INFLUENCE OF TEMPERATURE AND DIFFERENT POST CURING CONDITIONS ON THE MECHANICAL BEHAVIOUR OF POLYURETHANE-BASED ADHESIVE FOR CIVIL ENGINEERING APPLICATIONS

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Abstract: *Sandwich panels based on cold-formed-steel (CFS) face sheets and polyurethane foam (PUR) core were designed and manufactured to be used as a feasible solution for the rehabilitation of degraded floors. This panel is manufactured by a continuous process, whereby the polymerization and foaming of the PUR core is performed simultaneously with the face sheets assembling and their adhesive bonding in certain zones. A three-component polyurethane adhesive, manufactured with the same components as the PUR, is used on the bonding of these steel elements. However, the foaming process of the sandwich panel involves moderate heating at specific stages of its manufacture to enhance polymerization of the PUR, which may influence the adhesive mechanical response. This work intends to establish the best adhesive composition and its thickness to be used on this connection. Additionally, the influence of different curing and post-curing conditions on the shear response of the adhesive is assessed.*

Keywords: Polyurethane-based adhesive; Steel sandwich panel; Flooring system; Post-curing conditions.

1. Introduction

Historically, constructions in Europe (which precede the use of reinforced concrete and structural steel), were commonly composed by masonry walls and timber flooring systems [1]. The rehabilitation of these constructions requires special attention, since the existing timber floors often present high deformations (floor sagging) due to durability problems caused by biological attacks related to lack of maintenance [1,2]. This aspect, when combined to the demanding requirements stablished by current structural performance standards, usually results in the replacement of these floors by new flooring solutions. These could be new timber floors or new flooring systems composed by different materials (Reinforced concrete, structural steel or composite materials) [2]. In this context, the development of sandwich panel-based flooring systems, characterised by two relatively thin and stiff faces and a relatively thick and lightweight core, arise as potentially interesting solutions [3,4].

For such applications, within the scope of Lightslab R&D project, cold-formed steel (CFS) face sheets sandwich panel with polyurethane (PUR) foam core including longitudinal steel web reinforcements were designed and manufactured (as shown in Figure 1) [5]. Among the advantages of this flooring system, it can be highlighted its lightweight (which limits the dead load transmitted to the existing structure and consequently reduces the impact in terms of

seismic vulnerability) [4]. Moreover, its modular feature can minimize waste production and reduce overall construction/rehabilitation time, leading to a more sustainable construction [6].

In the manufacture process of these panels, the PUR foaming process takes place on the bottom face sheet, while the adhesive joint connects the webs with the top face sheet. For this connection, polyurethane adhesives can be adopted, as they are flexible, ductile and, due to their composition, present compatible properties with the core of the panels [5,7]. However, structural adhesives are sensitive to temperature and relative humidity (RH), both during their curing and service life [8]–[11], and the foaming process of the sandwich panel involves moderate heating at specific stages of its manufacture to enhance polymerization of the PUR. Thus, this work intends to establish the best adhesive composition and the layer thickness to be used on this connection, as well as to reproduce the temperature and RH conditions imposed on the adhesive during the sandwich panel manufacturing process, and furthermore, to assess the influence of different post-curing conditions on the adhesion of cold-formed-steel elements, namely the upper face sheet and the webs.

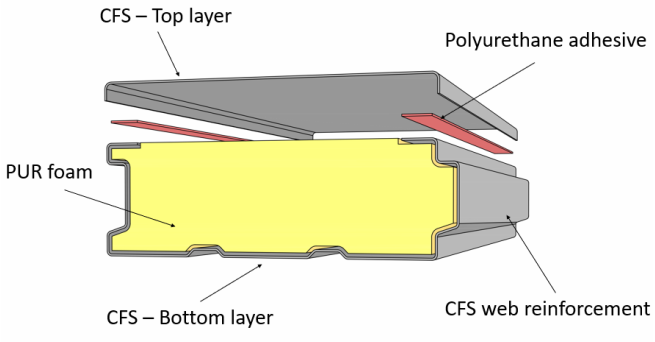


Figure 1. Schematic representation of the developed sandwich panel.

2. Influence of the adhesive's composition on their mechanical response

To maximize the mechanical performance of the three-component polyurethane-based adhesive, the influence of different proportion of components on their shear response was assessed in a preliminary experimental campaign. This assessment was done varying two different parameters: i) the proportion of the diIsocyanate component Voranate M 229 SH, by increasing it mass proportion from 25% to 50%, in respect to the total quantity of the polyol component Voratron EG711; ii) the proportion of the Voralast GM 817 catalyst increasing it in a rate from 0 to 0.8 wt.% of the total polyol quantity. The choice of these constituents for the adhesive was based on the PUR composition (same components).

The formation of the adhesive layer (i.e., curing) passes through a polycondensation reaction between optimized amounts of the diisocyanate and polyol components. The role of the catalyst (a clear, low-viscosity liquid) is to accelerate the curing time and limit the side reactions related to the formation of bubbles in the curing adhesive [3]. Summarizing, by the variation of the mass proportions of the three adhesive components it was possible to fine-tune the curing time and the shear strength of the bonded specimens.

The studied proportions were tested on lap shear strength tests performed on adhesively bonded specimens according to the ASTM D1002-2010 [12]. For this purpose, 10 different sets

of mixtures were experimentally assessed. For each set, tests were performed on 6 bonded specimens. For these tests, 120 steel specimens with nominal dimensions of 25.4×101.6×1.5 [mm³] were prepared and jointed in pairs with adhesive connection.

The procedure for assembling the specimens was as follows: i) the faces to joint were cleaned with acetone in order to remove any contaminants; ii) the pre-mixed adhesive were deposited over one of the metal specimens; iii) the opposite specimen is then assembled creating an overlap region of 12.7 mm; iv) A pressure equivalent to 1161.8 Pa/sample was applied over the joint; v) The assembled specimens (with the applied pressure) were left to cure under controlled conditions (temperature of 23°C, relative humidity of approximately 50%). The nominal thickness of the adhesive layer for this campaign was 0.12 mm.

This stage of the mechanical characterization tests was carried out using a universal tensile testing machine INSTRON 5969. The samples were attached to the machine by grips with a length of 25.4 mm and the distance between grips was 139.7 mm. The test occurred in quasi-static monotonic-instantaneous loading up to failure, under a displacement control rate of 1.3 mm/min. All the tests were carried out under the same conditions, being the adhesive composition used to bond both samples the only variable.

Table 1 summarizes the obtained results for the tests performed on adhesively bonded specimens with different proportions of polyurethane-based adhesive. The parameters analysed for the different mixtures were: i) the handling time of the adhesive; ii) the fixture/solidification time; iii) minimum ultimate shear strength for the set of 6 specimens; iv) maximum ultimate shear strength for the set of 6 specimens; and v) average ultimate shear strength obtained for the given set of specimens, with respective coefficient of variation (CoV). Note that the quantities of Isocyanate Voranate M 229 SH and Voralast GM 817 Catalyst are expressed as a percentage of the of the total Voratron EG711 mass.

Table 1: Solidification and shear strength obtained for different proportions of adhesive.

Isocyanate [%]	Catalyst [%]	Fixture/handling time [min]	Solidification time [min]	Min/Max Ultimate Strength [MPa]	Mean Ultimate Strength [MPa]	Coefficient of variation [%]
25.0	0	60-80	270	0.3 / 0.9	0.5	60.0
	0.25	25-30	45	0.5 / 1.9	1.0	70.0
	0.5	06-11	29	0.9 / 1.5	1.2	16.7
	0.8	07-10	30	1.1 / 1.4	1.3	15.4
31.3	0	30-50	190	1.8 / 2.1	1.9	10.5
	0.25	**16-23**	**48**	**3.0 / 4.0**	**3.5**	**14.3**
	0.5	05-07	17	3.2 / 4.9	4.5	15.6
50.0	0	27-48	180	1.4 / 2.0	1.6	18.8
	0.25	14-17	34	1.1 / 1.8	1.3	23.1
	0.5	06-08	16	2.0 / 2.8	2.3	17.4

As seen from Table 1, the experiments revealed that the adhesive composition comprising 31.3% M229 SH Iso and 0.5% of the GM817 Catalyst showed the best ultimate strength varying between 3.2 and 4.9 MPa. However, the handling time for this composition (5-7 min) was

considered inappropriate for the current industrial application (once the adhesive joint assembling is performed simultaneously to the core's PUR foaming process on the panels manufacture). For such, the adhesive composed by 31.3% M229 SH Iso and 0.25% of the GM817 Catalyst (highlighted in bold), which presents ultimate strength in a range from 3.0 to 4.0 MPa and handling time from 16 to 23 minutes, was considered the most adequate for this application. Therefore, this proportion of components was chosen to be used on the following tests.

3. Shear strength of bonded specimens

The best adhesive mixture solution obtained on the previous sections was also assessed in an in-depth shear strength experimental campaign. The first series of performed tests intended to identify the influence of the adhesive layer thickness on the shear response of the adhesive (section 3.1), and then the influence of different post-curing conditions (section 3.2).

The specimen's preparation and the bonding of the specimens was performed as described in section 2. Such as for the optimization of the adhesive composition, the shear strength experimental tests performed in this campaign followed the ASMT D 1002 [12]. However, in this investigation, modifications were done on the geometry of the samples to allow the fixing of 2 LVDTs to accurately monitor displacement during the tests (see Figure 2). The shear tests were performed with a universal testing machine, with 10 kN MicroTest loadcell.

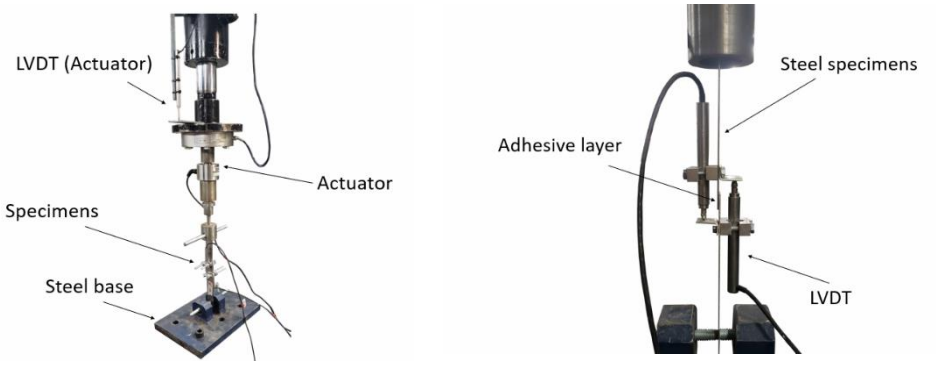


Figure 2. Test setup used for following shear strength experimental tests: a) overview and b) detail view of the test setup.

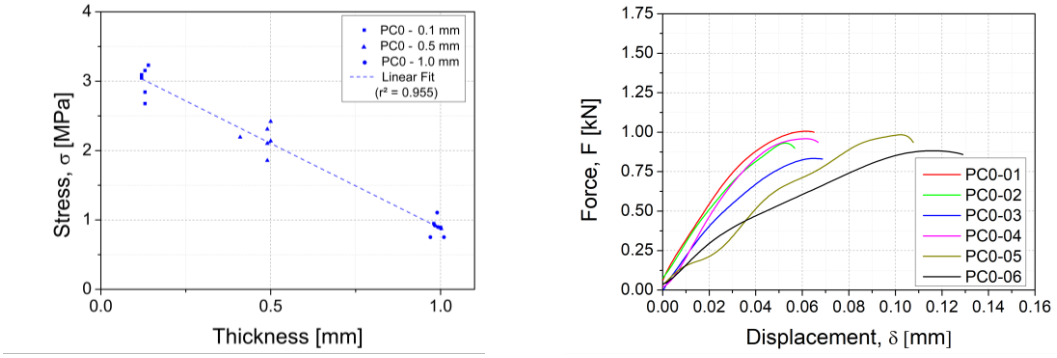
3.1 Influence of the adhesive layer thickness on their shear strength

Initially, this campaign was used to evaluate the influence of the layer thickness on the shear strength of the adhesives. Therefore, tests were performed on three sets of six specimens each with layer thickness of 0.1 mm (referred as PC0), 0.5 mm and 1.0 mm.

Figure 3a shows the ultimate shear strength obtained for each specimen of the different sets. From Figure 3a, one can see that an inversely proportional relationship can be stablished between the adhesive thickness and its ultimate shear strength. Specimens with 1.0 mm adhesive thickness presented an average ultimate strength of 0.89 MPa (CoV: 16.67%), while the average ultimate shear strength for specimens with 0.5 mm and 0.1 mm was 2.17 MPa (CoV: 8.89%) and 3.01 (CoV: 6.91%), respectively, with an increase of 143% and 238% when compared with 1.0 mm thickness. Furthermore, the decrease on the coefficient of variation with the reduction of the thickness suggests more regular and homogenous adhesive layers. This may be

related to a greater quality control over the thickness of the layer for the thinner specimens and this could be observed during the preparation of the specimens.

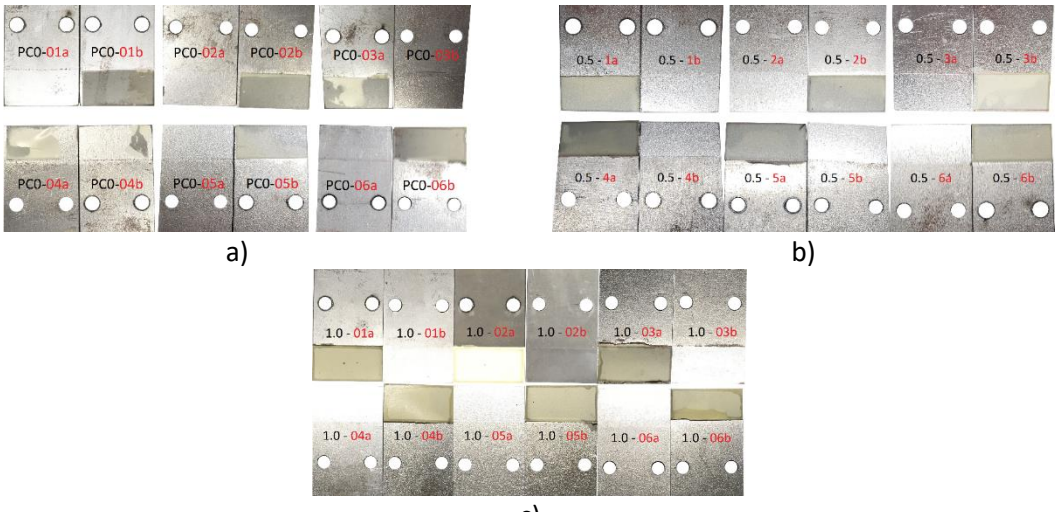
Figure 3b shows the evolution of the force vs. displacement curves obtained for the specimens with 0.1 mm thickness. Despite the differences on the ultimate shear strength for the three studied sets (depicted in Figure 3a) no major differences were observed on the evolution of the shear response curves for the different thickness of adhesive.



a) *b)*

Figure 3. Influence of the layer thickness: a) Ultimate shear strength for specimens with different layer thickness; b) force vs. displacement evolution obtained for specimens with 0.1 mm layer thickness.

Figure 4 shows that in all the specimens with 0.5 mm and 1.00 mm thickness, failures took place by debonding of the interface steel/adhesive, while one of the specimens with 0.1 mm thickness presented a mix between cohesive and debonding failure (specimen PC0-04).



a) b)

c)

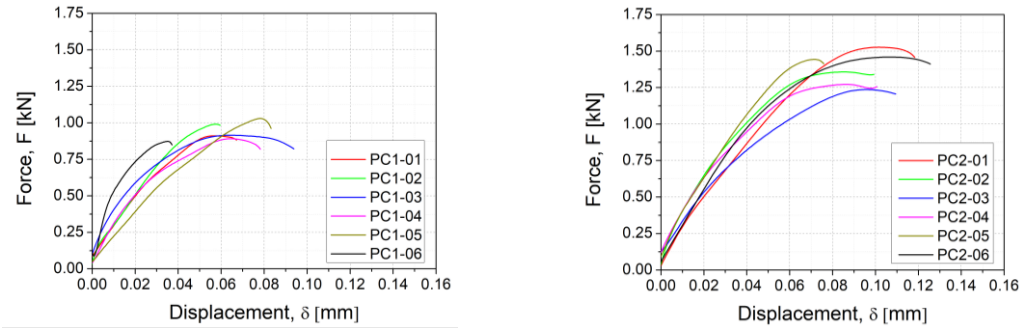
Figure 4. Aspect of the failure regions on specimens with different layer thickness: a) 0.1 mm; b) 0.5 mm; c) 1.0 mm.

3.2 Influence of post-curing conditions on the adhesive's shear strength

In a final stage of this investigation, two sets of specimens with 6 specimens each, bonded with the optimal layer thickness (0.1 mm) were manufactured and subjected to different post-curing conditions to assess its influence on their shear response. Therefore, three different post-curing

conditions were tested: i) values obtained on the previous campaign were used as a reference set (referred as PC0), without any additional post-curing procedures (despite being kept under controlled conditions); ii) a set (referred as PC1) subjected immediately after manufacture to 42 °C for 7 minutes (similar conditions as during manufacture of the panels); iii) a set (referred as PC2) subjected immediately after manufacture to 42 °C for 7 minutes, and additionally subjected to 80 °C for 12 hours after 3 days of manufacture, to reproduce eventual post-curing during the service life of the adhesive.

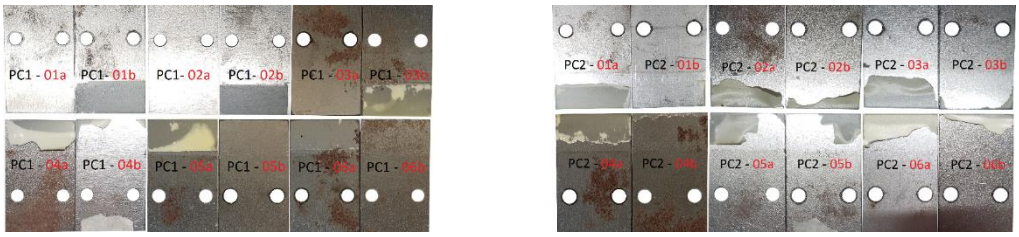
Figure 5 shows the relationships between force and displacement obtained for sets PC1 and PC2. Comparing these results with the reference set (Figure 3b) it can be seen that PC1 specimens present an increase on their shear stiffness (depicted by the increase on the curves slope). Likewise, PC2 specimens also presented a similar increase on their shear stiffness. Additionally, this set also revealed a considerable increase on their ultimate shear strength.



a) b)

Figure 5. Force vs. Displacement evolution obtained for specimens: a) PC1 set; b) PC2 set.

Figure 6 presents the failure modes obtained on this campaign. For the PC1 set, it can be noticed one of the specimens presented a mix of cohesive and debonding failure (PC1-04), and all other showed pure debonding failures (similarly as shown in Figure 4c for the reference set PC0). On the other hand, all the PC2 specimens presented a mix of cohesive and debonding failure, which reveals a stronger interface connection between the metal and the adhesive.



a) b)

Figure 6. Aspect of the failure regions on specimens subjected to different post-curing conditions: a) PC1; b) PC2.

Figure 7 summarizes the ultimate shear strength results obtained for specimens assembled with different adhesive thickness and subjected to different post-curing conditions. The average values for the shear strength of the sets were 3.25MPa (CoV: 11.10%) for set PC1; and 4.57MPa (CoV: 8.35%) for set PC2. These values, when compared to the obtained on section 3.1 and used as reference (3.01 MPa, CoV: 6.91%), represent an increase of 8% and 51% on the maximum shear strength for the two sets with specific post-curing procedures (PC1 and PC2, respectively).

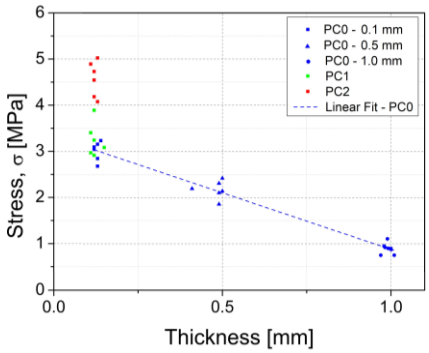


Figure 7. Ultimate shear strength for specimens with different layer thickness and subjected to different post-curing conditions.

4. Conclusions

This paper intended to assess the influence of different post-curing conditions on the mechanical response of polyurethane-based adhesive for civil engineering applications. For such, stepwise experimental campaigns were performed, in order to achieve a series of specific goals, namely: i) investigate the influence of different proportions of components on the adhesive; ii) investigate the influence of the layer thickness on the shear strength of the adhesive; and, finally, the main goal of the study, iii) investigate the influence of different post-curing conditions on the shear response of the adhesive.

From the different experimental campaigns of this work, it can be concluded that:

- The adhesive composed by 31.3% M229 SH Isocyanate and 0.25% of the GM817 Catalyst was considered the most adequate for this work, once it showed an ultimate strength in the magnitude of 3.0-4.0 MPa and 16-23 min of handling time (which is sufficient to allow the assembling of the CFS sheets simultaneously to the foaming of the PUR).
- Thinner layers increase the shear strength of the adhesive. An increase of 143% and 238% on the maximum shear strength for 0.5 mm and 0.1 mm thick specimens, respectively, was observed when compared to the values obtained for the 1.0 mm thick.
- Modifications on the adhesive layer thickness can modify the failure modes obtained on the shear strength tests. While for adhesive layers with 1.0 mm and 0.5 mm thick all the specimens failed by debonding on the steel/adhesive interface, one of the specimens with 0.1 mm thickness presented a mix of cohesive and debonding failure.
- Subjecting the panel to elevated temperatures during the curing of the polyurethane adhesives is an effective way to enhance their stiffness and shear strength. An increase of 8% on the maximum shear strength was observed for specimens of PC1 set. Likewise, specimens of PC2 set presented a 52% increase on their maximum shear strength when compared to the reference set.
- Post-curing conditions that encompass higher temperatures can also play an important role on the type of failure mode obtained on the tests. While for the PC1 set, 5 specimens presented debonding of the steel/adhesive interface failure modes and 1 presented a mixed failure (similarly as for the reference set), all specimens of PC2 set showed a mix of cohesive and debonding failure modes.

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