WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.155110

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 3 2025

 pp. 447 –458

Research paper

Experimental investigation of point-fixed laminated glass with enhanced post-breakage capacity

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Abstract: For many years, the transparency of glass has been a major feature that has excited architects to search for new applications for this material in architecture. Laminated glass is commonly used for structural elements. This requires a durable bond between at least two glass layers and an interlayer. When the glass is fractured, the interlayer holds the glass fragments together. Introducing reinforcement into the cross-section of glass laminates is a way to improve the load-bearing capacity in the post-failure phase. This paper summarises the main results of the research project "Innovative solutions for point-fixed laminated glass with increased load-bearing capacity" funded by the National Centre for Research and Development (NCBR) under the LIDER XI Programme. The article presents the results of destructive tests on laminated glass panes in three load configurations: in-plane, perpendicular to the plane, and combined loading. An important aspect of the work is the testing of full-scale elements. The results of the research can be applied directly to the safety analysis of glass structures, making them significant in terms of failure prevention.

Keywords: laminated glass, point-fixing, steel mesh, post-breakage capacity, reinforcement, fractured glass

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1. Introduction

For many years, the transparency of glass has been a major feature that has led architects to search for new applications for this material in architecture. Today, glass is being increasingly used in construction. In addition to typical applications of glass as filling for openings in external walls, it is also used to make load bearing elements such as facades, roofs, stairs and even glass beams or columns [1–3].

Glass is a fragile material, and when its strength reaches a threshold, it fractures abruptly. Unlike wood or reinforced concrete, it does not warn about the possibility of a load failure (which can be demonstrated by excessive deflection or cracking). Therefore, monolithic glass is not suitable for load bearing applications [4]. Laminated glass is commonly used for structural elements. This requires a durable bond between at least two glass layers and an interlayer [5]. When the glass is fractured, the interlayer holds the glass fragments together. [6]. As a result, damaged elements can maintain adequate load capacity and structural integrity to allow evacuation of people and prevent injuries. [7]. The topic of post-failure load-bearing capacity of glass elements has been addressed in a few publications. In the study [8], destructive tests were conducted on point-fixed laminated glass subjected to the impact of a 100 kg soft body. In cases where the glass was fractured, the samples were subsequently tested under constant load at various temperatures. The study also compared differences in the post-failure load-bearing capacity of samples with interlayers made of standard PVB film and much stiffer SG film [9]. The results indicate a clear dependence of load transfer time in the post-failure phase on temperature and the type of film used.

The research conducted by Zhao et al. [10] showed that the load-bearing capacity of structural glazing in the post-fracture phase leans on the glass fragments size, and thus on the type of glass used in the laminate. In the publication [11], glass laminates with varying degrees of damage and interlayers, and types of glass were studied. Static tests were conducted on simply supported panes loaded at the centre of the span. The studies found that the residual load-bearing capacity of laminated glass is influenced by the size of the glass fragments and the stiffness of the interlayer.

The introduction of reinforcements in the glass laminate cross-sections is a means of increasing its load capacity during the post-failure phase. Studies [12, 13] analysed the possibility of embedding rods of different materials into the cross section of laminated glass beams. During the testing of the elements, after the initial cracks appeared in the glass, ductile failure was observed similar to the behaviour of reinforced concrete beams. The reinforcement also improved the load-bearing capacity in the post-failure phase. Examples of reinforcing laminated glass by embedding other material within the interlayer were reported in [14, 15]. The specimens were reinforced with GFRP tape in the vicinity of the openings and subjected to tensile loading in the plane. The reinforcement resulted in strengthening the sample in the post-failure phase, achieving more than a twofold increase in load-bearing capacity in the post-failure phase. Another example involves studies in which laminated glass beams were equipped with prestressed GFRP strips [16]. The samples were tested in four-point bending setup. The elements exhibited ductile failure even upon the first cracks appearing in the glass.

This article summarizes the results of destructive tests on point-fixed laminated glass. Samples were subjected to various types of loading: in-plane tension, loading at 90° and 45° angles, and long-term tests conducted on full-scale samples. The research was carried out as part of the project “Innovative Solutions for Point-Fixed Laminated Glass with Increased Load-Bearing Capacity”, funded by the National Center for Research and Development (NCBR, LIDER XI Program).

2. The idea of strengthening the area around the hole of laminated glass

Within the completed project focused on the development of a new solution for point-fixed glazing with increased post-failure load-bearing capacity, the authors verified the concept of locally reinforcing laminated glass by embedding a steel mesh within the interlayer (Fig. 1) [17–19]. The idea involves placing a woven steel mesh between layers of interlayer film before laminating the glass panels in an autoclave. This way integrates the mesh within the interlayer, creating a composite structure. The reinforcement aims to enhance the load-bearing capacity of the specimen in the post-breakage phase by locally strengthening the interlayer near the point fixing hole, where the peak stress values occur and the interlayer undergoes plastic deformation. The main purpose of the reinforcement is to ensure robustness primarily for all elements that are installed above the heads of building users, known as overhead glazing. This is particularly important in the context of the developing standards for designing glass structures, which will be a part of the second-generation Eurocodes. The new standards for glass will require verified post-breakage load-bearing capacity for the critical building components.

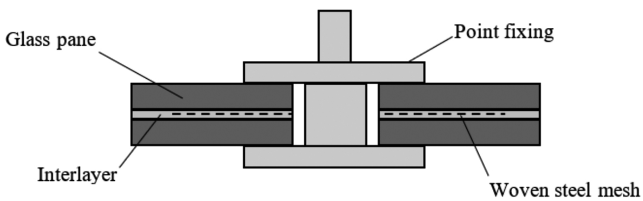


Fig. 1. Reinforcement of the area around the opening (patent application for the invention "Localized reinforcement of laminated glass" in UPRP No. P.437856)

3. Methodology and results

In the chapter, the methodology and results of experimental studies aimed at verifying the validity of localised reinforcement of laminated glass with locally embedded steel mesh were summarised. Studies were carried out under various loadings typical for point-fixed glass building components (e.g., canopies over building entrances).

Samples constructed with the same components were used in the experiments. The laminated glass consisted of two tempered sheets of soda-lime-silicate glass of different thicknesses. The lamination process involved using an ethylene-vinyl acetate (EVA) interlayer. A woven steel mesh with different diameters was used for reinforcement, consisting of wires with a diameter of 0.35 mm spaced at 1 × 1 mm intervals. The tests were carried out at a relative humidity of 50% and a temperature of 20 ± 2°C.

3.1. Phase I (in-plane loading)

The specimens measured 190×300 mm and composed two glass panes with two interlayers of 1.52 mm thick EVA Clear film. Each pane had three 26-mm diameter holes: two located at the bottom and one intentionally placed higher to induce failure in its vicinity (Fig. 2a). The reference samples were composed of only glass panes and the interlayer, while the strengthened samples additionally included a steel mesh covering the entire laminate surface. The study also considered three glass thicknesses (8, 10, and 12 mm). In total, 36 samples were tested (6 repetitions for each series).

Fig. 2b shows the schematic of the test set-up, which consisted of two grips and four mounting plates. The grips were constructed from two metal sheets measuring 60 × 140 mm with a 24 mm diameter hole. A pin at the bottom of each grip allowed attachment to the testing machine. The lower part of the sample was attached to the grips using two mounting plates measuring 130×150 mm, while the upper mounting plates measured 60×150 mm. Five 20 mm diameter screws were used to secure the sample. In order to minimize local stresses in the glass, elastic gaskets were placed between the steel and the glass. The tensile testing of the laminated glass was carried out on a displacement-controlled test machine at a speed of 10 mm/min.

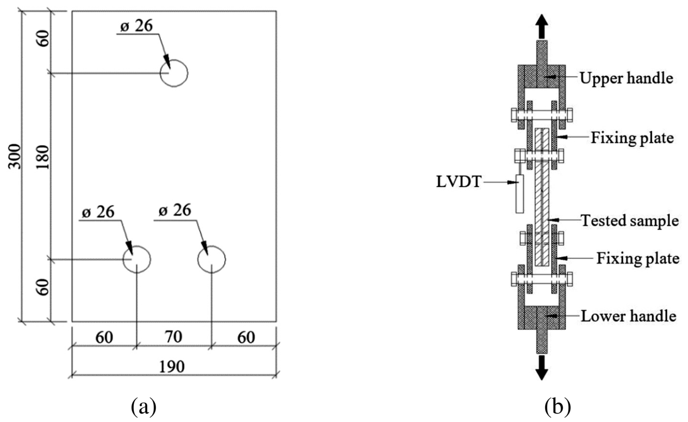


Fig. 2. In-plane loading: (a) sample, (b) test set-up

In the test, all samples showed similar behaviour. In the elastic phase, the force-displacement relation indicated an elastic response of the sample to the load. After the glass was fractured (Fig. 3a), a sudden drop in force was observed due to the abrupt loss of stiffness of the glass.

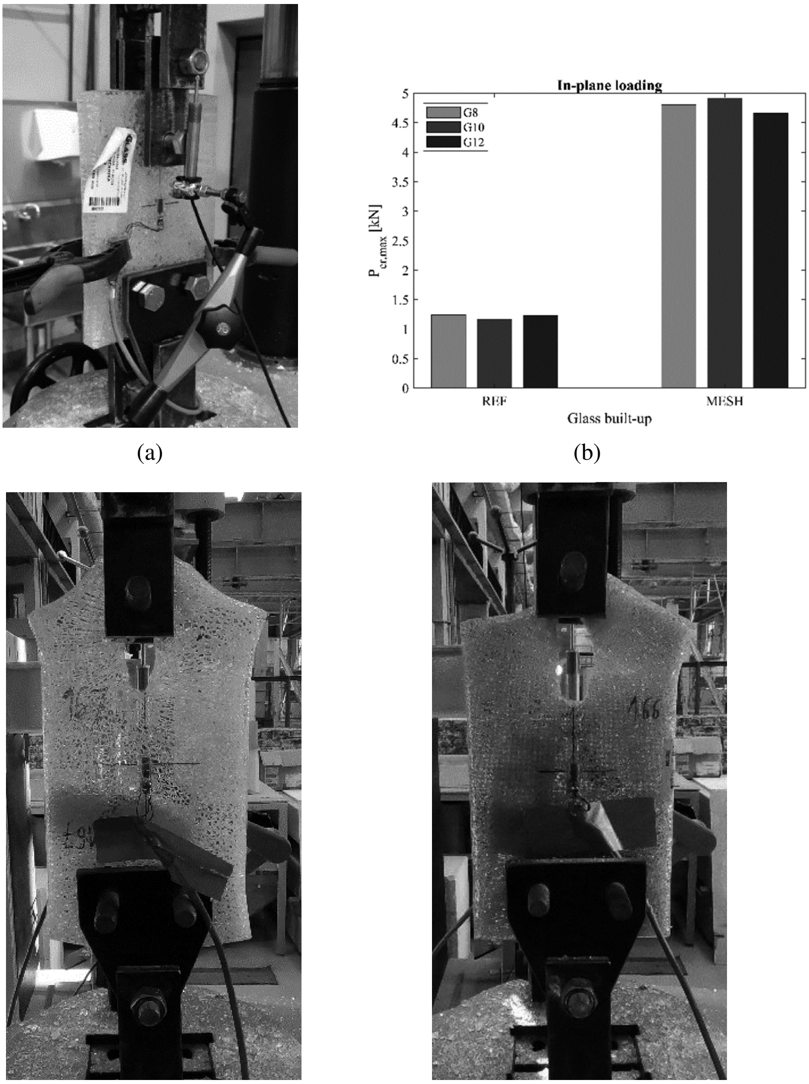


Fig. 3. In-plane loading: (a) test set-up, (b) results, (c) ultimate failure of reference sample, (d) ultimate failure of reinforced sample

Subsequently, the samples experienced gradual degradation as a result of further increase in loading (post-elastic phase). At this stage, the force increased initially and then decreased until the test sample completely failed. Figs. 3c and 3d depict ultimate failure of the reference and reinforced samples, respectively. It can be observed that in the case of reinforced samples, horizontal tearing of the sample occurred, whereas in the reference sample, the foil became plasticised. This indicates significant stiffening of the foil by the steel mesh.

In Fig. 3b the average results of experiments for reference (REF) and reinforced (WZM) samples with different glass thicknesses are presented. The force $P_{cr,max}$ represents the maximum load-bearing capacity in the post-failure state. As the research showed, reinforcement increases the maximum post-failure load-bearing capacity by nearly 300% in all test.

3.2. Phase II (out-of-plane loading)

The study used laminated glass elements depicted in Fig. 4a. The specimens measured 300 × 300 mm and were composed of two tempered glass panes of different thickness (8, 10, and 12 mm) with two layers of 1.52 mm thick EVA film. Each element had a central through hole with a diameter of 20 mm. Three different reinforcement diameters (75, 110, and 150 mm) were tested in 12 series, resulting in 48 samples.

The test setup included a pulling head and a fixed base (see Fig. 4b). The fixed base consisted of two 510×510 mm and 20 mm thick steel plates, each with a 12 mm diameter screw at the corners. The lower plate had a 20 mm diameter central hole to attach the eye bolt to the lower stance of the test machine. The upper plate of the fixed base had a hole of 150 mm diameter located in the center, allowing the pull head to pass through the hole sufficiently freely. The hole diameter was determined on the basis of preliminary numerical simulations and literature reviews.

The pulling head consisted of a threaded rod with a diameter of 12 mm, anBODY eye bolt connected to the machine head, and a 10 mm thick steel plate with a 50 mm diameter. The pulling head was used to apply perpendicular load to the tested sample. The tests were conducted on a displacement-controlled testing machine with 10 mm/min speed.

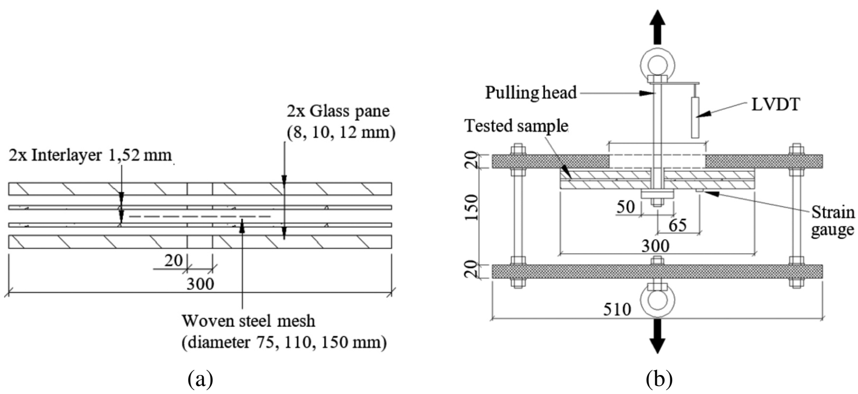
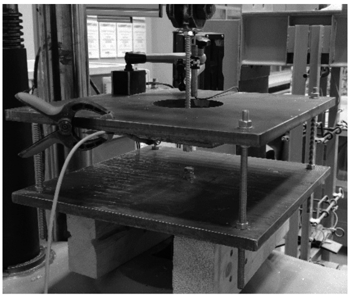
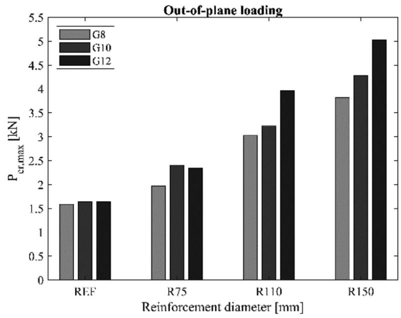


Fig. 4. Out-of-plane loading: (a) sample, (b) test set-up

In Fig. 5a, a specimen is shown in the testing setup. Similar to the case of the in-plane loading, all samples exhibited similar behaviour under loading. during the initial phase, the sample showed an elastic response to the loading, as evidenced by the force-displacement relation. When the glass fractured, a sudden drop in force was observed due to the almost complete loss of tensile stiffness of glass. Subsequently, the samples gradually degraded under additional loading, causing an initial increase and a decrease of force until the connector was completely torn out. The ultimate value of the study is considered the maximum load in the post-failure state of the glass ($P_{cr,max}$), the average values for reference (REF) and reinforced samples of are shown in Fig. 5b. The laminated mesh significantly increases the maximum load in the post-breakage phase of the glass. The study observed an average increase in load corresponding to the diameter of the reinforcement used of 38%, 110%, and 170%, respectively, compared to the reference samples.



(a)

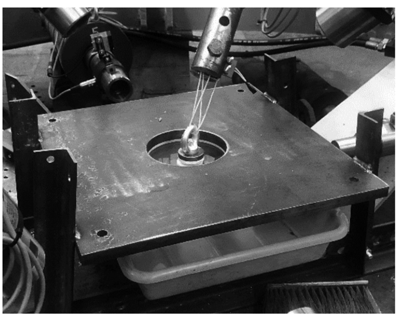


(b)

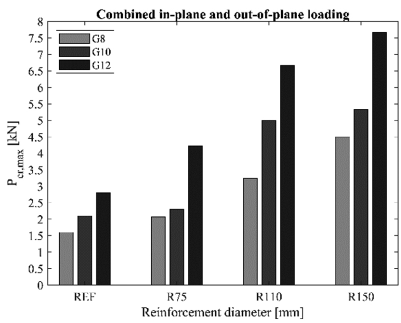
Fig. 5. Out-of-plane loading: (a) sample, (b) test set-up

3.3. Phase III (loading with force applied at a 45-degree angle to the surface of the pane)

The test was carried out to determine the load capacity of the element in a 45-degree angle load application. These tests were crucial in simulated loading conditions based on the typical glass roof mounted on steel ties. Custom-made spatial strength testing equipment was utilized in collaboration with the Warsaw University of Technology (see Fig. 6a). Force was applied at



(a)



(b)

Fig. 6. Loading with force applied at a 45-degree angle to the surface of the pane: (a) test set-up, (b) results

a 45° angle to the sample to simultaneously load perpendicular and within the specimen plane. The sample was loaded at a rate of 10 mm/min until reaching the maximum force after glass fracture. The results from the study indicate a significant increase in post-breakage strength when reinforced with woven steel mesh. The post-failure strength value increases with the diameter of the mesh reinforcement by 32%, 129%, and 169%, respectively, compared to reference samples, irrespective of glass thickness (see Fig. 6b).

3.4. Phase IV (real-scale sample experiments)

In the final stage of the project, tests were conducted on a sample measuring 1400×1000 mm, which corresponds to a typical canopy over a building entrance. The sample consisted of two 8 mm thick glass panes and two layers of EVA Clear film with a total thickness of 3.04 mm. Four holes for point fixings with a diameter of 25 mm were located in the sample (see Fig. 7a).

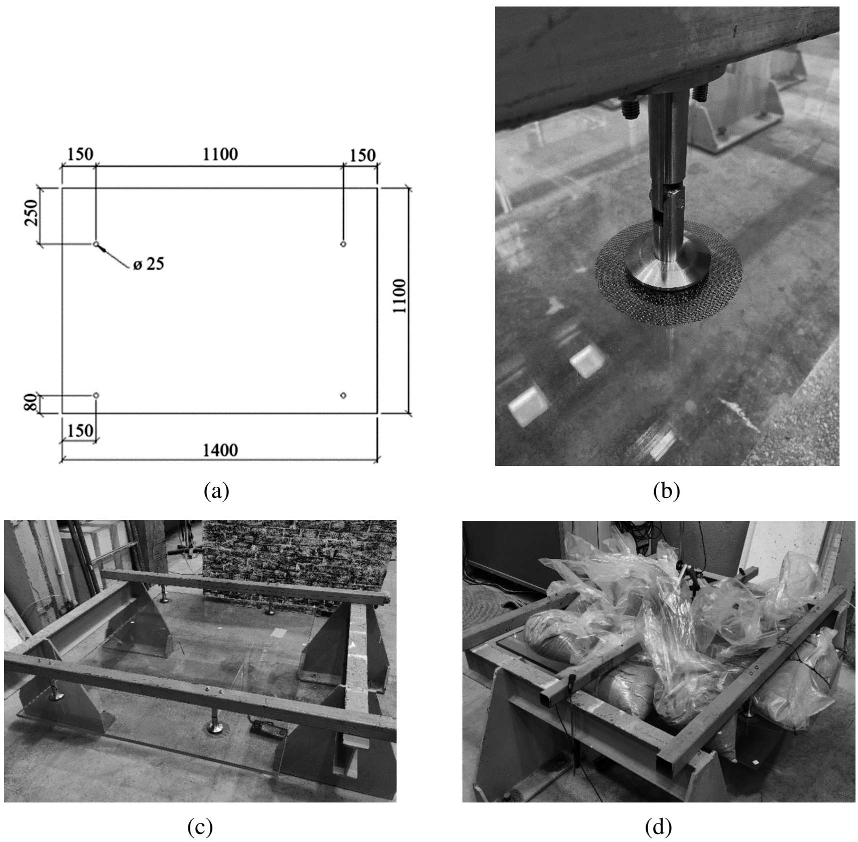
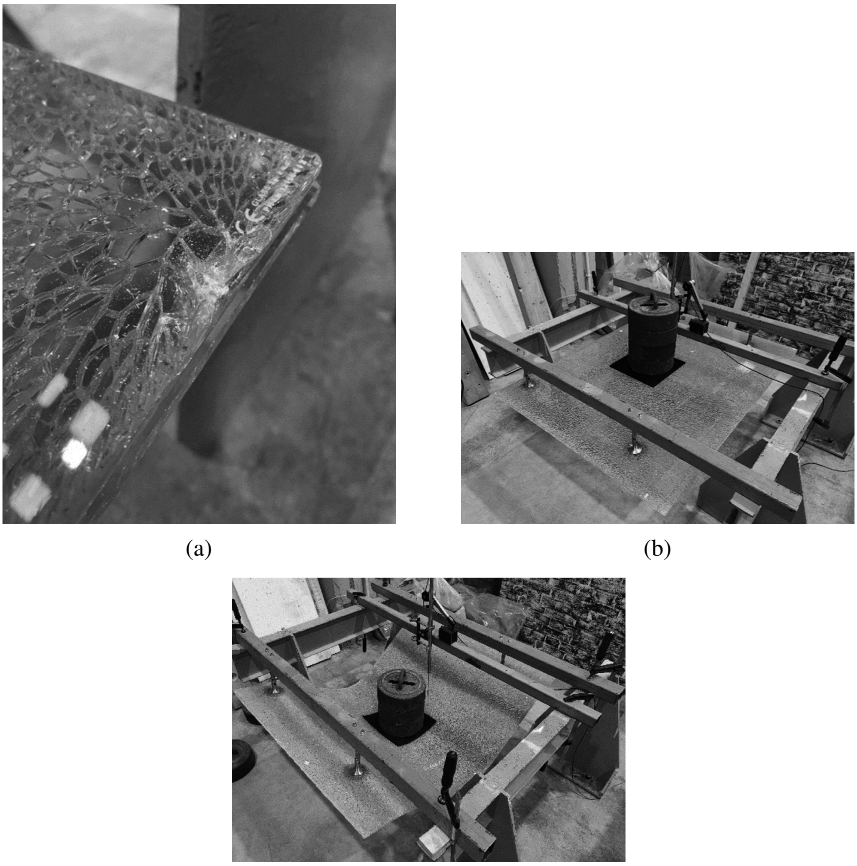


Fig. 7. Real-scale sample experiments: (a) sample, (b) test set-up, (c) close-up look of fixing, (d) 1st stage of tests

Reinforcement in the form of a woven steel mesh with a diameter of 110 mm was laminated around these holes (Fig. 7b). The test set-up is presented in Fig. 7c. The tests employed a proprietary multi-stage procedure to verify the post-breakage strength of laminated glass.

In the first stage, the sample was loaded with uniformly distributed weight of 2.0 kN/m^2 (achieved using sand-filled bags) for 48 hours (Fig. 7d). This load simulated snow loading for Zone I according to Eurocode 1, considering the possibility of its accumulation on the canopy. No glass breakage occurred.

In the second stage, the load was removed and the upper glass pane was fractured by impacting a steel cutter at the corner of the pane (Fig. 8a). The prepared sample was then loaded in the middle of the span with a concentrated force of 1.0 kN (distributed over a circular area with a diameter of 250 mm) for 48 hours (Fig. 8b).



(a) (b) (c)

Fig. 8. Real-scale sample experiments: (a) fracture location, (b) sample subjected to point loading, (c) sample after loading of 0.75 kN maintained for 120 hours

In the third stage, the glass pane was flipped so that the fractured pane was in the tensile stress zone. The load, applied as in the second stage, was reduced to 0.5 kN, and the duration of testing in the third stage was doubled to 96 hours.

Next, in the fourth stage, after removing the load, the second glass pane was fractured and the sample was left unloaded for 6 hours. Subsequently, the fifth stage of the testing began, involving a gradual loading of the sample with a load of 0.25 kN at intervals. After 90 hours, the load was increased to 0.5 kN, and after another 50 hours it was increased further to 0.75 kN, which was maintained for 120 hours. The total duration of the fifth stage of testing was 260 hours (over 10 days).

4. Conclusions

The main purpose of the research was to verify the validity of an innovative solution aimed at strengthening laminated samples using steel mesh laminated inside the interlayer. In this study, different load configurations were used to simulate varying conditions typical of fixed-point glass elements.

The following conclusions are drawn:

1. The samples exhibited a progressive failure mechanism. During the initial phase, the force-displacement relation indicated an elastic response of the sample to loading. However, after the glass fractured, there was a sudden decrease in force caused by loss of glass stiffness due to the fracture. In this stage, the load is mainly transferred by the interlayer. When loading is continued, the force initially increased and then decreased until final failure, which is associated with the plasticization (and tearing off) of the interlayer.
2. For all load configurations, a significant improvement in the ultimate load after glass failure was observed for the strengthened samples related to the reference samples. This demonstrates the validity and effectiveness of locally reinforcing laminated glass with a woven steel mesh laminated in the interlayer on the post-breakage load-bearing capacity.
3. The results of the full-scale test showed that local reinforcement around the openings is capable of effectively protecting the structure from detachment from supports caused by glass failure in various load combinations, while also providing sufficient time for evacuation of individuals near such elements. Research findings are directly applicable to the safety analysis of point-fixed glass structures, thus being significant in terms of preventing failures.
4. It should be noted that these conclusions are limited to specific studies conducted within the research project. Results may vary depending on the procedures and physical properties of the samples, including their geometric parameters and materials, as well as environmental conditions. Assessing the load-bearing capacity of glass laminates in a post-failure state is a complex task, and additional research is necessary for other configurations and variable environmental conditions.

Acknowledgements

This research was funded by the National Centre for Research and Development (NCBR) within the research project "Innovative solution for point-fixed laminated glass with improved capacity after glass fracture" (Grant No. LIDER/34/0125/L-432 11/19/NCBR/2020, LIDER XI Program). The APC was financed under the research grant BK-230/RB6/2024.

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Badania laboratoryjne szkła laminowanego mocowanego punktowo o zwiększonej nośności poawaryjnej

Słowa kluczowe: szkło laminowane, łącznik punktowy, stalowa siatka, nośność poawaryjna, wzmocnienie, zarysowane szkło

Streszczenie:

Praca podsumowuje główne rezultaty projektu badawczego "Innowacyjne rozwiązania dla szkła laminowanego mocowanego punktowo o zwiększonej nośności pokrytycznej", finansowanego przez Narodowe Centrum Badań i Rozwoju (NCBR), w ramach Programu LIDER XI. Artykuł przedstawia wyniki badań niszczących laminowanych tafli w trzech układach obciążeń: w płaszczyźnie tafli, prostopadle do jej płaszczyzny oraz obciążenie kombinowane. Ważnym elementem pracy są również badania elementów w skali rzeczywistej. Wyniki badań mogą mieć wprost zastosowanie w analizie bezpieczeństwa konstrukcji wykonanych ze szkła, a zatem są istotne w aspekcie zapobiegania awariom.

Received: 2024-06-24, Revised: 2024-07-30