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Influence of Friction on the Behavior and Performance of Prefabricated Timber–Bearing Glass Composite Systems

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Abstract: The basic concept of seismic building design is to ensure the ductility and sufficient energy dissipation of the entire system. The combination of wood and bearing glass represents a design in which each material transmits the load, and with the mutual and simultaneous interaction of the constituent elements, it is also earthquake resistant. Such a system has been developed so that the glass directly relies on the wooden frame, which allows the load to be transferred by contact and the friction force between the two of materials. Within the seismic load, friction between glass and wood is an important factor that affects both the behavior and performance of a wood–glass composite system. The set-up system consists of a single specimen of laminated or insulating glass embedded between two CLT elements. The friction force was determined at the CLT–glass contact surface for a certain lateral pressure, i.e., normal force. Friction depends on the way the elements (especially glass) are processed, as well as on the lateral load introduced into the system. Conducted experimental research was accompanied by numerical analyses. Experimental research was confirmed by numerical simulations.

Keywords: composites; timber; CLT; load-bearing glass; earthquake; friction; FEM analysis

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1. Introduction

In the current situation of increasingly acknowledging climate change as a threat to our environment and human society, binding agreements have been made during the COP26, taking place in Glasgow in 2021. The building sector has a huge impact and must provide answers on how to tackle climate change, develop a circular economy, and provide a sustainable environment. The building sector should base future technologies on environmentally friendly materials and construction processes. Timber is the leading bio-based material and, through newly designed engineered wood-based materials, the material of the future. One innovative engineering wood product, known as cross-laminated timber (CLT), was introduced in the early 1990s in Austria and Germany. Due to its good mechanical properties, good fire resistance as well as advanced durability, and rheological properties, it has been seen as a potential material to replace reinforced concrete in low- and high-rise buildings. On the other hand, there has been significant development and increase in the use of glass as a load-bearing material. Rajčić et al. concluded that load-bearing glass combined with a timber frame represents a load-bearing composite element, which has very good potential for excellent behavior under normal and seismic loads; it is cost-effective, energy-efficient, and aesthetically acceptable [1–3]. The lack of experience and scientific research as well as non-existing standards and codes covering the design of structural components made as composites from laminated glass and laminated timber limit the implementation of such structural elements in practice. Admittedly, there is a national guideline for the design of glass elements [4]. The purpose of these instructions is to seek to provide an overview that is as complete as possible for the various aspects that must be considered in the design, construction, and control of glass elements with regard to verifying their mechanical strength and stability. There are some existing harmonized standards for glass products, for instance [5,6], necessary for their CE marking, but there are no European harmonized standards that can serve as codes needed for the design of glass structures. Therefore, the European Committee for Standardization (CEN) started the preparation of a new code in the series of Eurocodes in order to clarify the design of safe glass-based structures [7]. Currently, they are in the form of technical specifications (CEN/TS 19100-1–CEN/TS 19100-3). Regarding composite elements of cross-laminated timber and laminated glass, extensive research work should be carried out, which will be a basis for implementation in code. Although there is a limited amount of research dealing with timber-glass composites, the need for large transparent surfaces led architects to use such elements. Adding the aesthetic value of timber and glass and the environmental friendliness of materials that can be fully recycled at the end of their life cycles, a new type of structural element was introduced as timber–glass composite structural systems. These types of structures are also built-in earthquake-prone areas (south Europe, Japan, China, USA). There is a significant concern that should be overcome. Generally, the opinion is that the glass has brittle behavior and cannot be used as a structural element in seismic zones. Antolinc, with his research [8], has contributed to the understanding of the behavior of hybrid structural components based on laminated glass and cross-laminated timber frames. Such a structural component, made of a cross-laminated timber frame infilled with load-bearing laminated glass, has a high potential for various applications. It may be used as for façade element timber houses, as a bracing element for newly built or existing frame structures, as a strengthening structural component in existing timber buildings, or as a supporting structural component in historic buildings during and after their retrofitting and restoration.

During the project financed by the Croatian scientific fund “VETROLIGNUM”, led by Prof. Vlatka Rajčić, the system was analyzed in terms of load-bearing capacity, stability, seismic performance, energy efficiency, water tightness, and airtightness. Building with wood is very fast and completely suitable for prefabrication in factories. The LCA (cradle to cradle) shows extremely good results in terms of cost-effectiveness and sustainable construction and a reduced CO_2 footprint [9]. Considering the complexity of the wood-bearing glass composite system and the intentions of presenting the most realistic performance and characteristics of such systems, the research is divided into two sections: laboratory testing and research on numerical models.

The contact between glass and wood, as well as a type of connection in the angles of the wooden frame, are the details that need to be given the utmost attention since it is precisely the manner of joining these elements that greatly determines the behavior of the entire composite system [10]. The most usual way of joining load-bearing glass and wooden structures is by adhesives and different types of mechanical fasteners [3]. Using steel mechanical fasteners results in complicated design solutions and details that damage the edge of the glass, which is the most sensitive part of the glass element. Using adhesives can provide a good connection, but that poses the question of the durability of such systems. In addition to said problems, the seismic load causes damage to the structure at the joint positions, and consequently, the failure of the entire load-bearing system [2,3]. In order to solve that problem and maximize energy dissipation during earthquake loading, a system was developed where the load-bearing glass was inserted into the wooden frame without additional mechanical fasteners and adhesives. The system is designed to allow the glass to move freely in a wooden frame while securing glass stability with additional wooden slats. Therefore, the load is transmitted by direct contact, i.e., friction between two elements [3,8,10,11].

During the experimental campaign, 45 cyclings (racking tests) of the composite panels were performed with four different types of connectors in the laminated timber frame. Tests have shown that failure of a composite panel occurs in a corner of a wooden frame [3]. Due to the partly free movement, the load-bearing glass panels remain intact, which is very important in such a composite system since the wooden elements are easily replaceable, while the mechanical characteristics and properties of the load-bearing glass are retained.

The problem of friction was investigated and discussed in the already mentioned project "Vetrolignum" led by Prof. Vlatka Rajčić Ph.D. The results of the research are presented here.

2. Timber–glass Hybrid Elements: A Brief Literature Overview

When designing hybrid timber–glass structural systems, special attention should be paid to the appropriate type of connectors to use. The main goal when choosing a connector and type of connection is to avoid the concentration of stress, such as the local crushing of glass on the edges as well as the occurrence of tensile stresses in the glass, which can lead to sudden failure. The usual way to deal with this problem is through the use of soft coating materials on the metal connectors. An overview of possibly used systems for joining laminated glass structural components is contained in Stepinac et al.'s research [12]. Hamm [13] discussed possible solutions for connecting timber with glass in a composite structural component as well as variants of possible practical application in buildings. Niedermaier, in his research [14], presented the connection of timber frame and glass sheets in a hybrid structural panel using two types of adhesives. In the first case, the glass panels were glued to the timber frame with polyurethane and silicone adhesive. In the second case, the bonding was achieved with an epoxy adhesive. The results of the panel racking test are also presented. The test results show that the distribution of tensile stresses and strains depends on the type of adhesive as well as the geometry of the specimens that are tested. Wellersho et al. [15] presented methods to stabilize the building envelope using glazing. A hinged steel frame was used in which a stabilizing glass sheet was inserted in the first case. The second model used the same steel frame but the glass sheet, in this case, was glued with acrylate and polyurethane adhesives. Weller et al. [16], along with Mocibob [17], further continued to examine the behavior of structural components composed of glass sheets inserted in steel frames using different types of adhesives. It was concluded that the thickness of the glass panel is very important because it determines the lateral in-plane stiffness of the hybrid structural component. Different authors (Hochhauser et.al, Neubauer, and Winter et al.) [18–20] examined a hybrid panel in which the main timber frame is connected with a timber subframe by screws and the glass is glued to the subframe. An analysis of the in-plane loaded hybrid systems by using mechanical modeling was carried out and described by Cruz et al. in [21].

It was discussed that glass sheets significantly participate in the transfer of horizontal and vertical loads. Additionally, they participate in the prevention of excessive deformations and may substitute the usual type of bracings of steel and timber frames. Blyberg et al. [22], along with Nicklish et al. [23], presented the test results of timber-laminated glass panels where the connection was made by gluing. The authors present the characteristics of adhesives that may be used for structural bonds. A special focus on the analysis of failure mechanisms of timber–glass glued composite wall panels was presented by Ber et al. [24]. Amadio et al. [25] discussed the problem of glass panel buckling. It was analyzed using extended finite-element (FE) investigations and analytical methods for the effect of circumferential sealant joints and metal supporting frames. In [26] Štrukelj et al. presented results of the racking experimental tests of hybrid walls consisting of a timber frame and glass infill connected using polyurethane sealing. Ber et al. [27] used a parametric numerical analysis in their research. The racking stiffness of timber–glass walls is affected by different parameters, and their influence was reported in this study. In [28] Santarsiero et al. analyzed the potential use of glass in earthquake-prone areas as well as the lack of design codes and standards for the design of earthquake-resistant structures designed with glass. This paper concludes that during the design of the earthquake-resistant structures from glass it is necessary to ensure high ductility and dissipation capacity to glass components in buildings. In [29] Bedon et al. reported and demonstrated how the optimal design of glass components can be efficient and beneficial for multiple design configurations.

Special mechanical joints were introduced to enhance the dynamic performance of the glass façade. It was reported that well-designed fasteners can introduce additional flexibility and damping capacities when using hybrid panels in a strengthening traditional building. The first published paper with results from the design and analysis of the innovative laminated timber frames infilled by the laminated glass, which is the main subject of this paper, was presented at the WCTE 2012, or the World Conference on Timber Engineering, 2012 [1]. The innovation in this hybrid element is the contact connection between the timber frame and the glass panels without an additional adhesive layer. The research started in 2007, and it was a collaborative research project between the University of Zagreb and the University of Ljubljana. Žarnić et al., in their research, followed the conclusions of the EU JRC ELSA Italy feasibility study [30]. The cooperation was established within the former CEN TC250/WG3 and the current TC250/SC11 and is still ongoing. Stepinac et al. recently introduced glued-in steel rods as a standard connector because of their wide use all around the world [31]. Since the innovative element showed very good performance, further cooperation on new parts of structural glass codes and the new parts of the timber structure design will be necessary to upgrade Eurocode 8 to introduce such a new type of hybrid structure for retrofitting and strengthening the existing structures made from various materials (masonry, concrete, etc.). Generally, Neugebauer et al. emphasized that emerging laminated materials and hybrid structures are not sufficiently covered in the Eurocodes [32].

3. Prototype of a Multifunctional Wood–Bearing Glass Composite System

The main objective of the research was to develop, design, and construct a new composite system that will be used as an independent prefabricated structural component for construction in seismically active areas. The solution, in this case, is simplicity, where the desired behavior of the system is achieved by friction, and therefore, without the use of mechanical connectors or adhesives. The purpose of the research was to design composites and construct details of joints that do not adversely affect the load-bearing glass and to develop systems with a high degree of energy dissipation exclusively by friction between wood and glass. Preliminary research shows that certain composite systems can be used in seismically active areas (such as Croatia) [2,3,10,33–35], but system optimization and parameter analysis have not yet been carried out.

In recent years, thanks to the collaboration of the University of Zagreb and the University of Ljubljana, preliminary testing of the wood–bearing glass composite system at monotonous static and cyclic loading has been carried out. The research and development of energy-efficient composite systems are planned in a three-year project entitled VETROLIGNUM (prototype of a multifunctional wood–bearing glass composite system) funded by the Croatian Science Foundation. This project will build on structure dimensioning knowledge and explore new ways to connect load-bearing elements and prepare a study on optimizing certain parts of the panel to maximize energy efficiency. Žarnić et al. [36] concluded that it is required to build a prototype of the wood–bearing glass composite system, which could be installed in a real building. Additionally, this type of hybrid element can be used as an independent element in the construction of wooden structures, as a temporary or permanent reinforcement, or to stabilize the elements of existing facilities and cultural heritage sites, and as an element for the construction of multi-purpose and adaptive façade systems (Figure 1).

One of the most important parameters when using the modal analysis is the horizontal stiffness of a building. Stiffness and mass determine the structure's vibration periods and hence the influence of an earthquake's frequency content on a structure's response. If a low-rise (only ground floor) building's vibration periods are overestimated (too long) the resulting seismic forces are too conservative. If the periods are underestimated (too short), the results are on the non-conservative side. The situation is just the opposite for higher buildings where the overestimated periods are on the non-conservative side and vice versa. Hence, great care must be taken in assigning the wall's correct stiffness. In the case of a timber–glass panel, the stiffness is predominantly dependent on the shear and hold-down behavior of joints in frame corners. However, glass infill greatly increases panel stiffness, whereby the influence of friction between timber and glass also needs to be considered. For the static calculation of frame building reinforced with a timber glass panel, the whole system could be replaced with only one element.

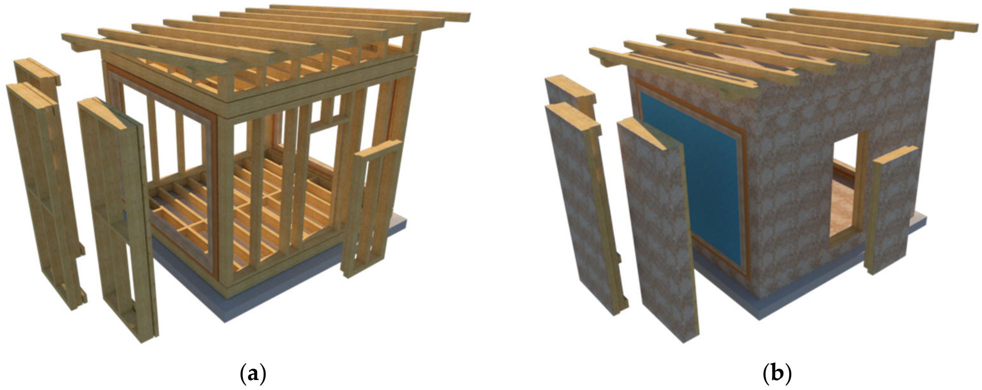


Figure 1. 3D—the prototype of a composite system: (**a**) timber frame; (**b**) timber—glass system.

The basic principle of panel installation is to connect the beams of timber frame with horizontal structural elements of the building. A connection derived by angular brackets has a higher bearing capacity than connections in frame angles (single glued-in rod). By such a solution horizontal force is transmitted directly to the panel without compromising the link between panel and frame structure. According to the analysis of the different types of frames with infill, such as concrete or steel frames with different types of infill (masonry infill as well as concrete, steel, and timber panels as infill), there are not many similarities to describe this system. However, certain similarities between the behavior of CLT panels and timber frame composite systems were found, where one of the important parameters is shear stiffness. The shear stiffness $k_{c,\,shear}$ of timber frame connections can be expressed with Equation (1) from [37]:

$$k_{c,shear} = 4 \cdot K_{c,shear} + \frac{0.6 \cdot q_{vert} \cdot L_{glass}^2 \cdot d_{glass} \cdot c}{u_{slip,Rd}} \quad (1)$$

where $K_{c,\,shear}$ is shear stiffness of a glued-in rod, $q_{vert,}$ is the vertical line load at the top of the panel, $u_{slip,\,Rd}$ is the slip of the weakest connector at the design strength, c is the dynamic friction coefficient of timber–glass contact, L_{glass} is the length of the glass panel, and d_{glass} is total glass panel thickness. In order to confirm this hypothesis, it is necessary to know each of the above parameters. Because there is a lack of data in the literature on the value of these stiffnesses, as well as friction coefficients, the main goal of further studies is to determine them experimentally [37].

Based on reverse-cyclic lateral loading tests on structural timber–glass panels [3], the data show a great way of spending seismic energy which contributes to the development of the forces of friction between wood and glass (Figure 2). The failure occurred in the timber frame corner, 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 corner of the timber frame.

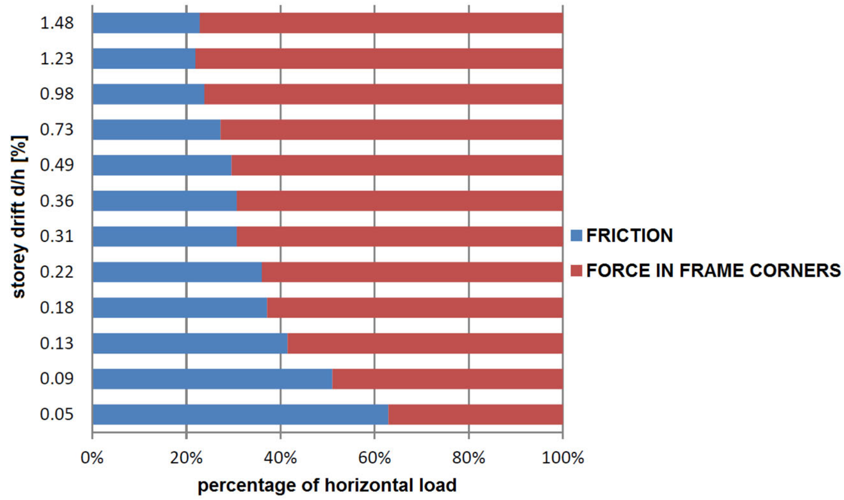


Figure 2. The relationship between the friction force and the bearing capacity of frame angles in horizontal loading (for a double-glazed panel). Reprinted with permission from Ref. [3]. Copyright 2015 Ph.D. thesis "Spojevi kompozitnih sustava drvo-nosivo staklo u potresnom okruženju" by Asst. Prof. Mislav Stepinac, Ph.D.

4. Materials and Methods

Examining the friction between wood and glass is crucial to understanding the operation of the entire timber–bearing glass composite system, in which the glass panel can slide in a wooden frame. It is the sliding, that is, the friction between glass and wood, that is one of the factors that transfers part of the horizontal load [10]. The set-up system consists of a single specimen of laminated or insulating glass embedded between two CLT elements. The positioning of the glass was achieved by making additional wooden slats that prevent the lateral displacement of the glass but do not press it laterally, and therefore, do not affect the force of friction. Based on the test, the friction force was determined at the wood–glass contact surface for a certain lateral pressure, i.e., the normal force). As a result, a coefficient of friction was obtained, which could be used to numerically model the contact between wood and glass in a calculation model. Numerical analysis was carried out with "Ansys" software support.

Description and Preparation of Specimens

The friction testing system consists of CLT elements, glass specimens, and steel elements (lateral force introduction). In order to optimize the system, glass specimens of various types and thicknesses were prepared.

Laminated safety glass is a "sandwich" of two or more glass surfaces that are glued together. "Glue" is a special transparent layer (PVB—polyvinyl butyral, EVA—ethylene vinyl acetate) with a thickness of 1–2 or sometimes more millimeters. In the event of glass breakage, shards and pieces of glass do not scatter but remain retained in the frame thanks to the plastic interlayer. This glass, too, absorbs wide-range sound vibrations and provides better sound insulation than float glass with the same thickness. It is most often single-laminated glass, which does not exclude the possibility of multiple laminating, i.e., joining several glass surfaces between which there is a transparent PVB (or some other) foil. Lamination is performed with PVB (polyvinyl butyral), EVA (ethylene vinyl acetate—transparent or opal), and TPU (thermoplastic polyurethane) foils. In our case, it was lamination with PVB foil.

Insulating glass consists of two or more glass panels that are interconnected at the edge (spacing 6 mm, 9 mm, 12 mm . . .). The connection allows for a flawless and long-lasting seal, and the interspace is filled with dry air or gas. The distance between the glass plates is provided by aluminum holders that are filled with drying agents. Insulating glass can be produced in combination with tempered or laminated glass. The properties of insulating glass are that it reduces heat exchange, reduces energy consumption, and does not allow drafts or condensation, so larger glass surfaces can be used for a given room temperature without increasing energy costs.

For this research, 21 glass specimens measuring 200 mm × 400 mm were prepared (Table 1). The specimens were as follows: 3× laminated glass 2 mm × 6 mm, 3× laminated glass 2 mm × 10 mm (Figure 3), 3× insulating (IZO) glass with double-laminated glazing of 6 mm and a cavity width of 12 mm (Figure 4), 3× insulating (IZO) glass with double-laminated glazing of 10 mm, and a cavity width of 12 mm, 3×—Laminated glass and wooden slat (2 mm × 6 mm) × 2, 3×—Laminated glass and wooden slat (2 mm × 10 mm) × 2, and 3× laminated glass 2 mm × 10 mm smooth ground edges.

Table 1. Specimens.

Specimen Type	Dimensions (mm)	Edge Processing Acc. To DIN 1249-11	Number of Specimens
Laminated glass—2 mm × 6 mm	200 × 400	Bordered edge	3
Laminated glass—2 mm × 10 mm	200 × 400	Bordered edge	3
Insulated (IZO) glass—4 mm × 6 mm	200 × 400	Bordered edge	3
Insulated (IZO) glass—4 mm × 10 mm	200 × 400	Bordered edge	3
(2 mm × 6 mm) × 2—Laminated glass and wooden slat	200 × 400	Bordered edge	3
(2 mm × 10 mm) × 2—Laminated glass and wooden slat	200 × 400	Bordered edge	3
Laminated glass—2 mm × 10 mm smooth ground edges	200 × 400	Smooth ground edge	3

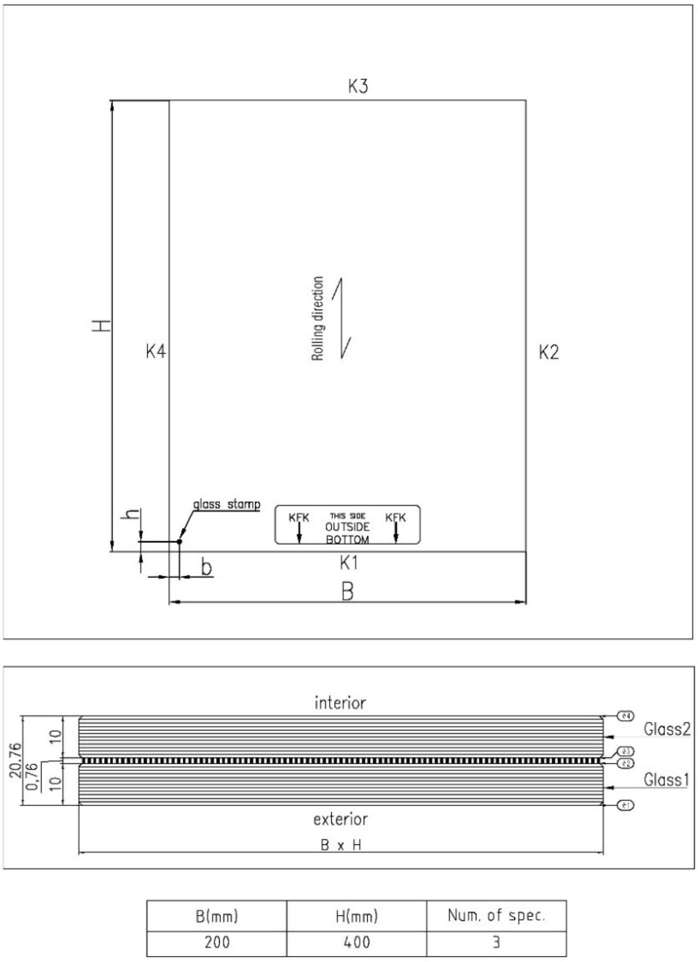


Figure 3. Laminated glass panel.

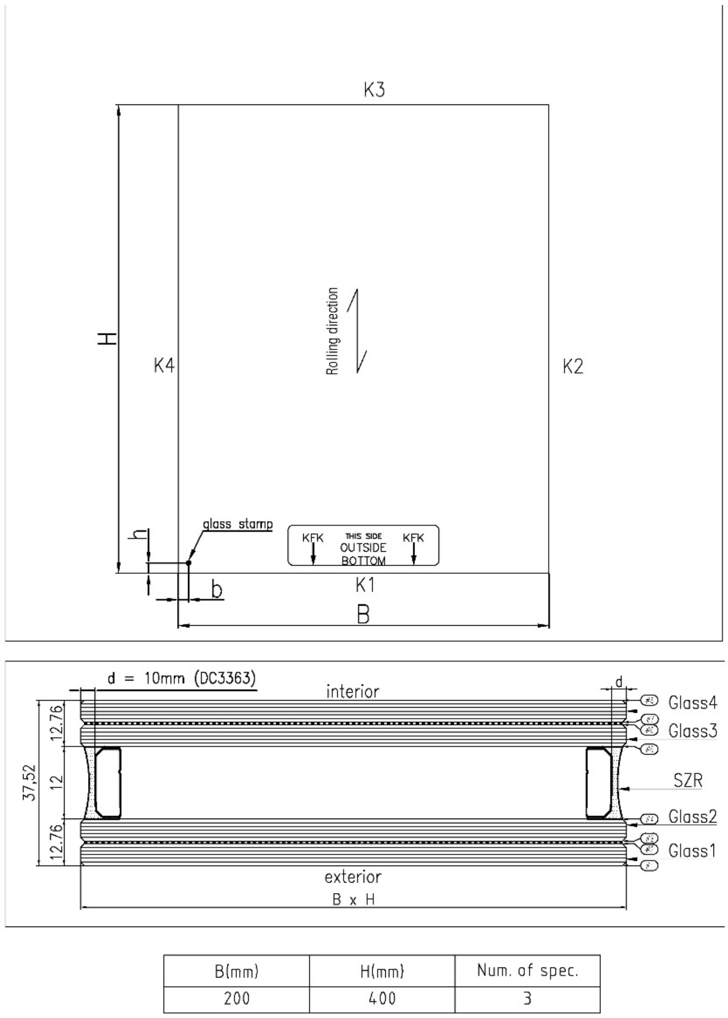


Figure 4. Insulating glass panel.

All specimens were ESG-toughened glass according to the EN 12150-1 standard [38]. The manufacturing tolerance was within the permissible limits according to the EN 14179-8 standard [39]. The edges of the specimens were roughly sanded [40]. Laminated glass panes were bonded with a 0.76 mm thick PVB membrane. A total of 90% of the cavity in insulating glass was filled with argon. The spacer was 12 mm wide and made of aluminum with respective DC 3363 butyl and silicone layers. Mechanical characteristics of the glass panels can be seen in Table 2.

Table 2. Mechanical characteristics of glass.

Properties	Value
E—Young's elasticity modulus	70,000 N/mm^2
G—Shear modulus	28.689 N/mm^2
μ—Poisson's ratio	0.22
α—thermal expansion coefficient	8.8×10^{-6}
ρ—density	2.5 g/cm^3
Compressive strength	700–1000 N/mm^2
Tensile strength	30–45 N/mm^2

The timber CLT elements (Figure 5) were processed in the structural testing laboratory of the Faculty of Civil Engineering, University of Zagreb. The CLT consisted of 3 layers, and each layer was 30 mm thick. The timber was class CL24h according to [41]. The additional wooden beams that support the glass were 30 mm × 30 mm. The material and mechanical properties (acc. to [42,43]) of CL24h timber are shown in Tables 3 and 4.

(**a**) (**b**)

Figure 5. CLT specimen: (**a**) wooden slats; (**b**) assembled CLT sample.

Table 3. Material properties of CL24h timber.

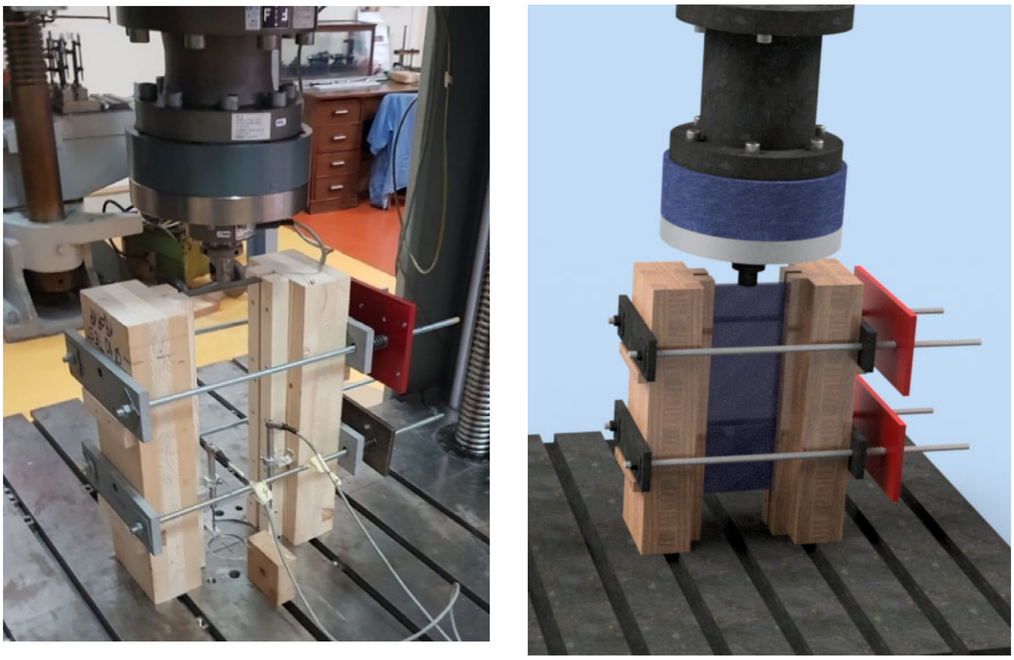
Properties	Index	Value
Density	ρ	420 kg/m^3
Young's modulus of elasticity	E_x E_yE_z	11,000 Mpa 600 Mpa 580 Mpa
Shear modulus	G_{xy} G_{xz} G_{yz}	600 Mpa 690 Mpa 580 Mpa
Poisson's ratio	ν_{xy} ν_{xz} ν_{yz}	0.3 0.25 0.6

Table 4. Mechanical properties of CL24h timber.

Strength	Index	Value
Bending	$f_{m,k}$	24 Mpa
Tension (parallel to the grain)	$f_{t,0,\ k}$	14 Mpa
Tension (perpendicular to the grain)	$f_{t,90,\ k}$	0.5 Mpa
Compression (parallel to the grain)	$f_{t,0,\ k}$	21 Mpa
Tension (perpendicular to the grain)	$f_{t,90,\ k}$	2.5 Mpa
Shear	$f_{v,k}$	2.5 Mpa

5. Experimental Work

The experiment was carried out by inserting a laminated or insulating glass specimen between two wooden elements. Before starting the experiment and introducing the vertical force, i.e., the force acting in line with the glass pane, it was necessary to secure certain lateral pressure between the glass and the wood. This way we could directly determine the contact point between wood and glass. The lateral force introduction system consists of six steel plates, four threaded rods with nuts, and four springs (Figure 6).



(**a**) (**b**)

Figure 6. Specimen set-up: (**a**) laboratory; (**b**) 3D model.

The system, dimensions, and positions of the elements are shown in Figure 7.

The introduction of lateral pressure of the desired amount (1 kN, 2 kN, or 3 kN) was achieved over a certain amount of spring displacement. Springs were positioned between metal plates. The spring displacement itself was achieved through the displacement of the metal plates that push the springs, that is, by controlled tightening and releasing of the nuts on the threaded rod. Such a system allows constant lateral pressure. In order to determine and control the lateral force that was introduced, a preliminary test was conducted to determine the spring stiffness, i.e., to obtain a force-displacement diagram. The diagram represents the force-displacement ratio for all four springs. The spring stiffness can be seen in Figure 8. The stiffness of one spring was determined in such a way that 25% of the amount of force in the diagram was read. The advantage of this system is its simplicity and accuracy. The distance between the two metal plates, that is, the length of the spring, determines the lateral force. The distance was controlled using a sliding caliper with an expanded measurement uncertainty of 20 μm. The simplicity was manifested in the ability to make spacers in desired dimensions that we could place between the two metal plates and then tighten the bolts.

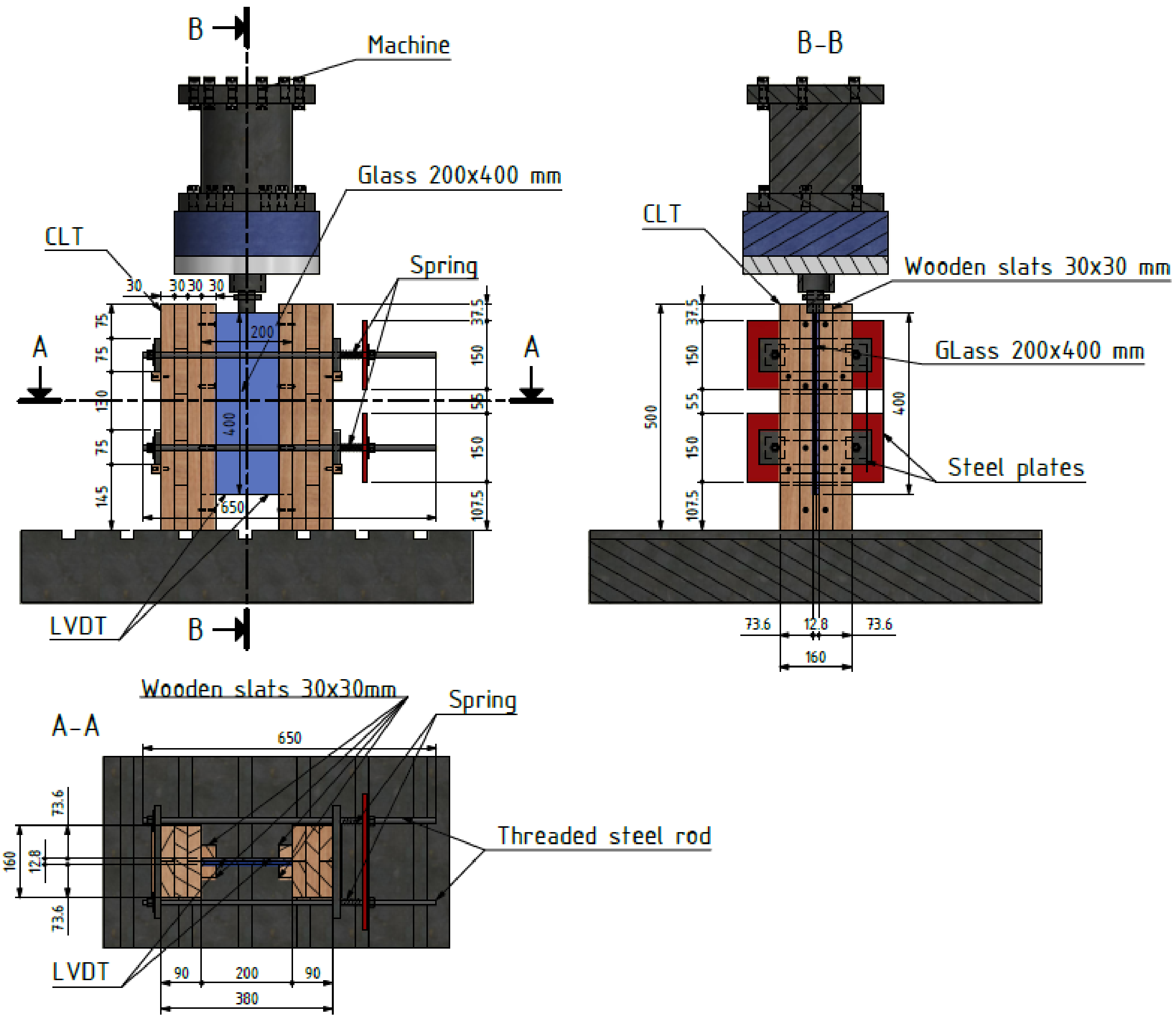
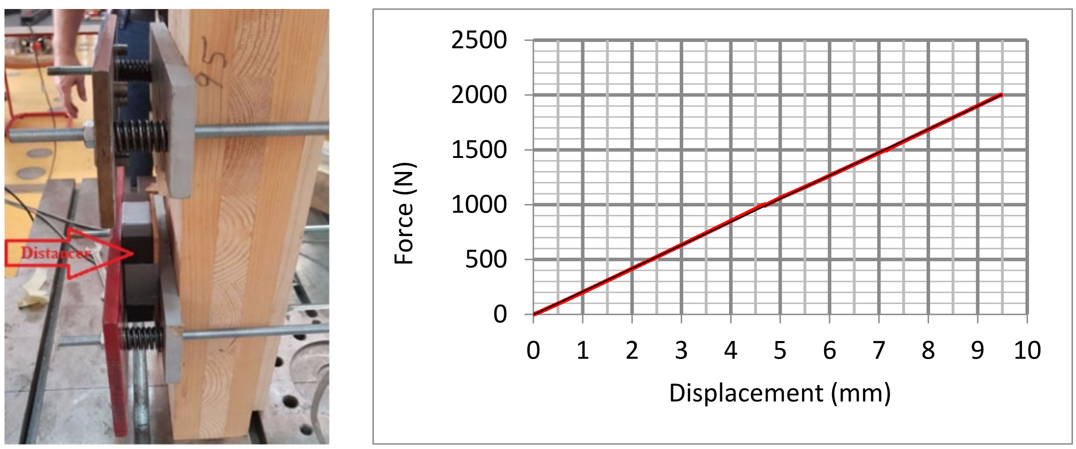


Figure 7. Dimension and positions of the test set-up.



(**a**) (**b**)

Figure 8. (**a**) Spacer position; (**b**) spring stiffness.

After achieving the desired lateral force (F_n) and centering the specimen, the force was introduced to the glass panel. In order to prevent direct contact between the press (steel) and the glass, a thin rubber washer was placed on the edge of the glass, i.e., at the point of load introduction. The load was applied using a universal electromechanical Zwick/Roell testing machine equipped with force sensor class 0.5 in the range from 1 kN to 50 kN according to EN ISO 7500-1:2018 [44] and displacement sensor class 1 according to EN ISO 9513:2012 [45]. The load was applied by displacement control at a speed of 1 mm/min.

The specimen differed in the thickness and type of glass elements (Table 1). Eighteen samples had rough edges, while three samples had smooth ground edges. The sample with smooth ground edges was tested subsequently to see the impact of the glass treatment itself. Each of the samples was tested with a lateral compressive load of 1 kN, 2 kN, and 3 kN. Figure 7 schematically shows the dimensions of the sample and the place of load input. During the experiment, the relative displacement of the glass panels was measured, regarding the fixed CLT elements. Displacement was measured using two LVDTs (Figure 6a) with an expanded measurement uncertainty of 5 μm. The load on the glass panel tangentially to the contact between CLT and glass was measured for a certain normal force F_n. In all experiments, unloading (and then re-loading) was performed in order to eliminate local defects, irregularities, and gaps in the timber material, until the samples fit on the machine surface perfectly, in order to avoid the noise in the data results. The result can be graphically represented as a ratio between the friction force F_t and the longitudinal displacement at a certain normal force (F_n), as shown in Figures 9–15. The friction force (F_t) is half of the force F required to move the glass panels. The coefficient of friction μ was obtained as the ratio of normal (lateral) force (F_n) and frictional force (F_t).

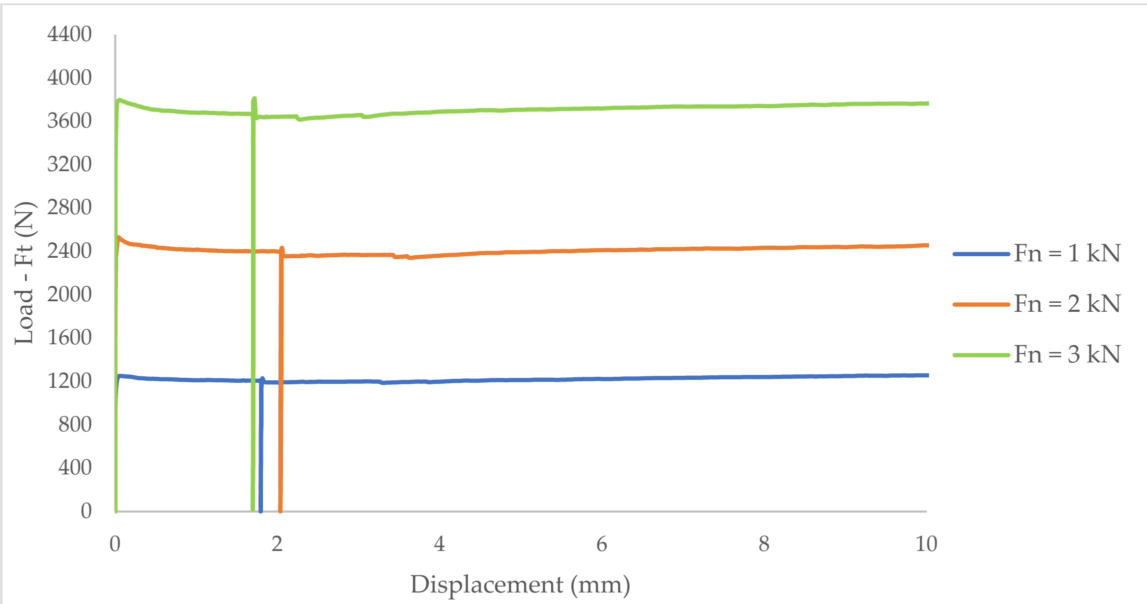


Figure 9. Laminated glass 2 mm × 6 mm.

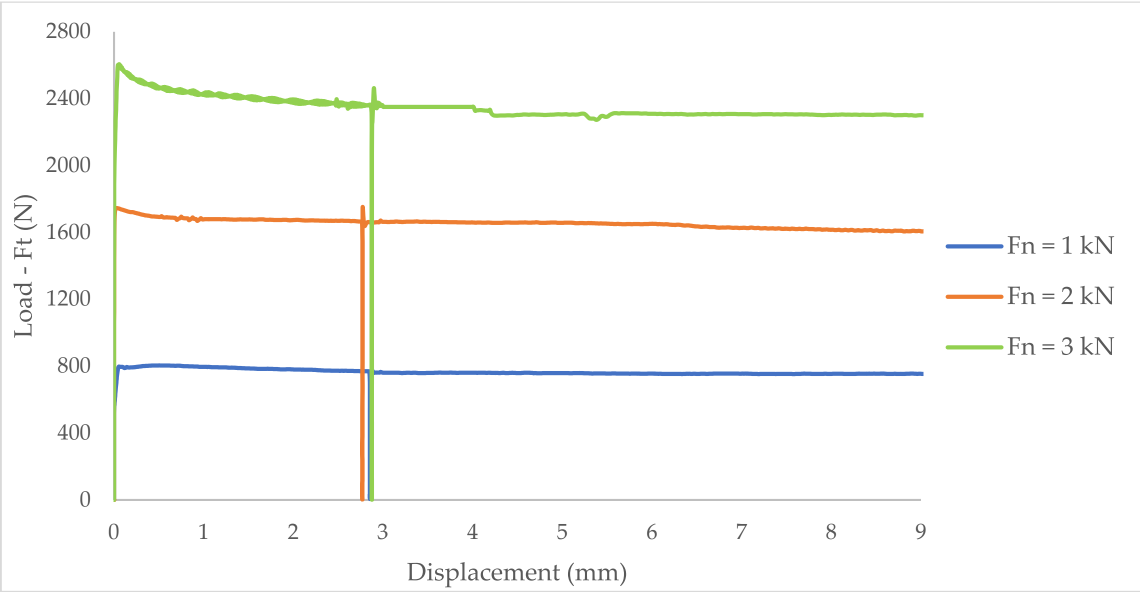


Figure 10. Laminated glass 2 mm × 10 mm.

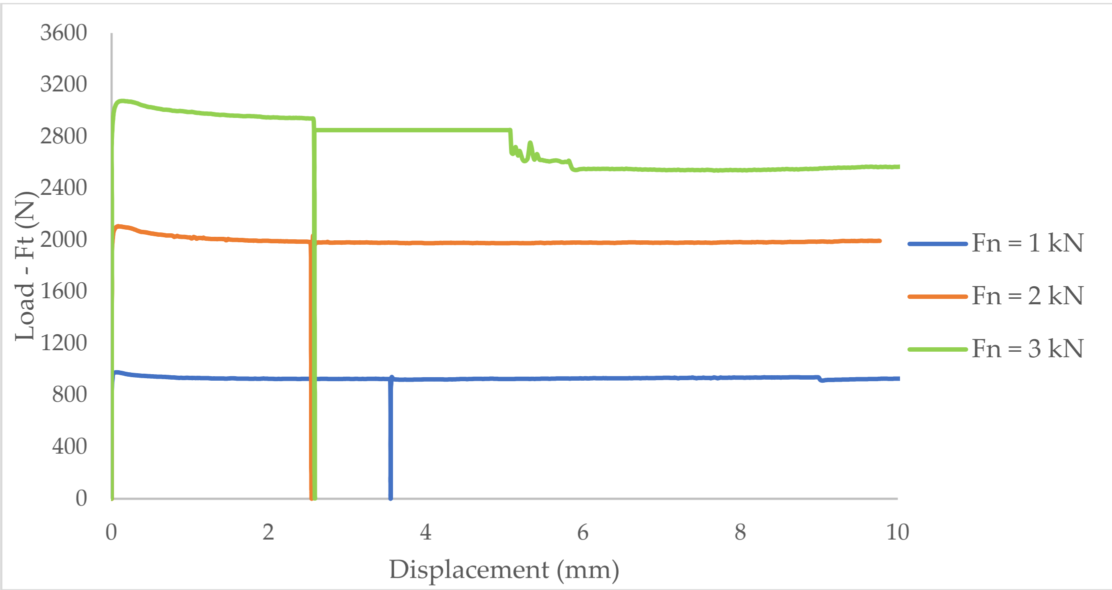


Figure 11. IZO glass 2 mm × 10 mm.

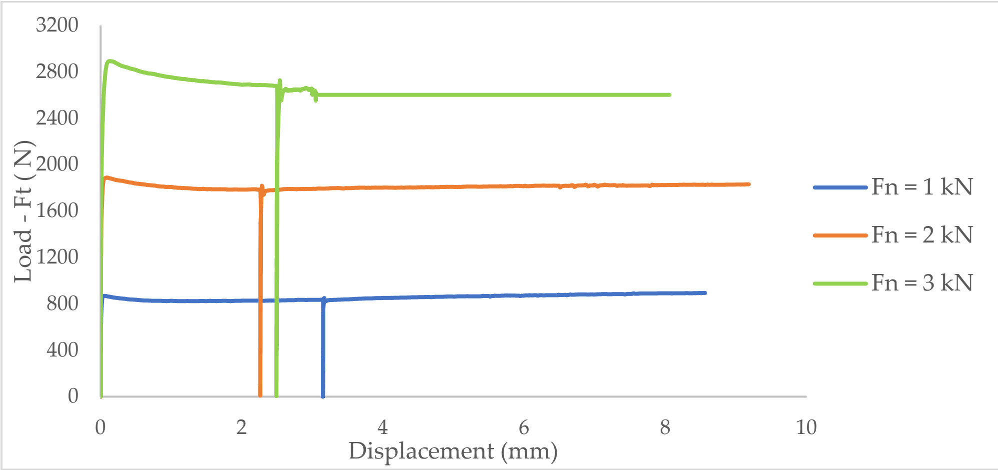


Figure 12. IZO glass 4 mm × 10 mm.

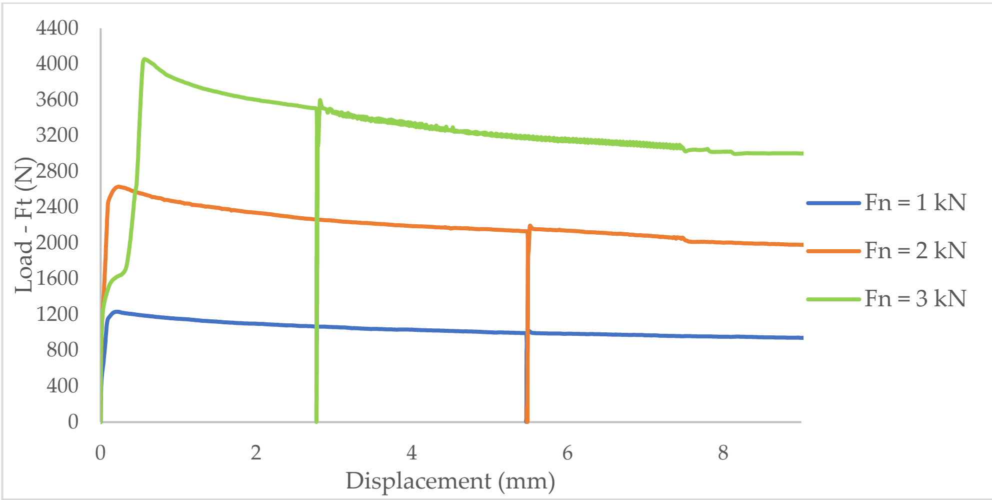


Figure 13. (2 mm × 6 mm) ×2—Laminated glass and wooden slat.

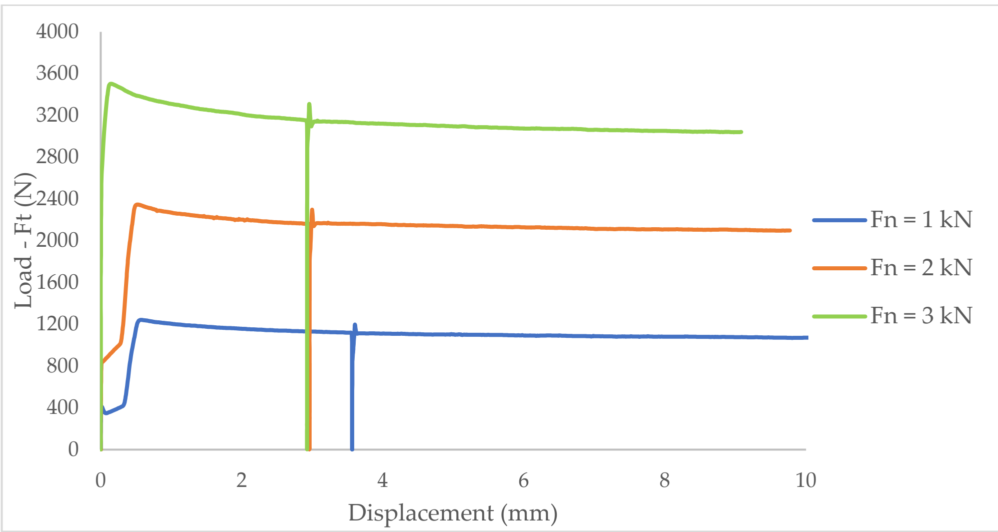


Figure 14. (2 mm × 10 mm) ×2—Laminated glass and wooden slat.

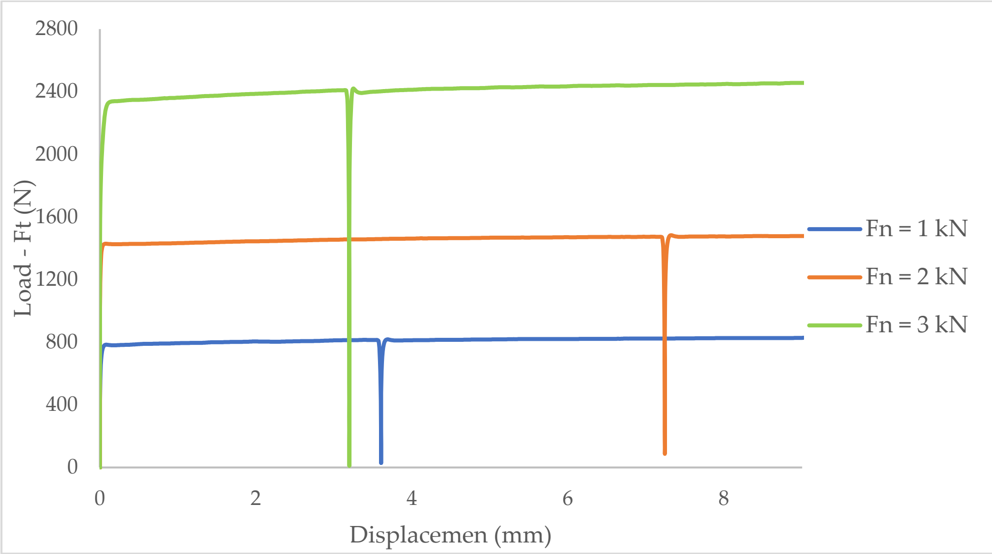


Figure 15. Laminated glass 2 mm × 10 mm—smooth ground edges.

6. FEM Research

The experimental studies carried out were accompanied by numerical analyses. The numerical analyses aimed to extend the knowledge of the behavior of the experimental research. Furthermore, the numerical simulations were performed to confirm and complement the experimental results. The analysis was conducted by Ansys software [46,47]. The entire geometry of the model was drawn by the software "Autodesk Inventor" and imported into "Ansys", where a finite element mesh was formed and in which further simulations were carried out (Figure 16). Element geometry, boundary conditions, loads as well as material characteristics were defined following the experiment.

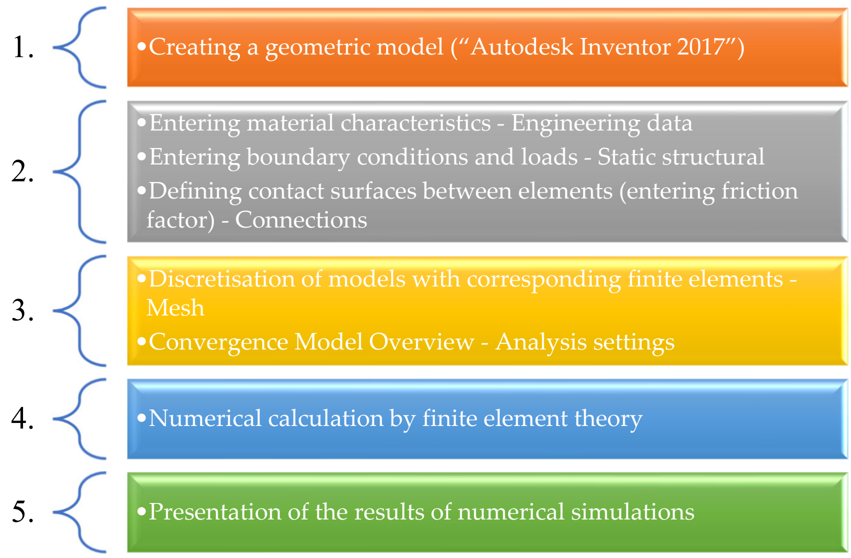
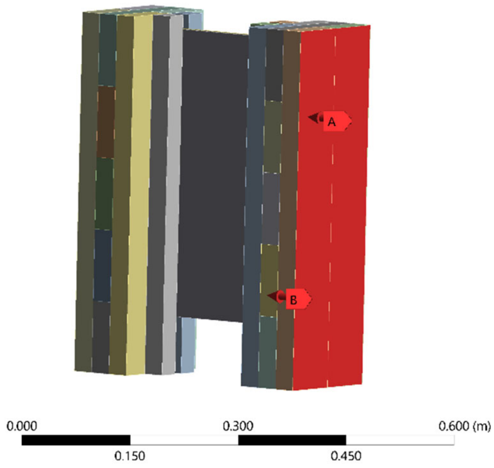
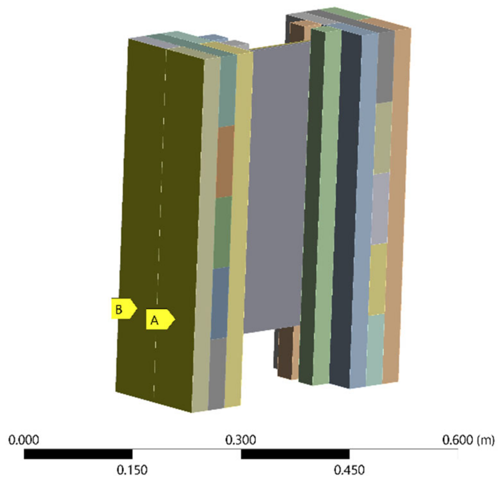


Figure 16. Schematic of numerical analysis procedures.

The model itself is composed of three different materials, namely CLT, glass, and PVB. Boundary conditions and lateral pressure were defined as can be seen in Figure 17.



(**a**)



(**b**)

Figure 17. Numerical model: (**a**) Normal force (lateral pressure-1 kN, 2 kN or 3 kN); (**b**) displacement (0 mm-fixed).

To discretize the model, the following Ansys mesh tools [48] were used: "edge sizing" and "sphere of influence". The methods MultiZone (allows the creation of models with a denser grid on the contacts) and Hex Dominant (allows the creation of models where the finite element mesh consists mostly of hexahedrons). Both methods were used to model the glass element (Figure 18).

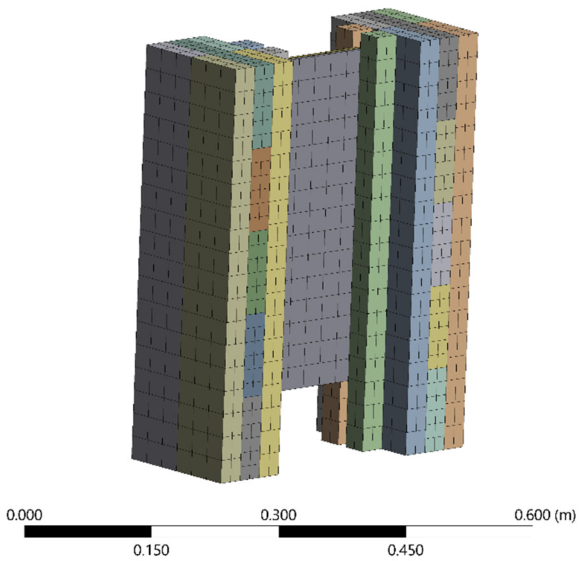


Figure 18. Finite element mesh.

For modeling contact surfaces, absolute stiffness for normal stresses was used, as well as the possibility of the tangential sliding of two surfaces (CLT and glass) with the corresponding coefficient of friction (Figure 19).

The load was introduced by displacement of the glass panel, according to the steps and data obtained from the laboratory. The result of the experiment, i.e., numerical analysis, is the friction stress that occurs on the contact surface.

FEM Results

The numerical analysis aimed to obtain a model and certain behavior legality, which would help the prediction of the behavior of such a system during a seismic event. The main parameter for the control and comparison of numerical simulations and experimental work is the frictional stress that occurs on the contact surfaces. The result obtained from the laboratory was the frictional force required to shift the glass element. In order to compare and evaluate the results of the FEM analysis, the frictional stresses occurring at the contact surfaces were calculated manually, based on the frictional force obtained from the conducted laboratory test. The friction force F_t is expressed as half the force F required for moving the glass element, as the frictional force occurs on the two surfaces where the glass and the timber connect. In addition to the results in the form of frictional stresses, the behavior of the sample (sliding) was obtained by numerical simulations as shown in Figure 20.

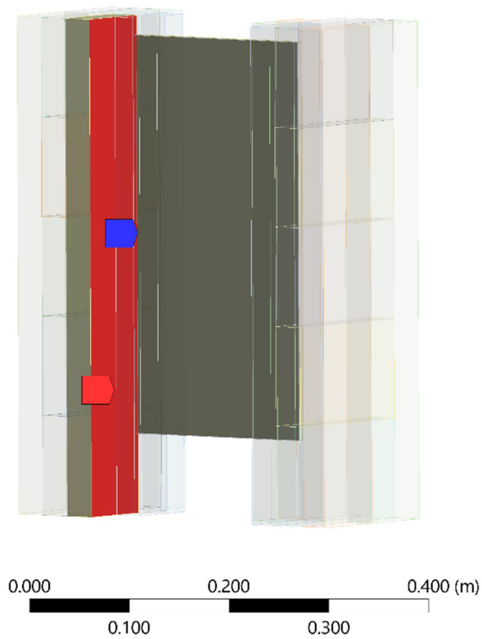


Figure 19. Defining contact surfaces.

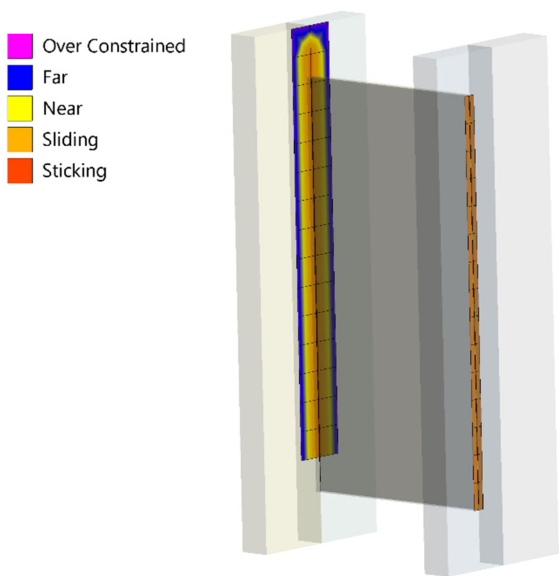
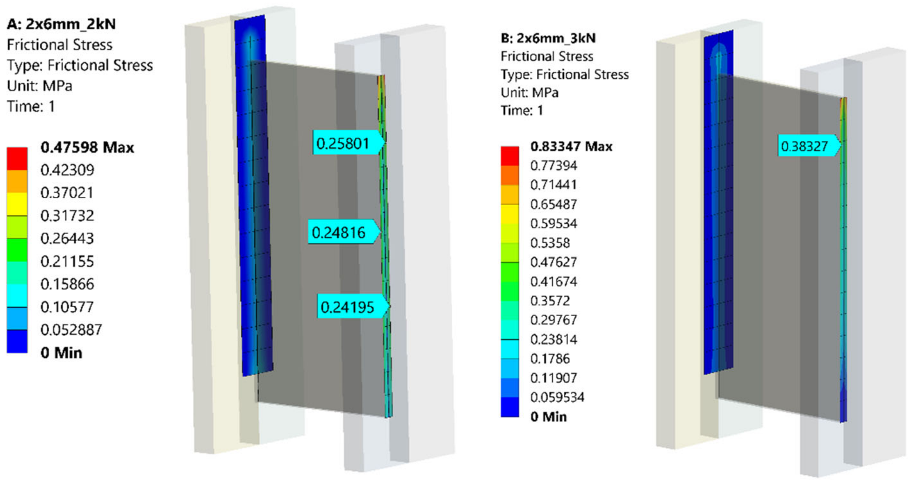


Figure 20. Sample behavior.

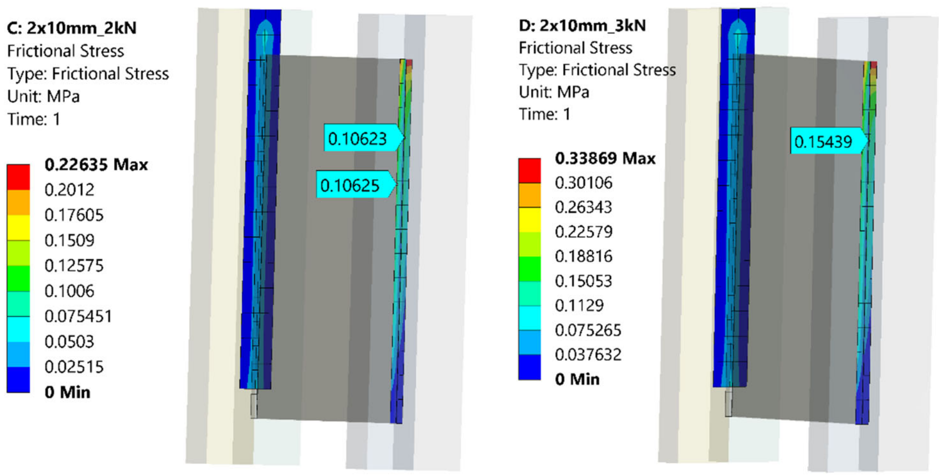
For the 2 mm × 6 mm laminated glass sample with a lateral force of 2 kN, the mean frictional stress calculated from the experiment data was 0.25 MPa, while the mean frictional stress obtained by numerical simulations was also 0.25 MPa (Figure 21a). The results of the numerical analysis in form of frictional stress can be seen in Figure 21a. For the same type of specimen, but with a lateral force of 3 kN, the maximum frictional stress was 0.38 MPa, and the same value was obtained by numerical simulation (Figure 21b).



(**a**) (**b**)

Figure 21. Stresses on contact surfaces of laminated glass 2 mm × 6 mm: (**a**) lateral load 2 kN; (**b**) lateral load 3 kN.

In order to confirm the FEM analysis, other types of specimens were subjected to numerical modeling as follows; for the laminated glass specimen 2 mm × 10 mm and a lateral force of 2 kN, the mean frictional stress calculated from the experiment data was 0.1 MPa, while the mean frictional stress obtained by numerical analysis was also 0.1 MPa. The results of the numerical analysis can be seen in Figure 22. For the same specimen, but with a lateral force of 3 kN, the mean frictional stress obtained by the experiment was 0.155 MPa, and the same value of frictional stress (0.155 MPa) was obtained by numerical simulation in Ansys.



(**a**) (**b**)

Figure 22. Stresses on contact surfaces of laminated glass 2 mm × 10 mm: (**a**) lateral load 2 kN; (**b**) lateral load 3 kN.

For all specimen types (lateral force of 2 kN), a comparative analysis is presented. Frictional stresses calculated in Ansys were compared with those obtained from the experimental tests. The maximum deviation in the results was 3.3% (Table 5). Furthermore, at different values of lateral pressure on specimens, an analogy can be established, which confirms the validity of the FEM analysis.

Table 5. Comparison of normal stresses between experimental tests and ANSYS.

Specimen Type	Frictional Stress—Lateral Load 2 kN (N/mm^2)		Deviation (%)
	Experimental Work	ANSYS	
Laminated glass—2 mm × 6 mm	0.25	0.25	0
Laminated glass—2 mm × 10 mm	0.10	0.10	0
IZO glass—4 mm × 6 mm	0.07	0.072	2.8
IZO glass—4 mm × 10 mm	0.04	0.041	2.5
(2 mm × 6 mm) × 2—Laminated glass and wooden slat	0.07	0.072	2.8
(2 mm × 10 mm) × 2—Laminated glass and wooden slat	0.05	0.051	2
Laminated glass—2 mm × 10 mm- smooth ground edges	0.09	0.093	3.3

7. Discussion

A comparison of the results of all samples is shown in Figures 23 and 24.

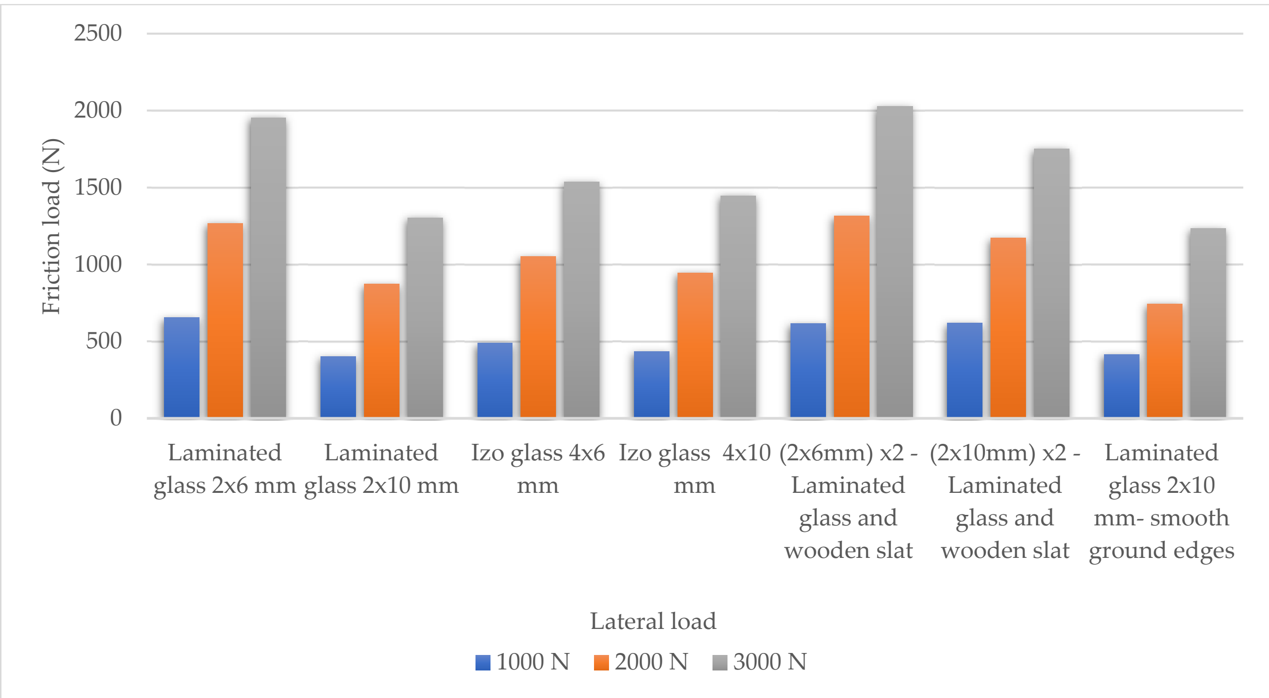


Figure 23. Friction load—comparison.

Based on the presented charts, it was concluded that the friction force increases linearly with increasing lateral force, as expected. Once the legality of the behavior has been determined, a coefficient of friction can be determined for each of the samples. However, to achieve the ultimate goal of the research, it is necessary to highlight and discuss the following findings related to the global behavior of the final product.

Figure 24. Friction coefficient—comparison.

The previous research [36] showed that the influence of glass infills on the lateral load-bearing capacity is significant. Recommendations for further research should be based on the following facts, taking into account the friction between the timber and the glass:

- Due to the vertical support of the timber frame lintel enabled by glass infill, frame joints are loaded in pure shear for which they have the biggest load-bearing capacity [36].
- Vertical load positively influences the lateral strength of the specimens, by 40%, due to the activation of friction between frame lintels and glass sheets.
- The number of glass sheets (single vs. double glazing) does not influence the lateral strength. The reason is that the friction force acting along the horizontal edges of the glass panel is almost the same.
- The intensity of vertical load influences strength degradation. In the case of specimens with low vertical load, the strength degradation was on average twice as high as in the cases of specimens with a high vertical load. The stiffness degradation was not influenced either by the intensity of vertical load or by the number of glazing panels.

It is possible to formulate this phenomenon with a common equation, which is needed for the definition of the future mathematical model of the tested type of structural hybrid panel components.

Energy dissipation is possible through friction and ductility of the timber frame angle joints. Ductility of the joints in timber structures is a prerequisite, especially in the seismic zones.

8. Conclusions

Insight into the existing literature and the current state of the art reveals a gap in the study of composite systems with load-bearing glass, especially on loads of horizontal forces of variable amounts and directions that occur during seismic loading. In the range of larger story drifts, the effect of glass-to-timber friction plays a major role in energy dissipation.

During horizontal loading, friction between glass and timber is a factor that affects the behavior of the timber—load-bearing composite system. Coefficients of friction were determined for CLT on glass surfaces; in particular, the effects of different lateral pressure levels were investigated. Friction depends on the way the elements (especially glass) are processed, as well as on the load introduced into the system. The difference between the coefficient of friction at rough and smooth ground edges is negligible. There are differences in the coefficient of friction when insulating glass or glass with wooden slats is installed instead of laminated glass, but it is not significant. The reason lies in the fact that samples with wooden slats have a higher friction surface, and in addition, do not act as a singular system, as is the case of insulated glass.

The investigation provided the necessary data for the development of design procedures and computational model design guidance for the new design codes.

In the future, glass elements with polished edges could be investigated, thus expanding knowledge about the behavior and interaction of these two materials. During load transfer of such a composite system, the contact surface on the wooden element changes and "disappears" over time. Furthermore, future considerations should include how atmospheric factors affect changes in wood surfaces (swelling and shrinkage) and the eventual deterioration of the wood surface, which would cause changes in the contact zone between the two materials, and consequently friction between them. Analysis and research of changes in the coefficient of friction over time and at cyclic loading would be of great importance.

Obtaining realistic values of friction coefficients for different types of glass elements is extremely important for numerical simulations. The use of extreme and theoretical values of friction coefficients in numerical simulations often does not represent a real situation and can lead to wrong conclusions and misinterpretation of results. This research emphasized that the effects of friction should not be neglected. Consequently, neglecting the effects of friction does not unavoidably produce a more conservative design situation by magnifying the stresses. Experimental tests have been confirmed by numerical simulations, but there is the possibility for a more detailed analysis of the system. The numerical analysis should be extended to the whole composite framework and realistic conditions, and thus evaluate all components and factors involved in load transfer

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