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Timber-structural glass composite systems in earthquake environment

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Subject review

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Structural glass combined with a timber frame is a composite system that has a predisposition for good behavior during an earthquake, it is energy-efficient and cost-effective, aesthetically acceptable and has a good load-bearing characteristics. In recent years, several research projects of composite systems timber - structural glass are in progress and according to the present results basic guidelines for further research can be determined.

Key words:
load-bearing glass, timber – structural glass composite systems, earthquake, Eurocode 5, Eurocode 8

Pregledni rad

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Kompozitni sustavi drvo - nosivo staklo u potresnom okruženju

Nosivo staklo u kombinaciji s drvenim okvirom predstavlja kompozitni sustav koji ima predispozicije za dobro ponašanje prilikom potresa, istovremeno je energetski efikasno i isplativo, estetski prihvatljivo te ima dobre nosive karakteristike. U novije vrijeme provedeno je nekoliko istraživanja kompozitnih sustava drvo – nosivo staklo te se prema rezultatima tih ispitivanja mogu odrediti osnovne smjernice daljnjih istraživanja.

Ključne riječi:
nosivo staklo, kompozitni sustavi drvo – nosivo staklo, potres, Eurokod 5, Eurokod 8

Übersichtsarbeit

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Holz-Glas-Verbundsysteme in erdbebengefährdeter Umgebung

Tragendes Glas in der Kombination mit Holzrahmen stellt ein Verbundsystem dar, das die Voraussetzungen für ein günstiges Verhalten bei Erdbebeneinwirkungen erfüllt. Gleichzeitig ist es energieeffizient und ökonomisch, ästhetisch angemessen und hat gute Eigenschaften in Bezug auf die Tragfähigkeit. In neuerer Zeit wurden bereits einige Untersuchungen von Holz-Glas-Verbundsystemen durchgeführt, so dass anhand von entsprechenden Prüfresultaten grundlegende Richtlinien für weitere Untersuchungen gegeben werden können.

Schlüsselwörter:
tragendes Glas, Holz-Glas-Verbundsysteme, Erdbeben, Eurocode 5, Eurocode 8

1. Introduction

In recent decades, there has been a rapid development of glass as a load-bearing material. Main advantages of glass are its extremely high compression strength and excellent transparency. Although glass is a brittle material, its qualities are enhanced by thermal or chemical strengthening, and by additional layers and lamination. On the other hand, a wider use of glass is partly limited due to the lack of available and appropriate regulations and standards, which would enable its greater use by designers and contractors, and enable construction of structures of adequate reliability. While there are many standards related to products made of glass (e.g. [1, 2]), the Eurocode on structural glass is still in preparation, and there are only rough guidelines for the use and design of elements made of glass [3]. Pre-standards prEN 13474 [4, 5] are currently in use, and they serve as the basis for creation of a common standard.

Development of structural glass over the past several decades has contributed to the advances in the use of composite systems with glass. In addition to their extremely high aesthetic and ecological value, timber-structural glass composite systems also excel in their cost-effectiveness, and are characterized by a significant load transferring capability. The load-carrying glass (structural glass), in combination with timber frames, presents a composite system with predispositions for good behaviour in earthquake environment. Former principles for the application of these systems involved their use for facades, winter gardens, and similar secondary structures. Several research projects on timber-structural glass composite systems have been undertaken in recent years, and the corresponding results have enabled creation of basic guidelines in this area. The biggest problems occur in the selection of fasteners. As glass is brittle, it must be fastened to timber with elastic adhesives or steel fasteners, which have to be coated with some other elastic material in order to avoid contact between the steel and glass and, therefore, possible collapse of individual elements due to stress concentration. Design models and European standards include utilisation of glass panels as secondary elements [6], which means that the positive impact of these elements in the transfer of transverse loads caused by earthquake has to be ignored [7]. According to European earthquake standards [6], primary structural elements have to be calculated within the displacements allowed for protection of secondary elements. Commercially available shear walls and facade panels can usually withstand 10-15 millimetres of story-drift displacements (0,3 %), which is sufficient to meet requirements for displacements caused by wind, thermal expansion, shrinkage, creep, and other actions that may occur during the lifetime of a building [8]. Additional displacements due to seismic load can significantly impair stability of the system and, therefore, lead to failure. If the problem is approached as defined in Eurocode 5 [9], timber wall diaphragms should be designed to resist both horizontal and vertical actions imposed on them. In addition, they should be adequately restrained to avoid overturning and sliding, and must provide resistance to racking by being stiffened in plane by board materials, diagonal bracing, or moment connections [9]. According to Method A from Eurocode 5 [9], wall panels containing door or window openings should not be considered to contribute to the racking load-carrying capacity. These requirements can be met by combining timber frames and structural glass.

2. Timber-structural glass composite systems

Although glass has been used since the Stone Age, the modern history of glass actually began in 1851 when English architect Joseph Paxton designed a glass pavilion named "Crystal Palace" for the world exhibition in London. This revolutionary building made of glass and steel prompted architects to start using glass as a building material. The twentieth century architecture used glass extensively, but only recently it has started to be used as a load-carrying material.

Figure 1. Glass as secondary structure (façade systems of residential buildings, Vancouver, Canada) and load-carrying material (the Apple store, Shanghai, China)

In most glass constructions, its components are required to withstand mechanical stresses. When glass is stressed beyond its strength, the breakdown occurs immediately without any warning as opposed to, for instance, steel or aluminium where plastic hinges form. Relevant tests have shown that glass strength is of statistical nature. Therefore, the strength of technical glass is not an absolute value but it is significantly exposed to microscopic and macroscopic defects of the glass surface. The strength of glass without thermal prestressing is significantly marked by the sensitivity to flaws that are formed under tensile loading of the glass surface. The resistance of glass to pressure is much higher and it is not of any interest for standard application in the field of civil engineering. Consequently, the glass strength is marked in practice mostly by the tensile strength or bending strength.

An increase in the application of glass in civil engineering is limited due to the lack of appropriate regulations that would enable designers and contractors to use glass more extensively and thus to ensure construction of structures of adequate safety. The problem can be solved by coordinated cooperation of the industry, organizations responsible for standardization, certification bodies and experts from institutes and universities, combined with the support of EU bodies responsible for further development of technical regulations. The framework for such cooperation is provided in the existing Construction Products Directive (89/106/EC) [10], "Guidance Paper L" [11] and the JRC (Joint Research Centre) report [12] on the basis of which the European Commission issued a special recommendation related to the introduction and use of Eurocodes, justifying the start of preparation of the Eurocode for glass structures. In the preparation of the common standard for glass, a special chapter is consecrated to hybrid i.e. composite glass structures.

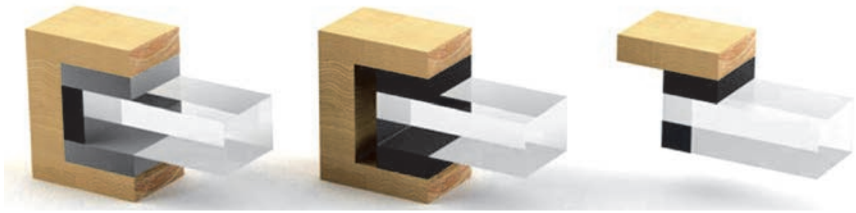

Figure 2. Bonded timber-structural glass composite systems, Niedermaier [16]

The composite system testing started with the laboratory research of steel frames with glass infill. In 2005 [13], Wellershoff presented two models in which compression elements were replaced with glass panes acting as stabilization. The first model was a hinged metal frame with glass infill, while the glass pane in the second one was bonded to the metal frame and functioned as a shear wall. The laminated and heat strengthened glass was used along with the acrylate and polyurethane adhesives. Similar research, but based on the use of different adhesives and behaviour of bonded glass elements, was conducted by Weller [14]. In his research on glass panes with steel frames, Močibob [15] noticed that the lateral in-plane stiffness increased in proportion with an increase n glass thickness, and the pane failed in a compression diagonal.
Niedermaier was one of the first researchers in the field of glass timber combination [16] (Figure 2). As in the research with steel, Niedermaier bonded glass panes with timber frames. He made and classified three different timber-structural glass composite systems; a bonded composite system with polyurethane and silicone adhesives, a double-sided composite system with epoxy adhesives, and a single-sided timber-structural glass composite system with epoxy adhesives. The research results showed that the deformability of the timber frame and the tensile stress distribution in glass depended on the geometry of the composite system and the type of adhesive.
Numerous tests of timber-structural glass composite systems were also conducted by Neubauer [17], Hochhauser [18], and Winter [19] who did not bond the glass directly to the timber frame but to a special sub-structure screwed to the main timber frame (Figure 3).

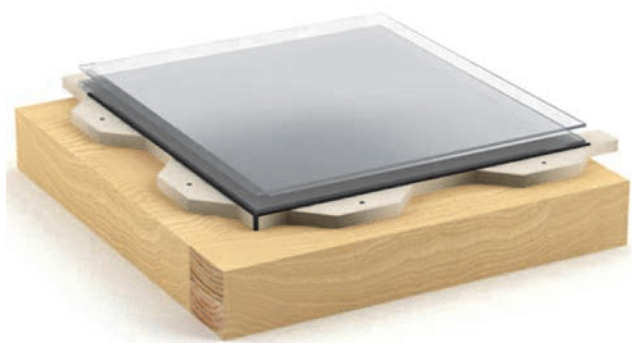

Figure 3. Composite system tested in research conducted by Neubauer [17], Hochhauser [18], and Winter [19]

Blyberg [20] tested a bonded composite system of laminated glass and timber by examining a shear wall as a façade

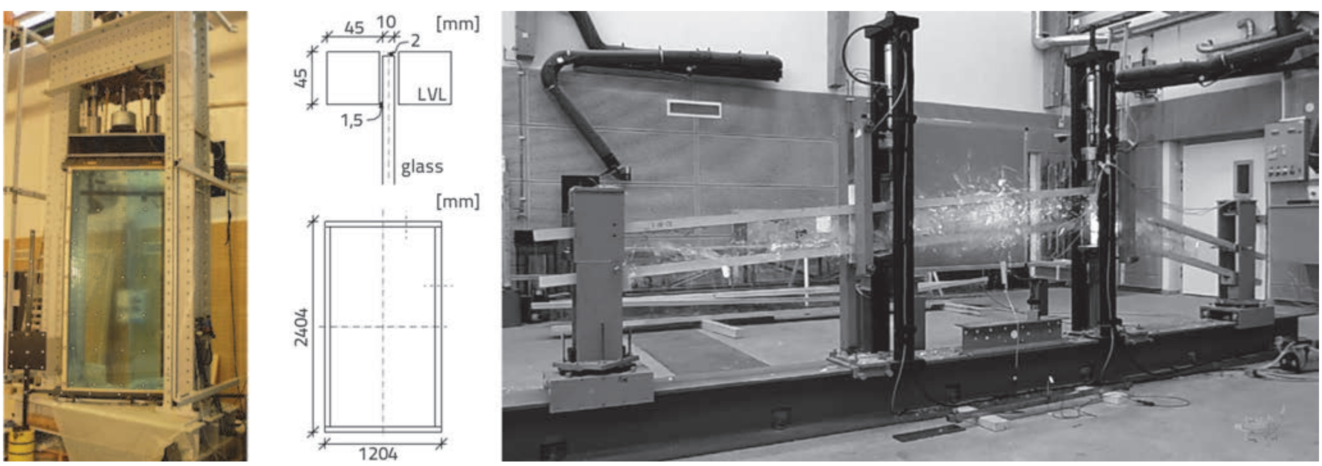

Figure 4. a) Composite system presented in Blyberg's work [20], b) displacement of composite I-beams in paper presented by Kozlowski and the others [22]

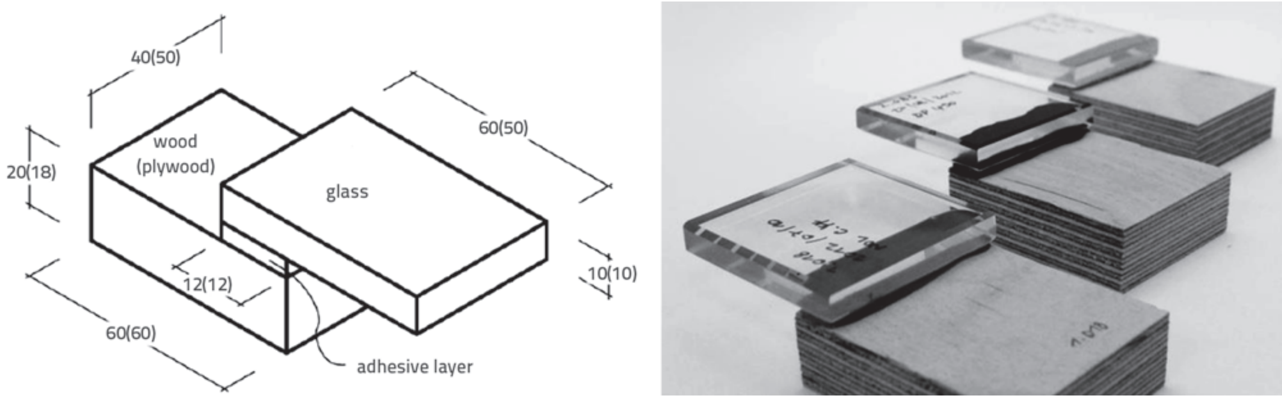

Figure 5. Shear samples tested in research by Niklisch and the others [23]

carrying element (Figure 4). The laminated glass was placed in the central part of the veneer frame and bonded with acrylic and silicone adhesives. Cruz and others [21] examined the composite systems and proved that glass elements contribute significantly to the transfer of vertical load and the increase of stiffness. Kozlowski and others [22] experimentally tested composite I -beams with timber flanges and glass web. The contact between the two elements was realized with adhesives (epoxy, acrylic, or silicone) and the bending strength of I-beams was tested. Two types of glass were used: annealed float glass, and heat strengthened glass. The beams with the web of heat strengthened glass broke by brittle failure without prior notice, although they have a much higher initial load-bearing capacity than the annealed float glass (Figure 4). The stiffness of beams glued with silicone adhesives is by about 20 % lower.

Nicklisch and others [23] tested material characteristics of adhesives applicable in timber-structural glass composite elements. The preliminary analysis was conducted to select only the adhesives with excellent adhesion to both materials. Silicone, acrylic, polyurethane and epoxy adhesives with various stiffness and strength levels were tested. Shear samples are shown in Figure 5. The researchers concluded that different types of adhesives behave differently and noted that even adhesives from the same group (e.g. polyurethane) differed, and that thorough analyses and tests of the adhesive must be conducted to achieve contact between timber and glass with big samples.

Rosliakova [24] conducted research on the use of timber-structural glass composites in architecture, and on environmental impacts of composite façades compared to conventional aluminium façades. Her research showed that composite timber-structural glass façades generate up to 16 times less CO_2 than the aluminium-made façades, while also exhibiting a greater energy efficiency.

3. Behaviour of timber-structural glass composite systems subjected to earthquake excitations

The market demand for "eco-friendly" products has grown exponentially over the years, and so new systems using ecological materials are being developed, and highly energy efficient buildings are constructed. As a very interesting architectural material, glass is often used in highly energy efficient buildings. An observation of architectural trends in which the south side of residential buildings tends to be as open and transparent as possible (while other sides are significantly less open) leads to the conclusion that the rigidity centre and the centre of mass are not located at the same place (Figure 6). This feature consequently leads to a significant torsional deformation of the above mentioned geometry of buildings in earthquake environment.

Figure 6. Residential building with glazed south side, rigidity centre shifted northward

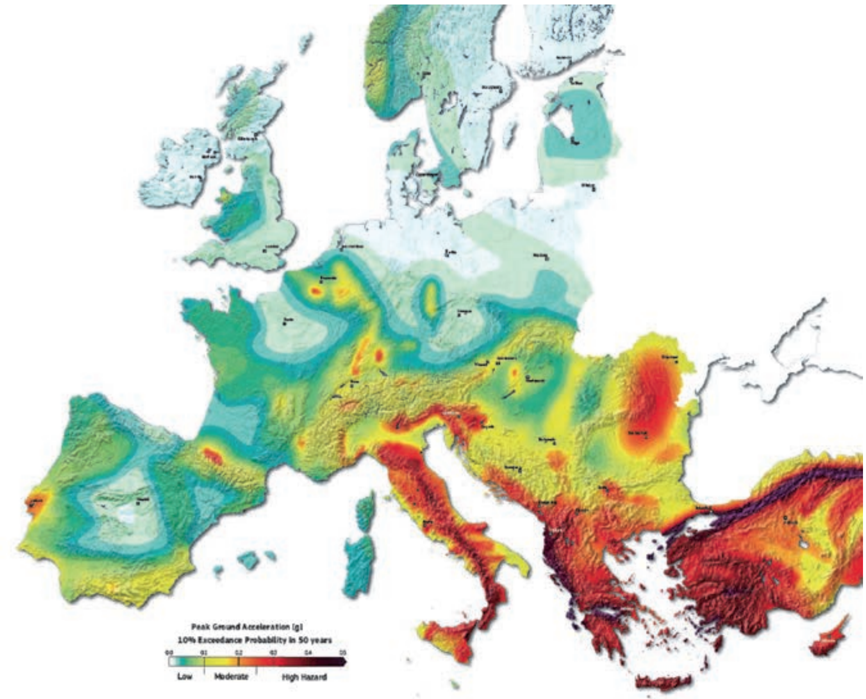

Figure 7. European Seismic Hazard Map [25]

of precast elements, glass helps to enhance the said criteria. Glass panels used as load-bearing structural elements can efficiently replace visible diagonal elements and secure the stability and an efficient transfer of horizontal in-plane load. The basic disadvantage of this assumption is the fact that glass is a very brittle material and can hardly fit into the concept of seismic calculations that are based on ductility of materials that dissipate energy and avoid brittle fracture mechanisms. One of the ways to avoid brittle failure is by binding the glass with the framework system with ductile fasteners whereby the static resistance of the structure can be maintained. This leads to the conclusion that composite systems must have both high ductility and sufficient load-bearing capacity, as well as the systems that will optimize both criteria to a suitable level.

There are currently very few researchers in the world who deal with this topic. In recent years, only several articles have been published on the topic of quasi-static and dynamic tests of timber-structural glass composite systems.

Ber and others [26, 27] tested behaviour of the system with glass elements bonded to the outer side or to the centre of a timber frame (Figure 8). Various types of adhesives and boundary conditions were applied. The testing showed that the racking resistance in all tested samples (except when epoxy glues were used) is much lower than the rigidity of standard load-bearing wall elements with, for instance, OSB panels, which added to the issue of meeting boundary usability state. The same group of authors (Ber, Premrov, Dujič, Šušteršič) published several articles on earthquake-resistant timber – glass composite systems [28-31]. Samples measuring 2.4 m × 2.4 m were tested, with glass being bonded to a timber frame with the single-component polyurethane epoxy glue. The epoxy adhesive enabled a full composite action between timber and

While this problem does not play a significant role in the northern and western European countries, countries located in the south and southeast of Europe are often affected by earthquakes, and there the use of glass is in a way limited due to the lack of research and regulations. A brief glance at the European earthquake map (Figure 7) reveals why the leading producers and "users" of glass come from the north of Europe.

The existing regulations contained in Eurocode 8 [6] do not regard glass parts as a load-bearing element, which means that glass elements should be disregarded when calculating the load-bearing capacity of structures exposed to lateral seismic load. According to Method A from Eurocode 5 [9], shear diaphragms with windows and doors do not contribute to stability of structures. Method B is less restrictive and it proposes to regard panel parts from each side of the opening as separate panels. Since the openings decrease the racking resistance while significantly reducing horizontal stiffness

Figure 8. Composite systems presented in research by Ber and others [26-31]; monotonic testing and shaking-table testing

glass. Great ratio of elasticity modulus caused brittle fracture of the glass in monotonic testing. The samples demonstrated an exceptionally high bearing capacity, but with a very limited ductility. When such systems are used in structures, the required ductility can be achieved through adequate selection of mechanical fasteners [31]. The system behaves differently when a polyurethane adhesive is used. During the testing, defects appeared on the line where glass was bonded to timber, but no composite system failure was registered. Even though the system's ductility level was satisfactory, the timber and glass separation occurred relatively quickly, and the basic load-bearing capacity was lost [31]. Tests with composites involving various adhesives served for further cyclic and dynamic testing. The samples were subsequently tested by quasi-static and dynamic protocols. Various composite-system failure modes were demonstrated and it was concluded that most composite systems fail at the contact between timber and glass due to adhesive failure. Samples were also tested on the shaking table. Four one-storey high timber-glass composite systems and four two-storey high systems were subjected to earthquake excitations [28-30]. The seismic energy dissipated in steel fasteners without any failure of the glass panel. The system lifted up from the foundation and the separation occurred at the angles of the frames [29]. Experimental tests represent the basis for the FEM analysis that will be conducted by the authors at the next stage of the project.

Based on the conclusion of the study regarding the need to work out a new Eurocode [12], Žarnić and Rajčić launched an initiative to develop a new structural element made of a timber frame and glass infill. In their joint research, a group of authors [7, 32-36] applied a model that is somewhat different from the model used by other researchers in the field of timber – structural glass composite systems. The objective was to create joints in which the negative impact of fasteners on glass is prevented, and to develop a system that will dissipate seismic energy and thus be acceptable in earthquake-prone areas. The system with glass directly leaning on the timber frame was developed, i.e. the system with load transfer through the contact between the two materials and the friction force between them. A timber frame with a glass infill was made with dimensions corresponding to real-life frames built into structures i.e. the composite height was 2722 mm, and the width was 3222 mm. The glass infill was composed of two identical panes of partly annealed float laminated glass measuring 2900×2400 mm, which were "inserted" into the timber frame. The laminated glass panels 10 mm in thickness were bonded together with an EVA layer 1.6 mm in thickness. The glass panels were separated from one another with the wooden separator equipped with lateral timber purlins preventing tipping over and falling, as shown in Figure 9. Timber frame elements (class C24) measured 90×160 mm in cross section (Figure 9).

The glass was intentionally not joined with steel fasteners due to its brittle behaviour and incompatibility with materials such as steel. In addition, it was not joined with adhesives, which would prevent the occurrence of friction force. Therefore, great attention was paid to the development of joints of timber elements. Numerous tests have been conducted with different boundary conditions, various details at the angles of the frame, and with the conduct of both monotonic and cyclic tests. Experimental tests have proven that timber-structural glass composite systems behave exceptionally well in dynamic and cyclic conditions [7, 32-36]. Many experimental tests have proven that numerous parameters affect behaviour of timber-structural glass composite systems subjected to horizontal

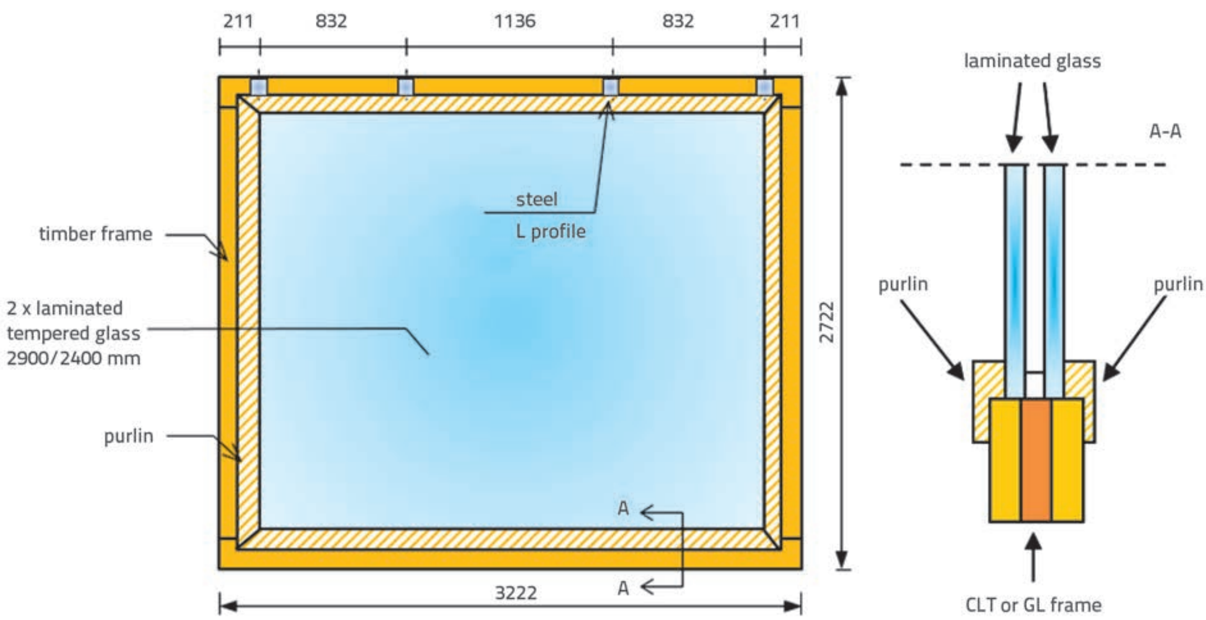

Figure 9. Developed composite system in research conducted by Rajcic and others [7, 32-36]

action, which makes the dimensioning and designing of such systems a very demanding process. Several variations in the shaping of frame angles were made; with one bolt, with two bolts, with one bolt and punch nailed plate, and with glued-in rods. Based on the tests, the failure mode of composite timber frames with glass infill was determined, and the layout of outside horizontal actions affecting separate composite elements was defined. The hysteresis effect in separate timber frame angle detailing methods was different in terms of ductility and bearing capacity. A detail with two bolts in the frame angles had an excellent bearing capacity, but a smaller energy dissipation, while the detail with glued-in rods had an exceptionally great ductility and an optimum bearing capacity. The first results of experimental research conducted by the authors of this paper are shown in Figure 10. The detail in the timber frame is realized with glued-in rods.

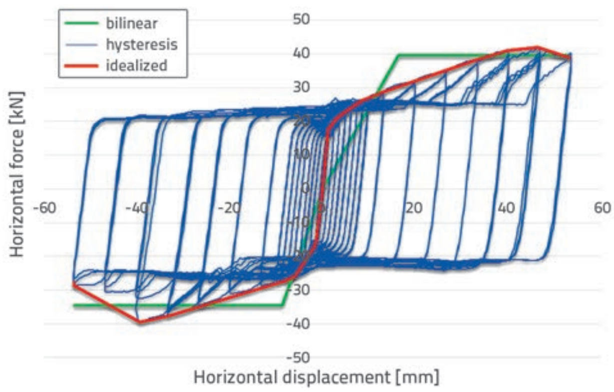

Figure 10. Hysteretic response obtained by quasi-static tests of composite system made "by inserting" glass in timber frame (detail in timber frames is obtained with glued-in rods)

The researchers have concluded that timber-structural glass load-bearing systems can be used in various structural applications, depending on the required bearing-capacity or ductility levels.

The sample was also tested on a shaking table at the IZIIS Institute in Skopje, FYROM (Figure 11). The results show that the same failure mode was registered during quasi-static racking tests and during the shaking table tests. The failure occurred in the angle of the timber element frame, followed by the friction force between timber and glass taking over a considerable amount of horizontal load, i.e., the seismic energy was dissipated through the sliding of glass on timber and activation of the joint in the angle of the timber frame. The timber frame protects the glass panels and, in combination with glass infill, it represents a system resistant to considerable earthquake excitations while, at the same time, it maintains its vertical stress bearing capacity.

4. Conclusion

Glass, as a structural material, is gaining a growing share in the marketplace through enhancement of its mechanical characteristics, its more precise processing, and a more economical production. Although the prevailing opinion is that glass is a brittle material exhibiting a small load-bearing capacity, the possibilities of the modern glass in civil engineering are tremendous. Until recently, it was only used as a secondary component or a façade element but, thanks to new improvements in technology, structural glass is now capable of transferring significant loads. Thus, the newly developed glass exhibits excellent tensile characteristics, but it is less applicable in the elements affected by significant tensile forces. As glass is a brittle material, many scientists try to combine it with other

Figure 11. Composite systems presented by Rajčić and Žarnić [7, 32-36]; quasi-static and shaking table tests

materials to develop composite systems with better behaviour in tension. Although glass elements in façade systems are not considered as load-bearing elements, glass is very much involved in load transfer in composite systems with structural glass. The modern architecture trend to glaze the south side of buildings causes an uneven distribution of an entire building mass, leading to a considerable torsional deformation in earthquake environment.

After review of the existing literature and the current state-of-the-art regarding glass facades and composite systems with structural glass, it can be seen that a great gap exists in the study of composite systems with glass in earthquake environment. Nevertheless, it is possible to devise a system with a timber and structural glass combination in which every material would transfer load and, in mutual interaction of constitutive elements, it would be resistant to earthquake. It may be concluded that glass panels, when used as load-carrying structural elements, can effectively replace visible diagonal elements and ensure stability and effective distribution of in-plane stress. A particular attention should be paid to the bond between timber and structural glass. Several extensive tests of timber-structural glass composite systems have been conducted with various timber and glass bonding methods. Bonding glass with timber has proven to be a good example for obtaining a high load-bearing capacity of composites, although deficiencies have been noticed in the level of ductility along with possible problems with the durability of the structure. Another approach is the "insertion" of glass in timber frames where excellent results have been obtained with regard to ductility and dissipation of seismic energy. In addition, proper attention must be paid to mutual binding of the timber frame elements in energy dissipation zones.

Timber-structural glass composites present a novelty on the market, and there is ample room for further research and improvement of the existing models.

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