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Evaluation of Behavior Characteristics of Reinforced Concrete Beam Shear Strengthening with Different FRCMs

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Abstract: This paper evaluated the structural behavior of shear-strengthened externally bonded FRCM composites. The additional shear strength of FRCM composites with three different types of textile grids (T1, T2, and T3) was analyzed for different crack patterns and failure modes. The influence of the internal transverse reinforcement ratio (ρ_w : 0.19%, 0.285%) and application method (SB: side bonding; UW: U-type wrapping) on the FRCM-strengthened beam was investigated. Furthermore, the interaction of FRCM composites with internal shear reinforcement was analyzed based on the strain distributions measured in the experiments. The experimental results showed that the failure modes (flexural, shear slippage, and shear debonding) changed depending on the type of textile grid applied. A reduction in shear reinforcement strain (interaction) due to FRCM strengthening was observed for all the strengthened beams, with differences depending on the shear reinforcement ratio and the type of textile grid. In addition, the ratio of the strain measured at the ultimate load to the strain of the textile grid in shear-failed reinforced beams was the lowest for the T3 grid, which had worse physical properties, and increased at lower shear reinforcement ratios. However, application methods (SB, UW) did not show significant differences.

Keywords: FRCM composite; textile grid type; RC beam; shear strengthening; strain; configuration method



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1. Introduction and Background

Existing reinforced concrete (RC) structures need strengthening due to the aging of concrete and rebar, changes in applied loads due to changes in use, and the upgrading of current design criteria [1]. The conventional strengthening method of enlarging the cross-section of concrete and using steel profiles made of ribs and plates is still in use worldwide. However, these methods have several disadvantages, such as the increased self-weight of the structure, changes in stiffness, and the need to handle heavy forced components. There is growing interest in developing reinforcement technologies to overcome these disadvantages. More recently, the use of composite-based reinforcement materials such as glass and carbon fibers has gained more attention. These materials offer various material properties and can be bonded to the surface of the existing structure in a plain or prestressed state [2].

Composites based on fiber-reinforced materials have been referred to by various names such as fiber-reinforced concrete (FRC), fiber-reinforced mortar (FRM), and a fiber-reinforced cementitious matrix (FRCM), depending on the matrix used. In this study, the term FRCM is used because a cement matrix is used [3]. Although research related to FRCMs is still scarce, their effectiveness in strengthening RC structural members in tensile and flexural, bond, shear, torsion, axial, and eccentric loads has been experimentally verified [4–15]. Studies related to the seismic performance improvement in RC column members have shown that the confinement effect of FRCMs under cyclic load can increase the strain capacity and energy dissipation in flexural performance [16]. In addition, recent

studies have confirmed that the type of textile grid (impregnation and surface treatment), which is a component of FRCM composites, directly affects the tensile properties and the reinforcement performance against flexural failure [17]. The current status of the shear strengthening of RC beams using externally bonded FRCM composites is summarized in reference [18]. An analysis of the database collected from the literature suggests that FRCM systems can increase shear strength by up to 195%, but different types of textile grids (carbon, glass, aramid, basalt, etc.) and experimental conditions show different shear strength increases, and the shear performance of the textile grid depending on the weave condition and surface coating is not well understood. In addition, this study reports that FRCM shear strengthening tends to decrease as the amount of internal transverse reinforcement increases. Further research is needed to directly investigate this decrease in shear strengthening.

According to Tetta et al. in [19], the types of shear failure of FRCM-reinforced beams were identified as (1) fiber slippage, (2) the partial failure of fibers across the shear crack, and (3) the delamination of the FRCM. Fiber slippage was evident in the side-bonded (SB) method, while FRCM delamination was found in the U-wrapped (UW) method. However, the failure mode due to the interaction of the internal shear stiffeners should be further investigated. In addition, current design equations for predicting the contribution of FRCM composites to the shear strength of RC beams are not able to accurately estimate the experimentally observed shear strength [17]. According to most design equations [20–23], the contribution of the FRCM to shear strength is simply expressed as the sum of the shear strengths of the unstrengthened beam. However, the shear contribution of the externally bonded FRCM is influenced by the shear contribution from the internal stirrups, and the maximum shear contribution may not be achieved simultaneously by both of these shear contributions.

2. Research Significance

Based on the existing studies, this paper evaluated the structural behavior characteristics of shear-strengthened externally bonded FRCM composites. The additional shear strength of FRCM composites with three types of textile grids (T1, T2, and T3) with different weaving methods was analyzed in terms of crack patterns and failure modes. Furthermore, the influence of the application method (SB, UW) on the FRCM composites was investigated. In addition, the interaction of FRCM composites with internal shear reinforcement was quantitatively evaluated using the amount of stirrup as an additional variable.

3. Experimental Investigation

The experiments consisted of 12 medium-sized RC beams with a shear-span-to-effective-depth (a/d) ratio of 2.0, organized into two series, G1 and G2, with different spacings of shear reinforcement bars. The G1 and G2 series consisted of six specimens each, including one unstrengthened reference specimen and five FRCM-strengthened specimens. The two reference specimens were identical except for the transverse reinforcement spacing in the shear span; the material and geometric details of the beams are shown in Figure 1. The total span of the beam was 2600 mm, and the clear span between reaction force points was 1940 mm. The details of the specimens and materials are described in the following subsections.

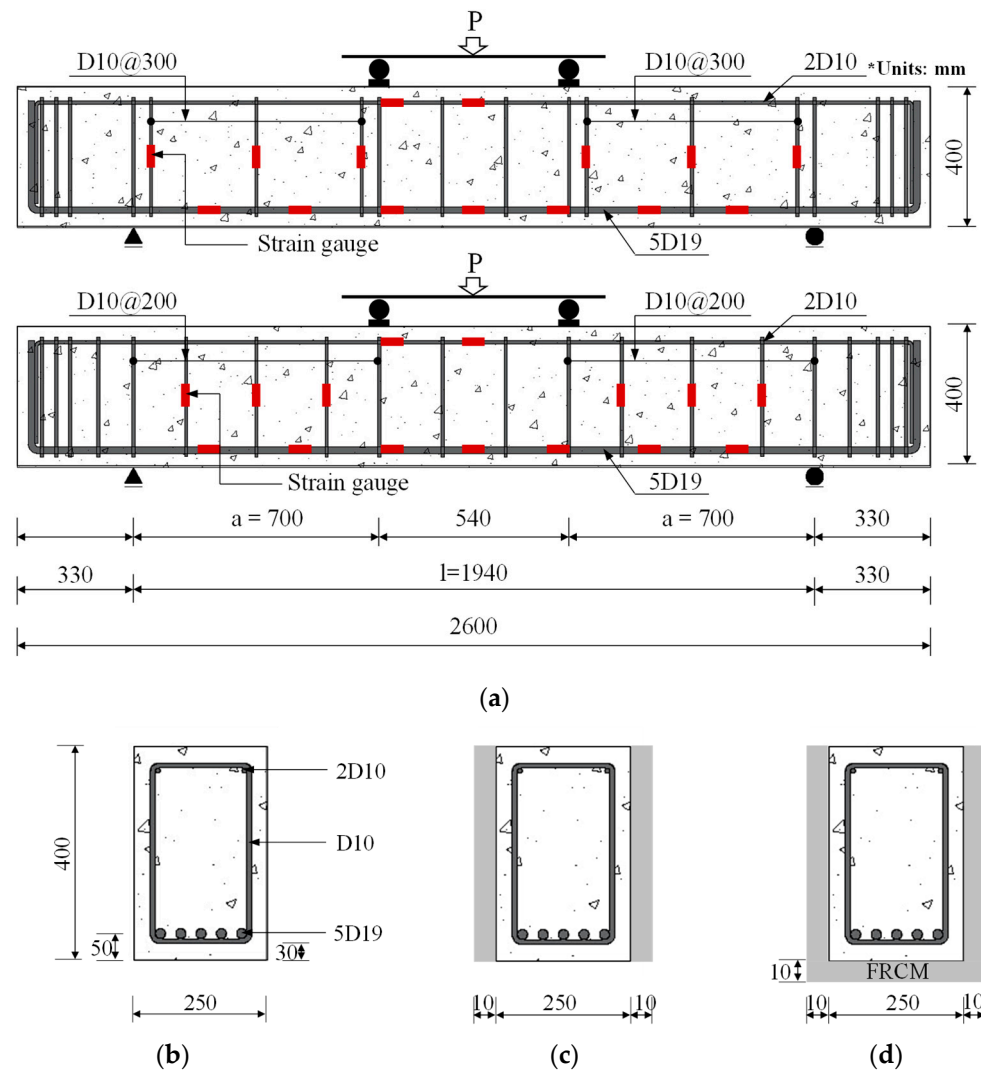


Figure 1. Details of beam specimens. (a) Longitudinal and transversal rebar detail (top: G1 series; bottom: G2 series); (b) control beam (G1, G2 series); (c) SB-FRCM-strengthened beam; (d) UW-FRCM-strengthened beam.

3.1. Description of Specimens

A total of 12 RC beams with a rectangular cross-section (250 mm × 400 mm) were used in the experiments. The details of the reference specimen before FRCM strengthening are shown in Figure 1. The longitudinal reinforcement used for bending reinforcement consists of two D10 bars of SD400 grade on the compression side and five D19 bars of SD400 grade on the tension side. For shear reinforcement, transverse reinforcement bars were placed at 300 mm intervals from the loading point to the point of reaction force in the G1 series and at 200 mm intervals in the G2 series. The yield strength of the longitudinal reinforcement on the tensile side was 450 MPa, and the strain at yield was 2700 $\mu\epsilon$. The longitudinal reinforcement and transverse reinforcement on the compression side had a tensile strength of 466 MPa and a strain at yield of 2300 $\mu\epsilon$. The concrete used for the test specimens was a normal-strength concrete with a nominal strength of 24 MPa, which is commonly used in structures. Ready-mixed concrete with a water–binder ratio (W/B) of 44.3%, a maximum coarse aggregate size of 25 mm, a fine aggregate ratio (S/a) of 49.9%, a slump of 150 mm, and an air content of approximately 4.5% was used. The fabricated RC specimens were cured for 28 days before FRCM strengthening. A standard concrete specimen with a diameter of 100 mm and a height of 200 mm was fabricated according to ASTM C39/C39M [24]. The compressive strength of the fabricated concrete specimens

was measured by performing compressive strength tests on the first specimens after FRCM strengthening (28-day curing) and the last specimen after the end of the test. The measured average compressive strength was 21.9 MPa.

3.2. Strengthening Materials

The external reinforcement system used three types of commercially available textile grids inside the FRCM composite. The T1 grid, as shown in Figure 2, has carbon and glass fibers laid crosswise with the carbon fibers in the warp direction. The glass fiber roving was 1200TEX, and the carbon fiber roving was 50 K. The weaving method consists of a pillar stitch with two sets of vertical threads that are tightly connected. The grid size is 27 mm $\times$ 27 mm, and the resin used for impregnation is SBR (Styrene Butadiene Rubber). The T2 grid uses carbon fiber for the warp and weft yarns. The carbon fiber roving that makes up the textile is 50 K. The same weaving method was used as that for the T1 grid, with a grid size of 21 mm $\times$ 21 mm. The resin used to impregnate the textile grid was epoxy; it is characterized by a stiffer weft and warp intersection compared to those of the T1 grid. The T3 grid uses leno weave, which is a bind-up weave with two strands of weft crossed over the warp.

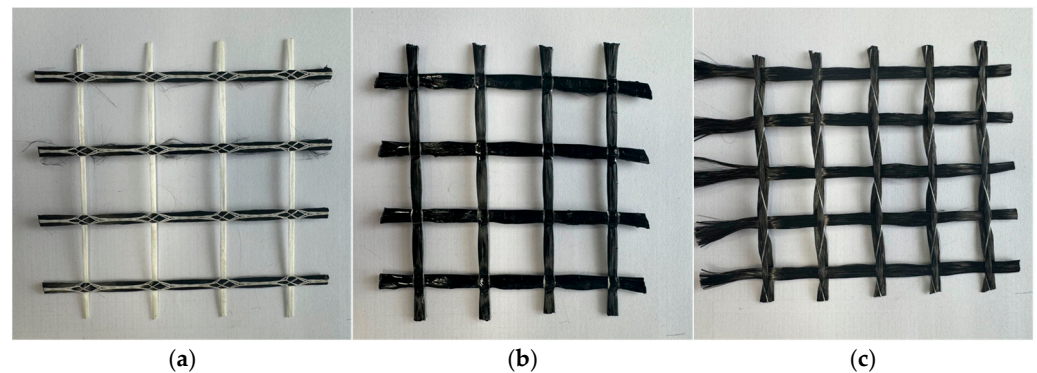


Figure 2. Three different types of textile grids. (a) T1; (b) T2; (c) T3.

Both the warp and weft yarns are carbon fiber; the carbon fiber roving is 12 K. The grid size is 20 mm $\times$ 20 mm, and because it is a dry grid without impregnation, the intersection of the warp and weft yarns is weak compared to that of other fibers.

Table 1 shows the mechanical properties of carbon fiber rovings placed on a textile grid in the warp direction. The tests were performed according to ISO/FDIS 10406-2 [25]. Tensile strength and the elastic modulus had the lowest values for the unimpregnated T3 grid. The T2 grid impregnated with epoxy resin showed the highest tensile strength and elastic modulus. Table 2 shows the physical properties of the inorganic matrix used for all FRCMs. The inorganic matrix used a high-strength mortar to improve bonding to concrete and textiles. The binder comprised cement, ground granulated blast furnace slag, and silica fume. EVA polymer and fibers were added to improve the bond strength; the water–binder ratio (W/B) was 37.8%. The flow of the inorganic matrix was 210 mm, with a compressive strength of 66.9 MPa, a flexural strength of 11.2 MPa, and a bond strength of 2.3 MPa.

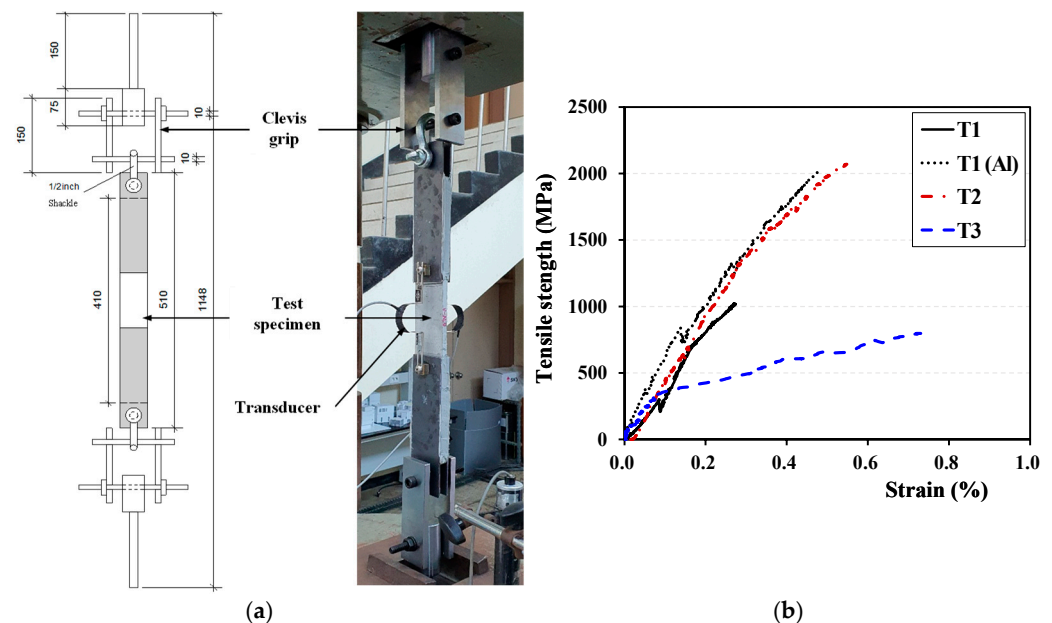
Table 1. Mechanical properties of fibers in warp direction.

Textile Type	Fiber (Warp Direction)	Area (mm ² /yarn)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Ultimate Strain (%)
T1	CF	1.856	1758	147	1.20
T2		1.856	2500	220	1.14
T3		0.856	757	89	1.48

Table 2. Mechanical properties of inorganic matrix.

Mix.	Flow (mm)	Compression Strength (MPa)	Flexural Strength (MPa)	Adhesive Strength (MPa)
FRCM	210.0	66.9	11.2	2.3

Figure 3 and Table 3 show the material properties of FRCM composites measured by a direct tensile test. The direct tensile test was conducted according to AC 434 [3], considering the slip of the inorganic matrix and the textile grid. In addition, a test specimen with aluminum powder applied to the T1 grid was added to confirm the physical properties of the FRCM as a function of the surface treatment of the textile grid. The physical properties showed differences depending on the type of impregnant applied to the textile grid and whether the Al surface coating was applied or not.

**Figure 3.** Direct tensile test setup and result. (a) Test setup; (b) tensile strength–strain relationship.**Table 3.** Mechanical properties of FRCM composites.

FRCM Composite	Type of Textile	A_f (mm)	f_{fu} (MPa)	ε_{fu} (%)	E_f (GPa)	$A_f E_f$ (kN)
T1	V	1.856	1008	0.27	333	618
* T1 (Al)	V	1.856	1949	0.43	398	739
T2	S	1.856	2122	0.52	372	690
T3	C	0.856	757	0.82	89	76

Note * Al: surface coating with aluminum powder; A_f : area of textile grid; f_{fu} : ultimate tensile strength; ε_{fu} : ultimate tensile strain; E_f : elastic modulus after matrix crack.

3.3. Specimen Preparation and Strengthening

In this study, FRCM composites were applied to 10 undamaged RC beams. The fabricated RC beams were cured for 28 days before strengthening. The main strengthening method was the side bond (SB) method; one U-type wrapping (UW) strengthening method was applied for each series. The FRCM composites were strengthened on both sides and at the bottom of the RC beams at the shear span location. The strengthening sequence is shown in Figure 4.



Figure 4. Strengthening methods. (a) Surface cleanup; (b) apply 1st matrix; (c) attaching textile grid; (d) apply 2nd matrix.

(1) The surface to be reinforced was ground to remove foreign matter and washed with water. (2) To improve the adhesion between the FRCM composite and the concrete surface, 3 mm deep stripes were formed at 50 mm intervals. (3) An inorganic matrix with a thickness of 5 mm was first applied to the concrete surface, and the textile grid was attached. (4) After applying 5 mm of inorganic matrix on top of the textile grid, it was sealed with plastic to prevent the evaporation of moisture and cured for 28 days before testing.

3.4. Experimental Test Setup

The strengthened specimen was subjected to a four-point load test in the form of a simple support beam using a Universal Material Testing Machine (UTM) with a capacity of 1000 kN, owned by the Smart Natural Space Research Center (Cheonan in republic of Republic of Korea), as shown in Figure 5. The distance between the load-bearing points was 540 mm; four LVDTs with a displacement capacity of 100 mm were installed at the bottom of the load-bearing points to measure the deflection (δ), and the average value of the deflection was measured. As shown in Figure 1, the strain of longitudinal and transverse reinforcement in the experimental section was measured by attaching strain gauges. The strain of the FRCM was measured by attaching strain gauges directly to the transversely placed fibers of the textile grid between the matrix.

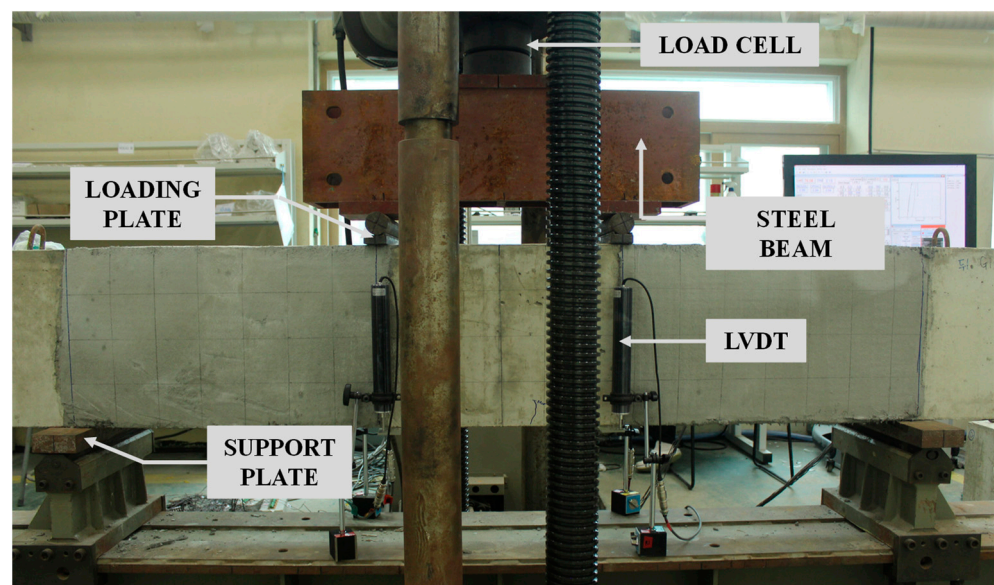


Figure 5. Experimental setup.

4. Experimental Results

4.1. Applied Load vs. Mid-Span Displacement

Figure 6a,b show the center displacement curves for the applied loads of the G1 and G2 series specimens. The maximum load $P_{\max}$ and maximum shear $V_{\max}$ ($V_{\max} = 0.5P_{\max}$, assuming perfect symmetry and ignoring the beam load) and the center displacement $\Delta_{P_{\max}}$ at the maximum load are shown in Table 4. The increase in shear strength (V_f)

due to the strengthening of FRCM composites was calculated as the maximum shear of the reinforced specimen minus the corresponding reference specimen (unstrengthened) and expressed as a percentage. The experimental results in Figure 6 and Table 4 show that the application of FRCM composites increases the shear strength compared to the unstrengthened reference specimen. In addition, the $\Delta_{P_{max}}$ values increased in all the reinforced specimens compared to the corresponding reference specimens. However, the stiffness did not significantly increase.

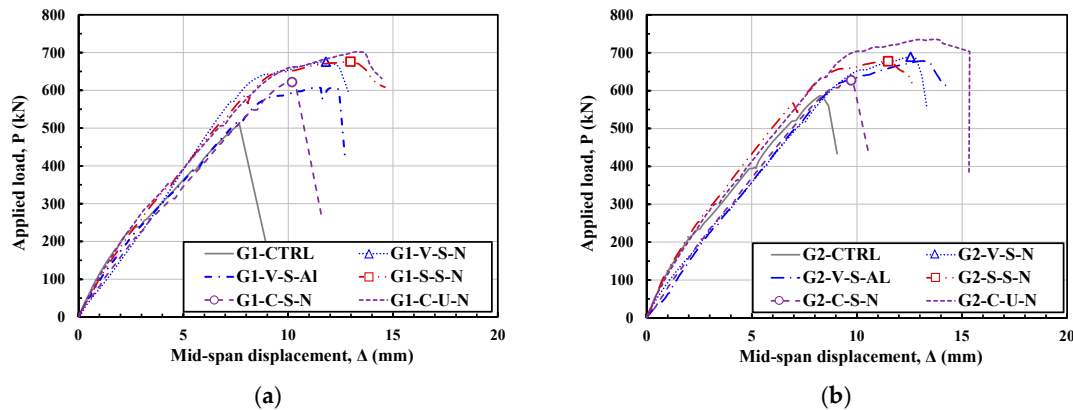


Figure 6. Applied load (P) vs. mid-span displacement (Δ) curves. (a) G1 series; (b) G2 series.

Table 4. Summary of test results.

Series	Beam	ρ_w (%)	ρ_f (%)	P_y (kN)	P_{max} (kN)	V_{max} (kN)	V_{mn} (kN)	V_f (kN)	Gain in V_{max} (%)	$\Delta_{P_{max}}$ (mm)	Failure Mode
G1	G1-CTRL	0.190	-	-	512	256	290	-	-	7.7	S
	G1-V-S-N	0.190	0.055	619	676	338	-	82	32.0	11.7	F
	G1-V-S-AI	0.190	0.055	516	607	304	-	48	18.6	12.2	S.D
	G1-S-S-N	0.190	0.071	509	679	340	-	84	32.6	12.9	F
	G1-C-S-N	0.190	0.034	547	622	311	-	55	21.5	10.2	S.S
	G1-C-U-N	0.190	0.034	597	702	351	-	95	37.1	13.3	F
G2	G2-CTRL	0.285	-	-	586	293	290	-	-	8.3	S
	G2-V-S-N	0.285	0.055	598	690	345	-	52	17.7	12.6	S.S
	G2-V-S-AI	0.285	0.055	495	678	339	-	46	15.7	13.1	F
	G2-S-S-N	0.285	0.071	628	677	339	-	46	15.5	11.5	F
	G2-C-S-N	0.285	0.034	605	628	314	-	21	7.2	9.7	S.S
	G2-C-U-N	0.285	0.034	682	735	368	-	75	25.4	13.7	S.S

Note ρ_w : internal transverse steel reinforcement ratio ($A_w/b \cdot s$); ρ_f : fiber reinforcement ratio per unit length (A_f/b); P_y : yield load of longitudinal rebar; P_{max} : maximum load; V_{max} : maximum shear; V_{mn} : shear strength at design's ultimate flexural moment; V_f : shear strength of FRCM; $\Delta_{P_{max}}$: mid-span displacement at P_{max} ; failure mode (S: shear; F: flexural; S.D: shear debonding; S.S: shear slippage).

4.2. Failure Mode and Concrete Cracking Behavior

The failure modes of the G1 and G2 series beams are shown in Figure 7 and summarized in the 10th column of Table 4. The reference specimens, G1-CTRL and G2-CTRL, exhibited typical beam shear failure, with a major diagonal crack developing in the test section (shear span) (Figure 7a,g). In addition to the main diagonal crack, diagonal cracks were formed and distributed along the test section. For the FRCM-strengthened beams, the G1-V-S-N, G1-S-S-N, G1-C-U-N, G2-V-S-AI, and G2-S-S-N beams exhibited flexural failure due to the compressive failure of concrete in the center of the beam (Figure 7c–e,h,j). As shown in Figure 7, the diagonal cracking of the beam surface in the shear span occurred, but the final failure exhibited flexural failure.

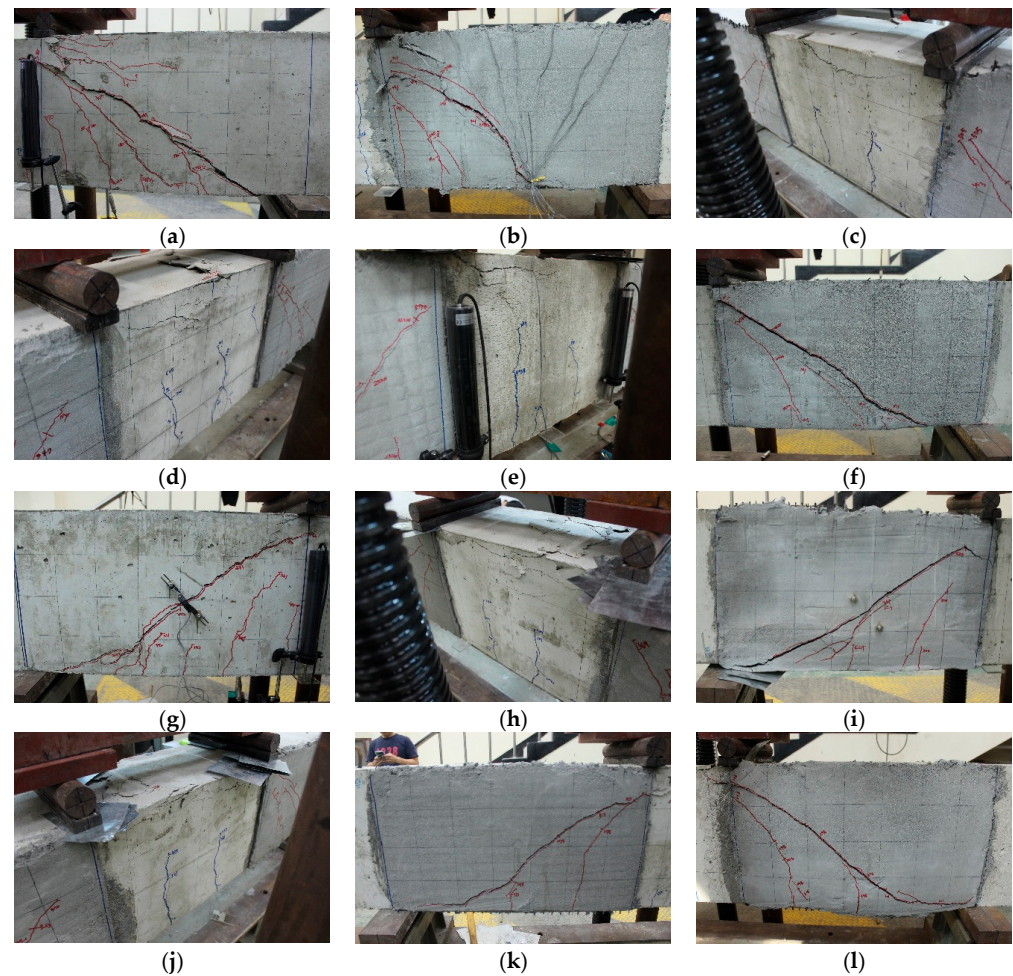


Figure 7. Crack pattern and failure mode of beam. (a) G1-CTRL; (b) G1-V-S-AL; (c) G1-C-U-N; (d) G1-S-S-N; (e) G1-V-S-N; (f) G1-C-S-N; (g) G2-CTRL; (h) G2-V-S-AL; (i) G2-C-U-N; (j) G2-S-S-N; (k) G2-V-S-N; (l) G2-C-S-N.

This is because the difference in the mechanical properties of the textile grid contributed to the increased shear contribution of the FRCM composite, resulting in an increase in shear strength over flexural strength. The FRCM-strengthened specimen that finally failed exhibited typical shear failure due to the development of a major diagonal crack across the shear span from the load point to the support point, the same as the reference specimen. In the G1 series, the G1-V-S-AL specimen with Al powder applied to the surface of the T1 grid showed a high angle of the main diagonal crack and finally failed by matrix delamination at the load point. The G1-C-S-N specimen with the T3 grid developed a main diagonal crack at the same location as the reference specimen and finally failed by the slip of the textile grid and matrix. This difference in failure mode is believed to be due to the difference in bond stress between the matrix and the textile grid depending on the weaving method, impregnation, and surface coating, even for textile grids composed of the same fibers as in previous studies [26]. In the G2 series, the main diagonal cracks of the G2-V-S-N and G2-C-S-N specimens with the T1 and T3 grids occurred at the same location; the G2-C-U-N specimen with U-shaped wrapping showed the same crack behavior.

4.3. Comparison of Measured Stirrup and Fiber Strain

The measured load and strain distributions of the shear reinforcements are shown in Figure 8. The location of the shear reinforcement and the crack behavior at failure are included in this figure for reference. For the G1-V-S-N, G1-S-S-N, G1-C-U-N, G2-V-S-AL, and G2-S-S-N specimens that failed due to flexure, the strain distribution of the stirrup was

analyzed up to the loading stage prior to longitudinal yielding. Strain gauges were attached to all shear reinforcement bars placed in the shear span, as shown in Figure 1, because the crack behavior and final failure location of the concrete were not known in advance. Therefore, in this section, the comparison of stirrup strains is based on the measurements obtained at the same locations for each beam, although it is highlighted that the strain measured by each gauge is affected by the proximity of the gauge to the diagonal cracks.

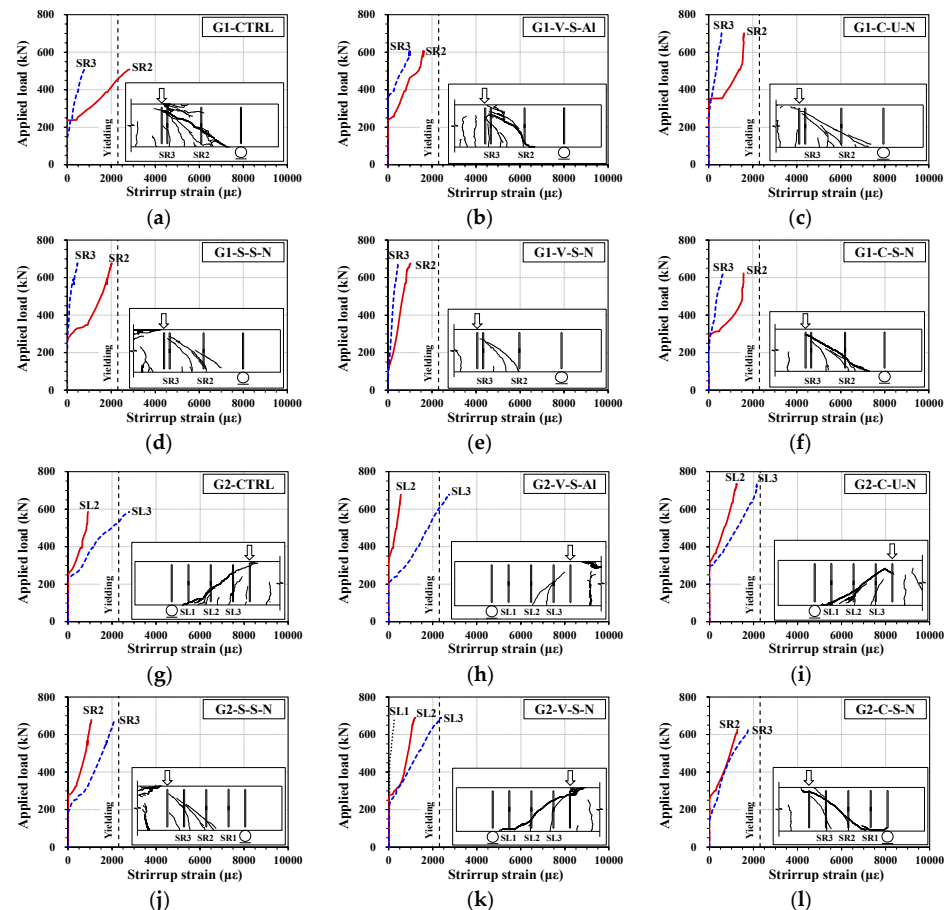


Figure 8. Applied load vs. stirrup strain for all beams. (a) G1-CTRL; (b) G1-V-S-AI; (c) G1-C-U-N; (d) G1-S-S-N; (e) G1-V-S-N; (f) G1-C-S-N; (g) G2-CTRL; (h) G2-V-S-AI; (i) G2-C-U-N; (j) G2-S-S-N; (k) G2-V-S-N; (l) G2-C-S-N.

All specimens showed that the strain in the transverse reinforcement increased after the diagonal crack appeared in the web concrete inside the shear span of the beam, contributing to the shear force. For the G1-CTRL specimen, shown in Figure 8a, the strain in SR2 at the location of the main shear crack penetration reached the yield strain, and the stirrup yielded. SR3, which is close to the tension point, also contributed to the shear. For the G2-CTRL specimen, the shear crack penetrated at SL2 and SL3, but the transverse reinforcement at SL3 was the largest contribution factor to the shear. For this reason, the shear reinforcement ratio (ρ_w) of the G2-CTRL specimen increased by 50%, but the increase in the beam's strength was low at 14%.

The strain distribution of the transverse reinforcement in the FRCC-strengthened specimen was the same as that of the reference specimen, showing a high strain at the point where the main shear crack occurred. However, compared to the reference specimen, the strain of the transverse reinforcement at the same location in the FRCC-strengthened specimen was generally lower. However, the AI powder-coated specimen (G2-V-AI) exhibited a higher strain compared to the reference specimen at low service loads (300 kN). This is thought to be due to the improved mechanical properties of the FRCC due to

the Al powder surface coating (see Table 3), which resulted in a reduction in the shear reinforcements contributing to shear (increasing the shear crack angle). The application of the FRCM resulted in a decrease in the strain of the transverse reinforcement.

The strain distributions for the transverse fibers of the textile grid placed inside the FRCM are shown in Figure 9. The strains in the textile grid of all the strengthened specimens showed the same strain distribution as the strains in the transverse reinforcement, with the strains increasing after the diagonal cracking of the web concrete in the shear span. It was also observed that the strain of the fibers increased at the location of diagonal cracking.

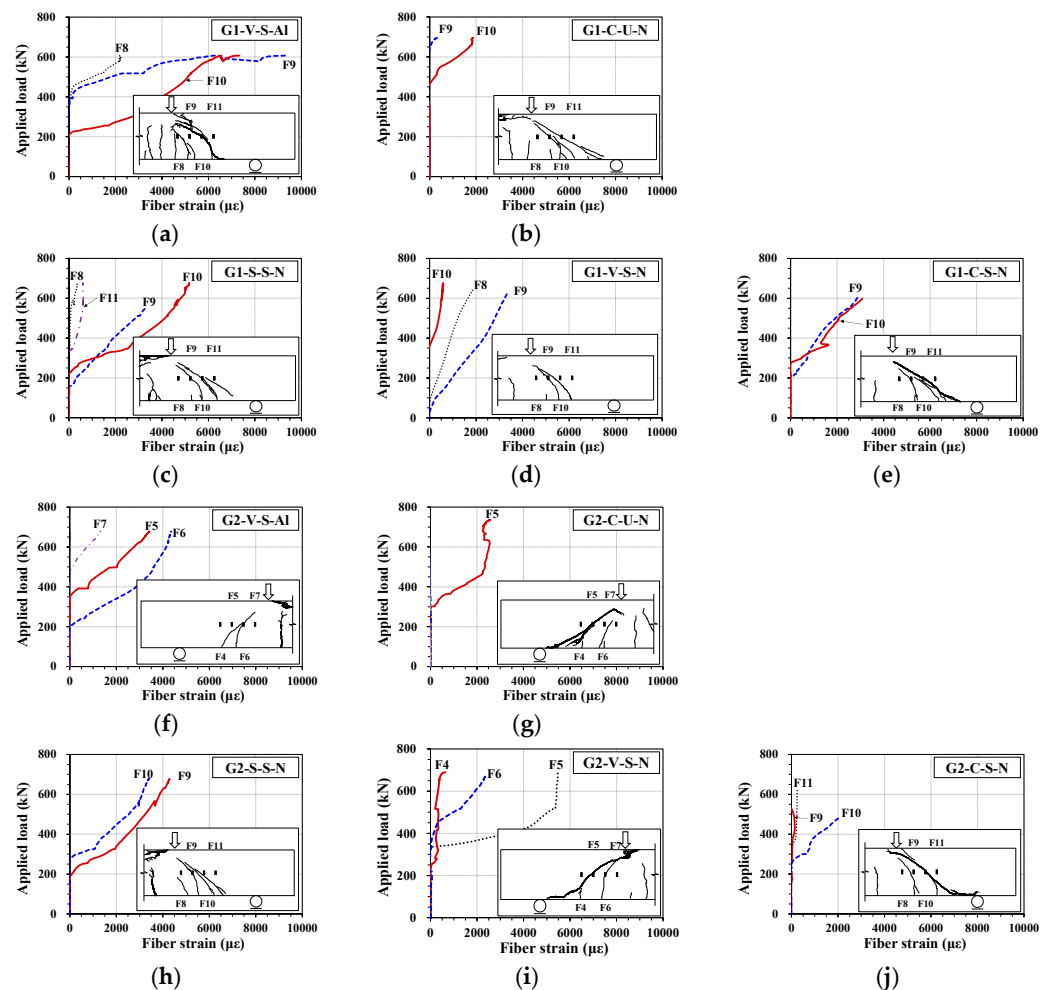


Figure 9. Applied load vs. fiber strain for strengthened beams. (a) G1-V-S-Al; (b) G1-C-U-N; (c) G1-S-S-N; (d) G1-V-S-N; (e) G1-C-S-N; (f) G2-V-S-Al; (g) G2-C-U-N; (h) G2-S-S-N; (i) G2-V-S-N; (j) G2-C-S-N.

As shown in Figure 9c–e, the strain distribution of the textile grid at F10, where the diagonal crack passed through at the applied load before the yielding of the reinforcement in the G1 series, varied depending on the fiber type. The G1-S-S-N specimen with the T2 grid exhibited the largest strain, while the G1-C-S-N specimen with the T3 grid exhibited the smallest strain. This is believed to be due to the difference in physical performance based on the type of fiber impregnation (Figure 3b, Table 3) [26].

In addition, the strain before yield for the G1-V-S-Al grid with Al powder applied to the surface of the T2 grid was higher than that of the G1-S-S-N grid. However, the strain distributions of the G1-C-S-N and G1-C-U-N specimens with different FRCM application methods did not show significant differences. As shown in Figure 9c–e, the strain distribution by grid type in the G2 series showed the same trend as that in the G1 series. However, the G2-V-S-Al specimen with Al powder applied to the T2 grid showed a higher strain

distribution compared to that of the G2-V-S-N specimen without Al powder; however, it was not significantly different from that of the G2-S-S-N specimen. In addition, the strain distributions of all specimens showed lower levels in the G2 series than in the G1 series. This is believed to be due to the increased shear contribution of the shear reinforcements due to the increased number of shear reinforcements [27].

5. Discussion

5.1. Stirrup and FRCM Reinforcement Interaction

Table 5 summarizes the strain values of the shear reinforcement and fibers at the maximum shear ($V = V_{\max\text{-CTRL}}$) of the reference specimens (G1-CTRL, G2-CTRL) and the maximum shear ($V = V_{\max}$) of each specimen. The maximum value of each strain was applied as the strain value corresponding to the shear reinforcement muscle and fiber where the diagonal cracks intersect as the maximum strain rate.

Table 5. Summary of maximum measured strain in stirrups and fibers.

Specimens	Maximum Strain Measured at Maximum Shear of Corresponding Control Beam ($V = V_{\max\text{-CTRL}}$)		Maximum Strain Measured at Maximum Shear ($V = V_{\max}$)		
	$\varepsilon_{s,\max}$ ($\mu\epsilon$)	$\varepsilon_{f,\max}$ ($\mu\epsilon$)	$\varepsilon_{s,\max}$ ($\mu\epsilon$)	$\varepsilon_{f,\max}$ ($\mu\epsilon$)	$\varepsilon_{f,\max}/\varepsilon_{fu}$ (%)
G1-CTRL	2439	-	2439	-	-
G1-V-S-N *	689	2842	1027	3344	27.9
G1-V-S-Al	1106	5184	1620	7334	61.1
G1-S-S-N *	1676	4254	2023	5174	43.1
G1-C-S-N	1528	2142	1583	3036	20.5
G1-C-U-N *	1429	298	1614	1825	12.3
G2-CTRL	2782	-	2782	-	-
G2-V-S-N	1743	5417	2382	5475	45.6
G2-V-S-Al *	2181	4079	2756	4365	36.4
G2-S-S-N *	1840	3817	2116	4295	37.7
G2-C-S-N	1575	2140	1763	2140	14.5
G2-C-U-N	1660	2496	2173	2583	17.5

* Failed in flexure.

Based on the results presented in the second column of Table 3, the maximum strains measured in the shear reinforcements of the FRCM-reinforced beams at the load level corresponding to $V_{\max\text{-CTRL}}$ are significantly lower than those measured in the reference specimens. In addition, for the G1 series, the strain in the shear reinforcement at $V_{\max}$ of each FRCM-reinforced beam did not reach the yield strain, as in previous studies [23,27], confirming the interaction between the shear reinforcement and FRCM. In contrast, the strain of the shear reinforcement at $V_{\max}$ in the G2 series showed values close to the yield strain, and in the case of the G2-V-S-N specimen, the yield strain was reached. This suggests that the shear reinforcement ratio may be a factor affecting the interaction with the FRCM.

In addition, the sixth column of Table 5 shows the ratio of the fiber strain ($\varepsilon_{f,\max}$) measured at $V_{\max}$ to the maximum strain at the limit presented in Table 1, as well as the effective utilization ratio ($\varepsilon_{f,\max}/\varepsilon_{fu}$). Only the specimens that finally failed in shear are compared here.

The results in Table 5 show that there is a difference in the effective utilization rate of the fiber depending on the type of textile grid applied to the FRCM. Also, there is no difference between SB (G2-C-S-N) and UW (G2-C-U-N).

5.2. Influence of Composite Type

As shown in the ninth column of Table 4, the different types of textile grids applied to the FRCMs showed differences in beam reinforcement performance. To compare the reinforcement performance of different types of textile grids, axial stiffness ($A_f E_f$) was

considered. However, it should be noted that the axial stiffness comparison does not take into account complex phenomena such as composite adhesion behavior, adhesion length, and effective adhesion length, which affect the contribution of the FRCM to the shear strength and failure mode of the reinforced beam.

Figure 10 shows the ratio of reinforcement performance (V_f/V_{CTRL}) to the axial stiffness ($A_f E_f$) of the shear fractured specimen. $A_f E_f$ was calculated based on the direct tensile test results of FRCM composites, as shown in Table 3.

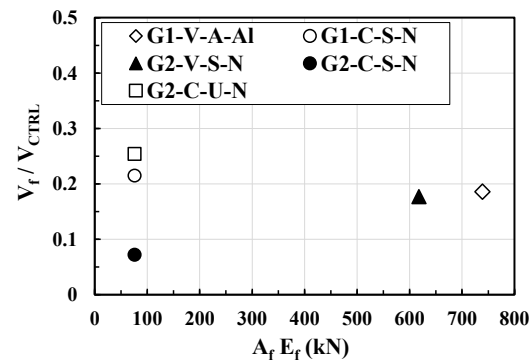


Figure 10. Variation in V_f/V_{CTRL} with $A_f E_f$.

Although the number of compared specimens is small because the bending failure specimens were excluded, the reinforcement performance ratio of the G2-V-S-N specimen with the T1 grid is about 2.4 times higher than that of the G2-C-S-N specimen with the T3 grid. These results show the same trend as the values of $\varepsilon_{f,max}$ (G2-V-S-N: 5475 $\mu\epsilon$, G2-C-S-N: 2140 $\mu\epsilon$), which is the maximum strain measured at the time of maximum load, shown in Table 5.

5.3. Effect of Stirrup Spacing

Previous studies have shown that the contribution of FRCMs to the overall shear strength of FRCM-reinforced beams is influenced by the shear reinforcement ratio (ρ_w). The shear strength contribution of FRCMs is expected to be lower for beams with higher ρ_w . Figure 11 shows the ratio of reinforcement performance to the shear reinforcement ratio for the shear-failed specimens. Although it is difficult to draw conclusions due to the small number of shear failure specimens, the reinforcement performance ratio of the G2-C-S-N specimens is lower than that of the G1-C-S-N specimens. This result is consistent with the comparison of the shear reinforcement strain ($\varepsilon_{s,max}$) at the maximum shear capacity (V_{max}) shown in Table 5, which is likely to reflect the effect of the interaction between the shear reinforcement and the FRCM described in Section 4.1. However, this effect needs to be further investigated due to the small number of specimens with shear failure.

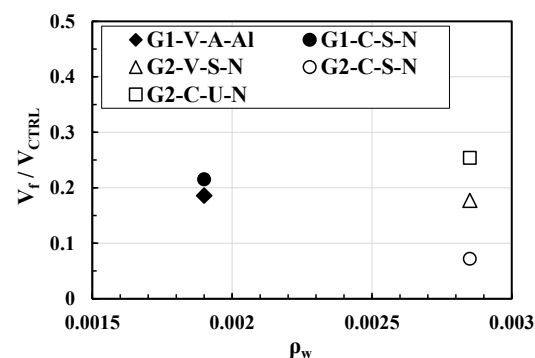


Figure 11. Variation in V_f/V_{CTRL} with ρ_w .

6. Conclusions

This paper presents the results of an experimental study conducted to investigate the behavioral characteristics of RC beams shear-strengthened with FRCM composites by external bonding. The experimental variables included the type of textile grid, shear reinforcement ratio, and application method. The main conclusions drawn from this study are as follows.

- (1) Shear failures in FRCM-strengthened beams were caused by the sliding of the textile grid along the main diagonal crack after the yielding of the longitudinal reinforcement, except for the G1-V-S-A1 specimen with a T1 (A1) grid (localized debonding failure).
- (2) The experimental results showed that the shear strength of FRCM-strengthened beams varied with the type of textile grid and increased with the increase in axial stiffness ($A_f E_f$), which is a physical property.
- (3) The strengthening effect of FRCM composites confirmed that, due to the large spacing of shear reinforcement rods, the reinforcement performance against shear (V_f) increased the most in the reinforced beam with a low internal shear reinforcement ratio.
- (4) The strain distributions of the transverse reinforcement and FRCMs confirmed that an internal–external shear reinforcement interaction was observed in all reinforced beams, with differences depending on the shear reinforcement ratio (ρ_w) and the type of textile.
- (5) The effective utilization rate ($\varepsilon_{f,max} / \varepsilon_{fu}$) for each type of textile grid was the lowest for T3 grids with worse mechanical properties; the effective utilization rate increased at a lower shear modulus (ρ_w). However, there was no significant difference in application method (SB, UW).

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