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Assessing the structural behaviour of square hollow glass columns subjected to combined compressive and impact loads via full-scale experiments

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ABSTRACT

Glass is largely used in buildings as a novel construction material. Due to the intrinsic mechanical properties of such material, however, specific design recommendations are demanded in order to offer appropriate "fail-safe" requirements. This is especially true in the case of load-bearing structural glass elements where redundancy, stability and residual resistance should be guaranteed. In this regard, based also on a past research effort, the paper experimentally investigates the structural performance of full-scale square hollow glass columns, whose resisting cross-section consists of four adhesively joined laminated glass panes. Impact tests are carried out on in-plane compressed specimens, including both a reference undamaged column and a deliberately, preliminary broken specimen. The effects of multiple impact test configurations (inclusive of various release configurations for the impact mass as well as type of impact body) are hence emphasized, with critical discussion of the observed overall results and failure mechanisms.

1. Introduction and research objectives

The use in practice of mainly compressed load-bearing glass members is relatively scarce in buildings, compared to glass beams or panels. Research in the field of structural glass columns, in this sense, has large scale potential aimed to provide additional knowledge and background towards the full design optimization of this structural typology. During the last years, several authors investigated the structural performance of mainly compressed glass elements composed of single monolithic or multilayer laminated glass panes, with careful consideration for their overall stability as well as for the implementation of practical design recommendations [1–7].

Non-rectangular glass columns with several resisting cross-sectional shapes have been also experimentally and numerically investigated, including T-shaped, cruciform and hollow sections, in which the overall structural performance is directly dependent on the mechanical properties of glass but also on the adhesives and sealants providing the connection between multiple panels, see for example [8,9]. In this regard, pioneering research efforts aimed to assess the potential of structural glass columns can be found in [10,11], while in [12,13] careful attention has been paid to the effects deriving from end details and restraints on the overall performance of glass columns.

In this paper, novel outcomes of a research study focused on the overall structural behaviour of glass column with square hollow cross-section, currently ongoing at the Czech Technical University (CTU) in Prague (Czech Republic), are presented. At a first stage of this research activity, buckling experiments were carried out on small-scale glass columns prototypes achieved by adhesively bonding four monolithic glass panes [14], including a critical analysis of the observed failure mechanisms, as well as validation and discussion of related Finite Element (FE) numerical models. In the past research contribution, it was shown that square hollow glass columns can offer appreciable overall resistance and stiffness, despite the intrinsic flexibility of the adhesive joints providing the connection between the glass panes. A crucial role was observed to derive especially from the columns end restraints, i.e. in terms of appropriate transmission of compressive stresses and avoidance of premature cracking phenomena which could lead to the earlier collapse of such columns. Additional uncertainties and need for further research efforts, in this sense, were found then to derive from possible initial geometrical imperfections (both deriving from the production of the single glass panes as well as from the assembly phase of the square hollow specimens), possible

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imperfections in the adhesive joints, sensitivity of the columns' overall performance to the restraints geometrical and mechanical features as well as to eccentricities of loads and/or restraints.

Glass, as known, is in fact a typically brittle material, whose traditionally accepted "fail-safe" design approach (see for example [15,16]) should be properly ensured by means of specific and experimentally supported design provisions. This is true especially in the case of novel structural glass applications – inclusive of specific loading/boundary conditions or specific materials combined with glass – as well as load-bearing elements in general subjected to exceptional loads, such as accidental impacts, fire or explosive events, natural hazards, etc.

In this regard, a huge effort has been devoted by several researchers, especially in the last years, to the performance of structural glass elements subjected to impact loads. Static or dynamic accidental impacts represent in fact one of the most common reasons of breakage in glass systems [17]. Possible disastrous effects due to impacts must hence prevented especially in the case of glass load-bearing elements like columns, where their overall stability and redundancy – as well as (in the case any damage occurs) the residual resistance – have a crucial role. For this purpose, relevant research studies were focused on the analysis of glass elements and assemblies under exceptional, high strain impacts (i.e. [18–20]), ballistic impacts (i.e. [21–23]), as well as under a series of additional loading configurations traditionally accepted to be subdivided in "hard-body" (i.e. dropped objects, hard wind born debris, etc.) or "soft-body" impacts (i.e. human bodies, soft wind born debris, etc.). Soft-body experimental tests were presented and discussed for example in [24,25]. The dynamic performance of single glass panes under soft-body impacts was theoretically and experimentally investigated by Schneider et al. [26]. In [27], operational modal analysis was applied to a frame-supported laminated glass panel subjected to soft-body pendulum test, highlighting the sensitivity of FE models to the supporting frame properties, hence the importance of an appropriate mechanical characterization of the full setup components for accurate FE dynamic estimations.

In this paper, a further extension of the previous research study described in [14] is hence proposed. The primary aim of this research contribution is in fact represented by the experimental assessment of the structural performance of full-scale hollow, laminated glass columns under combined in-plane compression and impact loads, including both a reference undamaged configuration and a preliminary damaged specimen. The observed overall performances and failure mechanisms are critically discussed for the two full-scale specimens, in order to provide additional knowledge on the feasibility and potential of the explored design concept, as well as an experimental background towards the full development of such systems. Additional experimental and FE numerical investigations will follow, in order to properly explore and optimize the use of adhesively bonded glass elements in the form of load-bearing columns in structures and buildings. In this regard, the geometrical and mechanical features of the tested specimens are first summarized in Section 2. Details on the testing setup and methods are then provided in Section 3. Finally, an extended discussion of the observed resisting mechanisms and failure scenarios are discussed in Section 4.

2. Square hollow glass columns

2.1. Geometrical and mechanical properties

The main components of the tested glass columns were represented by four basic parts (i.e. the laminated glass panels), plus the connecting and supporting details (i.e. the adhesive joints, the plastic pads and the steel shoe devices). Two full-scale columns were investigated, including a reference column (S01, in the following) and a preliminary damaged configuration (S02). For both the full-scale specimens, laminated glass panels composed of annealed floated glass (E = 70 GPa and $\sigma_{Rk,t}$ = 45 MPa the nominal modulus of elasticity and surface tensile resistance respectively [28])) layers and with identical nominal dimensions were used. The laminated glass panels were in fact obtained by adhesively bonding two glass layers, t = 10 mm in nominal thickness, and a middle Poly Vinyl Butyral (PVB) foil (t_{int} = 0.76 mm the nominal thickness).The nominal width of these panels was set equal to w = 150 mm, with L = 3000 mm the nominal length.

The nominal resisting area of the double layered laminated glass pane was calculated in A_g = 3000 mm^2, hence resulting in $A_{g,tot}$ = 12,000 mm^2 for the full assembled cross-section. In such specimens, see Fig. 1, a key role was assigned to the adhesive joints providing the structural interaction between the laminated glass components. The glass panes were in fact joined along the corners by means of a two component acrylic adhesive connection, 6 mm in width and 3 mm in thickness, composed of SIKA Fast® 5215 – NT ([29], with E_{adh} = 250 MPa and $\sigma_{t,adh}$ = 10 MPa the nominal mechanical features). The adopted adhesive represents a new generation of adhesives for structural glass applications, and already deserved various research efforts aimed to assess its mechanical performance (see for example [30]).

Careful consideration was then also paid for the column restraints, based also on a critical observation of the experimental test results derived from the past research experience carried out on the small-scale column prototypes [14]. Bespoke plastic pads were used, in accordance with [14], and adhesively connected to the column end sections, so that premature local peaks of stress could not compromise the overall structural performance of the tested specimens, as well as an uniform distribution of stresses through the columns ends could be ensured. Two pads composed of poly-methyl methacrylate (PMMA) were made from one piece of material and introduced at the base/top restraints. The typical cross-section – designed on the base of the columns' nominal dimensions and on the test setup restraint geometrical features – can be seen in the schematic representation of Fig. 1. Also in this case, a 3 mm thick adhesive joint was used to connect the PMMA pads and the glass surfaces.

The last component of the typical full-scale specimen was then represented by bespoke steel shoes, properly designed to transmit the imposed external loads into the column panes as well as to act as ideal restraints for the examined specimens, see Fig. 1(c).

For clarity of discussion of test methods and results, for both the S01 and S02 specimens, the laminated glass panels composing each column were marked, in sequential order, with 'A' to 'D' letters.

2.2. Preliminary measurements on single laminated glass panes

Before assembling the full-scale samples, the real dimensions of each laminated glass panel were properly measured by means of calibrated tools. The measurements were performed by taking into account three cross-sections for each pane (with ±0.1 mm the measurement tolerance of the adopted instrumentation), including the end sections (m#01 and m#02), as well as (m#03) the mid-span section. Minor deviations of the real dimensions from nominal geometrical properties were generally observed. Table 1 summarizes the so achieved geometrical properties, in the form of m#01-to-m#03 average values for each A-to-D pane, together with their Coefficient of Variation (CoV) and the corresponding dimension tolerance limits (see "Tol −" and "Tol +" in Table 1) as obtained on the base of product standard provisions [28].

A preliminary check on the amplitude of any global bow for the single laminated glass panes was also carried out, before the