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Laminated glass beams with thick embedded connections – Numerical analysis of full-scale specimens during cracking regime

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A B S T R A C T

Laminated and hybrid glass systems are typically realized by bonding or joining together several structural components and materials. Their structural performance and safe design is hence related to the optimal combination of several parameters, including material properties and degradation, geometrical ratios, connections type and features, etc.

This research paper is focused on the numerical assessment of the load bearing performance of full-scale laminated glass (LG) beams with thick embedded connections. There, the structural interaction between multiple glass segments is offered by thick metal inserts, being embedded in the LG sections during the production stage. The overall bending response of such assemblies, given the same glass beam segments, is strictly related to the connection detailing, namely including the number, position, size, etc. of embedded connectors. In this regard, Finite Element numerical models able to properly capture their actual local and global behaviour can represent a robust support for time/cost-consuming full-scale experimental investigations. Refined FE models are hence presented for selected specimen configurations, and validated towards four-point bending experimental tests carried out on LG beams with three different types of embedded connections and available in the literature.

In the typical FE model, the geometrical and mechanical properties of the reference specimens are properly taken into account, so to explore both the elastic and post-cracked performance of the LG beams object of study, under specific loading conditions. Comparative results are then critically discussed, giving evidence of major structural performances for the selected configurations, and including a concise parametric study.

1. Introduction

Given the typical brittleness of glass as structural material, as well as its increasing use in building components for load bearing assemblies, research studies aimed to ensure appropriate safety levels as well as to optimize novel design concepts are carried out by several researchers [1,2].

So far, various projects have been for example focused on the structural assessment of novel combination or assessment of materials under certain loading conditions [3–10], as well as on the load bearing performance of glass assemblies and composite / hybrid systems [11–17]. Different connection types have been also largely investigated [18–24], including mechanical, adhesive and laminated solutions (see [25] for a state-of-the-art review).

Structural glass beams are already widely used in design projects for roofs and floors, as well as vertical fins and stiffeners for facades and pavilions (i.e. [26,27]). The design concept of 'embedded laminated connections' to join together multiple glass parts, in this research scenario, currently represents a still novel solution requiring further investigations.

Experimental and Finite Element (FE) numerical studies reported in [28,29] gave evidence – at the small-scale component level, of the load bearing capacity of embedded laminated connections, as well as of potential critical aspects to further assess for their optimal design. In [30], full-scale experimental tests were presented for laminated glass (LG) beam segments in four-point bending, being mechanically connected by means of embedded laminated connections according to [28,29].

Following [28,29], the current paper aims to numerically investigate the load bearing performance of LG beams coupled together by means of thick embedded metal inserts. The reference beam configurations are derived from [30], so to assess the FE estimations towards past experiments. There, metal inserts are laminated within the reference resisting LG section, so to provide – based on geometrical and mechanical features of metal inserts to optimize – a certain interaction between the LG segments. However, multiple aspects can affect the

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overall structural response of such assemblies, and safe design requirements should be properly satisfied, giving also evidence of a certain redundancy and post-cracked residual resistance. It was recently shown in [28,29] via small-scale connection specimens, for example, that the examined solution can offer an appreciable load bearing capacity, even strictly dependent on possible local phenomena due to glass brittleness and adhesive bonding capacities. Test results reported in [30] further confirmed the high potential of the explored solution, but still suggesting detailed investigations to properly explore both local and global phenomena.

In this research study, non-linear Finite Element (FE) analyses carried out in ABAQUS [31] on LG beams with 3 different types of thick embedded connections according to [30] are presented and critically discussed, giving evidence of the actual elastic and post-cracked response of the selected specimens. In doing so, careful consideration is spent for the materials characterization and reciprocal interaction between the assembly components, based also on past literature studies on similar structural components. Given the rather close correlation between past experiments and actual FE estimations, a concise parametric study is then reported, so to emphasize the effect of some key influencing parameters of technical interest on the bending performance of the selected configurations.

2. Past experimental investigation

The numerical investigation presented in this paper takes advantage from past experimental efforts discussed in [30], where the bending performance of full-scale beam specimens with thick embedded laminated connections has been explored under monotonic loads. For sake of clarity, test materials and methods are briefly summarized in Sections 2.1–2.3.

2.1. Materials and specimens features

The typical full-scale specimen consisted in a LG beam made of two segments. The two segments are mechanically connected by means of laminated embedded connections. More specifically, embedded metal inserts (316 L the steel type, 10 mm in thickness) were laminated into the glass resisting section and used to transfer the forces between the LG beam segments (see Section 2.2).

Each LG component was made of three annealed glass layers, with 6-10-6 mm being their nominal thicknesses, bonded together by 1.52 mm foils of SentryGlas® ionomer interlayer. All the glass panels edges were polished, including the edges of the recess (middle, 10 mm thick glass panel only) used for the positioning of the embedded metal inserts. Annealed glass was chosen in order to better investigate the stress distribution and fracture pattern in the glass, hence to provide a mechanical interpretation to the structural behaviour of the embedded connections.

Three full-scale specimens of approximately 3 m total length were investigated, as obtained by joining together two LG segments of 1.5 m length via the laminated embedded connections mentioned above (see also Section 2.2). The so assembled LG beam segments were then also reinforced with 3 mm stainless steel bars (316 L type), along the top and bottom edges of the reference LG section. SG layers were used to bond mechanically the bars to the glass segment (Fig. 1). The latter choice derived – at the time of past preliminary studies – by the aim to focus the investigation at the embedded connections region and at adjacent glass regions, and prevent that bending cracks far from the connection would cause premature test interruption.

2.2. Laminated embedded connections

The main difference between the set of 3 full-scale LG beams was given by the geometrical details and position of the embedded connections.

Each connection type (‘A’, ‘B’ and ‘C’, in the following) had different location and geometry of the metal inserts (see Fig. 1). Based on earlier research studies on small-scale connection specimens (see [28,29]), the global dimensions of the metal inserts were set to 60 × 30 mm for type A, 210 × 30 mm for type B and 63.5 × 52 mm for type C, respectively. Each face of the insert was polished to R = 0.8 μm.

In the case of type A connections, two inserts were located at an intermediate position; a single metal insert (extended and in central position) was used instead for type B specimens; type C connections were finally assessed by considering two metal inserts located at top-bottom positions. All the embedded metal inserts were bonded to the adjacent glass plates by means of SG adhesive layers (i.e. two lateral faces and internal edges). In the latter case (type C beams), the embedded metal inserts were also connected to the top/bottom stainless steel reinforcement bars, by means of four M6 bolts (class 12.8). Given the metal inserts of the two LG beam segments, all the metal parts were finally connected with solid pieces of mild steel S355 and M8 bolts (class 12.8).

2.3. Test methods and protocols

Although the full experimental work presented in [30] included different testing methods and loading scenarios for the A-to-C connection types (i.e. monotonic tests, creep experiments and additional experiments on preliminary damaged beam specimens), the FE study presented in this paper aims to preliminary explore the overall load bearing capacity of the same specimens, hence it is focused on the simulation of monotonic bending tests only, as also briefly described in the following paragraphs.

The type A-to-C beam specimens were in fact subjected to monotonic, four-point bending tests (4PBT), see Fig. 2, so to induce a uniform bending field distribution between the two central forces, i.e. in the centre of the beams, with 1.5 m the distance between the two applied forces. In doing so, the out-of-plane displacements of each beam segment were restrained by 4 additional lateral restraints. A key role was hence given to PTFE plates interposed between the glass surfaces and the setup bracings, so to avoid possible local friction effects during in-plane bending deformations. All the tests were performed in laboratory conditions, at a temperature of 26 ± 2 °C.

Two 150 kN hydraulic jacks and electrical load cells were used to apply and measure the vertical forces (0.01 mm/s the imposed displacement rate). Vertical and horizontal displacements of the LG beam segments were hence monitored (10 Hz the recording frequency) by means of a set of LVDTs (see Fig. 2 for a schematic overview of their location). Additional strain gauges were also used to measure the strain field distribution on the external glass layers surfaces, during each test, see [30].

3. Finite Element numerical study

Three Finite Element numerical models representative of the A-to-C reference full-scale embedded connection specimens were realized in ABAQUS [31]. In doing so, given the past experimental research studies, careful consideration was paid for the geometrical and mechanical description of the specimens components, as well as for the bending experimental setup. Major advantages in FE modelling were derived from earlier investigations (i.e. [12,29,32,33]), including material properties and solving methods.

3.1. Solving and modelling approach

Given the test setup recalled in Fig. 2, the typical FE analysis consisted in a displacement-controlled simulation, carried out with the ABAQUS/Explicit solver in the form of a dynamic analysis with quasi-static linear increase of imposed displacements. To this aim, energy balance was hence continuously monitored, to ensure the quasi-static