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Shear Performance of the Interface of Sandwich Specimens with Fabric-Reinforced Cementitious Matrix Vegetal Fabric Skins

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Featured Application: The design and manufacturing of sandwich solutions using FRCM vegetal fabric skins improve sustainability because they provide solutions with a lower global carbon footprint.

Abstract: The utilization of the vegetal fabric-reinforced cementitious matrix (FRCM) represents an innovative approach to composite materials, offering distinct sustainable advantages when compared to traditional steel-reinforced concrete and conventional FRCM composites employing synthetic fibers. This article introduces a design for sandwich solutions based on a core of extruded polystyrene and composite skins combining mortar as a matrix and diverse vegetal fabrics as fabrics such as hemp and sisal. The structural behavior of the resulting sandwich panel is predominantly driven by the interaction between materials (mortar and polyurethane) and the influence of shear connectors penetrating the insulation layer. This study encompasses an experimental campaign involving double-shear tests, accompanied by heuristic bond-slip models for the potential design of sandwich solutions. The analysis extends to the examination of various connector types, including hemp, sisal, and steel, and their impact on the shear performance of the sandwich specimens. The results obtained emphasize the competitiveness of vegetal fabrics in achieving an effective composite strength comparable to other synthetic fabrics like glass fiber. Nevertheless, this study reveals that the stiffness of steel connectors outperforms vegetal connectors, contributing to an enhanced improvement in both stiffness and shear strength of the sandwich solutions.

Keywords: sandwich panels; FRCM; cementitious matrix; vegetal fibers; shear test

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1. Introduction

Sandwich panels crafted with concrete skins and insulating cores are a competitive solution for building structural components with energy-efficient added value (see a review in Oliveira et al.) [1]. The concern about climate change and sustainable solutions drives research towards greener and more bio-based engineering sandwich technologies according to Oliveira et al. [2]. In the present work, a solution based on the vegetal FRCM and polystyrene core serves as a lightweight construction solution with noteworthy insulating properties for building enclosures. The mechanical properties of these panels depend significantly on the composite action between materials. An adequate material connection is crucial, as insufficient bonding may result in a problematic stress distribution within the panel, potentially causing detachment failure or a substantial decrease in mechanical strength.

In this order, different authors like Cox et al. [3] developed a composite shear connector system of a glass-fiber-reinforced polymer (GFRP) used to transfer interface shear forces in a precast concrete sandwich panel. This study developed push-off, pullout, and flexural tests to evaluate the structural performance of the shear connectors, and the effect of the bond between concrete and insulation was evaluated with push-off tests. The results showed satisfactory performance with a lower bound of 90% of composite action for specimens with a 100 mm thick insulation wythe and full composite action for most panels with 50 mm thick insulation. Pantano et al. [4] studied a numerical model by evaluating zig-zag functions by enforcing the continuity of transverse shear stresses at layer interfaces, being able to predict accurately the distribution of stresses and displacements in laminated plates and sandwich panels. Another study by Portal et al. [5] presented experimental and numerical methods to analyze the structural behavior related to a sandwich panel with a glass-fiber-reinforced polymer (GFRP) plate connection system, where double-shear tests were conducted on sandwich specimens to characterize the available shear capacity provided by the connectors and panel configuration. The authors conclude that for well-balanced composite action, it is necessary to use the least amount of material in the plate connectors and an increased amount of bending capacity of the outer panel to avoid a significant drop in the load after the peak load. At the same line, Hulin et al. [6] presents an experimental campaign at elevated temperatures for panels stiffened by structural ribs, insulation layers, and steel shear connectors. The results highlighted insulation shear failure from differential thermal expansion at the interface with concrete, where the shear connectors induced stress concentrations, leading to local failure. A study presented by Tomlinson et al. [7] carried out push-through tests on a precast-concrete-insulated sandwich panel using combined angled and horizontal connectors, where basalt-fiber-reinforced polymer and steel connectors were used. This study evaluated various connector inclination angles and diameters, diagonal connector orientations relative to the loading, and panels with or without an active foam-to-concrete bond. The results show that steel connectors failed by yielding in tension and inelastic buckling in compression. In the case of larger-diameter basalt-FRP connectors, they pulled out under tension and crushed in compression, and smaller-diameter basalt-FRP connectors ruptured in tension and buckled in compression. Also, it is demonstrated that the strength and stiffness improved with the connector angle and diameter. Lou et al. [8] performed 24 double-shear tests on precast-concrete-insulated sandwich panels using stainless-steel plate connectors. The authors analyzed parameters like connector directions, insulation effects, cavity widths, and connector heights. The authors developed a consistent campaign with in-plane and out-of-plane shear tests and concluded that the cavity size and the presence of insulation significantly contributed to shear transfer. Choi et al. [9] analyzed some precast concrete sandwich panels used for exterior cladding. Specimens were experimentally tested with a push-out test, with and without corrugated shear connectors. The investigation of the in-plane shear performance showed a relevant impact of the core material in the structural response. And later, Choi et al. [10] extended the study of the shear flow to the type of connectors. There are other relevant contributions about the shear performance of sandwich insulation panels using other types of tests like Sylaj et al. [11], Hou at al [12], Meng et al. [13], or Wang et al. [14].

To advance towards the utilization of more sustainable materials compared to synthetic fibers and steel, the present study concentrates on the creation of sandwich panels comprising a vegetal FRCM and expanded polystyrene as insulation. Authors have previously presented other complementary studies about FRCM vegetal fibers (see Mercedes et al. [15,16]) and some bending tests for sandwich FRCM solutions (see Mercedes et al. [16]). For the present work, the innovation lies in the use of vegetal FRCM skins and the introduction of flexible connectors made from vegetal fibers. The connection between layers is a must to have the necessary mechanical properties to develop composite materials that are competent with those commonly used in the construction industry. In this study, sandwich specimens were created using different fabrics (hemp, sisal, and glass) and connectors (hemp, sisal, and steel). These specimens underwent a double-shear test to examine how these fabrics and connectors influence the panel's strength against shear.

Additionally, a simplified connector slip-load model was developed and compared to the experimental results.

2. Materials and Methods

The experimental campaign included the manufacturing of specimens of FRCM bonded to an extruded polystyrene core and shear tests. These specimens were produced using the following specific procedures and materials.

2.1. Mortar

To manufacture the FRCM component, a thixotropic commercial mortar was used. This mortar is a single-component mixture comprising cement, synthetic resins, and polyamide fibers, with the addition of silica fume. The choice of this mortar was based on its proven effectiveness in previous studies such as Mercedes et al. [15]. The average results of the compression and flexion tests using norm EN1015-11:2000 [17] have been previously presented in the cited work with values of 39.25 MPa and 6.56 MPa, respectively.

2.2. Fabrics

Two types of vegetal fabrics and another type of synthetic fiber were used to manufacture the FRCM part: hemp, sisal, and glass (contrast material).

Vegetal fabrics were crafted using hemp and sisal yarns (both with a diameter of 2.5 mm). This arbitrary choice was justified by the notable tension levels achieved by hemp and sisal FRCM specimens in a prior study by Mercedes et al. [18]. In that study, the fabrics and yarns were coated with epoxy resin. This was performed to prevent fiber degradation produced by the environment of cementitious matrix composites (high alkalinity and humidity cycles) (see Ardanuy et al.) [19].

The size of the free cells in the grids of vegetal fabrics was determined by referencing the geometry of a commercial glass fabric (see Figure 1). In the case of vegetal fabrics, it was necessary to craft meshes with a greater volume of material to achieve the load capacity of glass fabrics, producing thicker meshes than synthetic ones. Two yarns were utilized for each tuft, underscoring the fact that the tensile strength and effectiveness were comparable to synthetic fiber meshes just by simply increasing the volume of vegetal fibers.

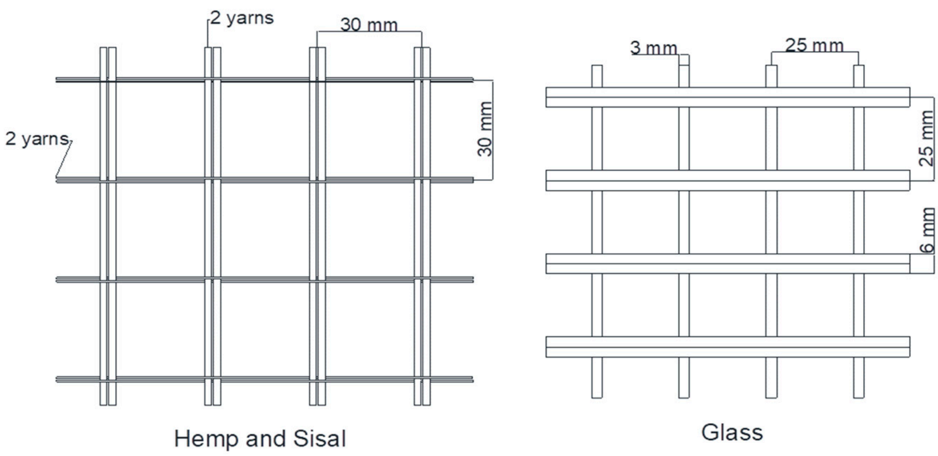

Figure 1. Reinforcing fabrics geometry: hemp and sisal (**left**); glass (**right**).

Weft yarns of hemp and sisal fabric were made of hemp yarns of 0.5 mm in order to reduce the thickness of the weft and wrap crossing point, and because the load capacity in the weft direction was not relevant for the shear test setup used in this study.

The fabrics were woven (Figure 2) with the same procedures used in Donnini et al. [20] and D'Antino et al. [21]. After one day of curing, the meshes were cut into pieces with dimensions of 45 mm × 35 mm.

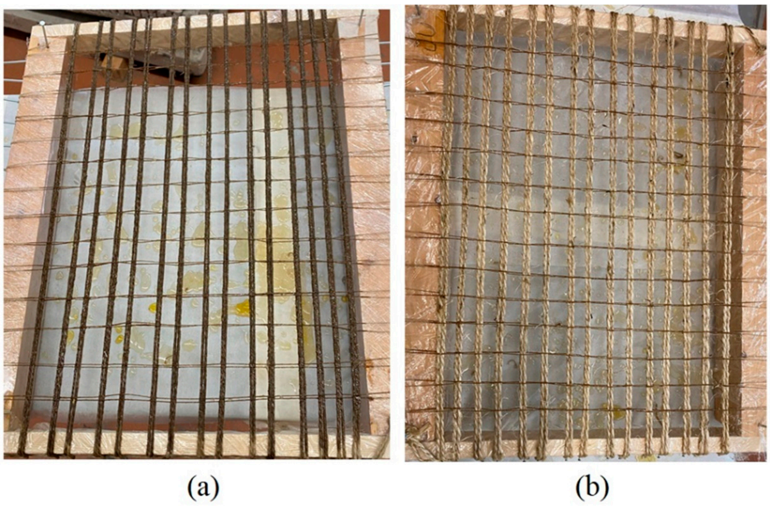

Figure 2. Vegetal fabric preparation: (**a**) hemp fabric and (**b**) sisal fabric.

The mechanical properties of the tuft (two yarns in the vegetal fabrics case) are shown in Table 1. The coated tuft data were obtained experimentally in this study using the tensile test procedure using norm EN ISO 13934-1/2 [22].

Table 1. Tuft properties ((%) = coefficient of variation, A_f = fiber area F_{fu} = maximum load mean, σ_{fu} = tensile strength mean, E_f = Young's modulus mean, ε_{fpick} = deformation peak mean).

Fibres	**Number of Test**	**A_f (mm^2)**	**F_{fu} (N)**	**σ_{fu} (MPa)**		**E_f (GPa)**		**ε_{fpick} (%)**	
Hemp	5	9.81	1701.00	173.35	(3%)	8.59	(11%)	1.45	(16%)
Sisal	5	9.81	1467.00	137.25	(16%)	4.87	(36%)	2.31	(14%)
Glass	5	1.05	708.00	668.50	(8%)	61.25	(2%)	1.32	(6%)

2.3. Connectors

To assess the impact of connectors on the shear behavior of FRCM bonded to an extruded polystyrene core, connectors of hemp, sisal, and steel were used. Hemp and sisal were selected as they are the vegetal fibers used in this study for crafting vegetal fabrics, while steel was chosen as it is the most commonly commercial material used for connectors in such types of sandwich solution.

Vegetal fiber connectors were crafted hook-shaped and impregnated with epoxy resin, featuring an equivalent area of 29.43 mm^2 (6 yarns). Steel connectors were in the shape of a pin or bolt with a cross-sectional area of 0.79 mm^2, accompanied by a nut at one end to enhance the anchoring effect with the mortar (see Figure 3).

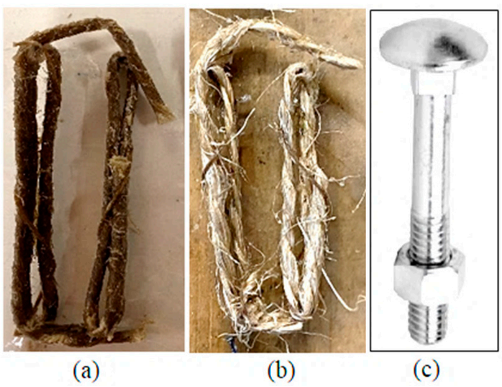

Figure 3. Types of connectors: (**a**) hemp, (**b**) sisal, (**c**) steel.

2.4. Extruded Polystyrene

Rigid extruded polystyrene foam boards with a thickness of 40 mm were used as the insulating core in the sandwich sample configuration.

2.5. Specimens

The experimental program included 40 specimens. The specimens consisted of a sandwich panel combining FRCM and extruded polystyrene, following the geometry in Figure 4.

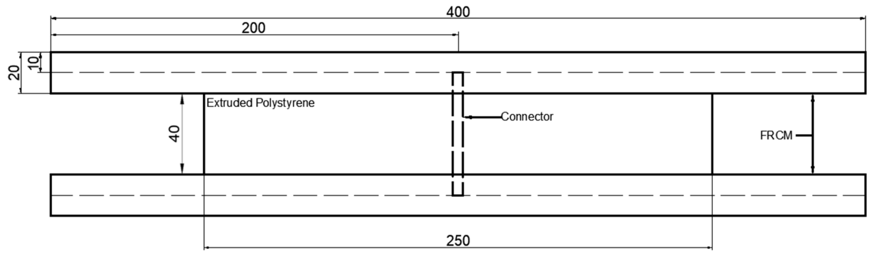

Figure 4. Specimen geometry in mm.

The dimensions of the FRCM were 50 × 400 mm with a thickness of 20 mm. These 40 samples included 3 different connectors (steel, hemp, and sisal) and 3 different reinforcement fabrics (hemp, sisal, and glass).

The mold to manufacture the FRCM specimens was prepared with a grid of wooden strips with 50 mm × 400 mm gaps (see Figure 4). These strips had a height of 20 mm. The manufacturing procedure was as follows:

- Prepare the mold base with a demolding agent (Figure 5a).
- Mix the mortar and pour it to a depth of approximately 15 mm.
- Place the fabric so that it slightly penetrates the first mortar layer (Figure 5b).
- Cover the fabric with a second layer of mortar to reach a thickness of 20 mm for the bottom FRCM layers.
- Place the extruded polystyrene boards. In the case of specimens with connectors, it has a hole in the middle.
- Place the mold of the other wooden strips (without a base) in the same location as the first mold.
- Add a third layer of mortar to reach the final thickness.
- Place the second fabric so that it slightly penetrates the first layer of mortar.
- For panels with connectors, place the connectors so that the top is above the fabric.
- Cover the second fabric (and connectors) with a fourth layer of mortar to reach a thickness of 20 mm for the top FRCM layers.
- Demold and leave samples to cure in laboratory conditions for 28 days. After this period, the specimens are ready for testing (Figure 5c).

The nomenclature used to identify the specimens is provided in Table 2.

Table 2. Nomenclature of sandwich panels.

Specimen	Fibres	Connectors	Numbers of Samples
SH-N	Hemp	Without	5
SH-H	Hemp	Hemp	5
SH-S	Hemp	Sisal	5
SH-St	Hemp	Steel	5
SS-N	Sisal	Without	5
SS-S	Sisal	Sisal	5
SG-N	Glass	Without	5
SG-St	Glass	Steel	5

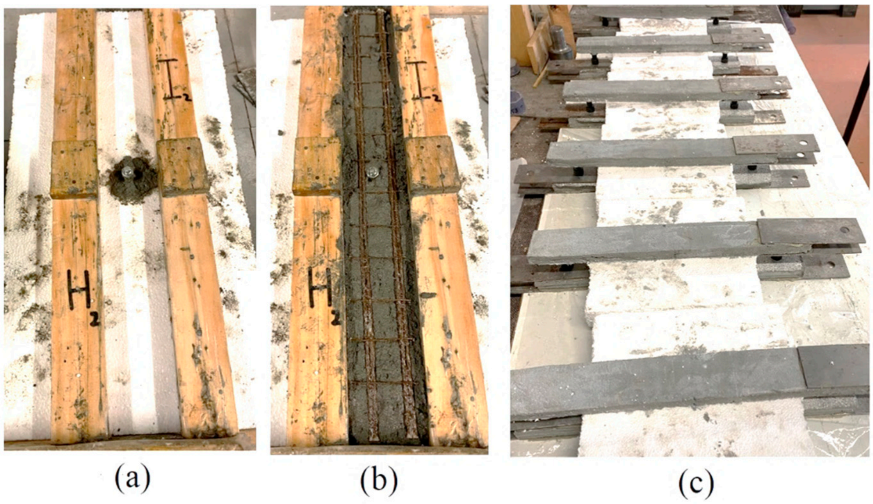

Figure 5. Manufacturing of sandwich panels: (**a**) mold, (**b**) fabric with steel connector and first layer of mortar, (**c**) final specimen.

3. Experimental Campaigns

3.1. Test Setup and Instrumentation

The specimens were subjected to a double-shear test (see Figure 6). In this test, metal plates (similar to those used in tension tests) were bonded to one end of the FRCM on each side of the sandwich specimen. This shear test is an adaptation inspired by the tension test with the clevis system according to AC434-0213-R1 [23]. In this configuration, auxiliary plates of aluminum were attached externally on opposite sides of the load application, simply to prevent the turning of the specimens during the test. An electromechanical press (MTS Insight 10 kN range) was used to perform the tests with a test rate of 2 mm/min.

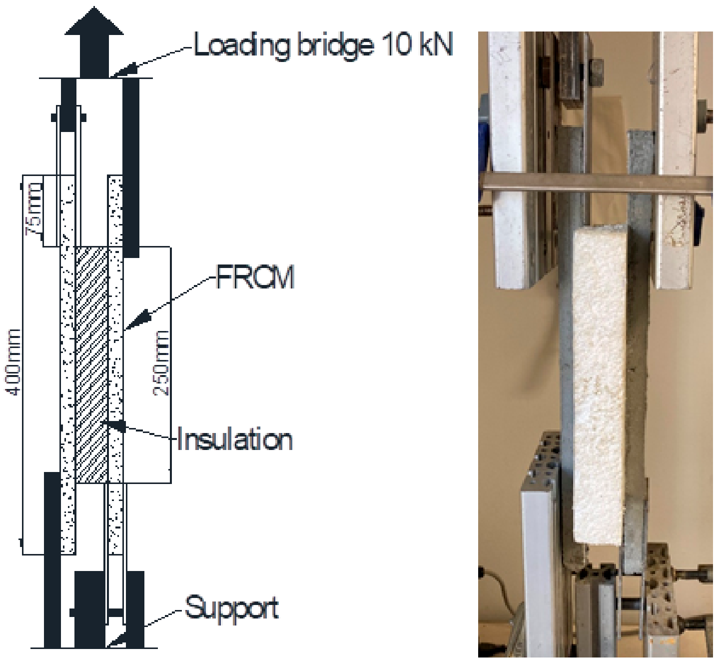

Figure 6. Double-shear test setup.

3.2. Type of Failures

In general, all the specimens had peeling failure because polystyrene is a low-strength material. Nevertheless, in the case of the samples with connectors, there was also a slippage of the connectors accompanied by the detachment of the mortar in the connector area, in some cases. Consequently, specimens with connectors displayed more cracking and ductile failure compared to the sudden and brittle failure observed in specimens without connectors (Figure 7).

(a) (b)

Figure 7. Type of failures: (**a**) peeling failures, (**b**) peeling failures and connector slipping.

3.3. Experimental Results

Table 3 shows the experimental results of the maximum load and shear stress (Fmax and τmax, respectively), the elastic stiffness (Ke), and the shear modulus (Ge) obtained from the linear stage in the load–displacement diagrams. Also, the following table presents the displacement (δmax) and angular distortion (δmax/te) at the maximum load, where te is the distance (60 mm) between the fabric embedded in the FRCM skins. To calculate the shear stress and shear modulus, the shear value from the dethatched FRCM skin (50 × 250 mm) was used.

Table 3. Experimental results.

Specimen	F_{max} (N)	τ_{max} (MPa)	C.V	K_e (N/mm)	G_e (MPa)	C.V	δ_{max} (mm)	δ_{max}/t_e (%)	C.V
SH-N	1409.20	0.11	(12%)	467.94	1.87	(10%)	4.85	9.70	(23%)
SH-H	1694.60	0.14	(6%)	601.05	2.40	(19%)	5.49	10.98	(21%)
SH-S	1684.40	0.13	(14%)	537.22	2.15	(15%)	4.50	9.01	(31%)
SH-St	2151.20	0.17	(8%)	653.73	2.61	(13%)	7.04	14.08	(22%)
SS-N	1369.75	0.11	(9%)	432.29	1.73	(7%)	4.89	9.79	(19%)
SS-S	1543.40	0.12	(9%)	479.70	1.92	(12%)	7.21	14.41	(24%)
SG-N	1340.40	0.11	(10%)	487.95	1.95	(7%)	5.60	11.19	(47%)
SG-St	1333.25	0.11	(12%)	608.29	2.43	(18%)	4.41	8.81	(40%)

The results in Table 3 show coefficients of variation ranging between 2 and 14% for maximum load and shear strength, respectively, indicating the good repeatability of the experiments, following Donnini and Corinaldesi [20]. It is noteworthy that specimens without connectors presented a similar shear strength. However, for stiffness and displacements, the variation was higher, ranging between 7 and 47%. This variability represents the expected scattering of data for elements composed of cementitious materials with a high non-linear behavior. The results presented in Table 3 are better appreciated in Figures 8–11.

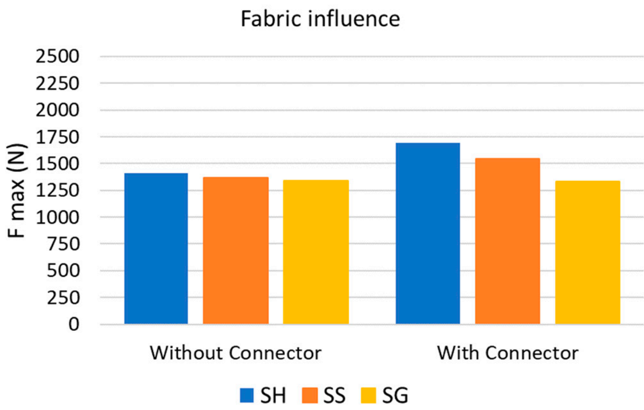

Figure 8. Fabric influence: maximum load.

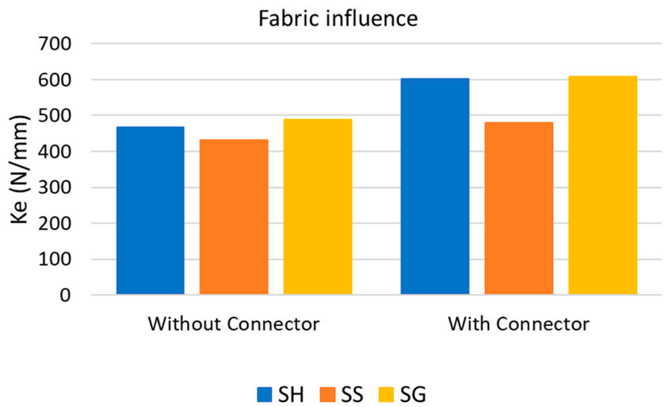

Figure 9. Fabric influence: elastic stiffness.

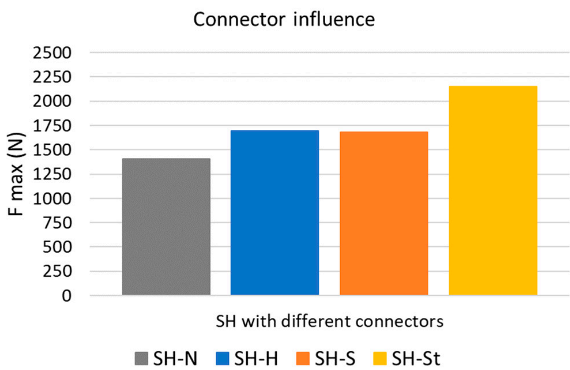

Figure 10. Connector influence: maximum load.

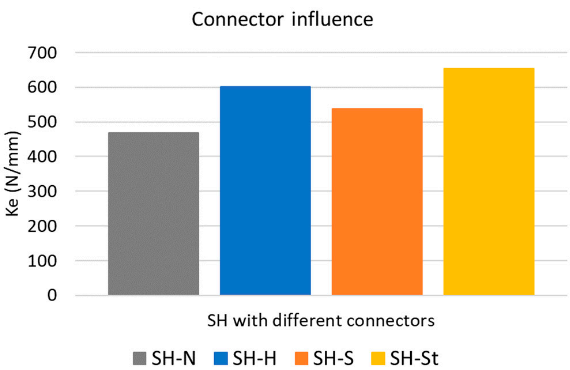

Figure 11. Connector influence: elastic stiffness.

Figures 8 and 9 show the impact of the fabric on the maximum load and elastic stiffness of the specimens. The performance of different fabric types remains consistent for both maximum load and stiffness values, regardless of the presence of connectors. Concerning maximum load, the inclusion of connectors significantly enhances the capacity for vegetal specimens, ranging from 13% to 53%. However, there is no notable change for glass fabric. This suggests that the FRCM skin may not reach the cracking strength required to activate the glass fabric, unlike what occurs with vegetal fabrics. Nevertheless, connectors play a beneficial role in maintaining cohesion between materials, activating vegetal fabrics at the achieved level of strain until significantly producing a higher ultimate load.

In terms of elastic stiffness, the response of the FRCM sandwich is directly tied to the Young's modulus of the fabric—a stiffer fabric correlates with higher specimen stiffness. Despite glass fabric being seven times stiffer than hemp fabric, this stiffness difference is not prominently reflected in the specimens. This is due to the initiation of non-linear behavior in the core deformation for low values of FRCM strain, minimizing the activation of fabric capacity in the composite and resulting in negligible stiffness differences.

Connectors prove efficient in ensuring strain compatibility among components, leading to an increase in stiffness values ranging from 11% to 40%. Although the influence of connectors during the elastic phase is minimal compared to the effect over the ultimate load, they play a crucial role in maintaining overall specimen compatibility.

Figures 10 and 11 illustrate the impact of the type of connector on the maximum load and on elastic stiffness for the hemp fabric specimens. The presence of connectors, independently of their material, increases both the maximum load and the elastic stiffness. The steel connector reaches the highest load and the highest stiffness. Therefore, the presence of stiff connectors maintains the strain field and the compatibility between layers in a more efficient manner than flexible vegetal connectors. The difference in stiffness between the fabric and the steel connector seems to not be a disadvantage, even though some local damage takes place in the mortar because of the concentration effects of the steel bolt.

Figures 12–16 show the load–displacement plots of the tested panels. It can be seen that specimens without connectors exhibit a quasi-brittle failure with a limited range of deformation (dashed lines) compared to specimens with connectors (continuous line). The presence of connectors enhances the activation of vegetal fabrics, effectively tightening the interfaces between materials and contributing to an increased strength of the sandwich structure. In the case of glass, the levels of strain are low in the FRCM and the fabric is not activated; therefore, there is no large difference in the load–displacement plots.

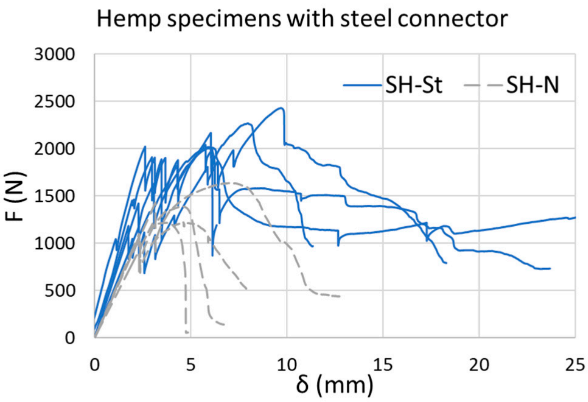

Figure 12. Load–displacement curves of SH-St compared with SH-N.

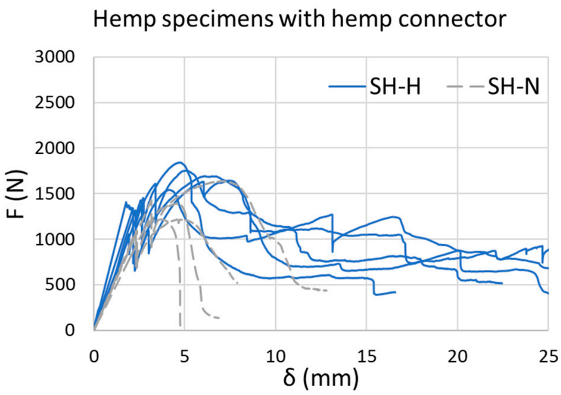

Figure 13. Load–displacement curves of SH-H compared with SH-N.

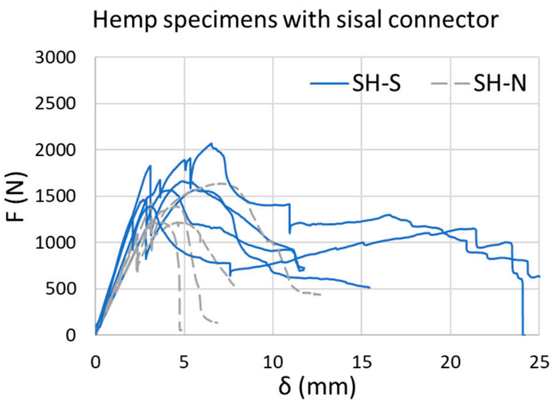

Figure 14. Load–displacement curves of SH-S compared with SH-N.

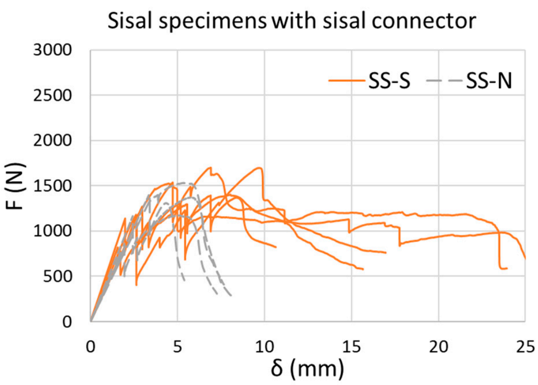

Figure 15. Load–displacement curves of SS-S compared with SS-N.

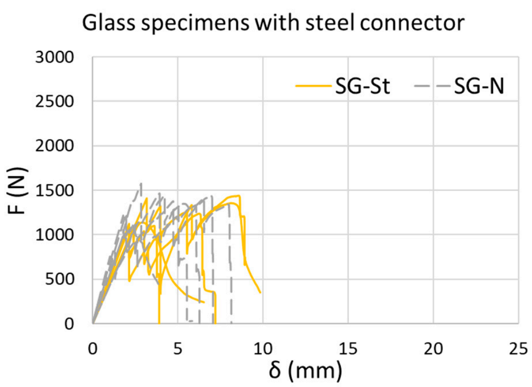

Figure 16. Load–displacement curves of SG-St compared to SG-N.

4. Connectors' Interlock-Slip Simplified Model

According to the experimental results, it is worth building a simple model to easily generate pre-dimension solutions for FRCM sandwich panels. Therefore, it is necessary to estimate the contribution of the connectors to the response of the structure. The problem is very complex, involving the nonlinear behavior of FRCM skins, interface interactions among materials, and debonding and slipping failure. A real model is far from the scope of the contribution. Nevertheless, a rough approach might take advantage of the comparison between the response of specimens without connectors and those with connectors. Therefore, in a simple manner:

$$\text{Fmax} = \text{Fmax\_none\_connector} + \text{Fmax\_connector}$$

From Table 3 and the plots of Figures 12–14, it is feasible to estimate the contribution of the interface of the FRCM and polystyrene. To study the effect of the connector, only hemp FRCM specimens (SH) were used because they contain all type of samples.

The connectors interact, exhibiting a bi-linear behavior. Each one interacts, increasing its contribution until the maximum load is reached, while after, they are capable of maintaining it without a significant reduction, due to its stiffness.

As stated in Figure 11, steel connectors showed the highest stiffness, followed by hemp and finally sisal connectors. This property explains the reason why steel connectors are those that contribute more significantly to the shear strength of the specimen, providing a contribution 165% more than the vegetal connectors. Hemp and sisal show a similar contribution, due to their similar mechanical properties seen in Table 1.

Therefore, Figure 17 estimates the connector contribution.

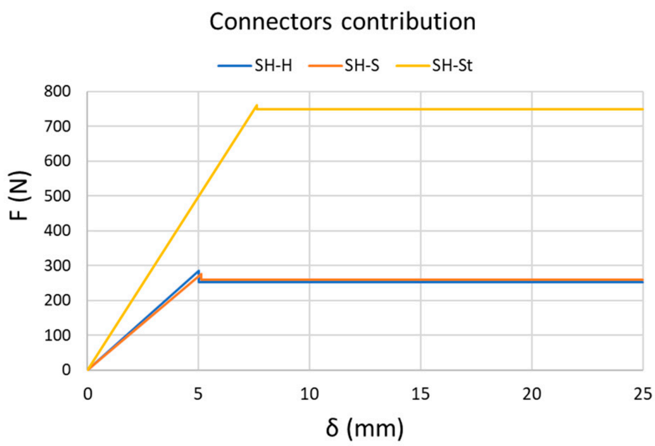

Figure 17. Connectors' contribution.

5. Conclusions

In this work, an experimental and analytical study was conducted to investigate the shear performance of a sandwich specimen with a vegetal-FRCM and polystyrene. According to the achieved results:

- All specimens experienced a peeling failure. However, specimens with connectors exhibited additional slippage of the connectors, resulting in more cracking and ductile failure compared to the fragile failure observed in specimens without connectors.
- The results showed that there was no significant influence of the kind of fabric in the maximum load of the specimen without the connector. This took place because the FRCM skin did not reach the cracking level required for the fabric to be activated and effectively contribute to the strength.
- In the case of the specimens with connectors, the levels of maximum loads and elastic stiffness were both increased. Vegetal fabrics were effectively activated by the cracking

while glass was very little activated. Therefore, the comparative performance produced a more ductile response in vegetal fabrics, due to their elongation capacity.

- All the types of connectors increased the maximum load and elastic stiffness of the sandwich specimens. The steel connector reached the highest maximum load and elastic stiffness. Hence, stiff connectors produced a tightening effect between the layers of materials, and the higher the stiffness in connectors, the higher the sandwich response.
- An interlock-slip model based on experimental evidence showed the potential to design FRCM solutions for sandwich applications with connectors. It showed that the connector contributes significantly.

The key findings indicate that FRCM vegetal fibers demonstrated mechanical competitiveness when compared to glass fiber. Sandwich solutions require connectors to enhance the mechanical capacity and, in this specific instance, steel connectors exhibit a more efficient performance than vegetal connectors. Therefore, future improvements could focus on designing vegetal connectors with increased stiffness and conduct additional tests to develop a more suitable interlock-slip model.

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References

1. Oliveira, T.F.; de Carvalho, J.M.F.; Mendes, J.C.; Souza, G.-B.Z.; Carvalho, V.R.; Peixoto, R.A.F. Precast concrete sandwich panels (PCSP): An analytical review and evaluation of CO_2 equivalent. *Constr. Build. Mater.* **2022**, *358*, 129424. [CrossRef]
2. Oliveira, P.R.; May, M.; Panzera, T.H.; Hiermaier, S. Bio-based/green sandwich structures: A review. *Thin-Walled Struct.* **2022**, *177*, 109426. [CrossRef]
3. Cox, B.; Syndergaard, P.; Al-Rubaye, S.; Pozo-Lora, F.F.; Tawadrous, R.; Maguire, M. Lumped GFRP star connector system for partial composite action in insulated precast concrete sandwich panels. *Compos. Struct.* **2019**, *229*, 111465. [CrossRef]
4. Pantano, A.; Averill, R.C. A 3D Zig-Zag sublaminate model for analysis of thermal stresses in laminated composites and sandwich plates. *J. Sandw. Struct. Mater.* **2000**, *2*, 228–312. [CrossRef]
5. Portal, N.W.; Zandi, K.; Malaga, K.; Wlasak, L. GFRP connectors in textile reinforced concrete sandwich elements. In Proceedings of the IABSE Congress, Stockholm 2016: Challenges in Design and Construction of an Innovative and Sustainable Built Environment, Stockholm, Sweden, 21–23 September 2016; pp. 1336–1343.
6. Hulin, T.; Hodicky, K.; Schmidt, J.W.; Stang, H. Experimental investigations of sandwich panels using high performance concrete thin plates exposed to fire. *Mater. Struct.* **2016**, *49*, 3879–3891. [CrossRef]
7. Tomlinson, D.G.; Teixeira, N.; Fam, A. New Shear Connector Design for Insu-lated Concrete Sandwich Panels Using Basalt Fiber-Reinforced Polymer Bars. *J. Compos. Constr.* **2016**, *20*, 04016003. [CrossRef]
8. Lou, X.; Xue, W.; Bai, H.; Li, Y.; Huang, Q. Shear behavior of stainless-steel plate connectors for insulated precast concrete sandwich panels. *Structures* **2022**, *44*, 1046–1056. [CrossRef]
9. Choi, K.-B.; Choi, W.-C.; Feo, L.; Jang, S.-J.; Yun, H.-D. In-plane shear behavior of insulated precast concrete sandwich panels reinforced with corrugated GFRP shear connectors. *Compos. Part B Eng.* **2015**, *79*, 419–429. [CrossRef]

10. Choi, W.; Jang, S.-J.; Yun, H.-D. Design properties of insulated precast concrete sandwich panels with composite shear connectors. *Compos. Part B Eng.* **2019**, *157*, 36–42. [CrossRef]
11. Sylaj, V.; Fam, A. UHPC sandwich panels with GFRP shear connectors tested under combined bending and axial loads. *Eng. Struct.* **2021**, *248*, 113287. [CrossRef]
12. Hou, H.; Wang, W.; Qu, B.; Dai, C. Testing of insulated sand-wich panels with GFRP shear connectors. *Eng. Struct.* **2020**, *209*, 109954. [CrossRef]
13. Meng, Y.; Wang, L.; Chen, B. Shear resistance and deflection prediction of steel–concrete–steel sandwich panel with headed stud connectors. *Structures* **2023**, *54*, 1690–1704. [CrossRef]
14. Wang, Y.; Chen, J.; Zhai, X.; Zhi, X.; Zhou, H. Static behaviours of steel-concrete-steel sandwich beams with novel interlocked angle connectors: Test and analysis. *J. Constr. Steel Res.* **2023**, *201*, 107723. [CrossRef]
15. Mercedes, L.; Mendizábal, V.; Bernat-Maso, E.; Gil, L. Performance of hemp-FRCM-strengthened beam subjected to cyclic loads. *Mater. Constr.* **2022**, *72*, e270. [CrossRef]
16. Mercedes, L.; Gil, L.; Bernat-Maso, E. Mechanical performance of vegetal fabric reinforced cementitious matrix (FRCM) composites. *Constr. Build. Mater.* **2018**, *175*, 161–173. [CrossRef]
17. *EN 1015-11*; Methods of Test for Mortar for Masonry. Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar. CEN: Brussels, Belgium, 2019.
18. Mercedes, L.; Bernat-Maso, E.; Gil, L. Bending and compression perfor-mance of full-scale sandwich panels of hemp fabric reinforced cementitious matrix. *Eng. Struct.* **2023**, *275 Pt B*, 115241. [CrossRef]
19. Ardanuy, M.; Claramunt, J.; Filho, R.D.T. Cellulosic fiber reinforced cement-based composites: A review of recent research. *Constr. Build. Mater.* **2015**, *79*, 115–128. [CrossRef]
20. Donnini, J.; Corinaldesi, V. Mechanical characterization of different FRCM systems for structural reinforcement. *Constr. Build. Mater.* **2017**, *145*, 565–575. [CrossRef]
21. D'Antino, T.; Papanicolaou, C. Mechanical characterization of textile reinforced inorganic-matrix composites. *Compos. Part B Eng.* **2017**, *127*, 78–91. [CrossRef]
22. *EN ISO 13934-1/2*; Textiles–Tensile Properties of Fabrics—Part 1: Determination of Maximum Force and Elongation at Maximum Force Using the Strip Method. ISO: Geneva, Switzerland, 2013.
23. *AC434-0213-R1(ME/BG)*; Proposed Revisions to the Acceptance Criteria for Masonry and Concrete Strengthening Using Fiber-reinforced Cementitious Matrix(FRCM) Composite Systems. ICC Evaluation Service Inc.: Brea, CA, USA, 2012.