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MODELLING OF DUCTILE JOINTS IN HYBRID SYSTEMS MADE OF TIMBER AND STRUCTURAL GLASS

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ABSTRACT: Structural glass combined with a timber frame is a composite system that has a predisposition for a good behaviour during an earthquake; it is energy-efficient and cost-effective; aesthetically acceptable and has good load-bearing characteristics. The main challenge is to develop, design and construct new structural system to be used as an independent prefabricated load-bearing structural component for construction in seismic areas. The aim of the research was to design composites with no negative influence of connecting means to the glass and so to develop the system which will dissipate energy. The answer is to be found in experimentally and numerically supported research work. The behaviour of the composite is crucial to the understanding of the entire system so numerical simulations were used to evaluate the results of laboratory testing and to obtain more information on stresses and deformations within composites. In this paper numerical modelling of timber frame with glass infill will be presented.

KEYWORDS: structural glass, timber, glued-in rods, FEM, numerical simulations

1 INTRODUCTION

In recent decades there has been a rapid worldwide development of structural elements and components based on load bearing laminated structural glass. On the other hand, an increase in the application of glass is partially limited because there are no available and appropriate regulations that designers and contractors can easily find.

The development of structural glass contributed to the development of composite systems with glass. Structural glass combined with a wooden frame represents the composite system with extremely high aesthetic and ecological value excel with their cost-effectiveness and the possibility of significant load transfer. Also, it has a predisposition for good behaviour during an earthquake. Timber framed glass panels are easy-to-fix structural elements suitable for creation of different layouts of low rising buildings or to be used as infill elements in high rising frame systems. In recent years, preliminary testing of composite system timber-structural glass with monotonous and cyclic loads has been carried out by collaboration of University of Zagreb and University of Ljubljana. Basic laboratory results from previous research [1–8] will be shown in this paper and special attention will be given to the numerical modelling of such composites.

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2 VETROLIGNUM PROJECT

The increase of glass application in the civil engineering is limited due to the lack of appropriate regulations which would enable designers and contractors' broader usage of glass and ensure building of structures of adequate safety. The problem can be solved with a coordinated cooperation of the industry, organizations responsible for standardization, certification bodies and experts from institutes and universities along with the support of EU bodies responsible for the further development of technical regulation. The framework for such cooperation is given by the requirements of existing Construction Products Directive (89/106/EC), "Guidance Paper L" and the report of JRC (Joint Research Centre) [9] on the basis of which the European Commission issued a special recommendation connected with the introduction and use of Eurocode, therefore justifying the initiation for the preparation of Eurocode for glass structures. In the preparation of the common norm for glass, a special chapter is given to hybrid i.e. composite glass structures. According to the European position on future standardization, harmonized technical rules shall be prepared for "common design cases" and shall contain "only commonly accepted results of research and validated through sufficient practical experience".

The main aim of the research in VETROLIGNUM project [10] is to improve the knowledge about load bearing timber-structural glass composite systems and also to design concept, which will be applicable as new bearing element in residential buildings. Because the behaviour of such systems is completely undefined for the seismic active environment, one of the objectives is to detect the principles of behaviour of composite panels for different boundary conditions as well as find out the technical requirements and application possibilities for the construction in earthquake-prone zones.

The project “Prototype of multipurpose composite timber-load bearing glass panel” (VETROLIGNUM project) is three-year project funded by The Croatian Science Foundation. This project will upgrade knowledge related to the required dimensions of the elements and investigate new ways of connection of load bearing elements as well as make the study about optimisation of certain parts of the panel regarding good energy efficiency performance.

3 HYBRID TIMBER-STRUCTURAL GLASS PANEL

Stepinac et al. [5] described in detail state of the art in the field of timber and glass composites. Several research groups are dealing with different aspects of timber - glass composites, and their published research is summarized here:

- Bonding of glass to secondary timber elements [11]
- Bonded composites acting as a shear walls [6,7,12,13]
- Architectural applications of composite panels and in-plane behaviour of the panels [14,15]
- Seismic behaviour and cyclic response of composite panels [1–3,5–7,16–18]
- Numerical modelling of timber-glass composites [4,19–21]
- Reinforcement or stiffening of existing structures with timber-glass composites [1,2,22,23]
- Energy efficiency of timber-glass composites [24,25].

The first step in building the energy dissipative hybrid system is to achieve ductility of the whole system. One way of achieving this is to use steel fasteners of smaller nominal diameter in the joints. In this study somewhat different model than the other researchers in the field of timber–structural glass composite systems have been used. The objective was to create joints in which the negative impact of fasteners on glass is prevented and to develop a system which will dissipate the seismic energy and thus be acceptable in earthquake-prone zones [5]. A system was developed with glass directly leaning on the timber frame, that is, with load transfer conducted through the contact between the two materials and the friction force between them. A timber frame with a glass infill was made whose dimensions correspond to realistic frames which are built in structures i.e. the composite height was 2722 mm and the width was 3222 mm. The glass infill is composed of two identical panes of partially annealed float laminated glass dimensions 2900×2400 mm and "inserted" in a timber frame. The laminated glass panels of 10 mm thickness are mutually bonded with 1.6 mm thick a layer of Ethylene-vinyl acetate (EVA). The glass panels are mutually separated with the wooden separator secured from tipping over and falling with lateral timber purlins. Hybrid panel is shown in the Figure 1.

Figure 1: *Hybrid system made of timber and structural glass* [1–7] *as tested in the laboratory of University of Ljubljana*

4 MODELLING OF CORNER DETAILS IN THE TIMBER FRAMES

The glass was intentionally not joined with steel fasteners due to its brittle behaviour and incompatibility with materials such as steel nor with adhesives which would prevent the occurrence of friction force and also induce tension stress in glass which should be always avoided. Therefore, great attention is paid to the development of timber elements’ joints. Numerous tests have been conducted with different boundary conditions, various details in the angle of the frame, with monotonic and cyclic testing being implemented as well. Experimental tests have proven that timber-structural glass composite systems behave exceptionally well in dynamic and cyclic conditions.

Several variations were made in the shaping of frame corners; with one bolt (sample A), with two bolts (sample B), with one bolt and punch nailed plate (sample C) and with glued-in rods (samples D), Figure 2.

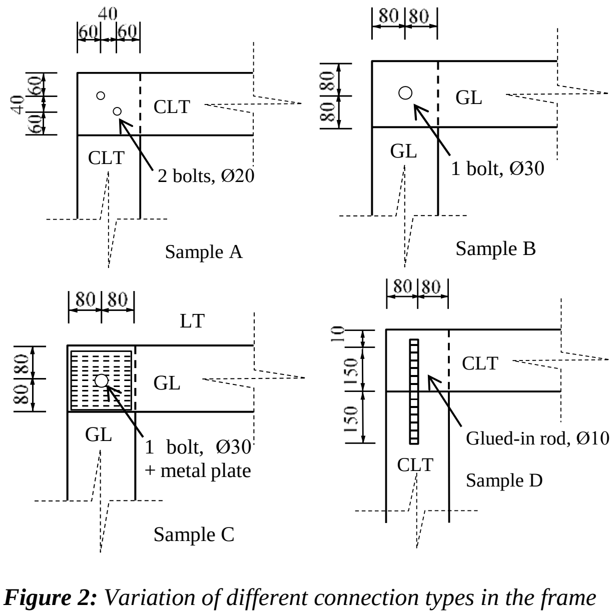

Figure 2: *Variation of different connection types in the frame joint*

Failure of the hybrid systems always occurs in the joints of timber frame, whilst glass pane remains without any damage. As expected, connection detail with two bolts

achieved the highest load bearing capacity. Nevertheless, the necessary ductility was not obtained and splitting of timber elements occurred. The other two panels with one bolt and bolt with punched steel plates shows more ductile behaviour and can achieve higher displacement level without total failure of the connection detail.
Connection with glued-in rods (GiR) have lower load bearing capacity but obtained ductility is much higher than in the cases of other types of frame joints . These kind of connection is characterized as the best one for systems in earthquake prone zones and further research was carried out with GiR in the frame joints. Behaviour and failure mechanism of GiR in different kind of elements and applications are presented by Steiger et al. [26]. Failure mechanism in hybrid systems made of glass and CLT elements starts with yielding of steel rod, followed by compression crushing of wood in CLT element. Experimental results are in detail presented in the published papers of research group by Rajcic & Zarnic [2,3,5–7].

5 NUMERICAL MODELLING

Experimental research of hybrid systems was followed by numerical modelling. The goal of the numerical analysis was to expand the knowledge of the behaviour of the examined systems. Simulations were made in the Ansys 14.5 [27] and Abaqus 6.10 [28] software packages. During the experimental research it was found that numerical models must include complex failure criteria of wood and steel in order to obtain as accurate results as possible. Complex modes of wood failure contain an occurrence of brittle failure in the tensile zone and a more ductile mode of failure in compression. The model itself is composed of four different materials (by characteristics and geometric values) and each part of the sample was carefully modelled and labelled.
In experimental research laminated glass with the total thickness of 21.6 mm was used (2 sheets of glass bonded with 1.6 mm thick EVA layer). In numerical analyses EVA layer was neglected because there were not significant stresses in the glass panes. In the experimental work CLT elements with lamellas of class C24 were used in numerical analyses. All of the timber properties were modelled as for the class C24. Special attention for numerical modelling was given on failure criterions, yielding and hardening of the materials. Steel parts and adhesive were assigned the features obtained by the producer. The steel rod was modelled without threads in order to achieve the best quality of the mesh of finite elements. Mechanical properties of the rod/bolt were given for non-linear steel. Steel plate, over which the load is introduced, was paired with high strength and high stiffness steel to avoid influence on the final results.
After definition of mechanical properties of materials, boundary conditions, contacts between elements, mesh characteristics and loading was defined. Contacts between timber elements and steel rods were defined as „bonded“ finite elements. Contacts between timber and timber elements and timber and glass elements were modelled by friction elements. Horizontal load was applied as monotonous in one direction. The FEM analyses was performed until the maximal force applied during the experimental investigations of hybrid elements.
The stepwise procedure of numerical modelling is presented in Figure 3.

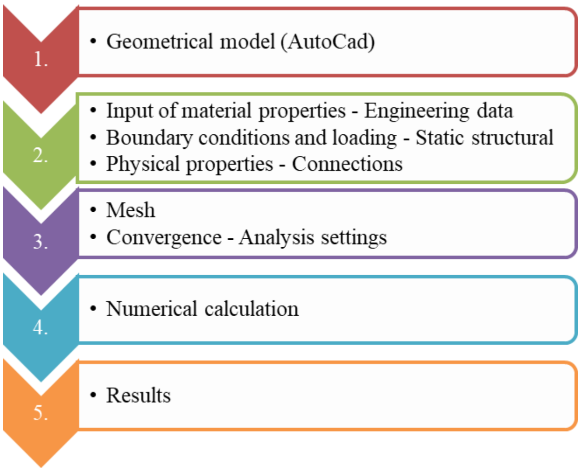

Figure 3: *Procedure of numerical simulation of response of hybrid element to unilateral monotonous loading*

5.1.1 Model with glued-in rods in the frame corner

The initial model served for the assessment of behaviour conditions in linear areas, and as the original model for all other models. To achieve calculation precision both plastic features and material hardening were introduced into the modelling. Steel rod was assigned the steel values which occur in non-linear area, and wooden elements were assigned yield criteria and hardening, together with non-linearity. Timber elements were made of three layers cross-laminated timber (CLT), so the failure always occurs in the middle lamella, the yield criteria were assigned only to the middle lamella in the area of the frame corner. The attention was paid to the assignment of local coordinate systems because the middle board of the CLT is placed perpendicular to outer boards.
Various contact formulations, node detection methods, contact compatibilities, penetration tolerances and stiffness properties were investigated.
Model mesh discretization was made with the basic programme package tool Ansys additionally using certain tools for a higher quality mesh with more finite elements in the contact zones. Volume elements used in the simulation were in the shape of a tetrahedron or a hexahedron. Following the described variation solutions, the model was loaded horizontally and vertically. The sole model was made of four different materials (regarding material characteristics and geometrical values) and every part of the sample was carefully modelled and marked. Figure 4 shows preliminary labels of elements. Description of the elements is given in the Table 1.

Table 1: *Description of the elements in numerical model*

Label	Description
A1-A4	Timber elements without significant stresses

TW1-TW8	Timber elements with significant stresses
Rod 1-4	Glued-in steel threaded rod
Adhesive 1-4	Adhesive which connects steel rod and timber elements
Glass	Glass pane
Steel plate	Steel part for the load input

It was concluded from experimental research that the critical parts of composite panels were the corners of the timber frame, so each individual wooden element was modelled in that manner. Each timber element was divided into two specific parts (Figure 4). The first part (elements A1-A4) is the part of the beam where there are no significant stresses and deformations and there is no damage to the timber.

Hill's yield criterion [29] for orthotropic homogeneous material was selected as the basic timber yield criterion. The second critical part of the system was the middle lamella of CLT elements which surrounds the glued-in rod. It was labelled as TW (TW1-TW8) element. For this part of the frame (timber around fastener) Tsai-Wu yield criterion [30] was used. For timber elements A1-A4 Hill yield model and anisotropic properties of timber for the class C24 were used.

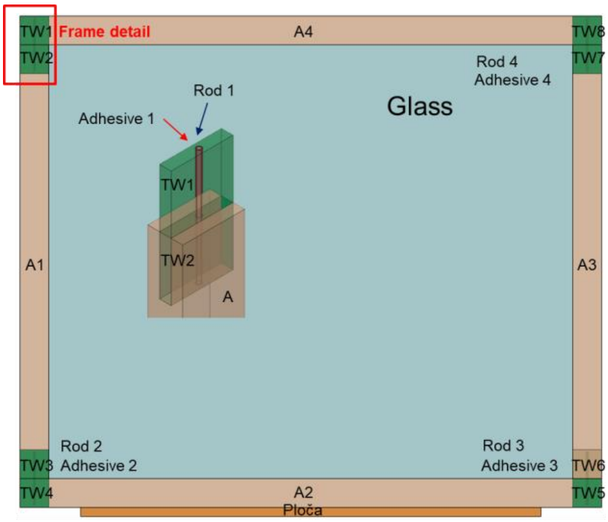

Figure 4: *Labelling of the elements in Ansys software*

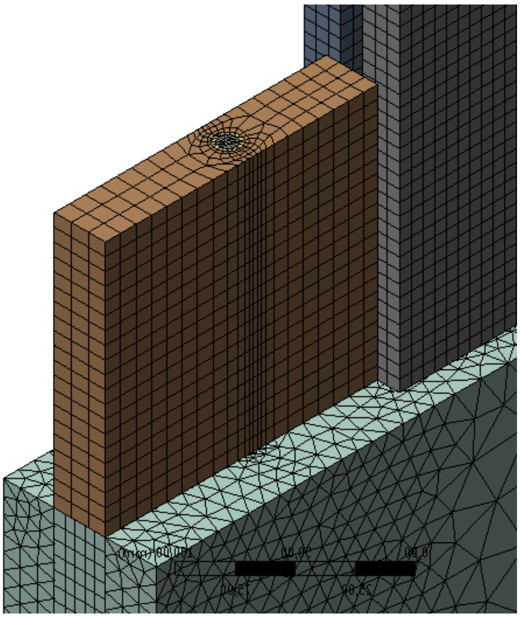

Figure 5: *Mesh of the elements in the frame corner*

Wood elastic parameters were given by: ρ=420 kg/m^3, E_x=11.000N/mm^2, E_y=600N/mm^2, E_z=580N/mm^2, G_{xy}=600N/mm^2, G_{yz}=580N/mm^2, G_{xy}=690N/mm^2, ν_{xy}=0,3, ν_{yz}=0,6, ν_{xz}=0,25. Wood strengths were taken as follows: $f_{t,0}$=14 MPa, $f_{t,90,y}$= $f_{t,90,z}$=0,5 MPa, f_c=21 MPa, f_v=2,5 MPa.

Steel rod mechanical properties were defined as follows (bilinear behaviour): E=205GPa, G=76.9GPa, f_y= 640MPa, f_u= 800MPa, ν=0,3. Tangent modulus of elasticity E_T was defined as 2.0% of MOE.

Threaded rod was encircled by 2 mm of adhesive layer. Adhesive properties were given as: density of 1080kg/m^3, MOE=29,5 MPa, compression strength 91.5MPa, tension strength 32,5 MPa, flexural strength 60.9MPa.

Laminated glass was modelled as stiff elastic material. For the means of simplicity of the FEM models, glass layers were not connected with the interlaying lamella, but a unique glass thickness of 2×10mm (thickness of glass) +1.6 mm (thickness of the EVA interface) was used (21.6 mm). Glass properties were: density of 2500 kg/m^3, MoE of 70 GPa, shear modulus of 28.46 MPa and Poisson coefficient of 0.22.

Timber purlins for stabilization outside the plane were not modelled because they have no influence to the in the plane response of structural element. Steel plate over which the force was introduced was modelled as stiff steel elastic element of high strength and stiffness. Numerical analysis was carried out by a non-linear analysis with the present geometrical and material non-linearity. Newton-Raphson method with automatic control of load step increment was used. Time step was t=1, with sub steps of Δt = 0.01 (Figure 6).

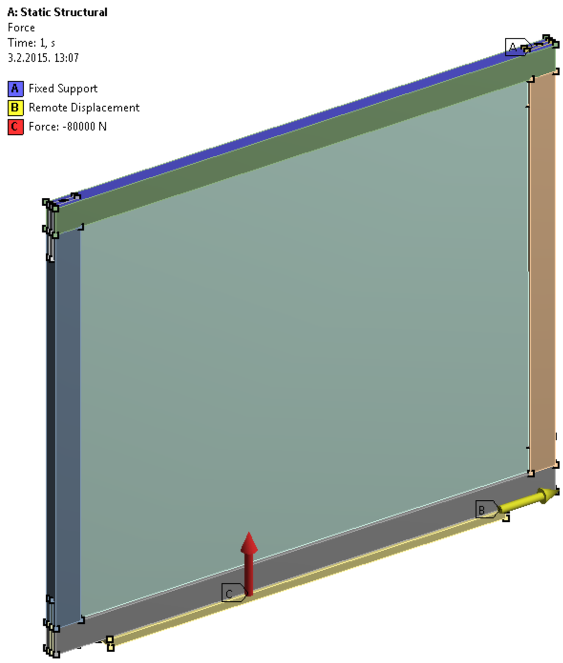

Figure 6: *Boundary conditions and loading*

The biggest problem in defining the FEM model was the proper definition of contact properties. Contact zones were modelled as absolutely rigid for normal stresses and possibility of tangential sliding due to friction. Contact of glass and timber was modelled with a friction coefficient of $\mu=0.15$, and contact between timber horizontal and timber vertical elements with friction coefficient of $\mu=0.3$. Used coefficients were result of the previous experimental research of the authors. Contact elements TARGE170 and CONTA174 which are fulfilling the basic Coulomb's law of friction ($\sigma_t=\mu\ \sigma_n$) were used.

Volume elements SOLID186 were used for the model parts: A1, A3, glass, steel rod, TW, steel plate and SOLID187 elements for the parts A2 & A4. Volume elements are defined by 8 nodes. The mesh of finite elements has been denser in areas of higher stresses and in the contact zones of two different materials.

The main parameter for the control of numeric and laboratory simulations is therefore the relation of the horizontal force and horizontal drift on the top of the composite system. It is exactly this relation which is more significantly analysed and compared. It may be concluded from the Figure 7 that the glass element is over-dimensioned and that the concentrations of the stresses occur, as expected, in the sole corner of the frame, that is, on the place where the glass „pushes“ the wooden element. The tensile diagonal in the glass just only started to form.

As far as wooden horizontals and verticals are concerned, there are critical stresses in the corners of the frame, that is, there is a crushing of the elements, the same as in laboratory testing (Figure 8).

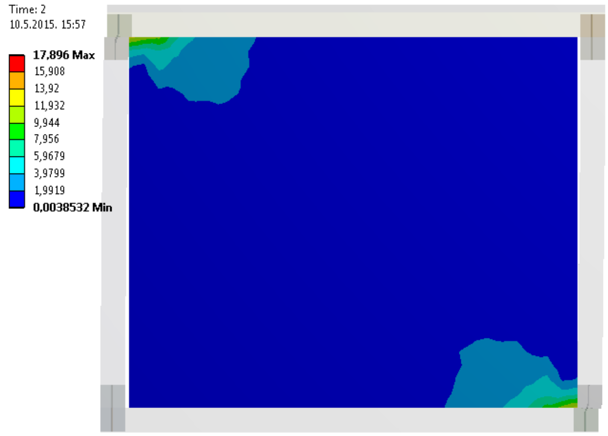

Figure 7: *von Mises stresses in the glass element*

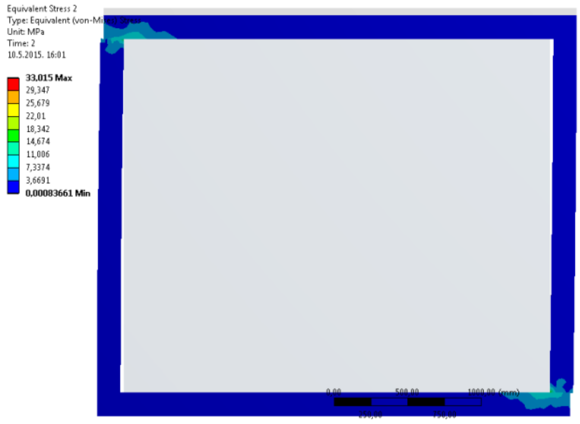

Figure 8: *von Mises stresses in the timber elements*

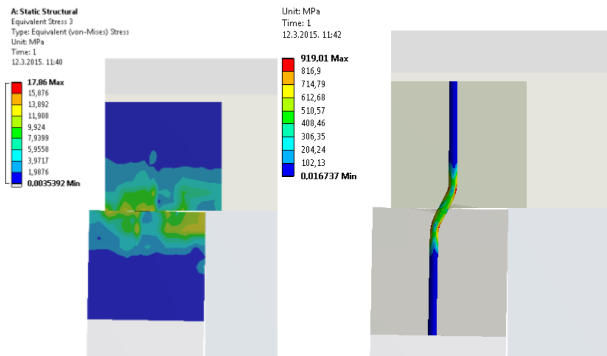

Figure 9: *von Mises stresses in the frame corner: a) TW element, b) steel rod*

In the next stage of VETROLIGNUM Project the parametric FEM analyses will be performed.

5.1.2 Model with one bolt in the frame corner

Numerical model developed by Antolinc [31] was upgraded in the ABAQUS/CAE ver. 6.10 software. The main difference is manifested in defining the basic material properties and yield criteria. Complex wood failure modes obtained in experimental research were modelled with UMAT subroutine with the orthotropic elastic–plastic wood behaviour and yield criteria. UMAT subroutine was developed and presented by Pavković et al. [32]. Hill’s yield criterion [22] for orthotropic

homogeneous material was selected as the basic timber yield criterion in UMAT subroutine for the elements where stresses were not identified as critical. For timber around glued in rods, Tsai-Wu yield criterion [30] was applied.
Numerical models were created with first-order volume finite elements C3D8. These finite elements are defined with eight nodes and they are using full integration method. For supports modelling, master–slave function was used with constrained displacement (Figure 10).

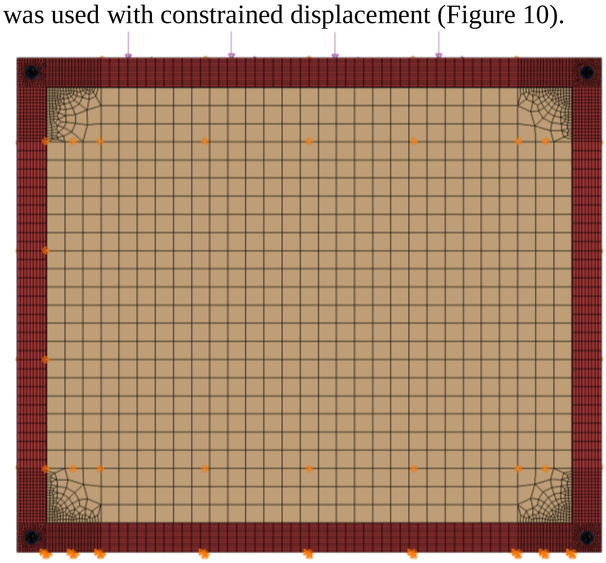

Figure 10: *Mesh and boundary conditions of the model with one bolt in the frame corner*

Analyses were conducted with Full Newton solution technique, and automatic control of load step increment. Contacts were modelled similar as models made in Ansys software: absolute rigidity in normal direction and in tangential direction friction coefficients 0.3 for timber-timber and 0.5 for timber-glass contacts. The material characteristic of other parts of the model were the same as the material properties mentioned in the previous chapter.

Obtained results shows small variations between tests and FEM results for slip modulus, yield and maximum force and relatively good overlapping in load-slip curve (Figure 12, 13 & 14).

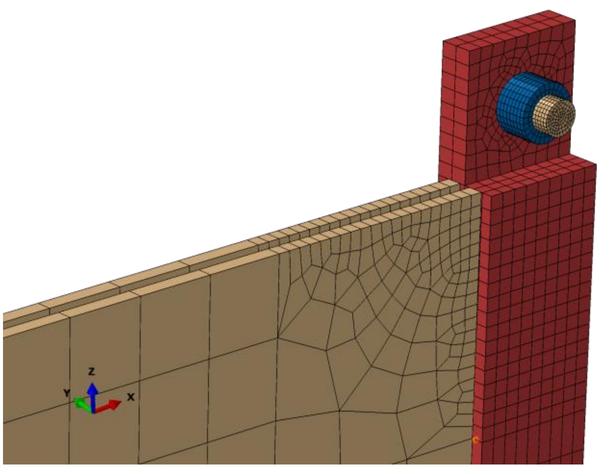

Figure 11: *Mesh of the model with preview of the element with Tsai-Wu yield criterion (blue colour)*

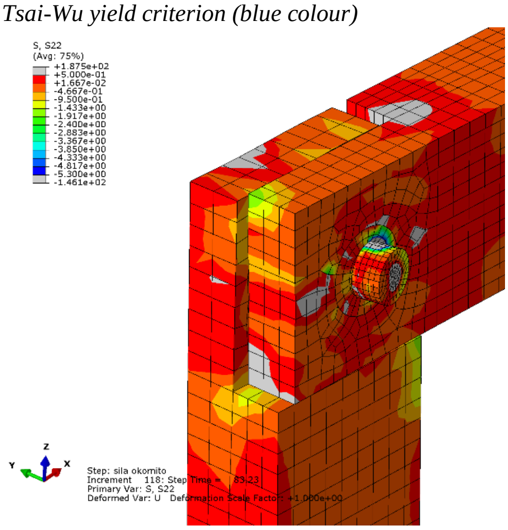

Figure 12: *Normal $\sigma_{y\text{-}y}$ stresses in the frame joint*

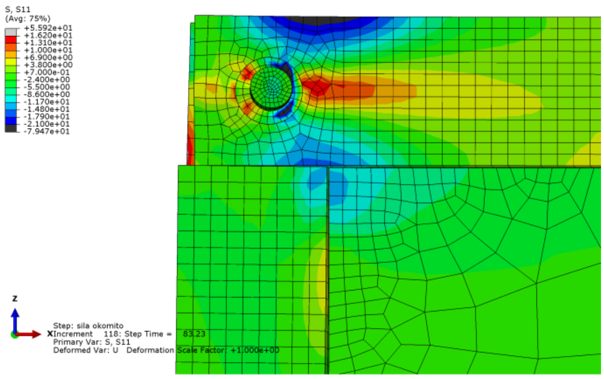

Figure 13: *Normal $\sigma_{x\text{-}x}$ stresses in the frame joint*

In the Figure 14 results of experimental data (FR9_boundary condition 1, connection with one bolt, [31]), FEM models from [31] and FEM model from this research were compared.

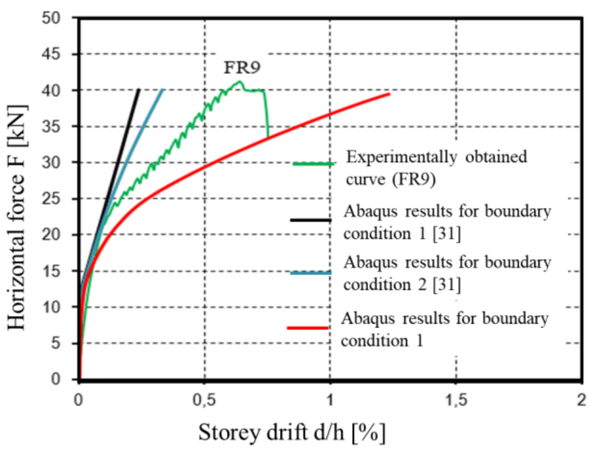

Figure 14: *Comparison of the numerical and experimental results*

Difference between tests and FEM results for joint ductility is out of satisfactory limits and the reason for that is exceeding of embedment strength in tests which is not defined precisely enough by FEM and UMAT subroutine.

6 CONCLUSIONS

Having reviewed the existing literature and the current state in the art of the glass facades and composite systems with structural glass, a great gap in the study of composite systems with glass is noticed. Several extensive tests of composite systems timber-structural glass have been conducted with various types of bonding of timber and glass. Bonding glass with timber has proved as a good example for accomplishing high load-bearing capacity of composites, but deficiencies are noticed in the level of ductility along with possible problems with the durability of the structure and behavior under the seismic load.

The authors have concluded that timber-structural glass load-bearing systems can be used in various construction applications, depending on the required bearing or ductility levels but it is necessary to devote attention to mutual binding of elements of timber frame where the energy is dissipated.

The aim was to design composites with no negative influence of connecting means to the glass and so develop the system which will dissipate energy. The system was developed in which the glass directly relies on the timber frame, that is, the transfer of the load occurs over the contact of two materials and the force of friction between the two. The glass was on purpose not connected with mechanical binds to timber elements due to its stiff behaviour and the incompatibility with materials such as steel, nor with the glues which would prevent the development of friction and. In this way, tension stresses in the glass element were avoided what we always want to achieve.

Numerical simulations were applied to obtain more information on stresses and deformations within composites. The behaviour of the composite is crucial to the understanding of the entire system so numerical simulations were used to evaluate the results of laboratory testing. Numerous simulations were made in the programme package Ansys and a model was developed which greatly contributed to the understanding of stress distribution within steel, wood and glass parts of the composite system. Also, in software package Abaqus, FEM models from the dissertation of Antolinc [31] were upgraded.

The combination of timber and structural glass obtained the system in which each material transfers a part of the load, and the mutual interaction of constitutive elements shows good behaviour in the seismic applications. Glued-in steel thread rods have proved as the excellent way to connect timber frames regarding capacity and ductility. It is by using glued-in steel thread rods of a low nominal diameter the systems were obtained which have a great capacity of dissipating seismic energy. Numerical simulations confirmed the behaviour of composite systems. Simulations were made in two commercially available programme packages (Ansys and Abaqus) and complex modes were used for yield of the timber such as Hill's and Tsai-Wu's yield criteria. Numerous boundary conditions and sample variations were varied and the guidelines for contact modelling and the manners of modelling critical parts of the system (detail of the frame corner) were given. It would be beneficial to use and enhance the models with cohesive areas in order to obtain more precise solutions. One of the solution is to use Abaqus UMAT sub-routines in parametric studies. Also, even though a part of hysteresis was obtained in a numerical manner, the same should be improved by varying contact zones, stiffness ratios and by using various finite elements. In this work the push-over analyses were carried out. One of the recommendations for the future work is numerical modelling and the behaviour simulation of all tested samples in a real earthquake, that is, the simulation of dynamic calculation by using time-history analyses.

The VETROLIGNUM project is trying to solve a gap in the field of hybrid systems timber and glass through experimental work and excessive numerical modelling.

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