Assessment of the deformation behavior of a tensegrity floor through photogrammetry

G Chiappini, M Coccia, M Rossi, F Marchione, P Munafò, C Scoccia and C Luca

1 eCampus telematic University, Novedrate, 22060 – Italy
2 Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche, Ancona, 60131 – Italy
3 Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Ancona, 60131 – Italy

gianluca.chiappini@uniecampus.it

Abstract. Tensegrity structures are interesting elements that can be used to create innovative building components. In this work, the deformation behavior of a new type of tensegrity floor (patent n. 0001426973) was investigated through image analysis and photogrammetry, using stereoscopic algorithms. The main innovation of the proposed tensegrity floor is the structural cooperation between glass tiles and steel components, obtained using suitable adhesive joints. In order to evaluate the deformation of the floor under different loading conditions a non-contact measurement system was developed and validated on a scale prototype of the floor. The used method is a stereoscopic optical technique based on the grid method, the validation was performed comparing the measured displacement with the one measured in the same floor with linear displacement sensors. The stereoscopic images were processed with Matlab®, furthermore, a combination of interpolation algorithms were employed to generate the full-field map of the displacement. Two configurations of the floor (with and without the adhesive joints) and three loading conditions were investigated. The analysis demonstrates that the adhesive joints produce a reduction of the overall deflection of the floor of about 60%, falling within the admissible values established by Italian building code. The measurement system is reasonably accurate and can be used in future applications where linear transducers cannot be installed.

1. Introduction

Tensegrity is a structural principle based on a series of components subjected either to tension or compression arranged in such a way that the compressed members (usually bars or struts) do not mutually interact while the pre-stressed tensioned members (usually cables or tendons) describe the geometry of the system. No structural member experiences a bending moment and there are no shear stresses within the system. This can produce exceptionally strong and stiff structures for their mass and for the cross section of the components. Renè Motro describes the tensegrity structures as “systems in a stable selfstress state, they include a discontinuous set of compressed components inside a continuum of tensioned components” [1].
Figure 1 shows a tensegrity floor, developed and patented by one of the authors [2, 3], which is a hybrid glass-metal structure characterized by a light-weight metallic sub-frame sustaining a glass deck. Due to its high transparency, the floor is particularly suitable for applications in case of coverage of archaeological sites and the revitalizing of historical buildings, where it is necessary to have a view underneath the floor level.

![Figure 1. Figure with short caption (caption centred).](image)

The idea of using tensegrity structures with a metallic subframe was already applied by architects for their aesthetic values, see for instance refs. [4, 5]. However, the main novelty of this tensegrity structure is the introduction of the glass plates as structural elements which contribute to the global stiffness of the system. Usually, the glass panels do not produce an increase of stiffness of the whole building and they do not contribute to the underlying metallic supporting structure, even in the glazing facades that are commonly named structural. In the patented solution [6, 7], which is the object of this study, instead, the glass is no longer in the simply supported configuration but it is connected to the structure through a specifically designed adhesive joint, and it contributes actively to the deformation reduction of the whole system, allowing it to satisfy the limits imposed by building codes.

In order to evaluate the effectiveness of such approach and assess the contribution given to the stiffness of the floor by the adhesive joint, load tests were carried out on a floor 1:2 scale prototype. The aim of this work was to develop a measurement technique that exploits photogrammetry to evaluate the displacements and deflection of the floor during load tests. The development of a reliable non-contact measurement method is particularly important for future applications such as the in-situ monitoring of the floor deformation and for the performance analysis of the proposed solution.

In this work, the measurements were carried out on the prototype under two conditions: (i) with the glass tiles adhesively bonded to the steel nodes and (ii) with the glass tiles simply supported to the metallic frame. The results of the optical measurements were compared with an independent displacement value measured using mechanical LVDT sensors.

2. Material and methods

2.1. Tensegrity floor prototype

The prototype of the floor is made of a 4×4 grid of glass tiles, measuring 30×30 cm² each, the overall size of the prototype is 1.2×1.2 m² (see figure. 2). As illustrated in the schematic of figure. 2, the glass tiles are supported by a series of metal cubes, named upper cubes, that constitutes the first level of the tensegrity structure, the structure is then composed by a second level of metal cubes, named the lower cubes. In each level, the cubes are connected to each other with a set of orthogonal strands subjected to axial tension, named upper and lower strands, respectively. Finally, the two levels are connected through
a set of lateral elements, named *lateral strands*, which are the compressed part of the tensegrity structure and are made of a series of rigid beams.

The cubes have holes for the passage of the cables while small connecting forks, realized on the external surface, are used to connect the beams of the lateral strands. Glass panels are bonded with the upper cubes with the epoxy adhesive 3M™ Scotch-Weld™ DP7240B/A.

---

**Figure 2.** Floor prototype.

2.2. **Experimental test**

The prototype was tested with three different loading conditions, as shown schematically in figure 3. The loading conditions were determined in accordance with the Italian building code NTC2018, i.e.:

- a uniformly distributed load of 400 kg/m²;
- a load of 200 kg/m² applied to the centre of the floor;
- a load of 200 kg/m² applied to one side of the floor.

Each load case was repeated three times and the results presented and discussed in the following sections are the average of the measurements obtained in the three repetitions.

**Figure 3.** Load conditions.
2.3. Experimental setup
The displacement and deflection of the floor was measured with two different techniques: one based on a stereoscopic optical technique applied to the upper glass surface and the other based on the use of displacement sensors applied to the lower part of the floor. In figure 4 the used equipment and the experimental setup are shown.

![Figure 4. Experimental setup.](image)

The displacement sensors used to measure the lower displacement of the floor, are the M.A.E. PT50T, i.e. spring loaded linear displacement transducers with a stroke of 50 mm.

| Feature                        | CAMERA 1                              | CAMERA 2                              |
|--------------------------------|---------------------------------------|---------------------------------------|
| Sensor                         | CMOS                                  | CMOS                                  |
| Sensor pixel size              | 6.8 × 6.8                             | 6.8 × 6.8                             |
| Sensor resolution              | 1280 × 1024                           | 1280 × 1024                           |
| Frame rate                     | 1                                     | 1                                     |
| Lens                           | C mount, 12                           | C mount, 12                           |
| Working distance               | 1500                                  | 1500                                  |
| Sensor noise                   | 0.94, −19                             | 0.94, −19                             |
| Displ. accuracy (st. dev)      | ±[0.02, 0.09]                         | ±[0.02, 0.09]                         |

| Calibration data               |                                       |                                       |
|--------------------------------|---------------------------------------|---------------------------------------|
| fx – fy                        | 1779 - 1775                          | 1792 - 1785                          |
| cx – cy                        | 621 - 495                            | 636 - 519                            |
| Tx – Ty – Tz                   | 784 – -36 – 212                      |                                       |
| ax – ay – az                   | 0.0053 – 0.7118 – 0.0285             |                                       |

The adopted optical technique [8, 9, 10] is a grid method that allows to measure the shape of the surface subjected to the testing loads. Operatively, a grid of circular markers was glued on the surface,
as depicted in figure 4, then a stereoscopic system made of two digital cameras (model Pixelink®B371F, CMOS sensor with 1280x1024 pixel resolution) was used to obtain the picture of the floor at two different angle in order to apply stereography, after a suitable camera calibration. Table 1 shows the characteristics of the cameras and the obtained calibration parameters.

Starting from the undeformed configuration, images were saved for each loading condition. The images were then post-processed by image binarization and bubble analysis, obtaining the 3D coordinates of the markers in a global reference frame by stereoscopic algorithms. Finally, the 3D coordinates of the markers in the deformed and undeformed configuration were used to calculate the vertical displacement of the floor. The whole process is described in figure 6; in the deformed images, the weights used to load the floor are visible, the position of cameras and markers was indeed optimized so that the weights do not interfere in the stereoscopic analysis. The last plot of figure 6 shows how each point of the undeformed (blue) and deformed (red) configuration can be expressed in the same coordinate system to derive the deformation of the floor.

2.4. Data processing

Figure 6 shows the results obtained for the first load case, where a uniformly distributed load of 400 kgf/m² was applied to the floor. The developed optical technique was used to measure the vertical displacement close to the optical markers (black dots in figure) while the linear transducers were applied in the lower surface close to the lower cubes (red dots in figure). Since the position of the optical markers and the linear transducer is not coincident, a difference is observed between the two measurements that, for certain points is rather high, see for instance in points 4, 6, 7 and 8. To overcome this issues and have a fair comparison, the measurement of the displacement was computed at the exact position of the linear transducer using an interpolation procedure which starts from a discrete grid of 9×9 points.

![Figure 5. Image analysis and stereoscopic results.](image)

![Figure 6. Resulting displacements with the two different measurement techniques. The values corresponding to the optical technique were calculated close to the optical markers (black dots) while the linear transducers measurement were performed close to the lower cubes (red dots).](image)
The interpolation was performed combining three different algorithms available in Matlab®, in particular, the final displacement was obtained as the average of the values obtained from the different algorithms. The used algorithms are:

- **cubicinterp** – bicubic spline interpolation;
- **biharmonicinterp** - biharmonic spline interpolation (Matlab® griddata method);
- **thinplateinterp** - Thin-plate spline interpolation;

**Figure 7.** Extrapolation of optical results

**Figure 8.** Results for the floor with glued tiles
From this interpolation, a continuous map of the floor displacement can also be derived. Figure 7 shows the displacement maps obtained with the three different algorithms for the first load case, the three methods provide similar results. From here on, therefore, only the maps obtained combining the three methods will be shown. The comparison between optical method and linear transducer will be conducted at the exact position of the linear transducer (red dots), obtained through interpolation.

3. Results and discussion
This section presents the results of all measurements made with the three different loading conditions for the prototype with adhesively bonded glass panels (figure 8) and with simply supported glass panels (figure 9). For each condition, a scheme of the applied load, a map of the vertical displacement and a comparison between the optical measurement and the linear transducer at the 9 control points is provided. The first row of figure 8 illustrates the results obtained for the first loading condition, which is the same discussed in figure 7. In this case, a better agreement is found between the measurement of the optical method and the one obtained with the linear transducer, the large difference observed in points 4, 6, 7 and 8 is consistently reduced. A residual error is still present, which can be ascribed to the fact that the linear transducer is applied in the lower surface of the floor while the optical measurement is performed on the top, however, the obtained accuracy is reasonably good for the sake of the intended application.

![Image](image_url)

**Figure 9.** Results for the floor with simply placed glass tiles
To show the potentiality of the method, figure 9 illustrates the displacement of the floor obtained when the tiles are simply supported in the metallic frame without the adhesive joint. A consistent increase of the displacement is observed in all cases, which is around the 60%. Figure 10 shows the comparison with respect to the first loading condition. The optical measurement allows to capture the stiffness reduction efficaciously and can be considered as a valid alternative to the standard measurement performed with mechanical transducer.

![Figure 10](image.png)

**Figure 10.** Comparison of the displacements measured between the floor with glued tiles and simply placed

4. Conclusion
In this work, the result of a series of experiments performed on a tensegrity floor scale prototype was presented and discussed. The prototype, patented by one of the authors, is a hybrid glass-metal structure characterized by a light-weight metallic sub-frame sustaining a glass floor decking. The peculiarity of the developed floor is that the glass is not simply supported but it is connected to the structure through a specifically designed adhesive joint. The tests were conducted to evaluate the contribution given to the global stiffness of the floor by the adhesive joints.

The aim of this work was to develop a measurement technique based on photogrammetry to evaluate the displacements and deflection of the floor during this type of load tests. The optical measurement was compared with the one obtained in the lower part of the floor with linear transducers: the comparison was made exploiting multiple interpolation functions of Matlab® to evaluate the displacement at the exact position of the sensor.

The tests and measurements showed a consistent contribution of the adhesive joint to the overall stiffness of the floor: with glued glass tiles there is a stiffness reduction of about 60%. The non-contact measurement technique is enough accurate and reliable to perform this type of test. In the future, the developed measurement technique will be used to evaluate different types of structural adhesives and to optimize the floor and the adhesive joint.

References
[1] Motro, R., 2003. Tensegrity: structural systems for the future. Elsevier.
[2] Munafò, P., 2017. Tensegrity floor, May 3. Patent N.0001426973.
[3] Alderucci, T., Terlizzi, V., Urso, S., Borsellino, C., and Munafò, P., 2018. “Experimental study of the adhesive glass-steel joint behavior in a tensegrity floor”. International Journal of Adhesion and Adhesives, 85, pp. 293–302.
[4] Quirant, J., Kazi-Aoual, M., and Motro, R., 2003. “Designing tensegrity systems: the case of a double layer grid”. Engineering structures, 25(9), pp. 1121–1130.
[5] Cimmino, M., Miranda, R., Sicignano, E., Ferreira, A., Skelton, R., and Fraternali, F., 2017. “Composite solar facades and wind generators with tensegrity architecture”. Composites Part B: Engineering, 115, pp. 275–281.

[6] Scoccia, C., Palmieri, G., Callegari, M., Rossi, M., Carbonari, L., Munafò, P., Marchione, F., Chiappini, G., Multibody Analysis Of A Tensegral Servo-Actuated Structure For Civil Applications, Proceedings of the ASME 2021 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 17-20, 2021, Online, Virtual

[7] Scoccia, C., Carbonari, L., Palmieri, G., Callegari, M., Rossi, M., Munafò, P., Marchione, F., Chiappini, G., Design of a tensegrity servo-actuated structure for civil applications, ASME Journal of Mechanical Design.

[8] Simoncini, M., Forcellese, A., Mancini, E. et al. Experimental and numerical investigation on forming limit curves of AA6082 aluminum alloy at high strain rates. Int J Adv Manuf Technol 112, 1973–1991 (2021).

[9] Sasso, M., Mancini, E., Chiappini, G., Simoncini, M., Forcellese, A., Adapted Nakazima test to evaluate dynamic effect on strain distribution and dome height in balanced biaxial stretching condition (2018) International Journal of Mechanical Sciences, 148, pp. 50-63.

[10] Eusebi, A.L., Bellezze, T., Chiappini, G., Sasso, M., Battistoni, P., Influence of aeration cycles on mechanical characteristics of elastomeric diffusers in biological intermittent processes: Accelerated tests in real environment (2017) Water Research, 117, pp. 143-156.