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Low velocity impact performance investigation on square hollow glass columns via full-scale experiments and Finite Element analyses

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ABSTRACT

Taking advantage of two full-scale experimental tests carried out on square hollow glass columns under low velocity impacts, the paper aims to further assess via Finite Element models the structural performance of such structural systems. In them, the resisting cross-section consists of four adhesively bonded laminated glass panes. Adhesive joints are also used for the connection between glass columns and top/bottom restraints. As a result, careful consideration in the analysis and design of these innovative systems is required, to guarantee appropriate *fail-safe* design principles for a typically tensile brittle material, as well as to account for possible accidental or exceptional loading conditions.

Simplified but computationally efficient FE models are validated in the paper towards the available full-scale test results. Key aspects in the observed overall performances under low velocity impact are then emphasized, with careful consideration for several loading configurations, including variations in the release distance for the impacting mass as well as in the type of impact (hard/soft body). In conclusion, a FE sensitivity analysis is also carried out, giving preliminary evidence of the effects of some main input parameters on the overall performance of the examined systems, including possible localized damage in glass, as well as geometrical and mechanical features in the column restraints.

1. Introduction, state-of-the-art and research objectives

Experimental research on the structural performance of glass elements and systems under impact loads continuously attracts a large number of scientists. Glass, as known, is typically characterized by tensile brittle behaviour, and – as such – requires specific, experimentally supported, design provisions voted to fail safe design purposes [1,2]. This is true especially for novel structural glass applications – inclusive of specific loading/boundary conditions or different materials combined with glass – as well as load-bearing elements subjected to exceptional loads, such as accidental impacts, fire or explosive events, natural hazards, etc. Structural glass columns, in this sense, still represent a relatively novel application of glass as load-bearing component in buildings. In them, design uncertainties or misleading assumptions under ordinary and exceptional loads could in fact result in severe damage or collapse. For this reason, various researchers already investigated their load carrying performance. Non-rectangular glass columns with several resisting cross-sectional shapes have been experimentally and numerically investigated in the past years, including T-shaped, cruciform and hollow sections [3–11]. In such systems, the overall structural performance was found to be directly dependent on the mechanical properties of glass, as well as on the properties of adhesives and sealants realizing the connection between multiple glass panels. The dynamic buckling performance of compressed glass members has been also numerically and analytically investigated in [12], while a research study focused on the overall structural behaviour of glass columns with square hollow cross-section is currently ongoing at the Czech Technical University (CTU) in Prague (Czech Republic). At a first stage of the research activity, buckling experiments were carried out in 2014 on small-scale glass column prototypes composed of four glued monolithic glass panes. A critical analysis of the observed failure mechanisms, as well as validation and discussion of test results with Finite Element (FE) numerical models is proposed in [13]. In 2015, based on [13], low velocity impact tests were also carried out on full-scale column specimens consisting of laminated glass (LG) panes. The novel aspect of the actual research contribution, in this sense, consists in the recapitulation of original full-scale experimental results (see Sections 2 and 3), as well as on the FE assessment of the structural performance of square hollow glass columns under impact loads.

The impact behaviour of glazing systems in general, represents a

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design issue of primary importance for designers. To this aim, a huge effort has been devoted by several researchers in the last years, aiming to explore the overall performance of such systems under exceptional, high strain impacts (i.e. [14–16]), ballistic impacts (i.e. [17–19]), 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 discussed for example in [20,21]. The dynamic performance of single glass panes under soft-body impacts was theoretically and experimentally investigated by Schneider et al. [22], while in [23] 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, 9 impact loading experimental configurations are first briefly presented for two full-scale column specimens, including a reference undamaged specimen (S01, in the following) and a deliberately, preliminary damaged specimen (S02, in the following). The observed overall behaviours and cracking/collapse phenomena are summarized and discussed (for the full description of experimental findings, see [24]). A crucial effect, for example, was observed to derive especially from the end restraints, in terms of transmission of compressive stresses and avoidance of premature cracking phenomena in the LG panes. Computationally efficient, FE numerical models are then assembled in ABAQUS [25] for both the S01 and S02 specimens, taking care for the description and calibration of the geometrical and mechanical features of each column component, as well as of their reciprocal interactions (see Sections 4 and 5). Validation and assessment of FE models is hence carried out towards the corresponding test results, showing a rather close correlation with the experimental findings. A FE sensitivity analysis, finally, is proposed, giving evidence of the effects that even small variations in the input data can have in terms of overall performance (see Section 6). At the actual stage of the research project, based on current outcomes and well-promising results partly summarized in this paper, it is expected that the design concept of hollow glass columns could be further enhanced and optimized, including further full-scale experiments, FE investigations as well as variations in geometrical and/or mechanical features and loading and boundary configurations for the reference columns.

2. Square hollow glass columns object of investigation

The main components of the examined glass columns are represented by four basic parts (i.e. the LG panels), plus the connecting and supporting details (i.e. adhesive joints and restraint devices). The LG panels are composed of annealed floated glass (with $E = 70$GPa and $\sigma_{Rk,t} = 45$ MPa the nominal modulus of elasticity (MOE) and characteristic bending tensile resistance respectively [26]), with $t = 10$ mm the nominal thickness. A middle Polyvinyl Butyral (PVB) foil, with $t_{int} = 0.76$ mm, provides structural coupling between them. The reference column has nominal height $L = 3000$ and square hollow cross-section, where $w = 150$ mm is the width of each LG panel. In accordance with earlier experimental investigations carried out on small scale prototypes of square hollow monolithic glass columns, see [13], the LG panes are assumed to be joined along the corners by means of a two-component acrylic adhesive, 6 × 3 mm the connection width and thickness, consisting of SIKA Fast® 5215 – NT glue (with $E_{adh} = 250$ MPa and $\sigma_{t,adh} = 10$ MPa the nominal mechanical features [27]). As such, see Fig. 1, a key role in the so assembled specimens is given to the adhesive joints providing the structural interaction between the four LG panes, as well as between the LG hollow section and the end restraints.

In terms of end supports, the typical restraint consists in fact of a bespoke plastic pad (poly-methyl methacrylate (PMMA)), adhesively bonded to the LG ends via a 3 mm thick joint, see Fig. 1. Due to relatively low MOE of PMMA, in accordance with earlier experimental findings [13], the choice was aimed to avoid the occurrence of premature local peaks of stresses in glass. Each PMMA pad is then positioned within bespoke steel shoes able to guarantee a planar, rigid support to the column ends as well as an appropriate connection with the structural background (Fig. 1(c) and (d)). At the time of the experimental program, in order to allow the correct positioning of PMMA supports within the steel devices, a small lateral gap (lying in the order of ≈0.5 mm) was also taken into account between adjacent PMMA and steel surfaces (see detail of Fig. 1(d)).

3. Summary of available experimental tests results

The Finite Element numerical study here presented takes advantage of full-scale experimental tests carried out at CTU in Prague (2015) on square hollow LG columns, see also [24]. Two specimens, with geometrical properties according to Section 2 and Fig. 1, were in fact assembled and subjected to a sequence of accidental, low velocity impacts. The reference full-scale experiments follows earlier small-scale tests carried out on a set of hollow glass columns prototypes, see [13]. As such, even small-scale columns consisted of monolithic rather than LG panes, the assembly and detailing of both the full-scale specimens took advantage of the previous experimental experience.

Above the identical geometrical features for the S01 and S02 columns, the major difference between them was given by the presence of deliberate, preliminary localized damage in the S02 specimen, aiming to preliminary assess the possible effects on the overall performance of such columns (see also Fig. 6 and related comments).

Two full-scale half-columns were hence first assembled, and glued together (see Fig. 2). The bonded LG panes were adhesively connected to PMMA pads, and finally positioned within the test setup, where the bespoke steel shoes were used to represent an ideal clamp and a spherical hinge at the base and top respectively of each column.

3.1. Test methods

The setup of full-scale tests was designed to simulate the accidental impact of a human body in the most vulnerable cross-section for the given specimens, i.e. the mid-span section. In doing so, test methods took inspiration from standardized provisions given in [28]. To this aim, both the S01 and S02 specimens were subjected to a preliminary fixed level of compressive stresses, and hence to a sequence of low velocity impact loads.

The impact mass consisted of a steel ball with 51 kg the actual weight and 230 mm its diameter, see Fig. 3. The steel sphere was suspended with hinged steel ropes, rigidly connected to the structural background. Through the full experimental program, a total of 9 impact scenarios were then taken into account (see Table 1), by assuming different distances for releasing the impact mass, as well as by changing the number of hits for each configuration, or the features of the impacting body (soft or hard, due to the presence of an additional rubber protection pad). For each impact configuration, the steel sphere was in fact preliminary positioned so that – with ropes vertically aligned – a distance of 100 mm from the external surface of the glass pillar could be ensured. Given the actual length of the supporting ropes ($L_{mass} = 3170$ mm), loading configurations characterized by expected impact velocity values given in Table 1 were considered, with:

$$v = \sqrt{2g \cdot L_{mass} \cdot (1 - \cos\alpha)} \quad (1)$$

In accordance with Table 1 and Fig. 3, the impact of a soft or human body was simulated by interposing an additional 3-layer rubber pad (48 mm the total thickness), at the interface between the glass column and the steel sphere. In it, the outside layers (15.9 mm each in thickness) were made of microporous rubber (3.5 MPa the nominal MOE), while the middle layer was stiffer (Styrene-Butadiene rubber, 15.5 mm thick and 8 MPa its MOE). The protection pad, see Table 1, was used for