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Experimental study of the adhesive glass-steel joint behavior in a tensegrity floor

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ABSTRACT

In this experimental study the mechanical performance of the adhesive joints in a steel-glass connection is investigated. The aim of this work is to verify the applicability of the adhesive bonds on the "Tensegrity floor" (Patent no 0001426973); "Tensegrity floor" is a hybrid system characterized by a particular steel-glass adhesive junction that permits an effective cooperation between the two structural elements (a glass panel and a steel sub-frame). The innovation of this structure is related to the cooperation of the above mentioned elements; in fact, in those applications where the glass represents the floor decking, the adhesive glass-metal junctions have already been used, but the glass panel has not been considered as a cooperating element.

For this reason, several adhesives - four epoxy, one silicone and one acrylic - have been herein tested in order to study the opportunity of using this connection to increase the stiffness of the system. Two types of characterization test, compression and tensile tests, have been carried out to obtain the mechanical properties of the adhesives. After this step some suitable component tests have been performed with a stepwise cyclic loading; the results showed the effectiveness of the system in terms of stiffness increasing and consequent reduction in terms of deformations. As a result of these experimental investigations the epoxy adhesives have shown a better behavior, both in compression and in flexion, in term of stiffness, than the acrylic and silicone ones, which, instead, have got highest deformability.

A numerical validation of the whole system has been done through a Finite Element Model of the tested samples; the analytical results confirmed the stiffness increase due to the adhesive joint compare to the simply-supported model.

1. Introduction

Recently, in the context of civil engineering, glass was widely used for several applications, such as wall façade systems, glass floor [1], glass columns and beams [2–5]. Additionally, an increasing interest was also addressed towards *technological simplification*. The reduction of the number of components leads to numerous advantages: ease of installation, saving of production time and decrease of the environmental impacts, thanks to the reduction of production processes and the relative CO_2 emissions. "Tensegrity floor" (Patent no 0001426973) is a clear example of this concept; it is a system conceived to create lightweight, neat, almost transparent modular composite floors supported by an efficient and rational structure able to enhance both aesthetical and physical properties of the whole system. The most peculiar parts of this structural system are the joints; indeed, the main problem in these types of structures is represented by the connection between their glass element and the metallic sub-frame. The classic bolted joints are not adequate because of glass brittleness, so the adhesive junction should be preferred; unlike mechanical ones, this type of joint offers relevant advantages, such as the lack of borehole and a uniform load transfer. Furthermore, materials with different mechanical and thermal properties can be joined together. These new capabilities of adhesives led to the development of hybrid structures composed of glass and steel [6].

Many experimental studies were carried out to characterize the adhesive joints. Among them Overend et al. [1] realized glass-steel joints using five different adhesives (one silicone, one polyurethane, one epoxy and two acrylic) and then investigated the mechanical performance of steel–glass adhesive joints by mechanical tests on specially adapted single-lap shear and T-peel specimens. Other authors [6,7] studied various adhesives (polyurethane, acrylic and silicone) glass and different metals (steel, stainless steel and aluminum alloy), doing a comparison between the tensile and shear mechanical performance and

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Nomenclature

ACR	Acrylic adhesive
A_t	Application temperature
EPX1	First epoxy adhesive
EPX2	Second epoxy adhesive
EPX3	Third epoxy adhesive
EPX4	Fourth epoxy adhesive
E_t	Young modulus in tension
SIL	Silicone adhesive
S_t	Service temperature
T_g	Glass transition temperature
W_t	Working time at 22 °*C*
ε_t	Tensile strain
σ_t	Tensile strength
σ_{ys}	Tensile yield strength
τ	Shear strength
ν	Poisson modulus

analyzing the effects of the environmental ageing (high relative humidity and UV-radiation, both low and high temperatures). In other studies [8–10], both tensile and compression properties of the adhesive and mechanical performances of the adhesive joints were used to validate analytical models for the design of steel-glass structures. Despite this, relatively few researches were performed on steel/glass adhesive connections. This is partly due to the enormous bandwidth of physical properties of adhesives together with their non-linear properties and unknown lifetime behavior [11]. Significantly, most researchers focused their interest on the application of glass as a non-resistant component, therefore we found scarce information about the effective contribute that glass-panel could give to the whole structure in terms of stiffness increase.

In this paper the mechanical performance of adhesive joints in a steel-glass connection is investigated. The goal is to verify the applicability of the adhesive bonds on the "Tensegrity floor" and to quantify the cooperation between the two structural elements: the glass panel and the steel sub-frame. As a consequence will be possible to select the best adhesive to be used for the "Tensegrity floor", in term of highest stiffness increase and smallest registered displacements.

In the experimental campaign, the following steps were performed:

- tensile and compression tests, to characterize the mechanical properties of each adhesive used in the hybrid system;
- flexural test on small-scale specimens, performed with a cyclic loading, to investigate the flexural behaviour of the whole system.

Experimental results showed the high stiffness increase of the whole system in presence of the adhesive joint, if compared with a simply-supported one, and the consequent reduction of deformations.

A numerical validation of the whole system has been done through a Finite Element Model of the tested samples; analytical results confirmed the stiffness increase due to the adhesive joint compare to the simply-supported model.

2. The Tensegrity floor

In this section few concepts of the Tensegrity systems are summarized in order to better understand the main topic of this paper. For this reason, it is important to highlight that this research work is focused on validating the basic hypothesis of the "Tensegrity floor" (Patent no 0001426973) (see Fig. 1), that is the collaboration between the glass panel and the metallic sub-frame.

Since the 50's, Tensegrity systems have been used by sculptors and architects in civil engineering [12–15]; according to Renè Motro these are "*systems in a stable selfstress state, they include a discontinuous set of compressed components inside a continuum of tensioned components*".

Differently from the previous applications of tensegrity structures as floors, such as the transparent glass floor of the National Museum of Reggio Calabria, developed by the Italian engineer Loris Manfroni, the "Tensegrity floor" (Patent no 0001426973) introduces a new structural element, namely the glass panel. In fact, even if the widespread glazing façades are called "structural", since glass is assumed to be primary structural member, the glass panels are not effectively cooperating with the metallic sub-structure; in fact the glass panel is not taken into account to contribute, in design phase, to the resistance of the whole façade. The adhesive joint, made of structural silicone, has the unique role to connect the glass panels to the metallic members, but a further support is needed in order to keep it on sight.

In the "Tensegrity floor", thanks to the designed adhesive joint, the glass is no longer in the simply-supported configuration, but it guarantees an actual contribution towards the reduction of the deformations of the whole system within the limits imposed by building codes. This lead to obtain a very lightweight metallic substructure, as it can be seen in Fig. 2.

This remarkable result is due to the mechanical behavior of the adhesive joint under load application; as it will be further explained in the analytical section, the mechanical performances of the Tensegrity floor cannot be explained through a simple 1-D analytical model. Results show that it works under compression conditions.

3. Experimental methods

This research work is a preliminary study in order to verify the applicability of the adhesive joint in the "Tensegrity" system and to quantify the collaboration between the glass panel and the steel sub-frame in terms of stiffness increase.

The experimental test include: i) tensile and compression tests to characterize the different adhesives; ii) flexural tests on the hybrid system. Since authors tested the effectiveness of the adhesive junction between GFRP profiles [16] and between GFRP profiles and steel [17], and since different adherents does not influence results of the shear test, shear mechanism has not been considered in this experimental campaign. In any case shear mechanism does not affect the mechanical behavior of the tested system.

3.1. Materials properties

3.1.1. Adherents

The two adherents tested in the present work are: AISI 304 steel grade and a security PVB laminated glass, according to the CNR-DT 210/2013 [18]. Both materials were supplied by ESIGLASS (Italy); the properties of the two materials, are summarized in Table 1.

It is important to point up that the effects of the roughness has not

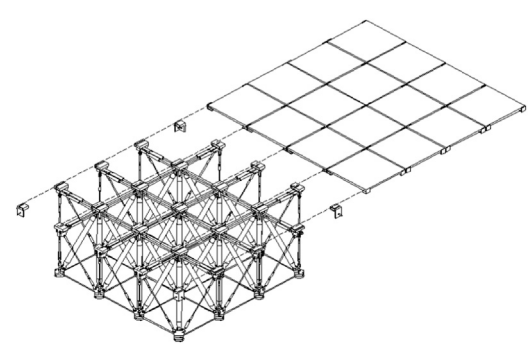

Fig. 1. Tensegrity axonometric view (Patent no 0001426973).

Fig. 2. Simulation of the installation of the Tensegrity floor in new and existing structures.

Table 1
Glass and steel mechanical properties according to manufacturer's data sheet.

Glass panels[a]			Steel profiles[b]			
E_t (GPa)	σ_t (MPa)	ν	E_t (GPa)	σ_{ys} (MPa)	σ_t (MPa)	ε_t (%)
70	120	0.22	200	241	586	55

[a] According to CNR-DT 210/2013 [18], tempered glass.
[b] According to EN 10025-2: 2004 [19].

been investigated, and no surface treatments were done on the adherents.

3.1.2. Adhesives

The selection of the adhesives was a difficult challenge, due to the lack of guidelines on the application for a steel-glass connection. In order to find out the best-set products, adhesive manufacturers and other researchers were consulted, and two selection criteria were followed: (i) the adhesive should be especially suitable for a steel-glass connection; (ii) the set should be heterogeneous in load capacity and stiffness. Then six different adhesives, four epoxy, one silicone and one acrylic, were considered in the experimental program, designated respectively EPX1, EPX2, EPX3, EPX4, SIL and ACR. The relative technical and mechanical characteristics, reported from manufacturers, are here summarized in Table 2.

The selected one-part silicone has been chosen only to compare results with epoxy and acrylic adhesives; in fact the tested technology does not allow the use of silicones as adhesives, since, in order to guarantee the expected performances, the thickness of the adhesive joint would have been too high and cause, therefore, functionality problems.

The mechanical properties were also experimentally evaluated (except for the acrylic adhesive, being a tape) and three specimens of each type of adhesive were subjected to tensile tests, according to EN ISO 527-1:2012, EN ISO 527-2:2012 [20,21]. The resulting small data scattering allowed avoiding further repetitions of the test. The dimensions of the dog-bone specimens are shown in Fig. 3. All specimens were cured at room temperature for about one month.

The results are summarized in Table 3 and confirmed the highest performance of ***EPX1*** and the worst load bearing capacity of ***SIL***; the latter shows the highest deformability among the tested adhesives. From the comparison between Tables 2 and 3, it can be observed that there is a slight difference between tested properties and the values reported in data sheets by the manufacturers. These results show how the manufacturing process can affect the mechanical properties of the adhesives. Furthermore, the mechanical behavior of the adhesives is strongly affected by both the environmental conditions, as reported in the technical sheets, and the test method, and then the test results can be significantly different from the ones provided by manufacturers.

A compression test was performed in order to characterize the behavior of the different adhesives under cyclic loading; this particular test has been done in order to reproduce the performance of the adhesive joint in the Tensegrity system. As it will be further explained in Section 5, the adhesive joint undergoes only compressive stresses under the applied cyclic loading; so the results of these tests have been used to characterize the analytical model in the numerical section, which validated the experimental behavior. The joint sample is reported in Fig. 4 during its preparation steps. In order to define the proper area of

Table 2
Technical and mechanical characteristics of the adhesives reported by manufacturers.

Adhesives	*EPX1*	*EPX2*	*EPX3*	*EPX4*	*SIL*	*ACR*
Chemical base	Two-part epoxy adhesive	Two-part epoxy adhesive	Two-part epoxy adhesive	Two-part epoxy adhesive	One-part silicon sealant	Acrylic
Consistency	Controlled flow	Controlled flow	Pasty	Pasty	Pasty	Tape
W_t (min)	90–300	20–30	16	17	15	/
A_t (°C)	15–25	/	15–25	15–25	15–30	21–38
S_t (°C)	− 40 + 120	/	− 40 + 80	− 40 + 84	− 50 + 150	− 35 + 90
T_g (°C)	/	23	55	54.6	/	/
Surface treatments	Sand	Sand and degrease	Sand and degrease	Sand and degrease	Degrease	Sand and degrease
τ[a] (MPa)	33.50	15.17	29.40	36.60	/	0.48
σ_t (MPa)	/	22.75	/	/	1.60	0.59
E_t (MPa)	3000	500	1800	2600	1.0	0.9
ε_t (%)	3	120	/	/	600	/
Use	Structural	Structural	Semi-structural	Semi-structural	Structural	Structural

[a] On aluminium-steel adherents.

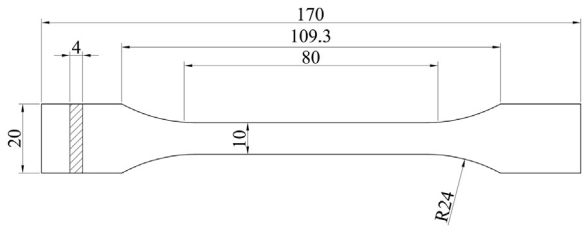

Fig. 3. Dog-bone specimens dimensions (mm).

Table 3
Data of mechanical properties in tensile test of the adhesives.

Adhesives	E_t (MPa)		σ_t (MPa)		ε_t (%)	
	Mean value	Range (±)	Mean value	Range (±)	Mean value	Range (±)
EPX1	2440.0	53.30	32.2	3.20	2.1	0.69
EPX2	102.2	4.64	12.2	1.30	49.5	9.60
EPX3	1774.0	30.28	17.1	0.70	3.8	0.23
EPX4	1751.4	69.27	38.0	7.06	2.5	0.71
SIL	0.5	0.15	1.0	0.03	151.2	55.05

adhesive and to facilitate the realization a soft tape of polychloroprene (3 mm) was used (Fig. 4a)).

To reproduce the actual adhesive connection of the hybrid system (30×30 mm^2), an aluminum-plate of 40×40 mm^2 has been realized; then the thickness of the joint has been set to 3 mm, the same thickness of the tensegrity adhesive joint, except for the acrylic tape, that was 2.3 mm. The geometric configuration is reported in Fig. 5.

The tests were done in laboratory conditions (temperature of $17 - 20$ °C, relative humidity of $60 - 70$ %) applying a displacement rate of 1.25 mm/ min, using a UTM by Zwick/Roell Z050, with a step-wise cyclic loading (see Fig. 6); this particular load history is typical of the test phase of traditional floors. Three repetitions for each adhesive were done and the average results are summarized in Table 4; in particular the maximum displacement $\boldsymbol{d}$ (mm) recorded at the maximum load and the stiffness $\boldsymbol{k}$ (N/mm) relative to the linearized load-displacement curves were obtained. The whole results have been compared with simply-supported (*S.SUPP.*) samples, where the adhesive junction is not present and therefore the glass panel is a non-co-operating element. It is worth pointing out that the polychloroprene tape has been used in the simply-supported sample too, in order to reproduce the connection realized in the corresponding specimen of the whole structure; in the simply-supported samples the glass panel is separated from the metallic substructure by the same tape, in order to avoid the brittle fracture of the glass element.

From the analysis of Table 4, the EPX1 adhesive shows the best results in terms of stiffness (7603 N/mm), while the acrylic shows the worst performance (1735 N/mm); same consideration can be done about the displacement values (0.27 mm). With regard to the simply supported sample, great differences came out, in terms of maximum displacement (2.35 mm) and stiffness (22 N/mm). Two important considerations can be done: i) the presence of the adhesive junction ensures a stiffness increase of the system; ii) the high displacement recorded in the simply supported sample is due to the compression of polychloroprene, negligible when the adhesive is present. In fact the adhesive, due to its higher stiffness, is loaded and the presence of the tape does not contribute to the stiffness of the whole system.

In Fig. 7 the trends of the three test repetitions referred to the best adhesive are reported; in the same figure the corresponding linearized curve is represented; the latter has been obtained by neglecting the first part of the experimental trend, where a small hysteresis, due to the settling of the sample, is observed. As evidenced in this figure, the trend is representative of a linear-elastic material, for this load range, and there is no residual deformation; although, from the analysis of Fig. 8, it is evident that in the simply-supported sample the high displacement and residual deformations are related to polychloroprene compression. For the same reason it is almost impossible to approximate the behavior of this element as a linear elastic one. In this last case the linearized trend has been obtained by interpolating the values contained in the same range of displacements (less than 1 mm) of the adhesive joints; once this range has been exceeded, polychloroprene is almost completely compressed and becomes rigid.

3.2. Experiments

The flexural tests were performed to reproduce the stress of the whole "Tensegrity" floor when it is subjected to the pedestrian live load. In fact this load condition occurs in the design of the structures belonging to the C2/C3 building category according to the Italian building code [22]. The geometry of the analyzed system is depicted in Fig. 9.

Twenty-one samples were tested: three for each adhesive and three

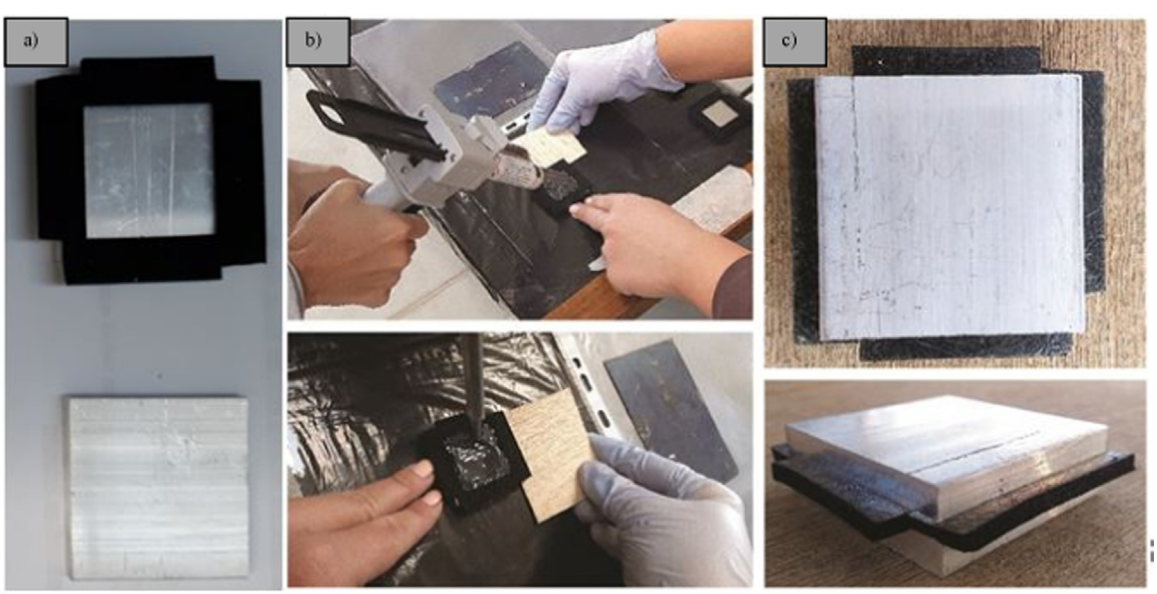

Fig. 4. Preparation steps of the adhesive joint sample: a) delimitation of the adhesive area through polychloroprene tape; b) adhesive positioning; c) tested sample.

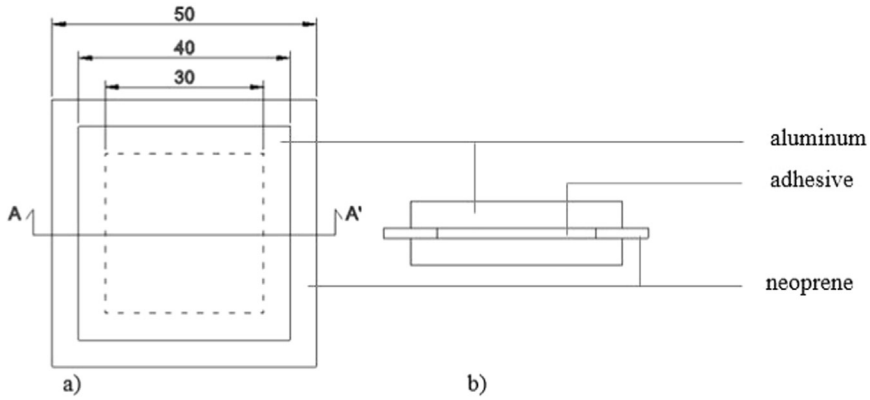

Fig. 5. Geometric configuration (mm) of the samples: a) plane view; b) cross section A-A′.

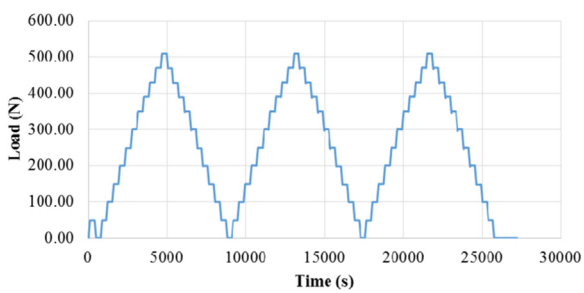

Fig. 6. Step-wise cyclic loading.

Table 4
Mechanical properties from compression tests.

Series	*d*[a](mm)		*k* (N/mm)
	Mean value	Range (±)	
EPX1	0.068	0.013	7603
EPX2	0.100	0.004	5065
EPX3	0.074	0.021	7260
EPX4	0.069	0.011	7396
SIL	0.239	0.105	2272
ACR	0.275	0.017	1736
S.SUPP.	2.352	0.064	22

[a] Corresponding to the maximum carried value equal to 511 N.

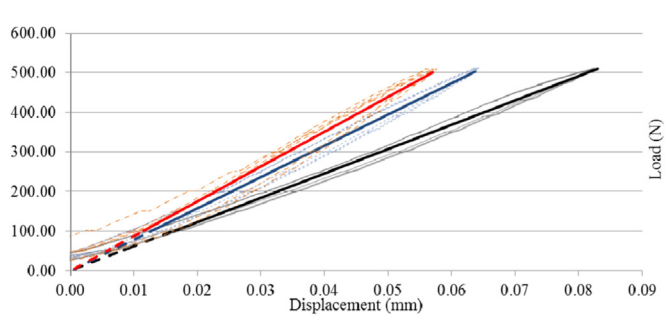

Fig. 7. Compression test of *EPX1*: experimental trend (thin line) and linearized trend (thick line): I sample (gray solid line), II sample (cyan dashed line), III sample (orange dash-dotted line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for the simply supported system, where the glass panel is not bonded on the steel sub-frame. The sample was composed by two steel squared tubular profiles of AISI 304 (thickness 2 mm) and a laminated glass panel (thickness 4/4 mm with PVB interlayer 0.76 mm), connected through a glued joint. The adhesive bonding thickness for all specimens was 3 mm, except for the acrylic tape that was 2.3 mm; in order to

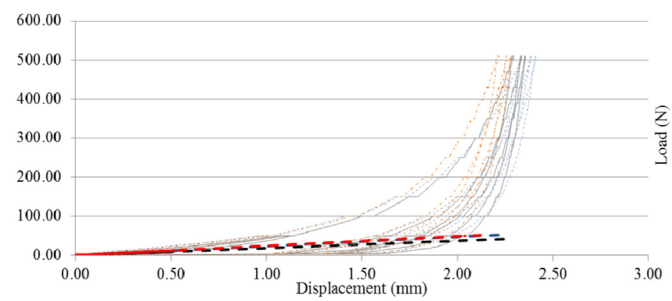

Fig. 8. Compression test of *SIMPLY-SUPPORTED*: experimental trend (thin line) and linearized trend (thick line): I sample (gray solid line), II sample (cyan dashed line), III sample (orange dash-dotted line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

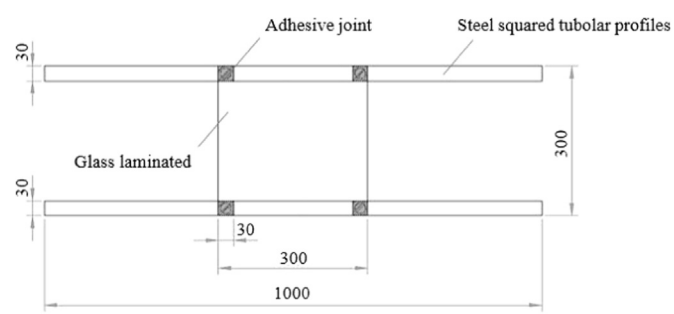

Fig. 9. Geometric configuration of the hybrid system [mm].

avoid, under load application, the contact between the glass panel and the steel elements, which can cause brittle fractures, a soft tape of polychloroprene (3 mm) was interposed between the glass panel and the steel profiles (see Fig. 10). All surfaces were cleansed with isopropyl alcohol except for the acrylic tape. For the latter two types of primer were used: one for glass and the other for steel profiles.

The samples were cured for 35 days in laboratory conditions and later were tested through flexural test with cyclic loading (see Fig. 11). Fig. 12 shows the flexural test set-up: the specimens were positioned on two steel beams, with a span of 800 mm (Fig. 12a); Fig. 12b shows the corresponding static scheme. To avoid undesired torsion deformations during the test, suitable clamps were manufactured, registering the displacements due to the loading conditions only (bending).

Displacements were registered in seven points using vertical transducers (system for data 24 bit MAE), depicted in Fig. 13, and located on the intrados (the bottom surfaces) of the profiles. The vertical transducers are analogue potentiometers (model PY2C-50P) supplied by MAE. In Fig. 12c the numeration of the transducers is depicted: points 1

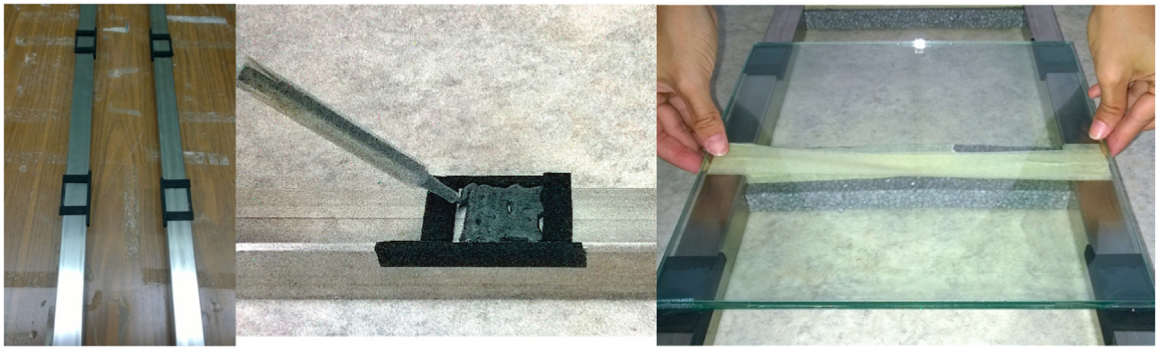

Fig. 10. Specimens manufacturing phases.

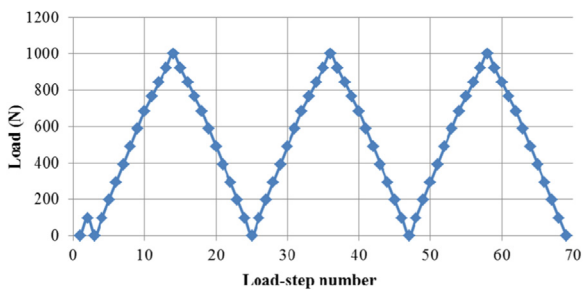

Fig. 11. Cyclic loading for flexural test.

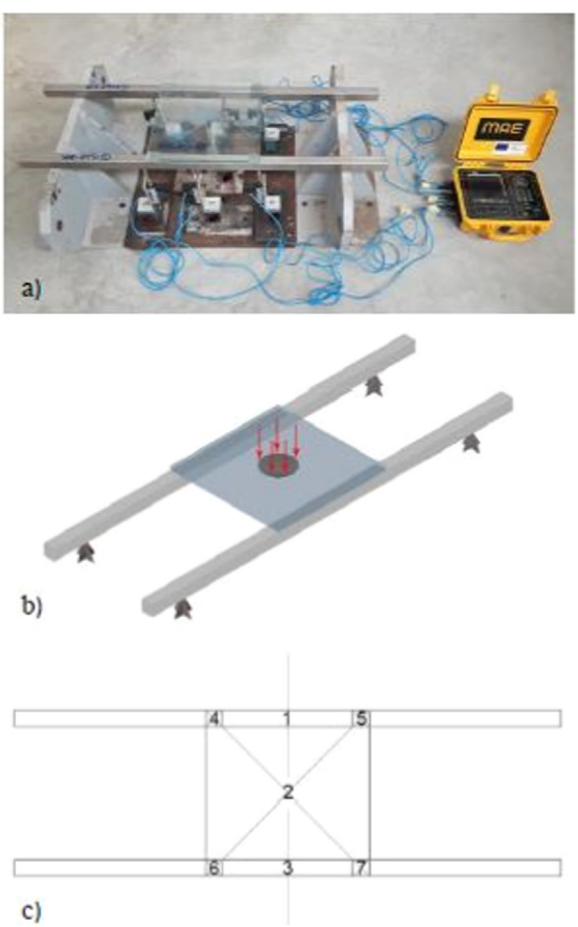

Fig. 12. Flexural test: a) test set-up; b) static model; c) transducers location.

and 3, the medium points of the steel profiles, register the maximum displacements of the profiles; point 2 registers the maximum

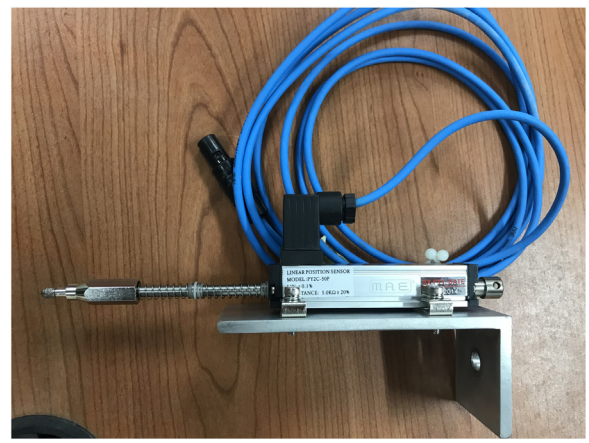

Fig. 13. Vertical transducers.

displacement of the glass sheets; points 4-5-6-7 register the displacements of the glass panels corners, where the glass-steel adhesive joints are positioned.

After the positioning of the sample and the application of the clamps, a metallic pivot was set in the center of the glass sheet. The sample was subject to a first-step load of 98 N in order to settle the hybrid system; then the test started by incrementally loading the cell plates, that are located on the metallic pivot, as shown in Fig. 14.

The experimental test is characterized by three steps of loading and unloading, reaching a maximum load of about 1000 N (see Fig. 11). In Fig. 15 the load application on the assembled hybrid system is shown.

4. Result and discussion

In this section, the mechanical response of the "Tensegrity" system specimen subjected to flexural test is presented and analyzed. The stiffness of the different samples is depicted in Table 5; in the same table the stiffness increase with respect to the simply supported sample is summarized, and it is evaluated as:

$$\Delta = \frac{k_{adhesive} - k_{S.SUPP.}}{k_{S.SUPP.}} \times 100 \quad (1)$$

Results are referred to the control points on the midpoint of the glass sheet (point 2), on the midpoint of the steel profiles (points 1–3), on the adhesive joints in the corners of the glass sheet (points 4-5-6-7). From the analysis of Table 5 we can draw out the following considerations: i) EPX1 results the best adhesive in term of stiffness increase; ii) EPX1, EPX2, EPX3 and EPX4 always present a stiffness increase with respect to the simply-supported sample; iii) SIL doesn't ensure the same behavior, recording stiffness reduction at point 2; iv) ACR presents stiffness reduction up to 30% Table 6.

This particular result suggests an immediate mechanical

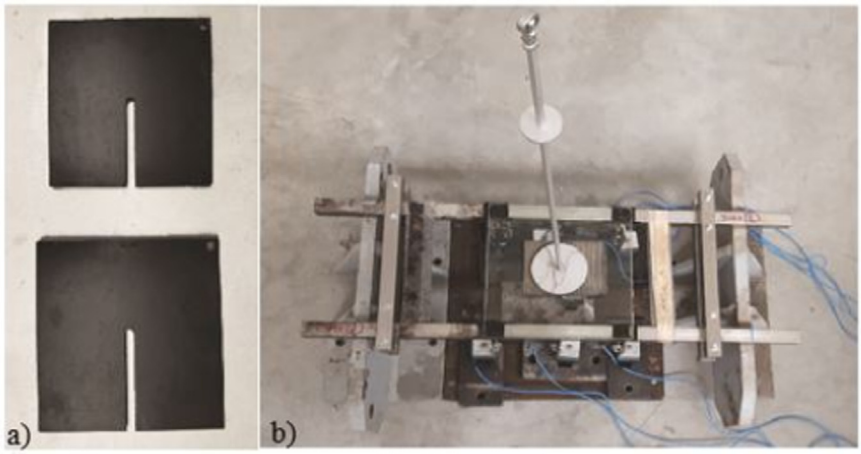

Fig. 14. a) Load plates; b) metallic pivot positioning.

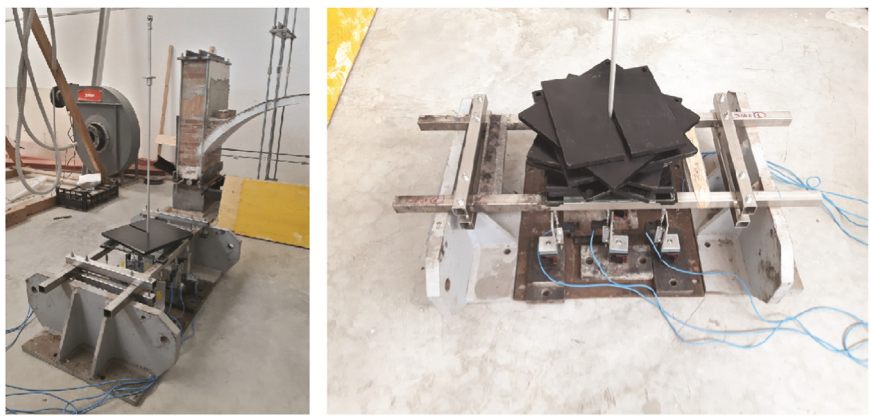

Fig. 15. Load application on the assembled hybrid system.

Table 5
Mechanical properties of hybrid sample, with or without adhesive connection.

Series	*Control point*	*k*[a] (N/mm)	Δ (%)
S.SUPP.	pt. 2	528.48	/
	pt. 1–3	1188.76	/
	pt. 4-5-6-7	1380.68	/
EPX1	pt. 2	465.23	+ 15
	pt. 1–3	1031.27	+ 29
	pt. 4-5-6-7	1215.63	+ 26
EPX2	pt. 2	464.05	+ 1
	pt. 1–3	1067.26	+ 12
	pt. 4-5-6-7	1126.91	+ 11
EPX3	pt. 2	484.45	+ 1
	pt. 1–3	1085.99	+ 16
	pt. 4-5-6-7	1215.93	+ 3
EPX4	pt. 2	348.43	+ 5
	pt. 1–3	993.32	+ 18
	pt. 4-5-6-7	1175.53	+ 11
SIL	pt. 2	320.78	− 24
	pt. 1–3	916.33	+ 8
	pt. 4-5-6-7	1075.1	+ 7
ACR	pt. 2	459.93	− 30
	pt. 1–3	921.83	− 1
	pt. 4-5-6-7	1097.36	− 2

[a] Corresponding to the maximum carried value equal to 1000.2 N.

interpretation: when the load is applied onto the center of the glass panel, the steel profiles undergo to a deformation, which is characteristic of the flexural behavior of the beam. If the glass panel is connected to the sub-structure through the adhesive joint, the junction is completely compressed; this is due to the greater deformability of the glass panel with respect to the steel beams (see Table 5). In this way the most rigid element, namely the glass panel, contributes to the stiffness of the system. Instead, a stiffness reduction is observed when the adhesive is much more deformable, then the surfaces slide onto each other.

Table 6
PVB mechanical characteristics.

PVB	
E_t (GPa)	ν
14.8	0.48

The load-displacement trends registered both for each adhesive and for the simply-supported sample are depicted in the Fig. 16. The trends are referred to the control points on the midpoint of the glass sheet (Fig. 16a), on the midpoint of the steel profiles (Fig. 16b), on the adhesive joints in the corners of the glass sheet (Fig. 16c).

From the analysis of this figure it is possible to notice an evident stiffness increase of the whole hybrid system when the adhesive connection is present, as a direct consequence the simply-supported sample shows higher deformations with respect to the ones with the glued joints. It is important to underline that the behavior of the simply supported sample during the first-load step, as in the compression tests, is due to polychloroprene compression; after this step the soft tape is almost completely compressed and the trend becomes rigid.

It is once again evident that the best glue is EPX1, providing the main stiffness increases while the ACR and SIL registers the worst behavior.

For a deeper analysis, the mechanical behavior of the “Tensegrity”

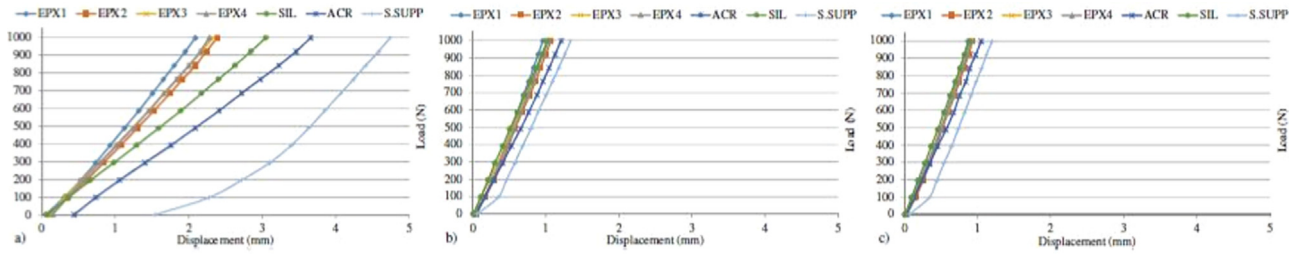

Fig. 16. Comparison between all adhesives used in "Tensegrity" samples with the simply-supported one: stiffness increase; a) point 2; b) points 1–3; c) points 4-5-6-7.

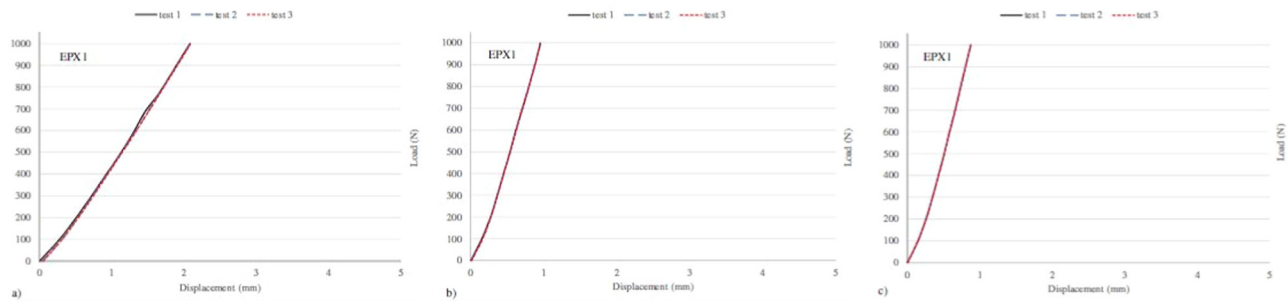

Fig. 17. Representative load-displacement trend of the "Tensegrity" sample with EPX1 adhesive: loading-unloading cyclic test: a) point 2; b) points 1–3; c) points 4-5-6-7.

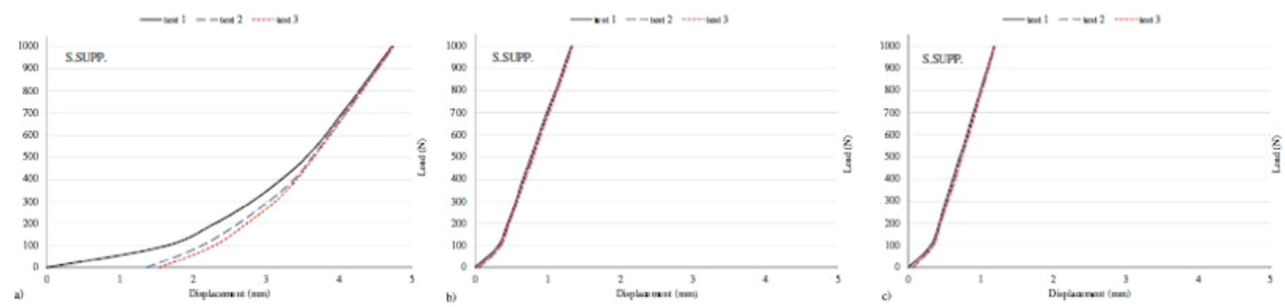

Fig. 18. Representative load-displacement trend of the "Tensegrity" sample without adhesive (simply-supported): loading-unloading cyclic test: a) point 2; b) points 1–3; c) points 4-5-6-7.

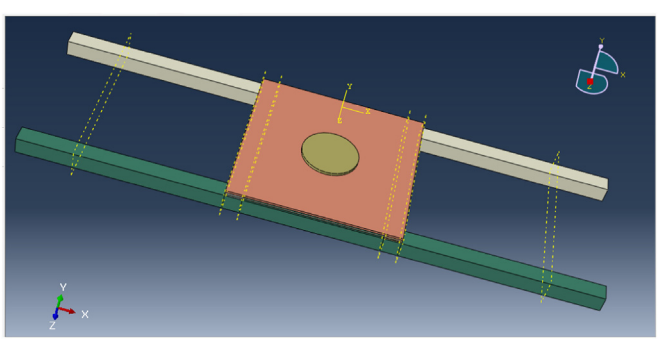

Fig. 19. FEM model.

sample where the glued joint was made with EPX1 adhesive is depicted in Fig. 17, where is noticeable an almost complete superposition of the three curves of loading-unloading steps, differently from the simply-supported system (Fig. 18). The residual displacements observed in the simply supported sample are due to the irreversible deformation of the polychloroprene tape interposed between glass panel and steel profiles; instead the compression of this element is avoided when the adhesive connection is realized.

Notice that the expected deflections of complete floors have been analytically evaluated, and are contained within the building codes provision [22]:

$$\frac{d_{\max}}{L} = \frac{1}{250} \tag{2}$$

in fact, considering a maximum extension of 10.80 m × 10.80 m and a distributed load of 5 kN/m^2, representative of the pedestrian live load the maximum deflection is about 30 mm, against 43.2 mm provided by (2).

5. Numerical analysis

The numerical analysis was performed with the FEM software ABAQUS®; in Fig. 19 the geometry of the modelled system is depicted. A circular element, reproducing the basis of the metallic pivot depicted in Fig. 14b, has been introduced in the FEM model, in order to define the load-application area.

The steel was modeled as an elastic-plastic material, while the glass was modeled as an elastic material, according to Table 1. The glass element was considered as a laminated element, with a PVB layer (0.76 mm thickness) interposed between two glass sheets (4 mm thickness). In fact the mechanical behavior of layered glass is determined by the capacity of the interface material, see PVB, to transfer cutting actions between the plates it joins together [23]. PVB is a material with temperature-depending mechanical characteristics; so, on the basis of the load and environmental conditions of the conducted

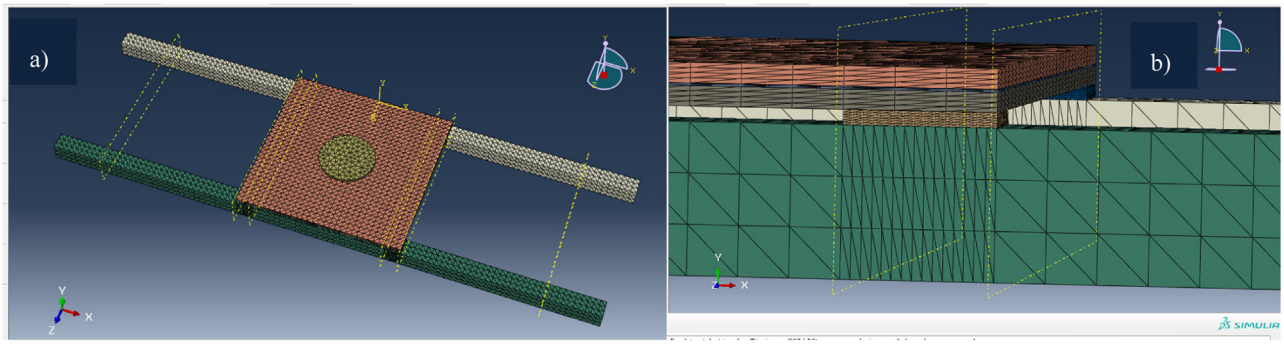

Fig. 20. Mesh configuration: a) whole system; b) particular of the meshed joint.

Table 7
Displacements of hybrid sample, experimental and FEM results.

Control point	$d^{a}_{experimental}$ (mm)	d^{a}_{FEM} (mm)	Δ (%)
pt. 2	1.990	1.936	2.71
pt. 1–3	0.795	0.802	− 0.88
pt. 4-5-6-7	0.728	0.696	4.39

[a] Corresponding to the maximum carried value equal to 1000.2 N.

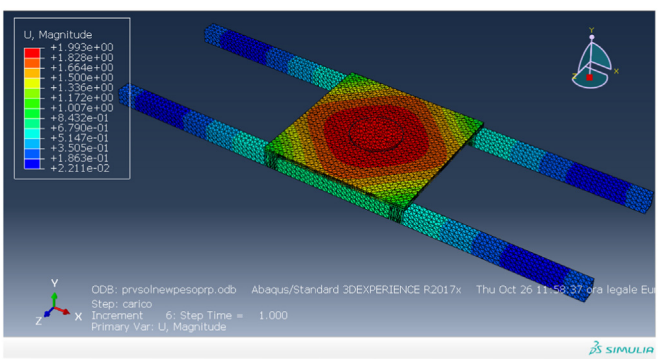

Fig. 21. Displacements map.

tests, the following parameters have been used:

The mesh has been modelled applying the finite element "3D STRESS"; Fig. 20 pictures the mesh configuration.

The selected adhesive is EPX1, as it resulted the best adhesive in term of stiffness increase; the adhesive has been modelled as an elastic material and its mechanical characteristics have been set according to Table 3.

The system has been subjected to the same load history of the experimental tests, depicted in Fig. 11; the resulting displacements are summarized into Table 7, together with the percentage error, evaluated as:

$$\Delta = \frac{d_{\text{experimental}} - d_{FEM}}{d_{\text{experimental}}} \times 100 \tag{3}$$

From the analysis of this table we observe a percentage error contained within 5%, so the FEM model proves the experimental results. Fig. 21 depicts the displacement maps.

Fig. 22 depicts the stress map where the compression of the joint is evident, as proposed in the analysis of the experimental results. Obviously, due to the flexural behavior of the tested system, shear stress could be present, proportional to the applied load; despite this, the stiffness increase is mainly due to the compression properties of the adhesive. In fact, thanks to the stress transmission allowed by the joint (compression), the glass panel is completely compressed under the applied load, and this fact permits the cooperation between glass and steel.

Furthermore these results justify the use of a 3-D model, which is the only way to correctly interpret the Tensegrity floor system.

6. Conclusions

In this paper an experimental campaign to investigate the bonding connection between laminated glass panel and steel sub-frame through six different adhesives is proposed. This preliminary study has been conducted in order to verify the applicability of the "Tensegrity floor". Both the stiffness increase and the cooperation of the glass panel to the resistance of the hybrid system were quantified and compared to the simply supported structure. Compression tests and tensile tests were carried out to obtain the mechanical properties of the adhesive. Furthermore flexural tests were performed to study the mechanical behavior of the hybrid system.

In this framework flexural test simulated the stress that occurs in Tensegrity floor when it is subjected to the pedestrian live load. This experimental results demonstrated the efficiency of the adhesive connection, registering average stiffness increasing values of about 29% with respect to the simply-supported sample; the best mechanical performance was observed in the EPX1 epoxy adhesive, confirming what

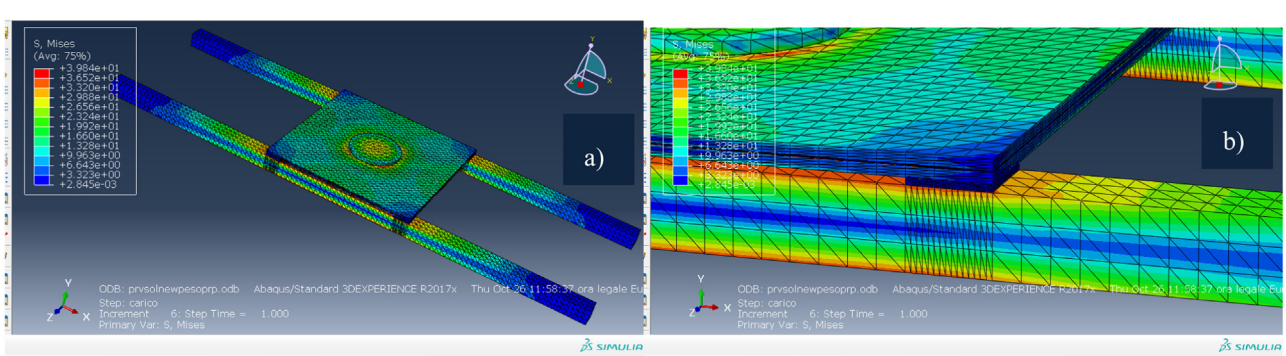

Fig. 22. Stress map a) whole system; b) particular of the joint.

observed in material characterization tests. In particular, the samples connected through EPX1 showed the highest stiffness and consequently the highest capacity to reduce deformations.

The aforementioned remarkable results demonstrated the effective collaboration between laminated glass panel and steel sub-frame thanks to the adhesive joint, which represents the innovation of the "Tensegrity floor".

The numerical analysis through a FEM model definitely confirmed the experimental results, with percentage errors within 5%.

In order to verify also the feasibility of production, the durability of the hybrid system should be investigated; in this regard, the characterization of the structure under environmental ageing is underway. The same samples used in this experimental campaign are currently subjected to an artificial ageing (humidity levels 100% and temperatures 40°) for, at least, nine months in a climatic chamber. The aged samples will be tested through flexural test.

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