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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

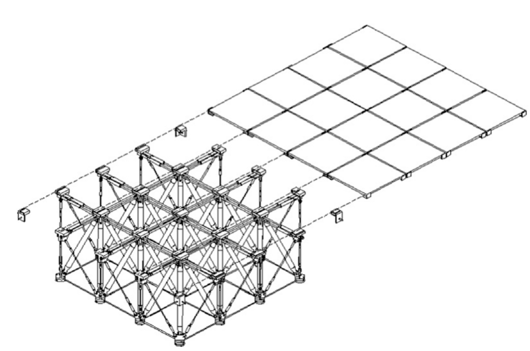

Fig. 1. Tensegrity axonometric view (Patent no 0001426973).