

Structural glass panels: An integrated system

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Abstract. In building envelope, transparent components play an important role. The structural glazing systems are the weak element of the casing in terms of mechanical resistance, thermal and acoustic insulation. In the present work, new structural glass panels with granular aerogel in interspace were investigated from different points of view. In particular, the mechanical characterization was carried out in order to assess the resistance to bending of the single glazing pane. To this end, a special instrument system was built to define an alternative configuration of the coaxial double ring test, able to predict the fracture strength of glass large samples (400 × 400 mm) without overpressure. The thermal and lighting performance of an innovative double-glazing façade with granular aerogel was evaluated. An experimental campaign at pilot scale was developed: it is composed of two boxes of about 1.60 × 2 m² and 2 m high together with an external weather station. The rooms, identical in terms of size, construction materials, and orientation, are equipped with a two-wing window in the south wall surface: the first one has a standard glazing solution (double glazing with air in interspace), the second room is equipped with the innovative double-glazing system with aerogel. The indoor mean air temperature and the surface temperature of the glass panes were monitored together with the illuminance data for the lighting characterization. Finally, a brief energy characterization of the performance of the material was carried out by means of dynamic simulation models when the proposed solution is applied to real case studies.

Keywords: aerogel; coaxial double ring test; energy analysis; integrated system; lighting; structural glass

1. Introduction

The shape and function of the building envelope have undergone substantial evolution over time, influencing also the use and experiment of materials. From the massive wall construction of historical buildings, where load transfer, thermal insulations, and thermal energy storage are performed by the building enclosure we arrived to light envelope consisting of structural stained glass, which makes the surfaces of the contemporary building immaterial. However, a light element such as a structural glass is the weak point of the casing in terms of mechanical resistance, thermal, and acoustic insulation. The technological evolution contributed over the years to improve such performance, and satisfactory results were reached from different points of view. Solar architecture or bioclimatic architecture has become one of the most promising alternatives to diminish energy consumption in buildings and consequently to reduce the environmental damage that fossil fuels are causing. For this objective, glass walls in multilayered panes and insulating glass units are of particular interest equipped with mechanical resistance, thermal insulation, and sound insulation characteristics. Several researches were aimed at mathematical models (Foraboschi 2013, Galuppi and Royer-Carfagni 2014) and experimental investigations of laminated glass (Louter *et al.*

2012), the interlayer behavior (Andreozzi *et al.* 2014), the interlayer viscoelastic response being time and environmental conditions dependent (Briccoli Bati *et al.* 2010), and the experimental analysis of buckling phenomena in plane compressive/tensile loads (Bedon and Amadio 2014).

The present project aims to study and develop a new technology for the fabrication and installation of structural glass panels as integrated systems, characterized by adequate resistant capacity, safety in the face of the risk to failure, better thermal and acoustic performance compared to the classic glazed surfaces and that contribute to the construction sustainability. To this aim, an insulating aerogel-based structural glass was studied and an extensive experimental campaign was carried out testing the mechanical resistance, thermal, acoustic, and energy performance. The experiments were performed on real size samples properly constructed.

The research initiated from the study of the coupling glass-insulating material to identify characteristics and problems to be solved for the realization of prototypes made of two panes of glass, separated by one space filled with granular aerogel and hermetically sealed along the edges.

The first experiment was the evaluation of the mechanical resistance to bending of the glass. To obtain the mechanical properties of the material, coaxial double ring tests were performed in accordance with EN 1288-5, on square samples of float glass with 400 × 400 mm size.

The research group was multidisciplinary since the research involved aspects that require different skills of structural mechanics, energetics, acoustic and thermal

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insulation. The proponents, experts in the respective fields, through this collaboration have developed their knowledge to apply them to the realization of the proposed glazing system.

2. In-situ thermal and lighting performance

2.1 Materials and methods: Experimental field CASSETTE

The energy performance of a granular aerogel glazing system was analyzed in an experimental field at pilot scale named C.A.S.E.T.T.E. (Coupled Advanced Systems for Experimentation on Translucent and Thermal-insulated Envelopes), developed at the Department of Engineering, University of Perugia (Belloni *et al.* 2021). It is composed of two boxes ($1.60 \times 2 \times 2 \text{ m}^3$) and of an external weather station able to acquire outdoor air temperature, relative humidity, wind speed and direction, and the total solar radiation on horizontal surface (Fig. 1). The rooms are identical in terms of size, construction materials, and orientation. They are equipped with a two-wing window in the south wall façade ($470 \times 1380 \text{ mm}^2$): a standard double-glazing system with air and an innovative one with granular aerogel were installed in the Reference and in the Test Rooms, respectively.

The first one is composed of two tempered float glasses 6-mm thick and 15-mm of air (total thickness of 27 mm), with a thermal transmittance U , visible transmittance τ_v , and solar factor g equal to $2.7 \text{ W/m}^2\text{K}$, 0.77 , and 0.73 , respectively. The innovative transparent solution consists of the same float glasses with 15-mm of granular aerogel in the gap, for a total thickness of 27 mm ($U = 1.2 \text{ W/m}^2\text{K}$, $\tau_v = 0.66$, $g = 0.70$). An aluminum window frame with thermal break (70 mm thick) is used and fixed with metal bars to the walls. The opaque envelope is composed of sandwich panels (50 mm thick for the walls and the floor, $U = 0.43 \text{ W/m}^2\text{K}$, and 40 mm thick for the roof, $U = 0.53 \text{ W/m}^2\text{K}$) consisting of insulating material into two metal layers. A rigid closed-cell polystyrene panel (80 mm thick, thermal resistance equal to $3.30 \text{ m}^2\text{K/W}$) was also glued to the walls and to the ceiling in the internal side, in order to reduce the total thermal transmittance of the envelope. During the experimental campaigns, the indoor air temperature, the

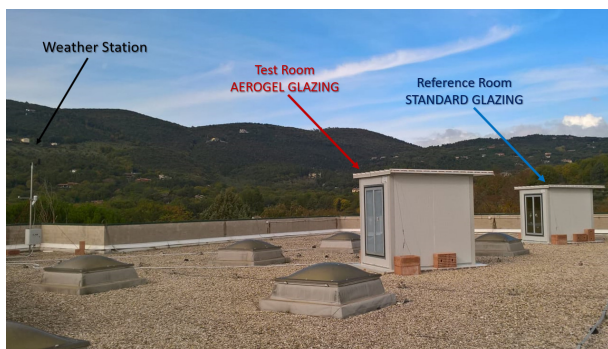


Fig. 1 The experimental field C.A.S.E.T.T.E. (Coupled Advanced Systems for Experimentation on Translucent and Thermal-insulated Envelopes)

illuminance in two different points (E_1 , 0.5 m far from the window and E_2 , 1.5 m far from the window), and the vertical solar radiation were monitored (Bidini *et al.* 2019).

2.2 Thermal and lighting results

Data collected in Winter 2018 were considered in order to compare the behaviour of the innovative glazing system with the standard one. Fig. 2 shows the inside temperatures measured in each box vs. the external temperature values: the innovative glazing system shows indoor temperatures always lower than the Reference one when the external temperatures are higher than $2\text{--}2.5^\circ\text{C}$; for lower values of the outside temperature, the indoor air temperatures are comparable. This is probably due to the absence of sun: during the night, when the outdoor temperatures are lower, the behaviour of the two glazing systems is quite similar. The maximum difference is obtained when the sunny contribute is highest (about 13°C). The trends both during night and day periods are shown in Fig. 3.

Figs. 4(a) and 4(b) show the measured illuminance trends in the same reference period (January-February 2018) as a function of the external solar radiation. The values of the illuminance in the Test Box are always lower than those of the Reference Box, thanks to the diffusing

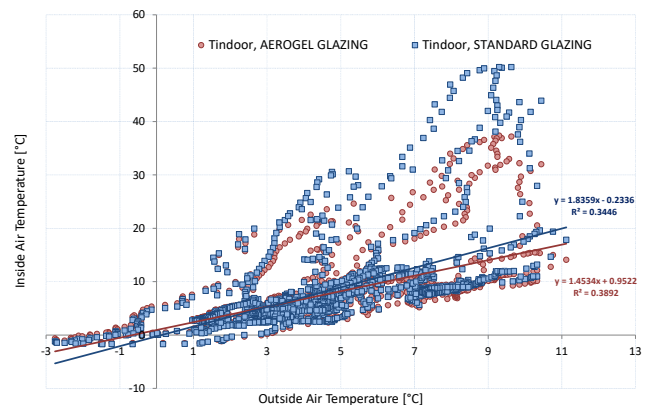


Fig. 2 Winter: Indoor air temperature trends vs. outside temperatures of the different glazing systems

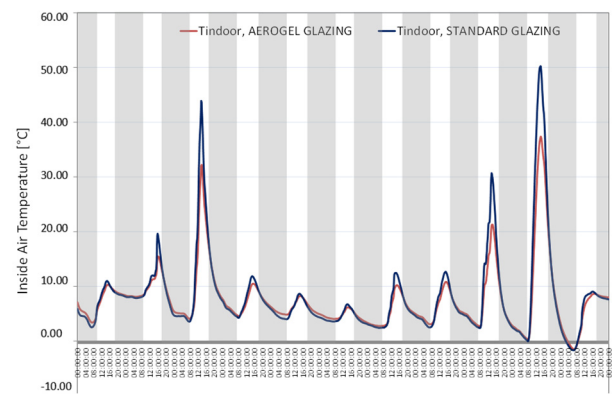


Fig. 3 Inside air temperatures vs. time in winter period (night time periods - from 6 pm to 7 am - are highlighted in grey)

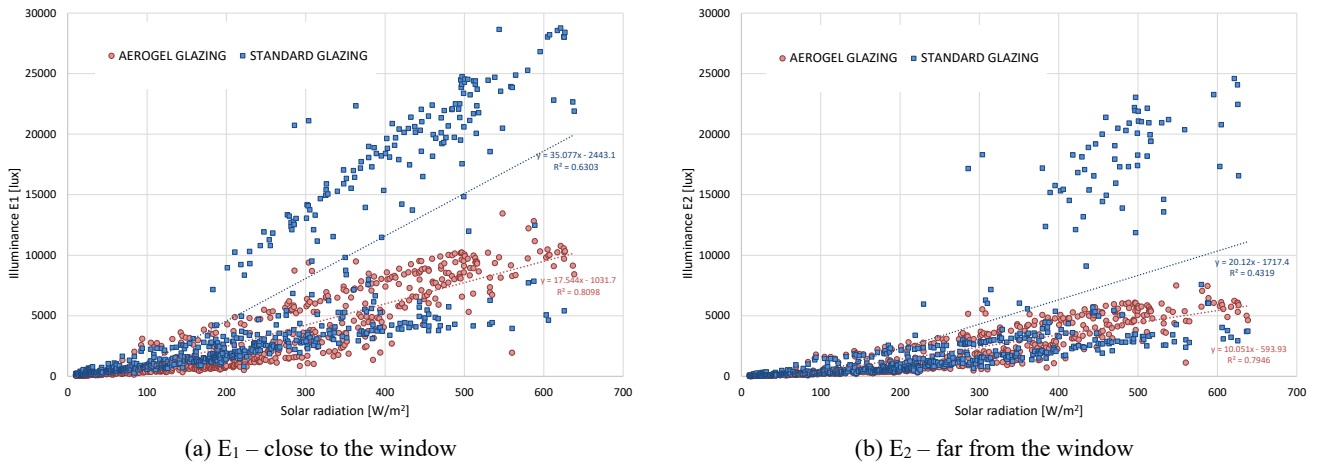


Fig. 4 Illuminance vs. solar radiation measured values

properties of the granular aerogel, both in E_1 (close to the window), and in E_2 (far from the window). In general, it can be observed that the trend of aerogel solution has a very good overlapping with a linear increasing trend line; it is not the same for the standard solution. For solar radiation higher than 200 W/m^2 , the illuminances in E_1 are about 10000-30000 lux with the standard glazing system and they are always lower than 10000 lux with the aerogel one. Lower values are observed far from the window in E_2 : for radiation lower than 200 W/m^2 , the behaviours of the two boxes are similar.

3. Mechanical measurements¹

Laboratory tests were carried out in order to assess glass tensile strength. This is relatively small and unreliable since depends on micro-defects on the surface of the glass, as a result of inclusions in the glass thickness or to scratches caused by damages to the edges of the sheets during the use or finishing and cutting process, so glass fractures easily and quickly without warning (Castori *et al.* 2021). A total of 393 bending strength measurements, that has served to develop a new standardized design-by testing procedure, were thus used to collect enough information for a control of the correctness of the failure data processing. Specifically, by varying the dimensions of the loading area, four different types of CDR configurations (series CDX, CDS, CDM and CDL) without overpressure (according to EN 1288-2 standard) were considered (Fig. 5).

A first set (CDX tests) of 215 square plates ($l = 100 \text{ mm}$) of various thicknesses (4, 5, 6, 8 mm) were loaded by two concentric rings (loading and reaction ring) of radii $R_1 = 9 \text{ mm}$ and $R_2 = 45 \text{ mm}$ ($R_1/R_2 = 0.200$), respectively.

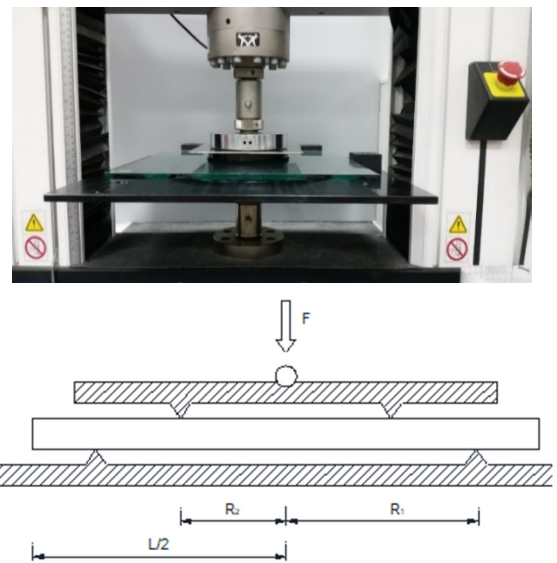


Fig. 5 Experimental layout: CDR configuration (glass plate is supported by the reaction ring and subject to the action of the loading ring)

A second set of 178 specimens, having side length $l = 400 \text{ mm}$ and different thicknesses (6, 8, 10 mm), were investigated, on the contrary, under three different types of CDR configuration, obtained by fixing the reaction ring radius ($R_2 = 150 \text{ mm}$) and varying the radius of the loading ring (R_1), which was: 75 mm ($R_1/R_2 = 0.500$) in the first series (CDS tests), 100 mm ($R_1/R_2 = 0.667$) in the second (CDM tests) and 125 mm ($R_1/R_2 = 0.833$) in the third (CDL tests). All specimens, supplied by a single manufacturer to reduce any source of uncertainty, were tested with the air-side downward under a constant stress rate of 1.6 MPa/sec ;

- the axial load ($P_{failure}$) applied by the testing machine producing the rupture of the specimen;
- the equibiaxial stress ($\sigma_{eqbx.in}$) in the loading area, computed (according to EN 1288-1 standard) as a function of the axial load ($P_{failure}$) by using a linear elastic solution (based on the Kirchhoff-Love theory):

¹ The first 2 letters (CD) identify the test configuration (Coaxial Double ring). The subsequent designation (X for extra-small, S for small, M for medium, and L for large) was used to specify the loading area dimensions.

Table 1 Experimental dataset

	n° of specimens [-]	Plate dimensions [mm]	Plate thickness [mm]	Failure load [N]	Bending strength [MPa]	Coefficient of variation CoV
CDX test	37	100 × 100	4	2870	187.14	0.27
	46		5	3252	135.73	0.20
	38		6	4646	134.63	0.23
	47		8	7453	121.50	0.26
CDS test	19	400 × 400	6	10591	135.41	0.38
	14		8	13832	99.48	0.40
	13		10	19094	87.89	0.27
CDM test	16	400 × 400	6	10877	83.85	0.33
	16		8	16248	70.46	0.24
	16		10	24176	67.10	0.25
CDL test	20	400 × 400	6	18221	65.17	0.27
	18		8	26580	53.47	0.19
	17		10	34831	44.85	0.22

$$\sigma_{eqbx,lin} = \frac{3P}{4\pi h^2} \left[2(1 + \nu) \ln \frac{R_2}{R_1} + (1 - \nu) \frac{R_2^2 - R_1^2}{2R_3^2} \right] \quad (1)$$

where ν denotes the Poisson's coefficient, h represents the specimen's thickness, whereas R_3 is an equivalent value of the radius of the specimen $\left(R_3 = \left(\frac{L}{4}\right)(\sqrt{2} + 1)\right)$ for square (side L) plates.

Referring to the strength data, it is possible to highlight how, as a rule, thicker glass specimens showed lower bending strengths. More specifically, while the 4 mm thick plates exhibit a mean value of the ultimate capacity equal to 187 N/mm², higher values of thicknesses lead to a significant decrease of the strength. The bending strength provided by the 10-mm-thick specimens was approximately 25% lower than that achieved in the 6-mm-thick plates for series CDL, CDM and CDS, whereas the use of CDX configuration provided a decrease of approximately 35% when the thickness of the plates was doubled (8 mm rather than 4 mm). Far from being exhaustive, this can be explained considering that ribbon-shaping technology may have effect on the dependence of the glass strength from its thickness.

Also, it worth to mention that a not negligible amount of scatter exists in the strength values highlighted by Coefficient of Variation (CoV): lower values were measured in the case of CDX and CDL tests (19427%), while higher values were obtained for CDM and, above all CDS tests (up to 40%).

4. Energy analysis

The thermal behaviour of two buildings, chosen as case-study, was analysed by considering the implementation of the double glazing system with aerogel. Therefore, both the characteristics of the innovative glass with granular aerogel

(as measured in the experimental field) and those of the conventional solution were used as input data in the dynamic simulations. The considered buildings of University of Perugia, representative of newly built medium/large buildings, are: the Biomass Research Center (CRB) and the Biotechnology Pole (BP) located in Perugia and Terni respectively. Buildings typology is evident in the pictures reported in Fig. 6. The corresponding climatic zones are E and D, in accordance with Presidential Decree 412/93 (D.Lgs n. 311/06). The CRB building (net area of 3286 m² and volume of 11523 m³) is characterized by external walls containing 10 cm of polystyrene, with a total thermal transmittance U of 0.236 W/m²K, while the roof and floor, in addition to the insulation, have an air gap ($U = 0.272$ W/m²K and 0.371 W/m²K respectively). The solar control windows (6-16-6 with air, $U = 1.429$ W/m²K) have a PVC frame. The BP building (net surface area of 840 m² and volume of about 2773 m³) has external walls constituted by cellular concrete blocks and 4 cm of polystyrene (total $U = 0.338$ W/m²K); the glazing systems are 4-16-4 with air ($U = 1.761$ W/m²K) installed on PVC frames. Both buildings are equipped with centralized air conditioning systems and are characterized by good thermal performance. The energy performance was assessed using a software tool, suitably developed and already applied in previous studies (Barelli *et al.* 2009, 2010), for the determination of buildings energy needs for both heating and cooling, according to the UNI/TS 11300-1 regulatory requirements (UNI/TS 11300-1: 2014).

Buildings primary energy consumption for heating and cooling were assessed first in their current state. Then, windows were replaced with the innovative glazing system obtaining a consumption reduction for heating:

- from 34 kWh/m² year with conventional glazing to 30 kWh/m² year implementing the innovative glazing (-11.7%), with a consequent transition from energy class B to A, for the CRB building.



(a)



(b)

Fig. 6 Pictures of the Biomass Research Center (a) and of the Biotechnology Pole (b) Buildings

- From 39 kWh/m² per year with conventional double glazing to 34 kWh/m² per year with granular aerogel (-12.8%) for the Biotechnology Pole.

During the summer period, the application of the innovative glazing does not entail significant benefits.

5. Conclusions

In this work, a particular glass panel was studied, in which the structural properties are combined with the thermo-energetic ones with the aim of creating an integrated system.

By varying the dimensions of the loading area, four different types of CDR configurations for assessing the flexural strength of large glass panels have been purposely developed, realizing a coaxial double ring device without overpressure. The experimentation, carried out using this test device on a great number of samples, confirmed the influence of sample size on the bending strength of the glass. The results obtained by using three rings of different sizes showed that the double-ring test configuration allows the sample to be subjected to a sufficiently large loading area and far enough away from the sample edges to avoid premature cracking due to edge finishing.

Considering the experimental campaign in the field named C.A.S.E.T.T.E., the main thermal and lighting parameters were monitored and the winter results are analyzed. The aerogel solution shows a reduction in the inside air temperature peak values of about 8–9°C with respect to a conventional window with an air gap of the same thickness. Also, the inside illuminance values are significantly reduced thanks to the aerogel solution, and a more uniform distribution of the natural light in the Test Box is observed; this is a better condition for visual comfort (reduction in glare risk). Obviously, the experimental campaign should be carried on in other seasons, but in general, the best impact of the use of aerogel glazing system is observed in winter.

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