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Shear Performance of the Interface of Sandwich Specimens with FRCM Vegetal Fabric Skins

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

Abstract: The utilization of 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 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 effective composite strength comparable to other synthetic fabrics like glass fiber. Nevertheless, the 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 fibres; 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 Oliveria et al. [1]. The concern about climate changes and sustainable solutions drive research towards more green and bio-based engineering sandwich technologies according Oliveira et. al. [2]. In the present work a solution based on vegetal FRCM and polystyrene core, serve 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. Adequate material connection is crucial, as insufficient bonding may result in problematic stress distribution within the panel, potentially causing detachment failure or a substantial decrease in mechanical strength.

In this order, different authors presented previous studies like Cox et al. [3] develop a composite shear connectors system of glass fiber reinforced polymer (GFRP) used to transfer interface shear forces in a precast concrete sandwich panel. The study developed push-off, pullout, and flexural tests, to evaluate the structural performance of the shear connectors, and the effect of bond between concrete and insulation with a push-off tests. The results showed satisfactory performance with a lower bound of 90% composite action for specimens with 100mm thick insulation wythe and full composite action for most panels with 50mm thick insulation. Other study by Portal et al. [4] presented experimental and numerical methods to analyzed the structural behaviour related to a sandwich panel with a glass fibre reinforced polymer (GFRP) plate connection system, where a 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 is necessary use least material in the plate connectors, and increased bending capacity of the outer panel to avoid a significant drop of the load after the peak load. At the same line, Hulin et al. [5] 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 to stress concentrations leading to local failure. A study presented by Tomlinson et al. [6] carry out push-through tests on precast concrete insulated sandwich panel using combined angled and horizontal connectors, where basalt fibre reinforced polymer and steel connectors were used. This study evaluated various inclination angles and diameters of connectors, orientation of the diagonal connector relative to 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 the larger-diameter basalt-FRP connectors 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 [7] performed 24 double-shear tests on precast concrete insulated sandwich panels using stainless-steel plate connectors. Authors analysed parameters like connector directions, insulation effect, cavity widths and connector heights. Authors developed a consisted campaign with in-plane and out-of-plane shear test and concluded that the cavity size and the presence of insulation significantly contributed to shear transfer. Choi et al. [8] analysed some precast concrete sandwich panels used for exterior cladding. Specimens were experimentally tested with 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. [9] extended the study of the shear flow over type of connectors. There are other relevant contributions about the shear performance of sandwich insulation panels using other types of test like Sylaj et al [10], Hou at al [11], Meng et al. [12] or Wang et al. [13].

To advance towards the utilization of more sustainable materials compared to synthetic fibres and steel, the present study concentrates on the creation of sandwich panels comprising vegetal FRCM and expanded polystyrene as insulation. Authors have previously presented other complementary studies about FRCM vegetal fibres, see Mercedes et al. [14] and [15] and some bending test 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 fibres. 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, simplified connector slip-load model is developed and compared to the experimental results.

2. Materials and Methods

The experimental campaign includes the manufacturing of specimens of FRCM bonded to an extruded polystyrene core and shear tests. These specimens were produced using next 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 Mercedes et al. [15]. The average results of the compression and flexion tests using norm EN1015-11:2000 [16] has been previously presented in the cited work with values of 39.25 MPa and 6.56 MPa respectively.

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2.2. Fabrics

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

Vegetal fabrics were crafted using hemp and sisal yarns (both with diameter of 2.5 mm). This arbitrary choice is justified by the notable tension levels achieved by hemp and sisal FRCM specimens in a prior study by Mercedes et al. [17]. In that study, the fabrics and yarns were coated with epoxy resin. This was done to prevent fibre degradation produced by the environment of cementitious matrix composites (high alkalinity and humidity cycles), see Ardanuy et al. [18].

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 the meshes with 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 that tensile strength and effectiveness were comparable to synthetic fiber meshes just by simply increasing the volume of vegetal fibers.

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 weft direction is no relevant for the shear test setup used in this study.

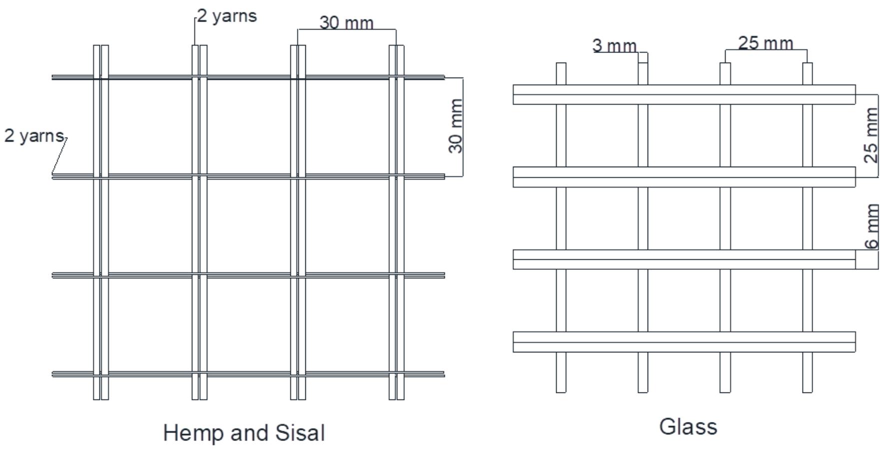

Figure 1. Design on reinforcing fabrics.

The fabrics were woven (Figure 2) with the same procedures used in Donnini et al [19] and D'Antino et al. [20]. After one day of curing, the meshes were cut into pieces with dimensions of 45 mm × 35 mm.

(a) (b)

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Figure 2. Vegetal fabrics: (a) hemp and (b) sisal.

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 [21].

Table 1. Tuft properties.

Fibres	Number of test	A_f (mm²)	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%)

(%) = Coefficient of Variation, F_{fu}= Maximum load mean, σ_{fu}= Tensile Strength mean, E_f= Young's Modulus mean, ε_{fpick}= deformation peak mean

2.3. Connectors

To assess the impact of connectors on the shear behavior of FRCM bonded to an ex-truded 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 connector in such types of sandwich solution.

Vegetal fibre connectors were crafted hook-shaped and impregnated with epoxy resin, featuring an equivalent area of 29.43 mm2 (6 yarns). Steel connectors were in the shape of a pin or bolt with a cross-sectional area of 0.79 mm2, accompanied by a nut at one end to enhance anchoring effect with the mortar (see Figure 3).

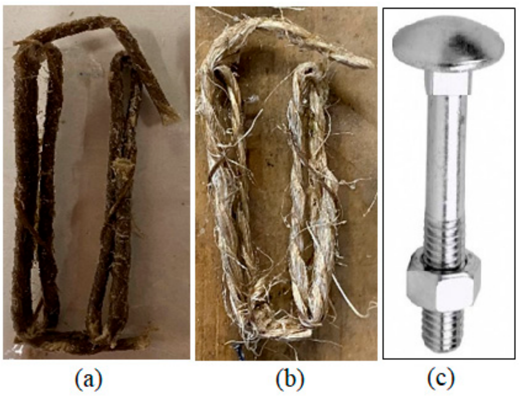

Figure 3. Connectors: (a) hemp, (b) sisal, (c) steel.

2.4. Extruded polystyrene

Rigid Extruded Polystyrene foam boards with a thickness of 40 mm were used as the insulating core in the sandwich samples configuration.

2.5. Specimens

The experimental program included 40 specimens. The dimensions of the FRCM were of 50×400 mm and a thickness of 20 mm. These 40 samples included 3 different con-nectors (steel, hemp and sisal) and 3 different reinforcement fabrics (hemp, sisal and glass).

The mold to manufacture the FRCM specimens were prepared with a grid of wooden strips defining 50 mm x 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.
- Mix the mortar and pour it to a depth of approximately 15 mm.

- Place the fabric so that it slightly penetrated the first mortar layer.
- Cover the fabric with a second layer of mortar to reach the thickness of 20 mm for the bottom FRCM layers.
- Place the extruded polystyrene boards. In the case of specimens with connectors it had a hole in the middle.
- Place other wooden strips mold (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 penetrated 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 the 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 were ready for testing.

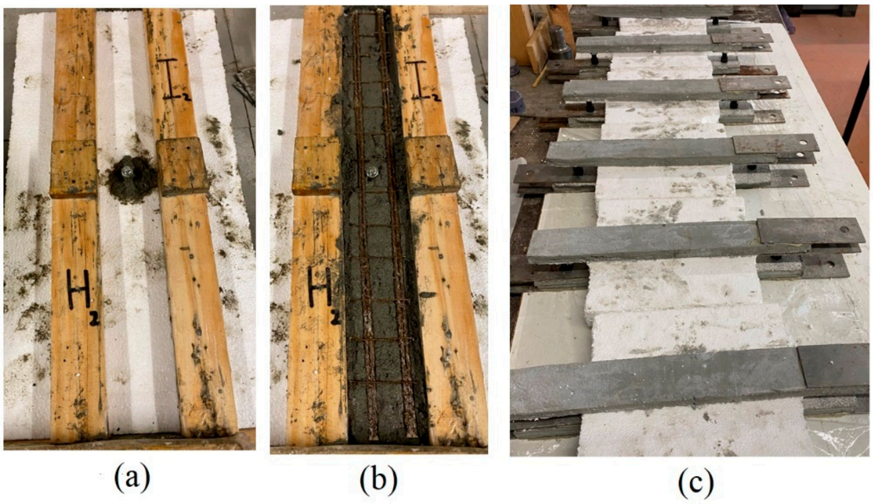

Figure 4. Manufacturing of sandwich panels: (a) mould, (b fabric with steel connector, (c) sandwich specimen.

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

3. Experimental campaigns

3.1. Test setup and instrumentation

The specimens were subjected to a double shear test (see Figure 5). 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 AC434-0213-R1 [22]. 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. The test rate was 2 mm/min.

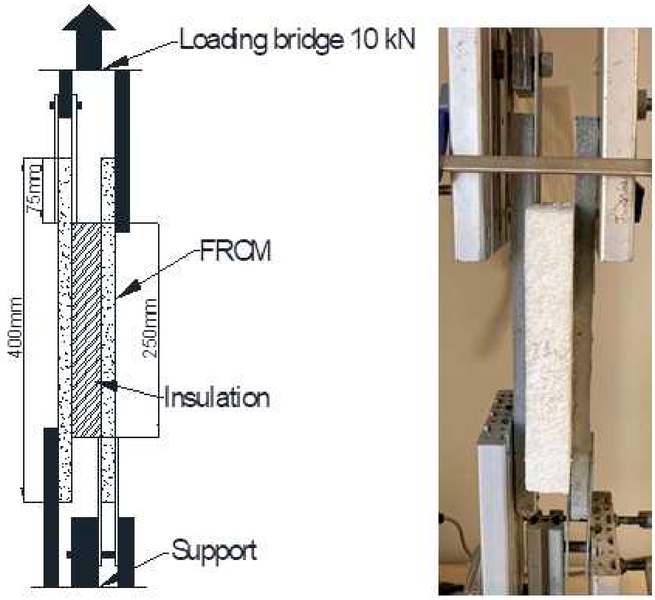

Figure 5. Test set up.

3.2. Type of failures

In general, all the specimens had a peeling failure because polystyrene is a low strength material. Nevertheless, in the case of the samples with connectors, there was also a slip-page 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 6).

(a) (b)

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Figure 6. Type of failures: (a) Peeling failures, (b) Peeling failures and connector slipping.

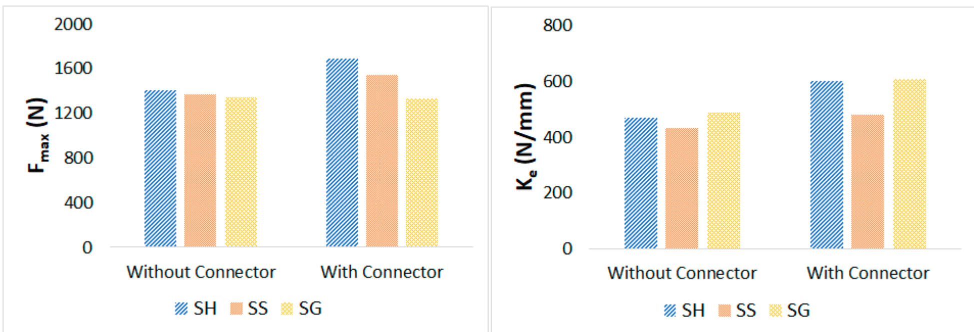
3.3. Experimental results

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

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 4 show coefficients of variation ranging between 2 and 14% for maximum load and shear strength, indicating good repeatability of the experiments. It is noteworthy that specimens without connectors presented similar shear strength. However, for stiffness and displacements the variation was higher, ranging between 7 and 47%. This variablity represents the expected scattering of data for elements composed of cementitious materials with a high no lineal behavior. The results presented in Table 4 are better appreciated in Figures 7 and 8.



(a) (b)

Figure 7. Fabrics influences: (a) Maximum load, (b) elastic stiffness.

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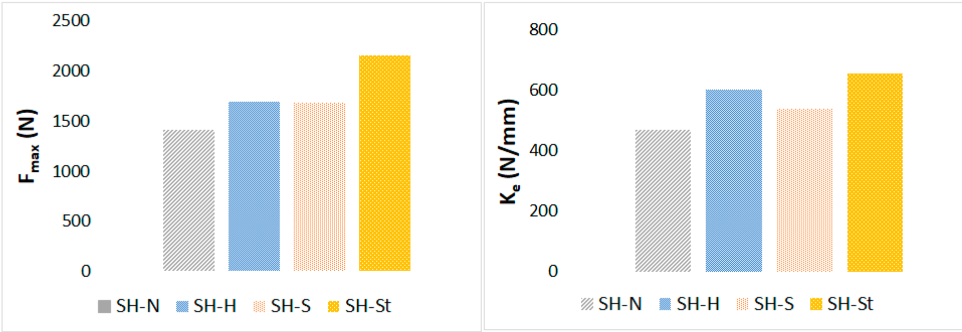

(a) (b)

Figure 8. Connectors influences: (a) Maximum load, (b) elastic stiffness.

Figure 7 shows 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 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 produce a higher ultimate load.

In terms of elastic stiffness, the response of the FRCM sandwich is directly tied to the Young modulus of the fabric—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.

Figure 8 illustrates 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. 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 of stiffness between the fabric and the steel connector seems not to be a handicap, even thought that some local damage happens in the mortar because of the concentration effects of steel bolt.

Figure 9 shows the load-displacement plots of the tested panels. It can be seen that specimens without connectors exhibit a quasi-brittle failure with 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.

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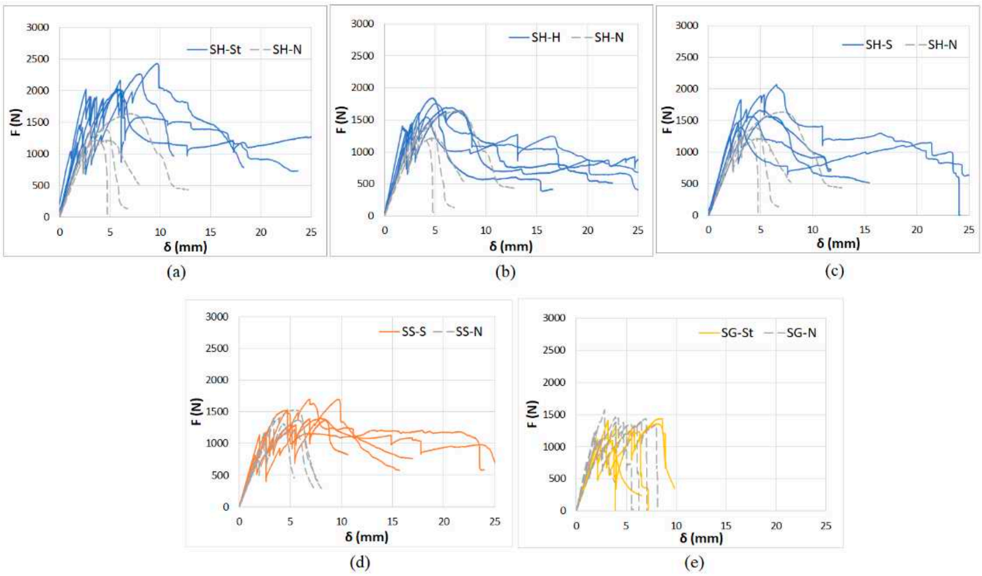

Figure 9. Load-displacement diagrams: (a) Hemp-fabric-with steel connector, (b) Hemp-fabric-with hemp connector, (c) Hemp-fabric-with sisal connector, (d) Sisal-fabric-with sisal connector, (e) glass-fabric-with steel connector.

4. Connectors interlock-slip simplified model

According the experimental results, it is worth to build a simple model to easily 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 nonlinear behavior of FRCM skins, interface interaction 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 the ones with connectors. Therefore, in a simply manner:

$$Fmax = Fmax\_none\_connector + Fmax\_connector$$

From Table 5 and plots of Figure 9 (a, b and c) it is feasible to estimate the contribution of the interface of FRCM and polystyrene. To study the effect of the connector, only hemp FRCM specimens (SH) were used because contains all type of samples.

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

As stated in Figure 8, steel connectors showed the highest stiffness, followed by hemp and finally sisal ones. This property explains the reason why steel connectors are the ones 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 its similar mechanical properties studied in Table 2.

Therefore, Figure 10 will make an estimation of the connector contribution.

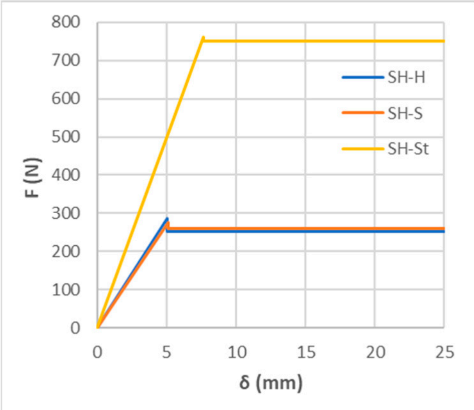

Figure 10. Connectors contribution.

5. Results

In this work, an experimental and numerical research was conducted to investigate the shear performance of sandwich specimen with vegetal-FRCM and polystyrene. According 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 shown that there is no significant influence of the kind fabric in the maximum load of the specimen without connector. This happens because the FRCM skin do 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 level 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.
- All the type 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 stiffness in connectors the higher sandwich response.
- An interlock-slip model based on experimental evidences shows the potential to design FRCM solutions for sandwich applications with connectors.

Author Contributions: Conceptualization, L.M .; methodology, L.M..; software, E.B..; validation, L.G, E.B. formal analysis, L.M., investigation, L.M., E.B., V.M, L.G..; resources, L.G.; data curation, L.G..; writing—original draft preparation, L.B.; writing—review and editing, L.G, E.B., V.M..; visualization, L.M, V.M..; supervision, L.G. E.B.; project administration, L.G.; funding acquisition, L.G. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data acquired are directly presented in plots being original and not inappropriately selected, manipulated, enhanced, neither fabricated.

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