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Experimental investigation for the structural performance assessment of square hollow glass columns

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ABSTRACT

In this paper, the results of pilot experiments carried out on glass columns are presented and critically discussed. The aim of this preliminary experimental study consists in the verification and assessment of the actual global behaviour of monolithic glass columns with square hollow cross-section under axial compression, as well as in the estimation of the compressive loading ratios leading to the opening of first cracks and collapse of the same specimens, respectively, together with the corresponding failure mechanisms. In order to properly interpret the obtained test results, the experimental predictions are first compared and assessed towards analytical calculations (e.g. in terms of Euler's buckling load) and Finite-Element (FE) models later (e.g. in the form of load–displacement response). In the first case, classical analytical formulations not able to take into account the effects deriving from a combination of several aspects (e.g. possible initial geometrical imperfections in each glass pane or in the assembled square hollow section, load or boundary eccentricities, as well as the actual bonding effect of the glued joints connecting the glass components) typically result in a marked overestimation of the actual load bearing capacity for the tested columns, hence suggesting more refined investigations. Rather close agreement is found in fact with properly assembled fully 3D solid FE models. In them, a key role is assigned to the geometrically refined description of each specimen component (including the glued joints and the end restraints), as well as to the accurate mechanical calibration of the materials, based also on further experimental tests carried out on small adhesive specimens. Finally, the feasibility and accuracy of simplified 2D FE-models – less time consuming than fully 3D assemblies – is also assessed, so that practical recommendations could be provided. In the latter case, as shown, higher sensitivity of FE results to the main input parameters is found, with consequent underestimation of the actual elastic resistance for the tested columns. Based on the current comparisons and findings, however, it is expected that the current research outcomes could be further extended to various glass columns typologies and configurations (e.g. including laminated glass specimens and several cross-sectional shapes, as well as full-scale experiments), in order to develop appropriate practical design rules.

1. Introduction and state-of-the-art

In current architectural applications, glass is largely used in the form of load bearing construction material able to carry on dead and live loads (e.g. crowd, snow, wind, etc.) deriving from the building, due to its intrinsic transparency and optical properties.

While the design of glass load bearing elements mainly subjected to bending (e.g. beams and fins, handrails, façade panels or stairs) is relatively frequent in practice, structural glass elements mainly subjected to pure compression are rather scarce, despite the typically high nominal compressive strength of glass compared to its tensile strength. Recent examples can be found in the Glass pavilion in Rheinbach [1], were all the vertical and horizontal reaction forces deriving from dead and external loads are sustained by glass columns with rectangular, laminated resisting cross-section, or in Nordborg (Denmark), in the form of glass columns with cruciform cross-section [2].

The major limitation for the use of glass columns in building practice is currently represented by the lack of an appropriate knowledge related to their structural behaviour and load carrying capacity under exceptional loading conditions. The fundamental role of glass columns consists in fact in transferring to the ground the actions deriving from the construction components (e.g. the

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inter-storey floors). In them, due to the intrinsic mechanical behaviour of glass, any local irregularity and geometrical or mechanical defect can lead to stress peaks and to the progressive cracking and damage of glass, thus to collapse of these resisting vertical elements. For safe design purposes, in this sense, glass columns should consequently offer both an appropriate initial resistance (e.g. in the pre-cracked stage) as well as a sufficient residual capacity (e.g. post-cracked strength), so that the damaged members could be able to carry the compressive loads even in case of an emergency situation.

Compared to compressed members composed of traditional materials like steel, concrete or timber, however, several aspects related to the intrinsic properties of glass as a construction material should be properly taken into account. The development and calibration of appropriate design methods and practical recommendations for mainly compressed load carrying elements composed of glass should in fact properly assess the local and global effects deriving from the supports, as well as the effects of production tolerances, possible initial geometrical imperfections, lamination processes, or the occurrence of maximum stress peaks and local damages in glass near corners, holes and edges (e.g. where a lower tensile strength – due to thermal processes and edge/surface treatments – is expected), etc.

Over the past years, several experimental, Finite-Element (FE) and analytical research studies focused on the structural behaviour of glass columns characterized by different cross-sectional properties.

In [3], experimental results and analytical models derived from classical sandwich theories for the Euler's buckling calculation of composite rectangular cross-sectional members under compression have been validated and proposed for the application tomonolithic or laminated glass columns. A standardized design curve validated towards FE simulations and test data has been also preliminary assessed. In [4], an analytical formulation for the buckling analysis of laminated glass columns with rectangular cross-section has been derived from the original Newmark's theory of composite members with flexible connections, so that the Euler's critical load, as well as the full load–deflection response of a given glass member under compression, could be rationally calculated by taking into account the effects due to possible initial geometrical imperfections and load/boundary eccentricities. In [5], based on extended experimental data available in literature for monolithic and laminated glass columns with rectangular cross-section, as well as additional analytical and FE data, a normalized design buckling curve has been proposed for a practical buckling verification of glass members under compression. Due to its general validity and applicability, the same design approach is currently implemented in standards for the design of glass structures [6]. Further analytical and FE assessment of the flexural–torsional buckling response and resistance of single laminated glass members under combined compression and bending has been proposed in [7], with a normalized resisting domain of practical use for their verification. In [8–11], extended experimental and analytical studies related to the compressive buckling response of single monolithic or laminated glass elements with rectangular cross-section have been provided. In [10], in particular, the effect of simultaneous compressive and bending loads on slender, monolithic glass members has been extensively investigated, based on a total number of 160 experiments, with careful consideration for the geometry of the specimens, the load condition as well as the member restraints of each series of tests. A refined analytical model able to properly take into account the geometrical non-linearity of glass members under combined compression and bending was also presented.

In [12–14], otherwise, new design concepts for glass structural members under main compressive loads have been proposed. Compared to the previously mentioned research contributions, the main feature of the studies collected in [12–14] is represented by the investigation of the structural performance of glass columns characterized by laminated tubular cross-sections [12,13], or stacked assemblies able to emphasize the high compressive strength of glass [14]. As far as glass members are obtained by assembly of multiple panes rather than a single rectangular-shaped element, appropriate studies are in fact required for a rational assessment of the expected load carrying behaviour, as well as possible failure mechanisms of defects deriving from the assembly itself.

For this purpose, experimental, numerical and analytical investigations related to the structural performance of glass columns composed by more than one panel only have been also proposed in [15–17], where careful consideration has been paid especially for structural glass members with open cross-section (e.g. X-shaped, I or T-shaped). In those works, it was shown that when glass members are composed of more than a single one-dimensional component, their structural resistance and stiffness can be strongly increased. However, the combination of multiple aspects, and first of all the adhesive connection between each glass element, can have a crucial role in their whole performance, hence requiring extended investigations and appropriate design methods, compared to assembled columns composed of traditional construction materials.

In this paper, based on [18], exploratory experimental investigations are carried-out on pilot prototypes of square hollow glass columns obtained by assembling four monolithic panels composed of annealed glass. The structural interaction between them is provided by glued joints interposed along all the edges of each pane. The aim of these pilot experiments is to provide additional background in the knowledge of structural glass columns. In doing so, a detailed description of the main experimental findings is first proposed, with careful attention for the pre-test assembling critical phases and test methods, e.g. the imposed restraints, the first cracking configuration and the post-cracked residual resistance of the tested pilot specimens.

An assessment of test results is then preliminary performed by mans of classical Euler's and torsional buckling expressions derived from literature [19], as well as pure compressive resistance considerations. As shown, since these analytical models are not able to take into account the effects of several influencing parameters like possible initial geometrical imperfections, load or boundary eccentricities, as well as the actual bonding effect of the glued joints and the brittle tensile behaviour of glass, strong overestimation of the expected failure loads is generally obtained, compared to test predictions. Based on this preliminary assessment, more detailed interpretation of the test results is successively carried out based on Finite-Element (FE) numerical investigations.

FE numerical studies are carried out both by means of a geometrically refined 3D model (ANSYS [20]) and a simplified 2D shell model (ABAQUS/Standard [21]). In doing so, the attention is primarily focused on the pre-cracked response of each specimen. In both of these FE approaches, careful consideration is given for the mechanical description of the column components and reciprocal interaction, as well as to the implementation of initial geometrical imperfections and to the calibration of the materials' constitutive behaviours, based also on further experiments performed on small adhesive joints.

As shown, rather good agreement is generally found between experimental data and FE models, in terms of overall structural response of the tested columns, especially for the fully 3D models. In them, a key role is assigned to the refined description of local mechanisms at the columns ends, e.g. in the vicinity of the devices representative of the specimens restraints. In the case of the geometrically simplified and less computationally expensive 2D