FIBRE REINFORCED POLYMER (FRP) CONNECTORS FOR STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE (SFRSCC) SANDWICH PANELS

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Abstract

Insulated sandwich wall panels are frequently composed of external concrete layers, mechanically connected through metallic connectors, such as trusses. Due to their high thermal conductivity, these connectors generally cause thermal bridges on the building envelope. In view of this problem, an innovative system is proposed where FRP connectors are used together with a thermal insulation layer. Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) wythes are also used to obtain panels that are both technically and economically advantageous. However, to present day there is no experimental data on the mechanical behaviour of the suggested connections. In this research, an experimental study is performed to characterize different types of FRP-SFRSCC connections under pull-out tests. Shear connection behaviour under monotonic loading is evaluated with slip controlled tests. Embedded and adhesively bonded connection solutions between SFRSCC layers and FRP connectors are studied.

Keywords: FRP connectors, Pull-out tests, Sandwich Panels, Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC).

1. Introduction

The main interest on using sandwich panels in construction is related to the structural and thermal efficiency that can be achieved. Traditionally, these sandwich panels adopt conventionally reinforced concrete layers and use metallic connectors between both concrete layers. Due to their high thermal conductivity, the metallic connectors in these insulated wall panels generally cause thermal bridges on the building envelope that result in additional transmission losses, lower inner surface temperatures and possibly condensation, together with mould problems.

Aiming to overcome this common limitation in traditional sandwich panels, an innovative system is being developed under the framework of a research project, where a new proposed precast sandwich panel plays an important role. The proposed system is intended to be cost competitive with focus on the reduction of construction time and material optimization, as to assure a final solution that is both structurally reliable and environmentally sustainable. The sandwich panel comprises two thin layers of Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) as facing material, separated by one layer of a rigid thermal insulation material (e.g.: polystyrene or polyurethane foam) and connected by partially embedded or adhesively bonded strips made of Fibre Reinforced Polymer (FRP). The FRP connectors seem promising for this application, due to their low thermal conductivity, improved durability under aggressive environments and low maintenance requirements.

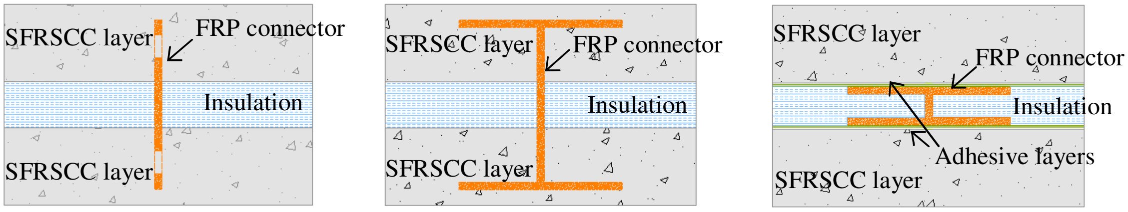
Different types of FRP connectors have been previously proposed by other researchers for reinforced/prestressed concrete sandwich panels [1, 2]. Furthermore, SFRSCC has already been suggested as facing material of sandwich panels in a solution where the connection between the concrete layers was assured by solid zones of concrete [3]. Nevertheless, no combined application of these two techniques was found in the literature.

A challenge on the development of this system is the coupling of FRP connectors to the thin layers of SFRSCC. This coupling influences the overall behaviour of the composite element in terms of strength, stiffness and deformability. Thus, care should be taken to guarantee enough strength and a rather ductile behaviour of the connection. So, to accurately predict the ultimate behaviour of a sandwich panel and to ensure that the ties remain in their elastic range, the response of the connectors must be well known.

This paper focuses on the mechanical behaviour of the FRP-SFRSCC connections developed for load bearing sandwich panels. The feasibility of using the proposed connectors as mechanical shear connectors was experimentally investigated with a series of pull-out tests, where failure modes, load capacity, stiffness and deformation capacity of the connections are analysed.

2. Proposed FRP connectors

The suggested sandwich panels are composed by continuous one-way connectors that span through the full height of the panel. Two main kinds of connectors are proposed and evaluated: embedded and adhesively bonded. The embedded ones pass through the foam core into both concrete layers. These connectors are pre-positioned before casting of the first concrete layer. Among the embedded connectors there are simply perforated plates and connectors with a profiled shape. The simply perforated type consists of a FRP plate with a number of uniformly spaced openings (Figure 1a). After casting the panels, SFRSCC dowels are formed that provide resistance between the connector and the panels. The profiled specimen consists of a “T-shaped” FRP that is embedded in the SFRSCC (Figure 1b) and the mechanical interlock provides the anchorage of the connector. Furthermore, there are the adhesively bonded connections that consist of a profiled FRP with similar geometry to the embedded profiled shape, but bonded later to the hardened concrete surface through an adhesive layer (Figure 1c).



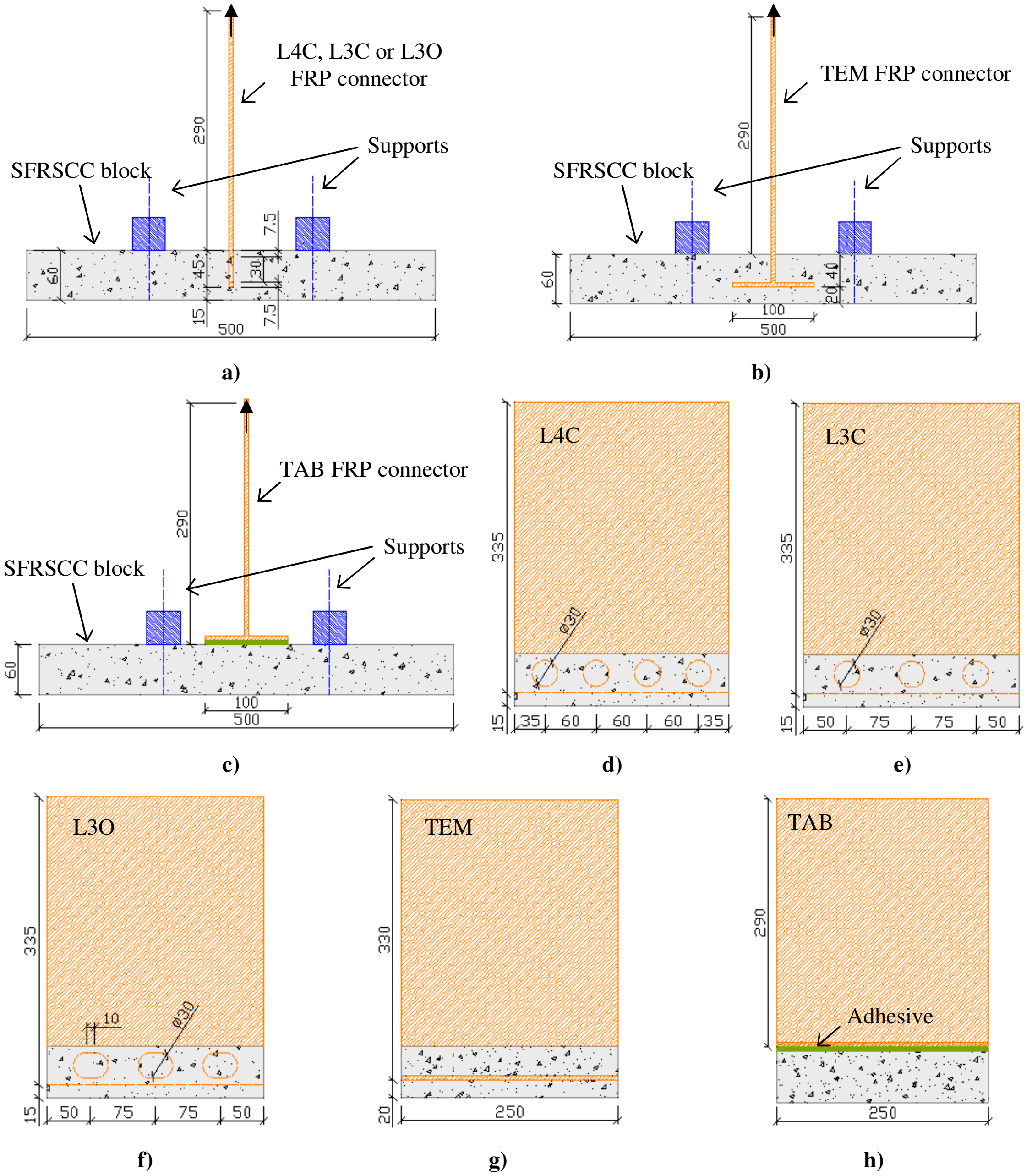
a) **b)** **c)**

Figure 1. Schematic representation of suggested connections for sandwich panels: a) embedded – simply perforated plate; b) embedded - profiled and c) adhesively bonded.

3. Experimental Program

3.1 Test specimen

Pull-out tests have been conducted on five connector geometries: four embedded connectors and one adhesively bonded (TAB). Among the embedded connectors, there were three types of simply perforated plates (L4C, L3C and L3O) and one connector with profiled shape (TEM). The connector types and the specimen geometry are illustrated in Figure 2.



a) b) c) d) e) f) g) h)

Figure 2. Pull-out test specimens. Front view: a) L3C, L4C and L3O; b) TEM and c) TAB. Lateral view: d) L4C, e) L3C, f) L3O, g) TEM and h) TAB. Units in millimetres.

To obtain a good simulation of the existing conditions in the real SFRSCC-FRP panel, all the specimens consist of a SFRSCC block with 60 mm thickness, which is the same thickness of the concrete layers of the developed sandwich panel. All specimens have 250 mm width and length of 500 mm. Due to geometrical and constructive limitations, the concrete cover of L3C, L4C and L3O are 15 mm while the cover of the TEM connector is 20 mm.

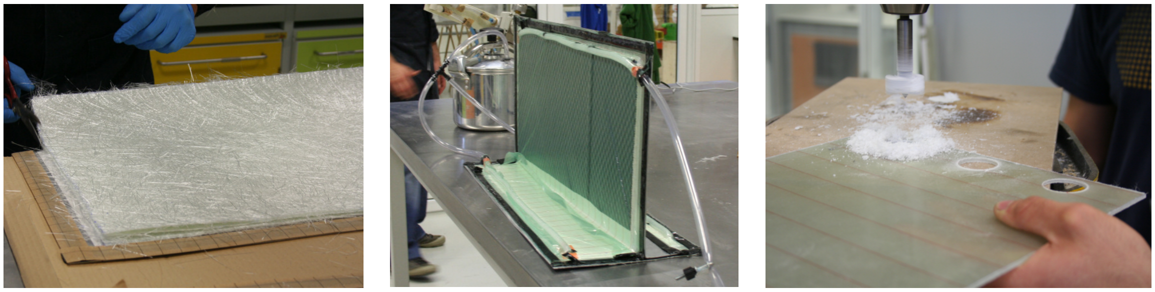
3.2 Materials and Components

3.2.1 Fibre Reinforced Polymer - FRP

The minimum requirements for these connectors, in terms of mechanical performance, were obtained through numerical analyses of the sandwich panels under service loadings [4]. The properties of the connector have been optimized with basis on these values. The strategy adopted to reduce the cost of the connectors consisted on giving priority to the use of low-cost raw materials and reducing the consumption of materials.

The connectors used in this research program were manufactured by Vacuum Assisted Resin Transfer Molding (VARTM) process using a Chopped Strand Mat (CSM) with 500 g/m² of E-glass fibres as reinforcement, and polyester resin matrix. In the CSM, the fibres are randomly oriented, producing a virtually isotropic laminate with equal strength and stiffness in all directions. This reinforcement was chosen because its price is reduced when compared with other materials and fabrics. The option for the VARTM process resulted from its relatively low cost, that allows obtaining parts with reduced dimensional variations through a highly automatized process.

All the connectors were manufactured in the PIEP (Pole for Innovation in Polymer Engineering) installations, one of the partners in the research project. The produced laminates are 2.5 mm thickness and consist of 6 layers of CSM and the necessary content of resin to impregnate the fibres. In the case of the perforated connectors, the plates were produced and then the holes were made afterwards using a drilling machine (see Figure 3).



a) b) c)

Figure 3. Manufacturing of FRP connectors by VARTM process: a) CSM layers; b) resin injection for the production of profiled connectors and c) drilling process in the perforated connectors.

Tensile tests were executed with representative samples of the FRP laminates used in this investigation in order to determine their tensile strength, stiffness and stress-strain relationship up to failure. Eight FRP samples with 25 mm width and 250 mm length were fabricated. A clip-gauge with reference length of 50 mm, fixed in the middle of each specimen, was used to measure the strain in the laminates. To provide appropriate anchorage during testing and to diffuse the clamping stresses, rectangular metallic tabs were glued at the extremities of each sample.

The mean value of the tensile strength obtained was 208.81 MPa (standard deviation of 8.69 MPa). The specimens had an ultimate strain of 17881 με (standard deviation of 969 με) and a mean modulus of elasticity of 12.65 GPa (with a standard deviation of 0.47 GPa).

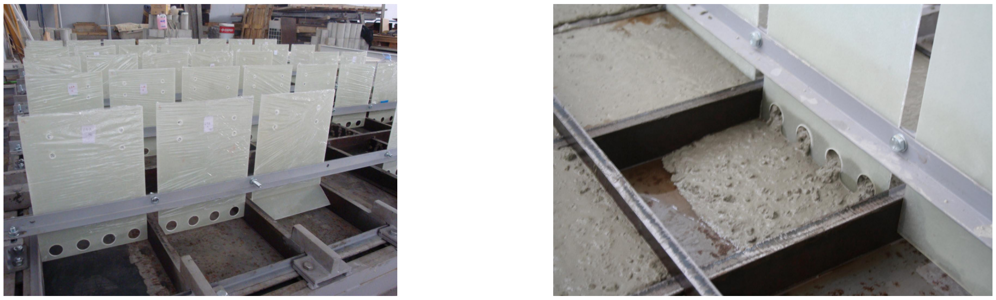
3.2.2 Steel Fibre Reinforced Self-Compacting Concrete - SFRSCC

The materials used in the SFRSCC composition were: cement CEM I 42.5R, limestone filler, coarse river sand, crushed granite 5-12mm, hooked end steel fibres, water and a superplasticizer of third generation based on polycarboxylates. The adopted fibre (Radmix RAD6535HW) had a length of 37 mm, diameter of 0.5 mm, an aspect ratio of 74 and a yield stress of 1300 MPa. A slump flow of the fresh concrete over 620 mm was observed when testing with the Abrahm's cone in an inverted position. Compressive strength and modulus of elasticity of SFRSCC were assessed by tests on cylinders with 150 mm of diameter and 300 mm of height. The average value of the concrete compressive strength for the 6 tested specimens at 28 days of age was 69.25 MPa with a standard deviation of 2.75 MPa. The average modulus of elasticity for the 5 specimens at 28 days of age was 35.45 GPa with a standard deviation of 2.05 GPa.

3.3 Fabrication and casting

All the SFRSCC specimens were cast in the CIVITEST, a partner in this research project. The connectors were previously positioned in the steel formwork in order to guarantee their alignment with the concrete block and the prescribed depth of concrete cover (see Figure 4a). Then, the SFRSCC blocks were first poured from the end of the mould, allowing the concrete to flow through the holes of the connectors (L4C, L3C and L3O), as shown in Figure 4b, or behind the connector (for TEM specimens). The casting was finally completed by pouring the concrete in the side of specimen corresponding to the other side of the connector. All the specimens were cast in the horizontal position to simulate the casting conditions required for the production of sandwich panels. Concrete blocks without embedded connectors were also produced for the adhesively bonded connectors. Cylinders were cast for the SFRSCC characterization. The specimens were cured in ambient conditions up to the tests.

In the case of adhesively bonded connection, after the curing of concrete, the FRP profiles were bonded to the concrete blocks with epoxy resin S&P Resin 220. According to the data provided by the manufacturer, the adhesive strength after 3 days of curing at 20°C is, at least, 3.0 MPa. To improve the bond, before the applying of the resin, the concrete surface was treated, by removing the superficial cement paste layer. The specimens were kept in a room with temperature of 20°C and humidity of 60% for 7 days up to the test while the adhesive cured.



a) **b)**

Figure 4. Casting arrangement: a) connectors pre-positioned for pouring; b) detail of pouring.

3.4 Test setup and procedure

The test setup is shown in Figure 5. The setup includes the hydraulic machine, the 50 kN load cell, the clamp, the supports, the transducers and the data acquisition unit. The vertical load is applied at the top of the FRP by using a clamp that distributes the load on a 150 mm ×

200 mm area of the FRP surfaces. The supports consist on a pair of steel bars with 40 mm width and 500 mm length disposed on the top surface, along the width of the concrete block. Each steel bar is spaced of 200 mm from each other, on either side of the connector. These bars are fixed to the rigid base of the test machine with 4 steel threaded Φ14 rods positioned in the ends of the bars, providing the needed reaction.

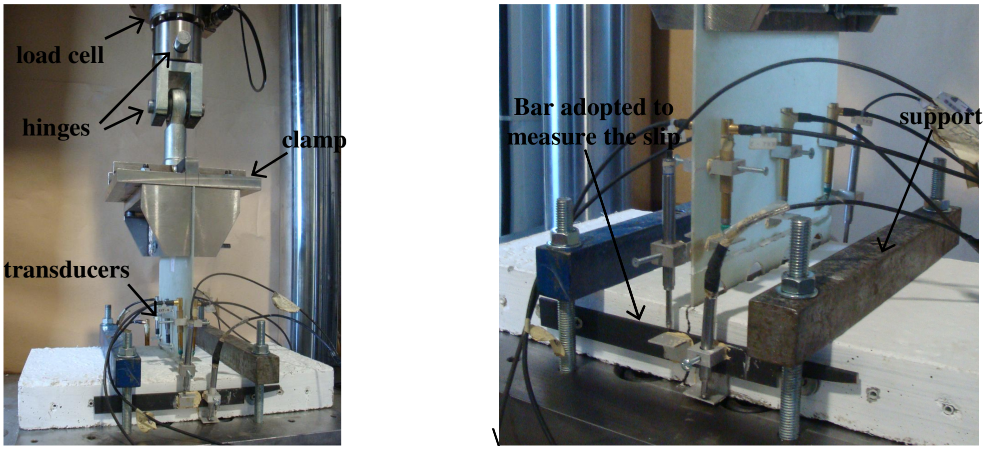


Figure 5. Pull-out test setup: a) overall view: b) detail.

To measure strain evolution in the free full sections of FRP, located between the concrete block and the clamps, 6 transducers are applied between two points of the lateral surface of the FRP. The strain in the FRP is obtained by taking into account the relative displacement between these points and the reference length of 60 mm. The slip between the FRP and the concrete is measured in the front and rear side of the specimen by applying one transducer in the FRP surface nearby the concrete top surface. A metallic bar is adopted, as reference point, to measure the slip relatively to a point on the concrete surface aligned to the supports, excluding extraneous deformations due to deformations of the machine or of the specimen supports. Another transducer, fixed to this bar, measures the midspan deflection of the concrete block and this value is subtracted from the measures of the transducer fixed to the FRP to obtain the relative slip between the FRP and the concrete block. All the specimens were tested under monotonic loading at a constant rate of 0.03 mm/s.

4. Results and analysis

4.1 Failure mechanisms

In the simply perforated plate connectors (L3C, L4C and L3O), all the failure mechanisms observed are associated to the failure of the FRP in the vicinity of the holes (see Figure 6a). In general, when these local failures of the connectors occurred, the load has dropped, and the obtained load decay patterns indicate that these failures were progressive, contributing for the relatively high ductile behaviour of these connections. This possibly occurs due to the non-uniform distribution of stresses within the FRP, caused by differences of stiffness between the concrete dowels and due to localized imperfections in the connector. However, all the perforated connectors show a significant residual load capacity after peak load. It was also noticed that the surfaces of the L3C, L4C and L3O connectors were scratched after the tests, showing some adherence/friction to the concrete. This friction is a possible reason for the high post-peak residual strength of these connections. With the exception of specimen L3O 01, all the other specimens with simply perforated plate connectors show failure lines in the SFRSCC corresponding to a failure cone mobilized by the connector (see Figure 6b). In the case of the TEM and TAB connections, the FRP connectors were intact at the end of the tests.

For the TEM connector, the failure lines in the concrete block appear suddenly with an inclination of about 45°, progressing from the flange of the connector up to the top surface of the SFRSCC block (see Figure 6c). In the case of TAB connections, the typical failure has started from an extremity of the connector and rapidly progressed, causing a complete debonding that resulted in a sudden decrease of the connection load capacity. It was further observed that, in both TAB specimens, the failure occurred within the concrete block, by tearing off the superficial layer of the cement paste.

a) **b)** **c)**

Figure 6. Typical failure mechanisms: a) perforated connectors; b) L4C 01; c) TEM 01.

4.2 Strain in FRP

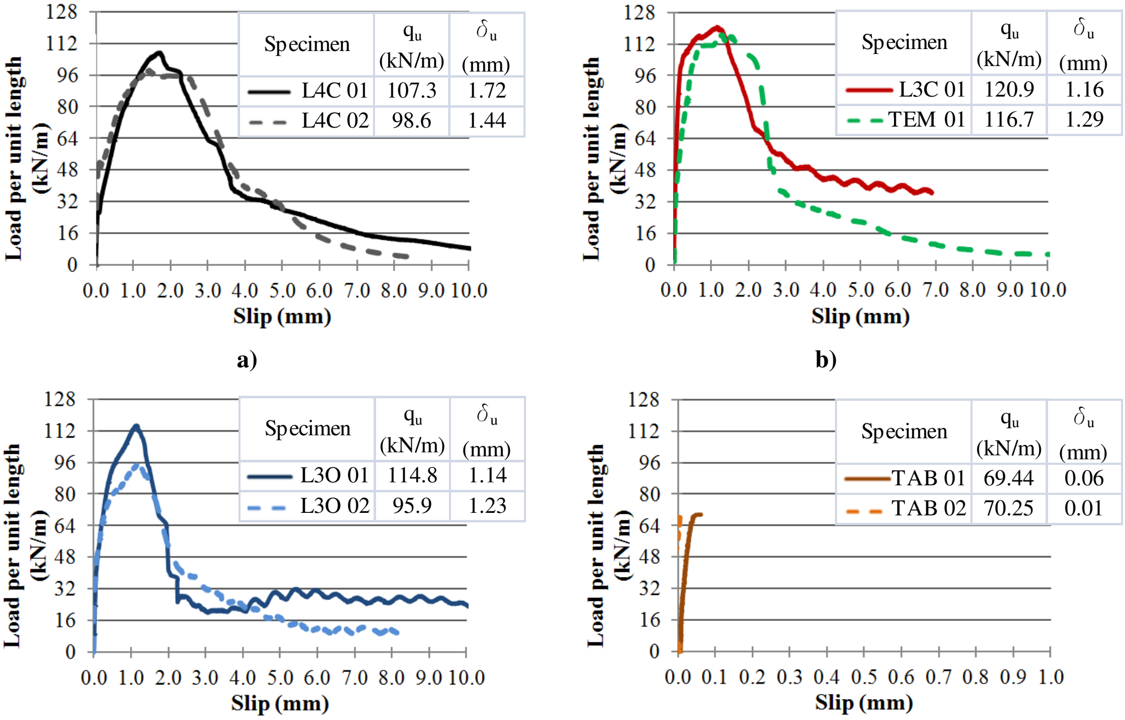
In general, the measured strains in the free full sections of FRP were very reduced, with values between 1462 με and 3234 με. As the mean ultimate strain of the FRP adopted in the connectors is 17881 με, the maximum measured strain values show that these sections of the connectors are far from failure in all the pull-out tests performed.

4.3 Load capacity and load-slip behaviour

Figure 7 presents the failure load per unit length (q_u), the average slip correspondent to the failure load (δ_u) and the load per unit length vs. average slip relation between FRP connectors and SFRSCC block. By comparing the values of the failure loads, it can be concluded that all perforated connectors have load capacities that are similar to the ones obtained for the TEM solution. Furthermore, the TAB connectors prove to be the type of connector with the lower load capacity (64% of the load capacity of the mean load capacity of others studied connections). The slip corresponding to the failure load of all embedded connectors ranged between 1 and 2 mm, with a linear segment followed by a pronounced nonlinear branch. The L4C specimens presented the most ductile behaviour with a quite smooth load decay after the peak load (see Figure 7a). Among the simply perforated connectors, the L3O is the typology that presents the higher load decay after the peak, however, develops a very appreciable residual resistance to high values of slip. The adhesively bonded connector presents a singular behaviour, with more sudden failure and showing slip levels that are lower than the ones observed for the other studied typologies.

5. Conclusion

Perforated connectors take advantage on the simplicity / practicality of its production, on the low consumption of material and on the easiness of casting, resulting on a low cost and attractive solution to be used in sandwich panels. The circular openings disposed along the connectors' length proved to have the desired structural behaviour, adding significant load capacity to the connection. Though the FRP adopted for the connectors seems to be oversized when the stress level obtained in their full sections is taken into account, the still relatively high decrease of load after peak load registered in the connectors indicates that it is necessary to put more effort on the optimization of type, thickness of FRP or arrangement of the holes in order to enhance the ductility of the connection. Therefore, SFRSCC properties could be better used in the connections if the failure mode did not occur in the connector. On the other hand, preliminary numerical studies of the sandwich panels, presented in [4], indicate that, considering the results obtained in this experimental program, the studied connectors could be adopted with a slack safety margin, and all the studied types of connectors would be working on a load range that is 50% below their load capacity.



a) b)

c) d)

Figure 7. Load-slip relationship: a) L4C; b) L3C and TEM; c) L3O and d) TAB.

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