 to B-4 prevented interface separation and increased the average shear stress to 23.3 MPa, a 28% increase from the pultrusion method. It should be noted that 23.3 MPa is a low shear strength compare with many commercial products available today, but the improvement of the shear strength is notable, which means that the proposed manufactory method can be used to some extent. Lastly, the S_{xy} - γ curves of pultruded specimens showed a linear increase until brittle fracture, while the post-molded specimens showed significantly improved ductility as the pultruded part fractured and the remaining parts continued to hold the load, resulting in a higher ultimate strain of 2.82 times that of pultrusion. The ultimate stress and strain can be seen in the scatter diagram of Figure 6.

**Figure 6.** Distribution of ultimate shear stresses/strains.

The S_{xy} – γ curves in Figure 5 reveal the presence of two stages in the loading process of the post-molded FRP specimens (B-1, B-2, B-3, B-4), indicating the presence of pseudo-ductility [28,30,33]:

- (i) Elastic stage: The three parts of the web work together to resist the load, causing the shear stress to increase linearly until the load peak.
- (ii) Debonding and crack stage: The shear load/stress slightly decreases at the load peak, after which the hand-up sandwich part holds the main load and contributes most to the constantly increasing deformation until failure. The viscous deformation is a result of the absence of high curing temperatures of the matrix in the hand-up laminated webs, as high temperature and high pressure increase brittleness. The S_{xy} – γ curves demonstrate pseudo-ductility in this stage.

In this study, pseudo-ductility can be considered evident from these curves. The load peak in the first stage behaves as the ultimate bearing capacity, while, in the second phase, ultimate deformation provides sufficient redundancy. Hence, when determining the safety factor in shear design, material pseudo-ductility, which is fundamentally different from brittle materials, can have its potential fulfilled by the deformation redundancy.

There was study on how to define the ductility index of the curves, as shown in Figure 5. According to Ye et al. [32] and Feng et al. [43], quantitative analysis of the safety redundancy index for FRP materials was proposed in a similar way to take the pseudo-ductility into consideration. The theory defined a design point D and a structural member resistance curve (load–deformation curve, Figure 7). After determining this point, the following indicators can be calculated: capacity redundancy index (K_F)—the ratio of ultimate bearing capacity (P_u) to that of the design point (P_D), Equation (1); deformation redundancy index (K_D)—the ratio of ultimate deformation (D_u) to that of the design point (D_D), Equation (2); general index (K_I)—the product of the two above indicators, Equation (3). In this study, the design point was determined as (12 MPa, $2 \times 10^4 \mu\epsilon$); the three indices are shown in Table 1 and Figure 8.

$$K_F = P_u / P_D \quad (1)$$

$$K_D = D_u / D_D \quad (2)$$

$$K_I = K_F K_D \quad (3)$$

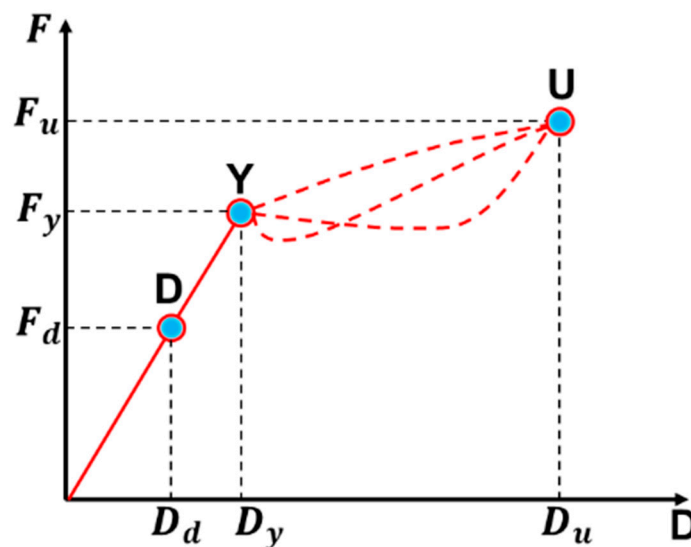


Figure 7. Resistance curve and the design point.

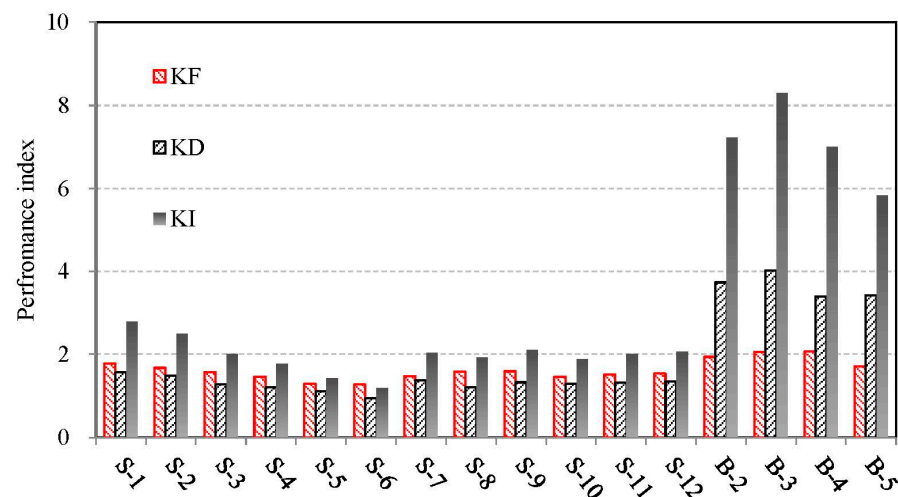


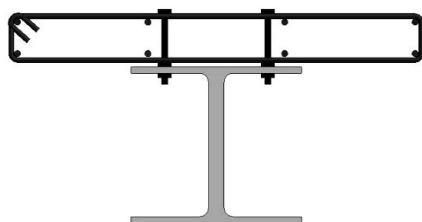
Figure 8. Comparison of performance index.

5. Experimental Validation Using FRP–Concrete Composite Beams

In addition to direct shear test, experimental validation using FRP–concrete hybrid beams using the proposed built-up sections was performed to verify whether they can provide more shear strength and more ductile behavior.

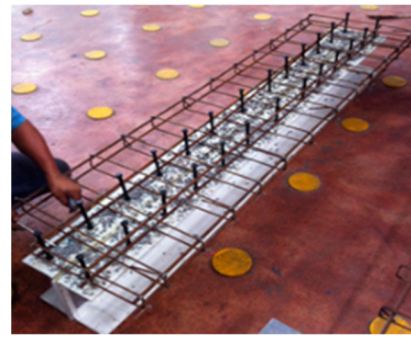
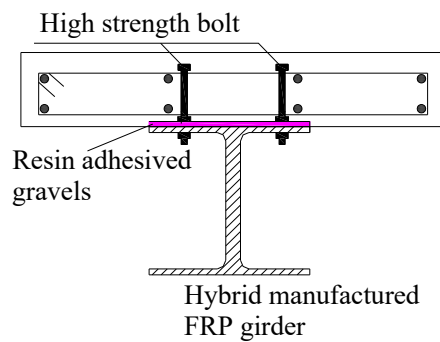
5.1. Method

Two large-scale tests on FRP–concrete beams with small shear span ratios (as low as 1.5) were conducted to evaluate the shear performance of the proposed built FRP webs. Beam_1 had steel bolts along the interface, while Beam_2 had steel bolts together with epoxy bonded gravels along the interface. Hence, it was expected that Beam_2 had less interfacial slip, i.e., more composite action between FRP and concrete. To avoid buckling of the FRP flange plates and improve their local bearing capacity and overall flexural rigidity, concrete slabs were cast above the FRP beams (as illustrated in Figures 9 and 10). The longitudinal reinforcement and stirrups were made of 10 mm diameter and 6 mm ribbed bars, respectively. The bolts had a diameter of 12 mm and a high strength rating of 8.8. The adhesive used was a 1:1 ratio of epoxy resin, and the perforated FRP connectors were connected to the post-molded FRP girder using the aforementioned adhesive and 6 mm diameter bolts with a yield strength of 400 MPa. In this study, the design strength grade of concrete had a target strength of 40 MPa. The mixture ratio of the C40 concrete was 1.00:0.46:1.24:2.84 (cement, water, sand, and gravel, respectively) in mass. Per Chinese code GB 50010-2010 [44], 150 mm × 150 mm × 150 mm cubes were cast during the pouring process of the tested beams. The average compressive strength of concrete cubes was measured to be 44.1 MPa (CoV = 0.15) under standard curing conditions (temperature at 20 ± 2 °C, relative humidity $\geq 95\%$) after 28 days.

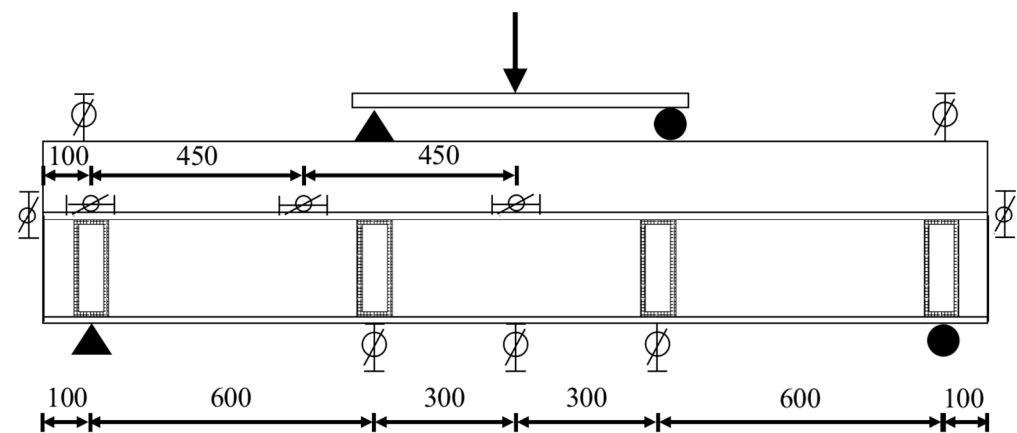


(a) Beam1

Figure 9. Cont.



(b) Beam2

Figure 9. Illustration of FRP–concrete composite beams.**Figure 10.** Loading instrument of FRP–concrete composite beams (units in mm).

5.2. Test Observations and Load Responses

The two specimens exhibited similar test observations, and the whole process of the beam test could be divided into 4 stages:

- (i) The elastic stage ($0-0.2 P_u$): the concrete slab cracked at about $0.15 P_u$, albeit without really affecting the overall flexural stiffness, see Figure 11. The cracks formed at the mid-span of the beam at the bottom of RC slab, and then propagated to the upper vertical direction, see Figures 12 and 13. Interestingly, Beam_2 had a higher rigidity, which was attributed to the improved shear connection compared with Beam_1.
- (ii) The local failure stage ($0.2-0.5 P_u$): new concrete cracks continuously sprung out within the pure bending section of the concrete slab, and the cracks became wider and longer. Interface debonding between the sandwiched layer and the pultruded layers could be observed, see Figures 12 and 13, and acoustic activities were then heard in the built-up FRP webs.
- (iii) The highly damaged stage ($0.5-0.8 P_u$): the natural bonding force along FRP and concrete interface was destroyed, see Figure 13, as proven by the acoustic activities released; consequently, the bolt stress soared dramatically, and the flexural stiffness of the beam decreased instantly. A neutral axis appeared in concrete and FRP, and the shear span webs cracked horizontally.
- (iv) The destruction stage ($0.8 P_u$): the FRP webs failed in shear span, while the concrete diagonal cracks of concrete extended to the top and finally led to concrete failure when coupled with compressive stress (Figure 13).

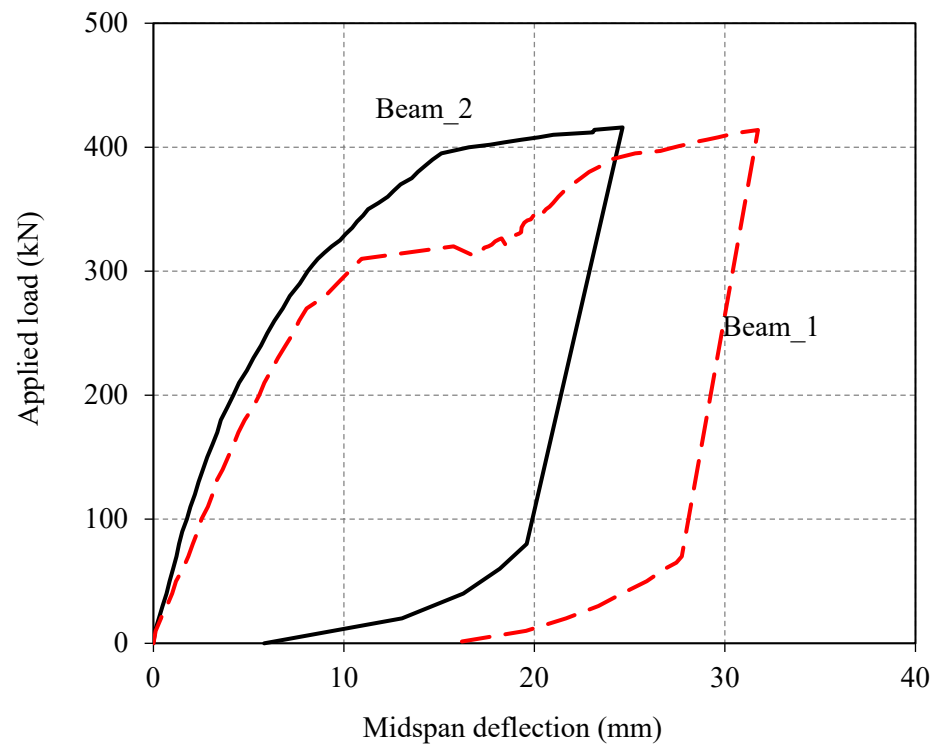


Figure 11. Applied load-midspan deflection curves.

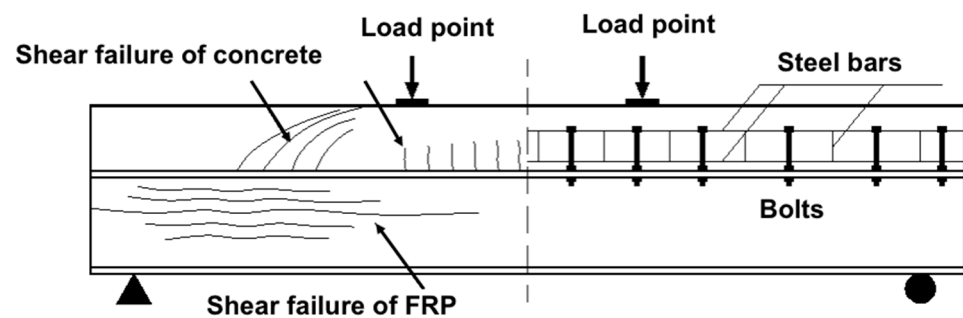


Figure 12. Failure modes for FRP-concrete composite beams.

The characteristic loads of specimens are shown in Table 2. Note that P_{cr} is the load at concrete crack, $P_{slip,i}$ is the load when slip first occurs, $P_{slip,u}$ is the load when slip occurs throughout the span and rigidity reduced, $P_{web,sh}$ is the load when FRP webs cracked instantly, $P_{web,u}$ is the load when FRP shear fractured, and P_u is the ultimate load of the beam.

Table 2. Characteristic loads of specimens.

Beam ID	P_{cr} (kN)	$P_{slip,i}$ (kN)	$P_{slip,u}$ (kN)	$P_{web,sh}$ (kN)	$P_{web,u}$ (kN)	P_u (kN)
Beam_1	100	100	310	310	-	414
Beam_2	80	100	225	280	410	410

where A_{web} is the section area of FRP webs (mm^2), τ_{FRP} is the shear strength of FRP webs (MPa), as experimentally determined previously, λ is the shear span ratio of the concrete

slab, f_t is the tensile strength of concrete (MPa), b_c is the width of the concrete slab (mm), h_c is the height of the concrete slab (mm), f_{sv} is the strength of the stirrups (MPa), A_{sv} is the area of the stirrups (mm²), s_{sv} is the spacing of the stirrups (mm), and h_{c0} is the effective height of the concrete slab (mm). The results of ultimate shear bearing capacity are listed in Table 3.

Table 3. Verification of shear capacity.

Beams	τ_{FRP} (MPa)	V_{FRP} (kN)	f_{cu} (MPa)	V_{cs} (kN)	V_{total} (kN)	V_{test} (kN)	$\frac{V_{test}}{V_{total}}$	$\frac{V_{cs}}{V_{total}}$
Beam_1	27.02	161.58	33.40	69.18	230.76	207.00	1.11	0.30
Beam_2	27.02	161.58	32.80	68.42	230.00	205.00	1.12	0.30

The shear capacities in the above table show good agreement between theory and test. Thus, the equation can be used to design the FRP–concrete hybrid beams. It is important to note that the conclusions presented in this study are limited by the small number of experimental tests performed, in which the capacity carried by concrete amounts to about one-third of the total, indicating the importance of the concrete slab in shear behavior. Additionally, the large contribution of concrete used in the present study can be attributed to its large cross-sectional area and overly low shear strength.

7. Conclusions

This study presented the findings of an investigation into the design and performance of a hybrid composite–concrete beam. The results demonstrated that it is possible to achieve both adequate stiffness and the desirable ‘pseudo-ductile’ behavior in such structures. The following conclusions can be drawn:

- (i) To address the low shear capacity of unidirectional fiber-reinforced polymer (PFRP) materials, a built-up technology based on the pultrusion process was proposed, which involved adding a layer of hand-up fiber sheet between the two pultruded webs, allowing the overall capacity and safety of all-FRP structures and FRP–concrete hybrid structures to be improved.
- (ii) The results of direct shear tests of 12 PFRP and 4 built-up FRP profiles showed that the PFRP profiles failed in a brittle manner at an average shear strength of 18.2 MPa, whereas the built-up FRP specimens exhibited relatively higher shear strength (23.3 MPa) and near-triple shear deformation capacity.
- (iii) This study also proposed a safety redundancy index for FRP shear failure to quantify the pseudo-ductility of built-up FRP. The results showed that built-up FRP had 1.5 times the capacity and 2.8 times the ultimate redundancy compared to pultruded FRP.

It is important to note that the conclusions presented in this study are limited by the small number of experimental tests performed. Additionally, the core layers were established using hand lay-up, which resulted in a low composite action with the pultruded parts. Therefore, it is suggested for future researchers and engineers that the surface of the pultruded part should be treated to increase its interfacial strength. Further testing is recommended to more accurately assess the structural behavior of these hybrid FRP–UHPC beams under fatigue loading.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature and Abbreviations

A_{sv}	cross-sectional area of stirrups
A_{web}	section area of FRP webs
b_c	width of concrete slab
CFRP	carbon fiber-reinforced polymers
D_u	ultimate deformation
EB	externally bonded
f_t	tensile strength of concrete
FRP	fiber-reinforced polymers
f_{sv}	strength of stirrups
h_c	height of concrete slab
h_{c0}	effective height of concrete slab
K_D	deformation redundancy index
K_F	capacity redundancy index
K_I	general index
P_u	ultimate bearing capacity
PFRP	pultruded fiber reinforced polymers
s_{sv}	space of stirrups
UHPC	ultra-high-performance concrete
V_{cs}	shear capacity carried by concrete the reinforced bars
V_{FRP}	shear capacity carried by FRP webs
V_{total}	total shear capacity of the section
λ	shear span ratio of concrete slab
τ_{FRP}	shear strength of FRP webs

References

- Hollaway, L.C. A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. *Constr. Build. Mater.* **2010**, *24*, 2419–2445. [\[CrossRef\]](#)
- Liu, T.; Liu, X.; Feng, P. A comprehensive review on mechanical properties of pultruded FRP composites subjected to long-term environmental effects. *Compos. Part B Eng.* **2020**, *191*, 107958. [\[CrossRef\]](#)
- Syamsir, A.; Ean, L.W.; Asyraf, M.R.M.; Supian, A.B.M.; Madenci, E.; Özkılıç, Y.O.; Aksoylu, C. Recent Advances of GFRP Composite Cross Arms in Energy Transmission Tower: A Short Review on Design Improvements and Mechanical Properties. *Materials* **2023**, *16*, 2778. [\[CrossRef\]](#) [\[PubMed\]](#)
- Aksoylu, C.; Özkılıç, Y.O.; Madenci, E.; Safonov, A. Compressive behavior of pultruded GFRP boxes with concentric openings strengthened by different composite wrappings. *Polymers* **2022**, *14*, 4095. [\[CrossRef\]](#)
- Habibi, T.; Rhode-Barbarigos, L.; Keller, T. Fiber-polymer composites for permanent large-scale bending-active elastica beams. *Compos. Struct.* **2022**, *294*, 115809. [\[CrossRef\]](#)
- Chen, Y.; Duan, M.; Zou, X.; Feng, Y.; Li, G. Experimental and Numerical Investigation of Joints for a Pultruded Fiber-Reinforced Polymer Truss. *Polymers* **2022**, *14*, 4810. [\[CrossRef\]](#)
- Zou, X.; Lin, H.; Feng, P.; Bao, Y.; Wang, J. A review on FRP-concrete hybrid sections for bridge applications. *Compos. Struct.* **2021**, *262*, 113336. [\[CrossRef\]](#)
- Yang, X.; Bai, Y.; Ding, F. Structural performance of a large-scale space frame assembled using pultruded GFRP composites. *Compos. Struct.* **2015**, *133*, 986–996. [\[CrossRef\]](#)
- Keller, T.; Bai, Y.; Vallée, T. Long-term performance of a glass fiber-reinforced polymer truss bridge. *J. Compos. Constr.* **2007**, *11*, 99–108. [\[CrossRef\]](#)
- Zou, X.; Feng, Y.; Zhong, R.; Fang, T.; Wang, J. An experimental study of FRP truss side plate joint. *Constr. Build. Mater.* **2023**, *365*, 130012. [\[CrossRef\]](#)
- Zou, X.; Wang, J. Experimental study on joints and flexural behavior of FRP truss-UHPC hybrid bridge. *Compos. Struct.* **2018**, *203*, 414–424. [\[CrossRef\]](#)
- El-Hacha, R.; Chen, D. Behaviour of hybrid FRP–UHPC beams subjected to static flexural loading. *Compos. Part B Eng.* **2012**, *43*, 582–593. [\[CrossRef\]](#)
- Correia, J.R.; Branco, F.A.; Ferreira, J.G. Flexural behaviour of GFRP–concrete hybrid beams with interconnection slip. *Compos. Struct.* **2007**, *77*, 66–78. [\[CrossRef\]](#)

14. Siwowski, T.; Rajchel, M.; Kaleta, D.; Własak, L. The first Polish road bridge made of FRP composites. *Struct. Eng. Int.* **2017**, *27*, 308–314. [\[CrossRef\]](#)
15. Zhang, P.; Hu, R.; Zou, X.; Liu, Y.; Li, Q.; Wu, G.; Sheikh, S.A. Experimental study of a novel continuous FRP-UHPC hybrid beam. *Compos. Struct.* **2021**, *261*, 113329. [\[CrossRef\]](#)
16. Keller, T. Recent all-composite and hybrid fibre-reinforced polymer bridges and buildings. *Prog. Struct. Eng. Mater.* **2001**, *3*, 132–140. [\[CrossRef\]](#)
17. Zou, X.; Feng, P.; Bao, Y.; Wang, J.; Xin, H. Experimental and analytical studies on shear behaviors of FRP-concrete composite sections. *Eng. Struct.* **2020**, *215*, 110649. [\[CrossRef\]](#)
18. Zhang, P.; Lv, X.; Liu, Y.; Zou, X.; Li, Y.; Wang, J.; Sheikh, S.A. Novel fiber reinforced polymers (FRP)-ultrahigh performance concrete (UHPC) hybrid beams with improved shear performance. *Constr. Build. Mater.* **2021**, *286*, 122720. [\[CrossRef\]](#)
19. He, J.; Xian, G. Debonding of CFRP-to-steel joints with CFRP delamination. *Compos. Struct.* **2016**, *153*, 12–20. [\[CrossRef\]](#)
20. Biscaia, H.C.; Cruz, D.; Chastre, C. Analysis of the debonding process of CFRP-to-timber interfaces. *Constr. Build. Mater.* **2016**, *113*, 96–112. [\[CrossRef\]](#)
21. Zou, X.; Mirala, A.; Sneed, L.H.; Al Qaseer, M.T.; Donnell, K. Detection of CFRP-concrete interfacial debonding using active microwave thermography. *Compos. Struct.* **2021**, *260*, 113261. [\[CrossRef\]](#)
22. Zhou, X.Y.; Qian, S.Y.; Wang, N.W.; Xiong, W.; Wu, W.Q. A review on stochastic multiscale analysis for FRP composite structures. *Compos. Struct.* **2022**, *284*, 115132. [\[CrossRef\]](#)
23. Bank, L.C. Shear properties of pultruded glass FRP materials. *J. Mater. Civ. Eng.* **1990**, *2*, 118–122. [\[CrossRef\]](#)
24. Bai, Y.; Keller, T. Shear failure of pultruded fiber-reinforced polymer composites under axial compression. *J. Compos. Constr.* **2009**, *13*, 234–242. [\[CrossRef\]](#)
25. Gui, L.L.; Zhou, H.W.; Wang, H.W. Theoretical analysis of young's modulus for unidirectional fiber reinforced composites with different fiber orientations. In *Advanced Materials Research*; Trans Tech Publications Ltd.: Chongqing, China, 2011; Volume 216, pp. 773–776.
26. Guo, L.; Dong, G. Ways to elevate the transverse strength of pultrusion composites. *Fiber Reinf. Plast. Compos.* **1998**, *1*, 17–19. (In Chinese)
27. Hu, X.; Ma, Y. Strength analysis of RTM continuous GF reinforced composites. *Fiber Reinf. Plast. Compos.* **1997**, *2*, 3–4. (In Chinese)
28. Jiang, K.; Chen, L.; Zhao, Q. Study on the moulding process and bending properties of multi-directional laminated pultruded thin-walled FRP beam. *Eng. Plast. Appl.* **2011**, *39*, 42–46.
29. Liu, T.; Feng, P.; Tang, J.; Liu, X. Pullwinding technique for realizing hybrid roving architecture in pultruded GFRP composites. *Compos. Struct.* **2023**, *305*, 116483. [\[CrossRef\]](#)
30. Alajarmeh, O.; Alhawamdeh, M.; Shelley, T.; Mohammed, A.; Nicol, L.; Schubel, P.; Zeng, X. Influence of post-processing on the compressive behaviour of full-scale pultruded FRP columns: Holes and inserts. *Eng. Struct.* **2022**, *266*, 114547. [\[CrossRef\]](#)
31. Liu, Y.; Zhang, H.T.; Tafsirojman, T.; Dogar, A.U.R.; Alajarmeh, O.; Yue, Q.R.; Manalo, A. A novel technique to improve the compressive strength and ductility of glass fiber reinforced polymer (GFRP) composite bars. *Constr. Build. Mater.* **2022**, *326*, 126782. [\[CrossRef\]](#)
32. Ye, L.; Feng, P.; Lin, X. Analysis of safety margin indices for structural members with FRP. *China Civ. Eng. J.* **2009**, *42*, 21. (In Chinese)
33. Vedernikov, A.; Gemi, L.; Madenci, E.; Özkılıç, Y.O.; Yazman, Ş.; Gusev, S.; Safonov, A. Effects of high pulling speeds on mechanical properties and morphology of pultruded GFRP composite flat laminates. *Compos. Struct.* **2022**, *301*, 116216. [\[CrossRef\]](#)
34. Madenci, E.; Özkılıç, Y.O.; Aksoylu, C.; Safonov, A. The effects of eccentric web openings on the compressive performance of pultruded GFRP boxes wrapped with GFRP and CFRP sheets. *Polymers* **2022**, *14*, 4567. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Özkılıç, Y.O.; Gemi, L.; Madenci, E.; Aksoylu, C. Effects of stirrup spacing on shear performance of hybrid composite beams produced by pultruded GFRP profile infilled with reinforced concrete. *Arch. Civ. Mech. Eng.* **2022**, *23*, 36. [\[CrossRef\]](#)
36. Gemi, L.; Madenci, E.; Özkılıç, Y.O. Experimental, analytical and numerical investigation of pultruded GFRP composite beams infilled with hybrid FRP reinforced concrete. *Eng. Struct.* **2021**, *244*, 112790. [\[CrossRef\]](#)
37. Gemi, L.; Madenci, E.; Özkılıç, Y.O.; Yazman, Ş.; Safonov, A. Effect of fiber wrapping on bending behavior of reinforced concrete filled pultruded GFRP composite hybrid beams. *Polymers* **2022**, *14*, 3740. [\[CrossRef\]](#)
38. Kitane, Y.; Aref, A.J.; Lee, G.C. Static and fatigue testing of hybrid fiber-reinforced polymer-concrete bridge superstructure. *J. Compos. Constr.* **2004**, *8*, 182–190. [\[CrossRef\]](#)
39. Aref, A.J.; Kitane, Y.; Lee, G.C. Analysis of hybrid FRP-concrete multi-cell bridge superstructure. *Compos. Struct.* **2005**, *69*, 346–359. [\[CrossRef\]](#)
40. Mufti, A.A.; Labossière, P.; Neale, K.W. Recent bridge applications of FRPs in Canada. *Struct. Eng. Int.* **2002**, *12*, 96–98. [\[CrossRef\]](#)
41. Deskovic, N.; Triantafillou, T.C.; Meier, U. Innovative design of FRP combined with concrete: Short-term behavior. *J. Struct. Eng.* **1995**, *121*, 1069–1078. [\[CrossRef\]](#)
42. Zou, Y.; Wu, C.; Zhang, Z.; Jiang, J.; Yu, K.; Wang, X. Investigation on flexural behavior of novel GFRP grid web-concrete hybrid beam. *Eng. Struct.* **2023**, *278*, 115489. [\[CrossRef\]](#)
43. Feng, P.; Qiang, H.; Ye, L. Discussion and definition on yield points of materials, members and structures. *Eng. Mech.* **2017**, *34*, 36–46. (In Chinese)
44. GB 50010-2010; Code for Design of Concrete Structures. China Building Industry Press: Beijing, China, 2011. (In Chinese)

45. Nie, J.; Cai, C.S. Steel–concrete composite beams considering shear slip effects. *J. Struct. Eng.* **2003**, *129*, 495–506. [[CrossRef](#)]
46. Nie, J.; Xiao, Y.; Chen, L. Experimental studies on shear strength of steel–concrete composite beams. *J. Struct. Eng.* **2004**, *130*, 1206–1213. [[CrossRef](#)]

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