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NEW APPROACH IN DESIGNING ENERGY-EFFICIENT TIMBER-GLASS BUILDINGS

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Abstract: *This paper offers a new approach in designing energy efficient prefabricated timber buildings using a strong interlink between an architectural and structural approach. Using building materials with quite different material properties in a way to optimally consider all of their possible advantages applied in a hybrid structural composition could be a relatively new approach in designing high-quality energy-efficient buildings. Therefore, timber and glass could be an attractive design solution in developing architectural highly attractive residential buildings. The first step in the design process of such buildings should be considered through an effective architectural approach respecting rational passive design strategies towards exploitation of maximal possible solar radiation through the glazing by the development of an optimal position and size of glass elements on the building envelope. Consequently, such an attractive building form with the non-symmetric position of timber-glass wall elements usually results in many structural problems, which can be somehow avoided if glass panes are considered as load-bearing structural elements. As a final result of the presented study load-bearing timber-glass wall, structural elements with three-layered insulating glazing were developed in a sense to increase the total racking resistance of such constructed timber-glass buildings.*

Keywords: *Timber, Glass, Energy Efficiency, Structural Resistance*

Introduction

Climate changes of the last few decades do not only encourage researches into the origins of their onset, but they also mean a warning and an urgent call for a need to remove their causes and alleviate the consequences affecting the environment. Eco-friendly solutions in residential and public building construction remains our most vital task, whose holistic problem solving requires knowledge integration. Therefore, the domain of energy consumption is witnessing a worldwide trend whose aim is to reduce primary energy consumption and greenhouse gas emissions. The domain of energy consumption is witnessing a worldwide trend whose aim is to reduce primary energy consumption and greenhouse gas emissions.

Constructions are, besides the fields of transport and industry, one of the main users of the primary energy from fossil sources. However, it is important to set out that residential buildings forming 70% of the total buildings' surface consume and are responsible for 63% of the total energy demand required to satisfy the demands of the hosing stock, Itard and Meijer (2008). The reason for a so high energy consumption usually lies in the age of the buildings and their very high thermal transmissions through the building envelope; walls, roofs and windows. Additionally, in these old buildings because of a very high thermal transmission through old non-insulating windows the transmission losses are very high and therefore such buildings were constructed usually with relatively small window areas and without any fixed glazing, which were also commonly uniformly placed on all four cardinal directions of the buildings.

The use of glazing in buildings has always contributed to openness, visual comfort and better daylight situation. Although characterized by weak thermal properties in the past, glass has been gaining an ever-greater significance as a building material due to its improved thermal, optical and strength properties, resulting from years of development. Development of new type of insulating glazing simultaneously with the load-bearing capacity opens many new opportunities in designing of new buildings to satisfy strong conditions in a view of energy efficiency and living comfort as well. The features of new developed insulating glass elements and in the same time to have in mind that wood is an organic material with very low grey energy footprint, the strong progress leads to development of a new type of buildings, the so called timber-glass structures. In such buildings an optimal proportion and an appropriate orientation of the glazing surfaces play an important part due to exploitation of solar radiation as a source of renewable energy in a passive use of energy for heating. In cold climate conditions the largest part of glazing is usually placed to the south, Žegarac Leskovar and Premrov (2011), Figure 1.

Figure 1: Timber-Glass Buildings with Primary Glazing Orientation to The South

However, due to very different material characteristics (density, thermal conductivity, strength, thermal expansion, moisture sensitivity, etc.) use of timber and glass as building materials in composite load-bearing elements is extremely complicated, from the point of energy-efficiency and the constructional point of view as well and sets multiple traps for designers. It is very frequently that the best results from the architectural design affect in a negative sense on the structural applicability. For instance, like an effect of torsion on wall elements in a storey if the glass areas are not uniformly placed on the building facades and the wall stiffness is not similar on the building vertical envelope elements. In that case the mass centre (M) can be placed away from the centre of wall rigidity (R) and effects on high torsion influence on resisting wall elements especially by seismic actions, as schematically presented in Figure 2.

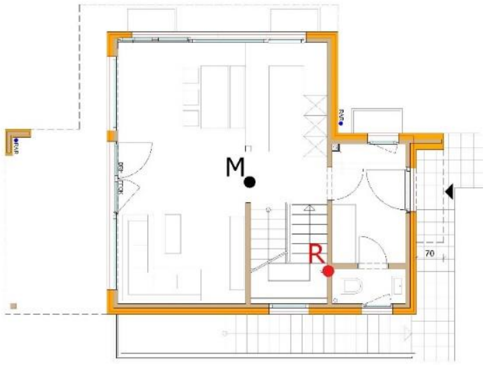


Figure 2: Ground Floor Plan with Indicated Mass Centre (M) And Centre of Rigidity (R) Placed Away From Each Other

In this case structural stability against horizontal load impact, like wind load and especially earthquake, rapidly decreases and can become a serious problem for structural designers. Consequently, a novelty value of modern glass is seen in its being treated as a load-bearing material replacing the "classical" bracing elements (diagonal elements, sheathing boards) which normally provide horizontal stability of timber structures. A good knowledge of advantages and drawbacks of timber-glass structures is thus vitally important, Žegarac Leskovar and Premrov (2013), Premrov et al. (2014), Winter et al. (2010), Niklisch et al. (2015).

The aim of the paper is therefore presenting how timber and glass can be used together in contemporary timber buildings to get a high as possible energy efficient building product with a maximal available living comfort. The question is how to incorporate these building materials with quite different material properties in an optimal structural hybrid system with the highest architectural, energy-efficient and structural standard in the same time, and especially how to find interlink between architectural and structural aspects. As a final result load-bearing timber-glass wall structural elements with three-layered glazing were therefore developed in a sense to avoid any additional steel diagonal elements or additional load-bearing internal walls to satisfy the prescribed conditions for seismic or wind structural stability.

Structural Systems of Timber Buildings

Selecting a timber construction system depends primarily on architectural demands, with the orientation, location and the purpose of a building being of no lesser importance. Most used timber structural systems differ from each other in the appearance of the structure and in the approach to planning and designing a particular system. As presented in Kolb (2008), timber systems can be classified into six major structural categories, Figure 3. Log construction and solid timber construction are classified as massive structural systems since all load bearing elements consist of solid timber elements. Other construction systems consist of timber-frame bearing elements and are therefore can be treated as lightweight structural systems. According to the load-bearing function of the resisting wall elements they can be subdivided into classical linear skeletal systems where all vertical and horizontal loads are transmitted via linear bearing elements and planar frame systems with sheathing boards as bracing elements.

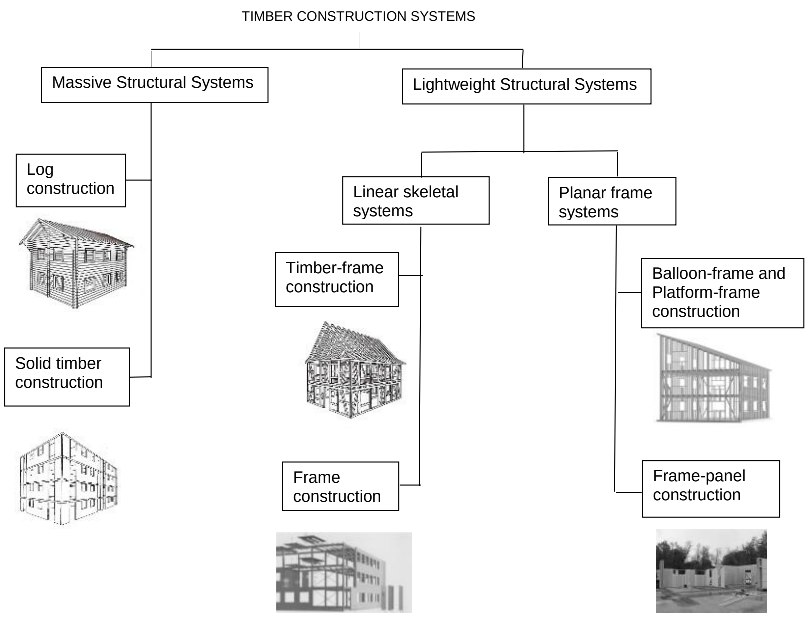


Figure 3: Classification of Timber Structural Systems According to Their Load-Bearing Function, Source: (Žegarac Leskovar and Premrov, 2013)

The main focus of the paper will be laid on the frame-panel construction system which will be in details analysed in combination with the glazing is the subject matter of the analyses presented in the following chapters. As the panel construction system (Figure 4a) consists of timber-frame elements (studs and girders) and sheathing panel boards the term "timber frame-panel construction" will be used a substitute in further parts of the paper. Composition of a classical timber frame-panel wall element with a classical sheathing board (OSB or fibre-plaster boards) is schematically presented in Figure 4a. However, the main idea in prefabricated timber-glass wall elements is to replace the classical sheathing boards with thermal insulating glass panes, as seen in Figure 4b. It is now possible to combine the "classical" wall elements with the timber-glass wall elements to get an optimal box-house model (Figure 4c). Therefore, the theoretical box timber-glass house model, schematically presented in Figure 4c, consists of timber-glass wall elements as well as of timber-framed wall elements with classical sheathing boards which proves essentially higher racking resistance and stiffness under the monotonic point load than the timber-glass wall elements, Premrov et al. (2014).

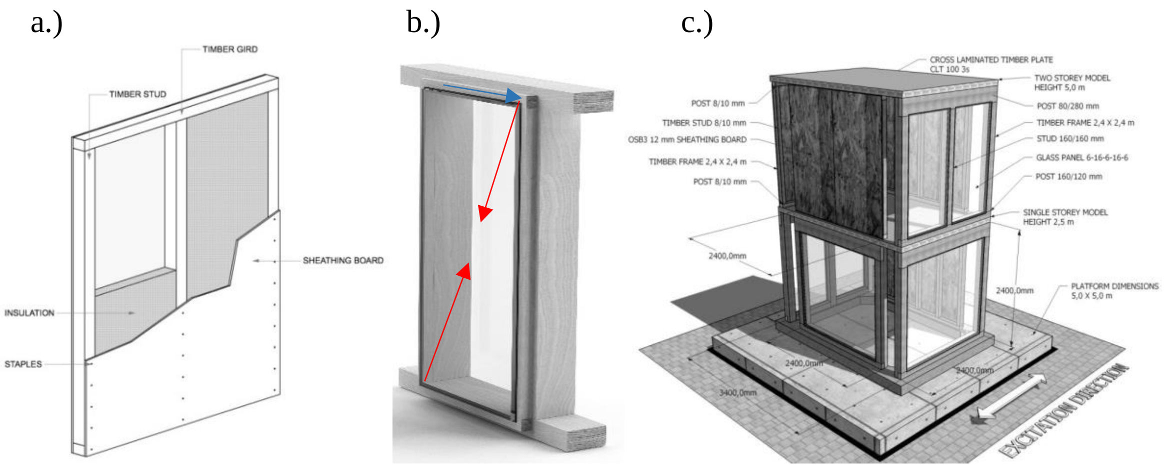


Figure 4: A.) Timber Frame-Panel Wall Construction, B.) Timber-Glass Wall Construction, C.) 3-Dimensional Timber-Glass House Box Model

Architectural Aspect

An optimal proportion and appropriate orientation of the glazing surfaces in timber-glass building models play an important part due to exploitation of solar radiation as a source of renewable energy within the passive use of energy for heating. Therefore, transparent areas of fixed glazing or windows have to be of appropriate size and orientation to transmit an adequate amount of solar energy into a building in order to assure natural lighting and heating. An appropriate placement of large glass areas enables better energy performance of a building, where the daily obtained solar gains through the glazing can be evidently higher than the transmission losses throughout the night. A basic design principle in such way integrates the building components into a system taking maximum advantage of the building's environment, like climate conditions and available renewable energy sources. Identifying the building parameters which significantly impact the energy performance is therefore a complex and an important step towards enabling the reduction of the heating and cooling energy loads in the design stage, with a special focus on implementing passive design techniques like exploitation of solar gains. Most of the parameters influencing on the building energy demand are also interconnected to each other and have to be analysed simultaneously in the scope. For instance, the influence of the building shape (the aspect ratio and the number of floors/heights of the building) is strongly connected with the climate conditions.

In professional practice, the most used index to describe the shape of the building is the *shape coefficient* (F_S) defined as the ratio between the envelope surface of the building (A) and the inner volume of the heated volume of the building (V) given in the form:

$$F_s = \frac{\mathrm{A}}{\mathrm{V}} \tag{1}$$

To minimize transmission losses through the building envelope a compact shape indicated by a low shape factor is desirable. On the other hand, a dynamic form with larger transparent surfaces enables provision of higher solar gains. Integrating the aspect of solar access into the phase of determining the building shape is an essential part of energy-efficient building design. According to general design guidelines for energy-efficient houses a compact rectangular shape is seen as the optimum, Persson (2006). However, some studies show that under certain location and climatic conditions a dynamic shape might be even more efficient as far as energy gains are concerned, especially for buildings located in strong winter conditions, but at the same time with a high solar potential. In Europe it is mostly a case for areas located in the southern side of the Alps, for example, Premrov et al. (2017).

A parameter which can produce a significant impact on the amount of solar gains and consequently on the total energy demand for heating and cooling is the glazing-to-wall area ratio (*AGAW*), described as the ratio between the total area of glazing (A_{gl}) to the total area of the wall (A_{wall}), $AGAW = A_{gl}/A_{wall}$. One of our general critical remarks referring to the first studies focusing on the impact of windows on the heating and cooling demand was that most of them are just calculations for a single building based on a large number of parameters affecting the energy demand. In Žegarac Leskovar and Premrov (2011) an attempt at a more systematic approach was made, with the model of a building being performed in many variations of timber construction systems. An extensive parametric analysis served as a basis for the generalisation of the problem concerning the optimal glazing area size ($AGAW_{opt}$)

dependence on one single variable, the U_{wall}-value which becomes the only variable parameter for all contemporary prefabricated timber construction systems, independently of their type. From the existing research findings, we summarize that the process of defining the optimal model of a building is very complex. The most important parameters influencing the energy performance of buildings are location of the building along with climate data for a specific location, orientation of the building, properties of the materials installed, building design, selection of active technical systems, etc. It is therefore important to investigate the influence of the above listed parameters with utmost care. Due to the absence of a direct correlation between the different parameters, it is more convenient to conduct separate examinations of their influence on the energy demand for buildings. The latter is of particular relevance to the influence of the building's orientation and its glazing size on the one hand and to the influence of the building shape, which results are briefly presented in the following simple numerical interconnected approach.

Such interconnected study approach of the building form impact on energy demand according to the very different climate conditions is presented in parametric numerical study performed on box-house models with varying geometry according to the horizontal and vertical extension, Premrov et al. (2017). Three groups of rectangular models are parametrically analysed using a systematic variation of the building aspect ratio ($AR = L/W$), ranging from 0.83 to 1.69, with a doubled horizontal (Model group B) and vertical extensions (Model group C), schematically presented in Figure 5:

- Model group A: single-storey models with a constant occupied floor area $A_{TFA} = 81\ m^2$ and a heated volume of $V = 243\ m^3$.
- Model group B: single-storey models with a doubled constant occupied floor area $A_{TFA} = 162\ m^2$ and a heated volume totally of $V = 486\ m^3$.
- Model group C: two-storey models with a doubled basic occupied floor area of each storey $A_{TFA} = 81\ m^2$ and a heated volume per storey of $V = 243\ m^3$ and totally of $V = 486\ m^3$.

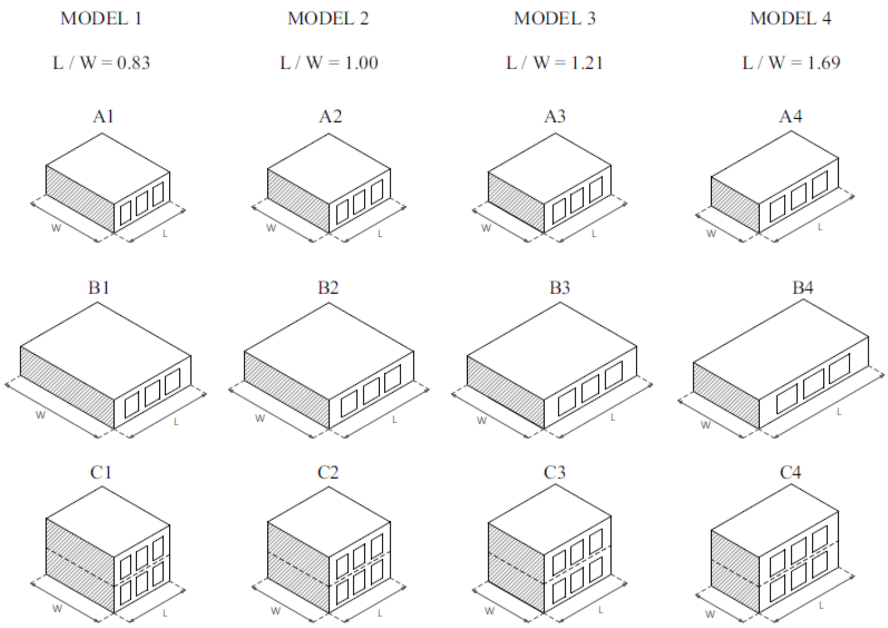
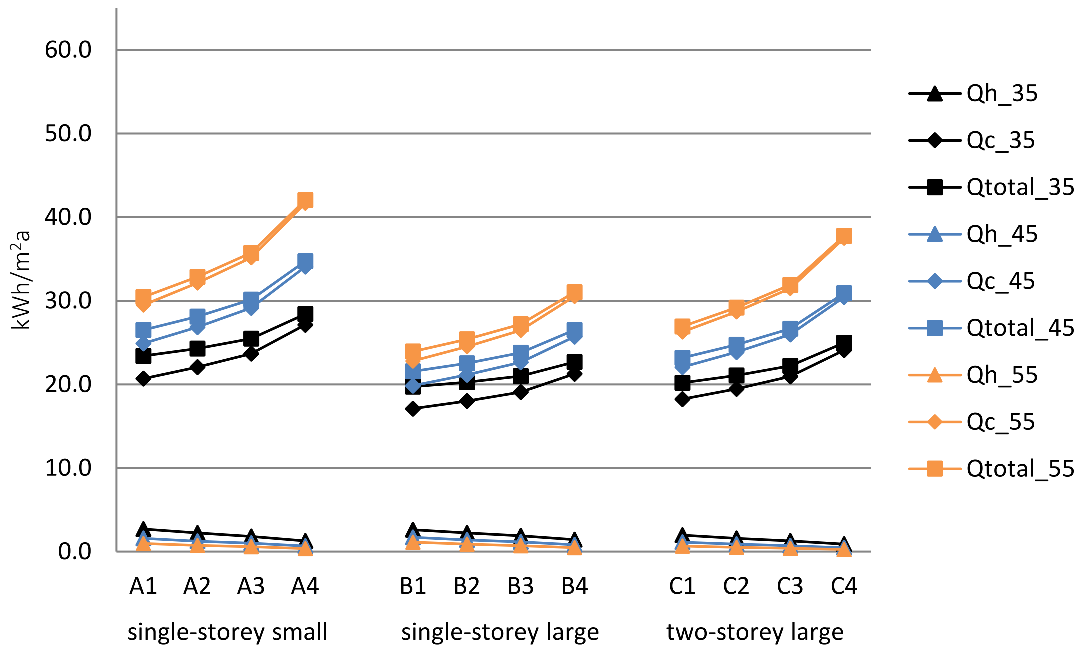


Figure 5: Schematic Presentation of The Analysed Box-House Models, Source: (Premrov et al., 2018)

In this study the same building models from Figure 5 with the constant thermal transmittance and the same type, size and position of glazing, were parametrically exposed to six very different climate conditions; Ljubljana, Helsinki, Munich, London, Athens and Madrid. It was generally concluded from the presented study Premrov et al. (2017) that the building shape can have an important influence on energy behaviour of buildings. It was additionally demonstrated that this influence strongly depends on the selected climate conditions. For Helsinki, the city with the most northern selected location among the analysed cities, where the total annual energy need mostly consists only of that for heating, the increasing aspect ratio showed a positive influence on the total annual energy demand. On the other hand, in regions with a higher average annual temperature and solar potential and the subsequently lower transmittance losses, the influence of the increasing shape factor on the energy demand is less strong. Moreover, the energy need in cold climate conditions is generally higher for the single-storey house than for the two-storey one with the same occupied floor area. The recommendation for cold climate regions therefore is to design buildings with at least two storeys and a higher aspect ratio.

However, the situation of timber-glass buildings located in warm climatic regions is completely different, since the energy demand for cooling represents a major contribution to the annual energy demand. It is well known from many previous studies that the energy demand for cooling is in this case usually the main contributor to the total annual energy demand owing to a higher solar heat transfer through the glazing, whereby the energy need increases with the increasing aspect ratio. For example, Bouden (2007) investigated the appropriateness of glass curtain walls for the Tunisian local climate. The influence of windows on the energy balance of apartment buildings in Amman, Jordan, was analysed in the study performed by Hassouneh et al. (2010). It was generally concluded from all such studies that the optimal solutions in such cases should avoid overheating, which has, however, not been extensively analysed in scientific literature discussing timber buildings. Therefore, the same building models from Figure 5 we additionally exposed to very warm climate conditions, Sevilla for example in this study. First, it was parametrically studied the influence of the *AGAW* value with the glazing separately placed on the south façade (Figure 6a) and north façade (Figure 6b). The examples with the specially selected *AGAW* values of 35%, 45% and 55% were analysed. The obtained numerical results with the U-value of 0.10 W/m^2K for the envelope elements are presented in Figures 6a and 6b.

a.) Sevilla (U_{wall} = 0.10 W/m²K, south glass orientation)



b.) Sevilla(U_{wall} = 0.10 W/m²K, north glass orientation)

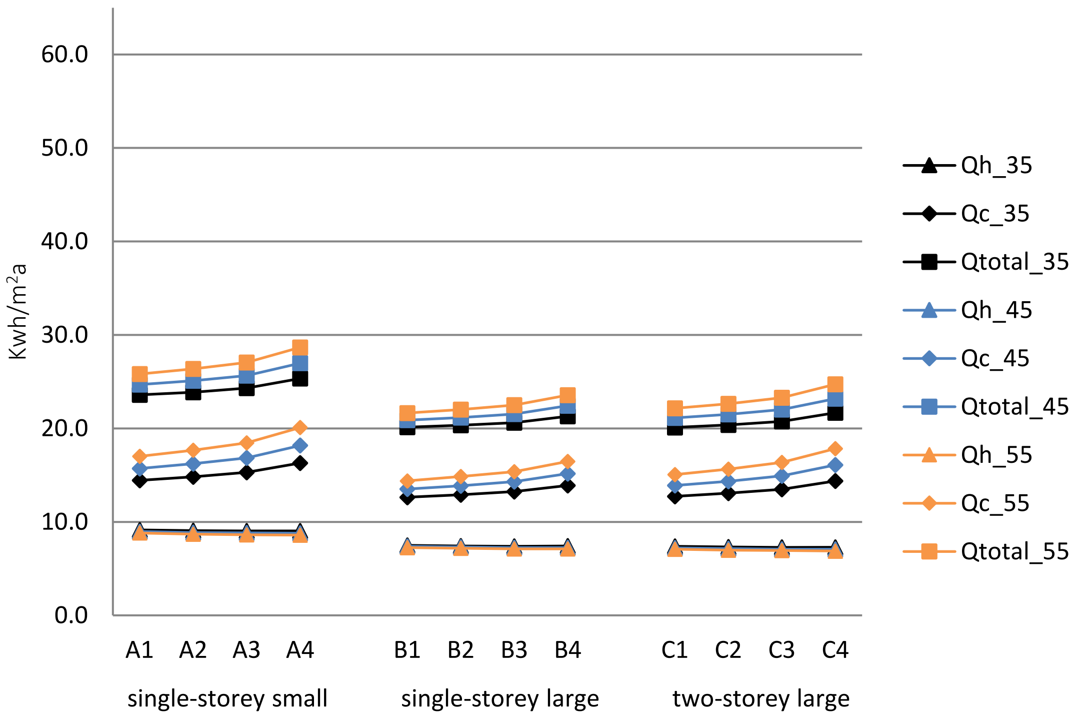


Figure 6: Calculated Results For The Heating (Q_h), Cooling (Q_c) and Total Annual Energy Need (Q_{total}) for Sevilla by South-oriented Glazing and Same Thermal Transmittance

Observing the obtained results lead to a conclusion that in both analysed glazing positions the energy demand increases with the aspect ratio. However, this influence id essentially lower for the northward orientation of glazing. Additionally, the total energy demand, which mostly consists of that for cooling, is lower at the northward orientation. Moreover, increasing the glazing size in both façades caused an almost linear increase in the cooling load, which accords with the findings in Hassouneh et al. (2010) for the Jordanian climate conditions. The comparison of the presented results with the basic findings from Premrov et al. (2017) showed that the building form (aspect ratio, horizontal and vertical extension for example in this study) has in warm climate conditions an evidently smaller impact on the total energy demand than in the cold climate conditions. Consequently, the designers are less limited in choosing a proper building shape of timber buildings in warm European climate conditions, as compared to cold ones, which is particularly relevant to north-oriented glazing.

Structural Aspect

The presented benefits from the architectural and energy aspect can lead at the same time to specific technical challenges in the field of structural behaviour of the building with enlarged size of glazing if the glazing elements do not produce any racking resistance. Furthermore, un-symmetric position of glazing in the building envelope can be, despite their energy efficiency, very problematic and leads to a certain amount of plan irregularity. The problem particularly escalates when building is horizontally loaded (mostly wind or earthquake). More problematic of these two main horizontal actions is definitely earthquake, which implies a rapid high intensity inertial load to the building with the possibility of catastrophic consequences if the building is not properly designed.

Due to the previously presented architectural and energy facts irregularity is an issue concerning high energy efficient buildings in cold climate conditions that have large glazing areas predominantly placed on southern facades and evidently smaller glass areas especially on the north side. Hence, such position results in an uneven wall stiffness over their floor plan and an important previously described dislocation between the centre of gravity and centre of rigidity. In the case that the timber-glass wall elements are not treated as load-bearing bracing elements the rest of the walls (external and internal) without any openings should be able to transmit horizontal load actions to the basement. Another possibility is to insert visible diagonal steel or timber elements as main bracing elements; however, this is not an advisable solution in residential buildings. To avoid this fact, it is important to consider most of the external walls as racking elements which means that also the walls with fixed glazing areas, but not windows, should be treated as resisting elements be able to transmit a considerable part of horizontal forces to the basement. However, this problem has not be widely analysed around the world yet, because glass cannot dissipate energy due to the inability to achieve plastic deformation, Wurm (2007). Another problem is to get a stiff connection between the timber frame and the glass panes, Niedermaier (2003), Kozlowski et al. (2015), Amadio and Bedon (2016), Bedon and Amadio (2018). The research project WoodWisdom, Premrov et al. (2014), aims at development of new applications of timber-glass elements which could assure a certain level of structural resistance and consequent decrease of the effect of torsion on external wall elements. Also in this case the racking resistance of the whole analysed building can be essentially increased which results in improvement of its seismic stability. Thus, it can finally result in decreasing number of resisting additional internal walls or external diagonals to be used to assure at least a necessary horizontal stability of the whole building according to the prescribed standards.

However, combining timber and glass to get an appropriate load-bearing element is a very complex process. We have to consider that we combine two materials with quite different matherial characteristics. For example, taking into account that the external timber-glass wall elements will be mostly placed in the south facade of the building, they will be exposed to the extreme temperature difference. Consequently, an increased shear stress can appear in the bonding line between the both materials. Moreover, in the process of designing timber-glass wall elements as racking resisting elements against dynamic loads is important to assure a high range of ductility as well, not only a static load-bearing capacity of the building. It opens many questions how to balance between strength and ductility of such composite elements. Therefore, a ductile connection system between timber and glass should be somehow developed, but on the other hand to keep a high degree of static resistance as well to take over mostly the static loads (wind actions for example). The parameters which predominantly influence on horizontal resistance of timber-glass wall elements are predominantly material characteristics and thickness of glass panes, position of the glass panes and consequent type of the bonding line, type of the adhesive in the bonding line (flexible, semi-rigid, rigid) and thickness and width of the bonding line. All of them have already been studied experimentally and numerically as well by several authors, for example Niedermaier (2003), Luible (2004), Holzforshung Austria (2008), Cruz et al. (2010), Blyberg (2011), Ber et al. (2014) and many others. According to the presented facts we can conclude that selection of the boundary conditions between the timber and glass can be classified as the most important role in designing of such composite structural elements. In the following two subchapters will be presented two experimental studies performed first on prefabricated timber-glass wall elements which will be further implemented as main resisting elements on simple prefabricated box-house timber-glass building models subjected to the seismic load excitation on the shaking table, and already from the energy aspect analysed in the previous chapter.

Monotonic and Cyclic Racking Resistance of Timber-Glass Wall Elements

The main aim of the study is to define a type of bonding and glazing which will be able adequately to transmit the horizontal load and consequently to assure the racking stability of the building in a way to replace the usage of visible diagonal elements. The horizontal point load (F_H) acting at the top of the element is transferred over the shear connecting area and the fictive board tensile diagonal to the supports in the manner as schematically presented in the scheme in Figure 7:

- the adhesive takes over the shear stresses in the bonding line - shear connecting area in the scheme,
- the tensile diagonal of the glass pane with an effective width of b_{eff} shifts the force to the support - board tensile diagonal in the scheme.

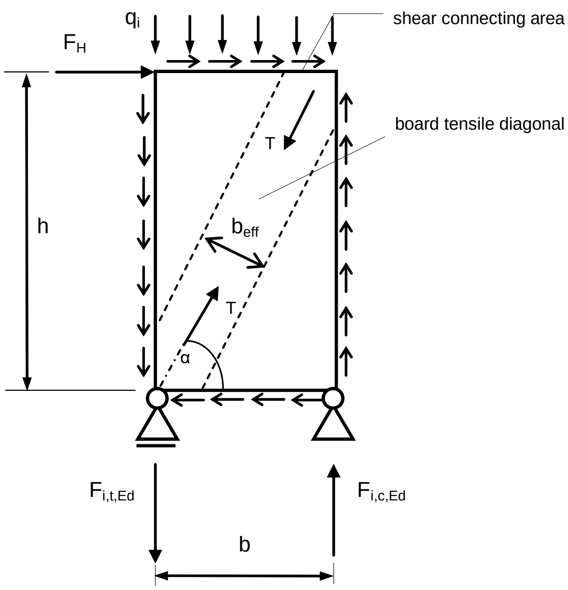


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Figure 7: Schematic Presentation of The Stress Transfer in Timber-Frame Wall Element Under A Horizontal Load (F_H)

Experimental approach of defining load-bearing capacity of timber-glass wall elements will be first demonstrated on a real-scale prefabricated wall element with the total height and width of 2400 mm and with the three-layered thermal-insulating glazing (6-16-6-16-6) common used in modern timber buildings. The bonding line was made of 5.0 mm thick one-component polyurethane adhesive and it was applied circumferentially around the glass panel into a groove in the timber frame. Two different types of the test samples were tested in a sense to investigate the influence of the number of the bonding line connections on racking resistance and stiffness of the wall elements, as presented in Figure 8:

- the test samples labeled as TGWE-1 where the glass panes were made in one piece in dimensions of 2.11m x 2.03 m,
- the test samples labeled as TGWE-2 where the glass panes were made in two pieces in dimensions of 0.99 m x 2.03 m each (one additional vertical bonding line).

Besides the monotonous horizontal point loading according to EN 594:2011 an additional vertical load of $q_i = 25\ kN/m$ is applied onto the specimens to simulate the dead load of the roof and upper floors. An optical measuring system is used to follow the global displacement (w) of the sample. According to EN 594:2011 under the monotonic horizontal point load *(F_H)* the first test sample from each group is tested to define the maximal possible destruction horizontal point load as an information for defining further cyclic load procedure.

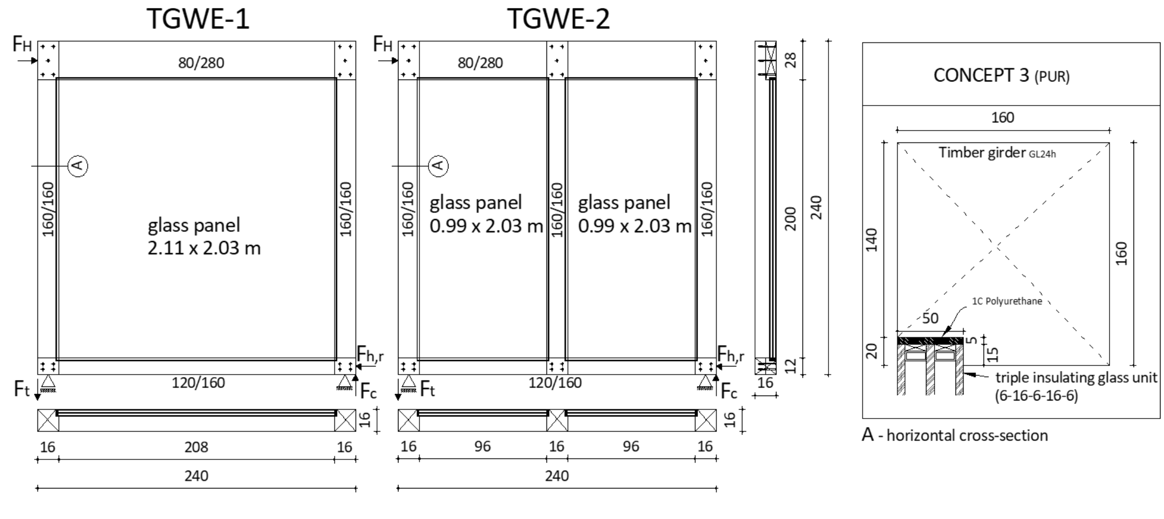

Figure 8: Geometry of Both Testing Groups, TGWE-1 and TGWE-2, Source: Ber (2014)

It was observed during the monotonic tests that the both groups of the test samples demonstrated very similar type of failure procedure which can be described in the following three stages:

- Stage 1: yielding of the adhesive which results in total destruction of the bonding line (F_y).
- Stage 2: destruction in the corners of the timber elements connections which produces the maximal reached acting horizontal force (F_{max}), ductile failure.
- Stage 3: brittle final glass failure which appears as the final destruction step by already decreasing horizontal load action.

Photos of the both test samples after the final collapse under the maximal reached monotonic horizontal point load (F_{max}) are presented in Figure 9.

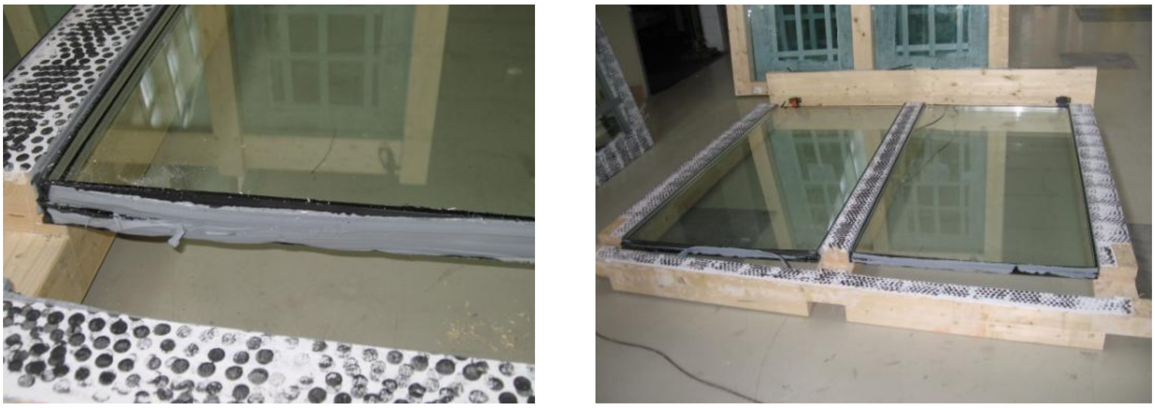

Figure 9: Photo of The Collapsed Test Samples

The measured values for F_y, F_{max}, maximal horizontal displacement (*max. w*), as well as for the calculated racking stiffness (*R*) according to EN 594:2011 are listed in Table 1.

Table 1: Measured Experimental Results

Type of the test samples	R [N/mm]	max.w [mm]	F_y [kN]	F_{max} [kN]	1st stage of failure
TGWE-1	4991.9	42.7	71.0	83.8	yielding of the adhesive
TGWE-2	2799.0	69.8	62.0	71.9	yielding of the adhesive

It is evident from the presented results that the racking stiffness (*R*) of TGWE-1 (one glass pane) is essentially higher than by TGWE-2 (two glass panes). But, on the other hand, the ductility is higher in the case of TGWE-2. Force-displacement diagrams (*F*-*w*) for both test samples are presented in Figure 10 added with additional remarks about points of yielding (F_y), timber corner destruction (F_{max}) and final brittle glass failure.

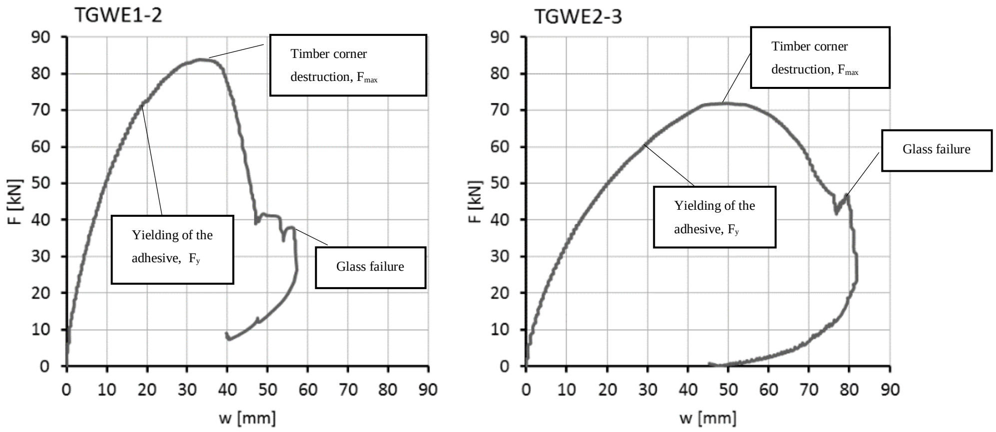

Figure 10: F-w Diagrams for the TGWE-1 and TGWE-2 Test Samples Under Monotonic Horizontal Point Load, Source: Ber et al. (2014)

Comparing the both types of the test samples it can be finally concluded:

- the TGWE-1 test sample demonstrated a higher racking strength (for 16.6%) and especially essentially higher stiffness (for 78.3%) than TGWE-2,
- the TGWE-2 test sample demonstrated essentially higher ultimate deformation and consequently a higher ductility.

Therefore, it could be concluded that the ductility is achieved over the flexibilty of the adhesive in the lateral area of the bonding line. It is a very important fact for our further cyclic and seismic tests.

The same types of the test specimens are further tested under a cyclic horizontal point load following the prescribed ISO 16670:2003 loading procedure with 10 steps. The measured results for all four test specimens are graphically presented in Figure 11. From all four diagrams it can be found out that:
- The maximal measured horizontal point load and therefore the racking resistance of the wall elements of the group TGWE-1 is higher than by the TGWE-2 for 11.7% respectively.
- From the inclination of the hysteresis it is evident that the racking stiffness of TGWE-1 samples is essentially higher than by TGWE-2 samples which is in good correlation with the conclusions from the monotonic test results.

Additional facts about the results are very deeply presented and analysed in the final project report WoodWisdom, Premrov et. al. (2014) and will not be presented at this point.

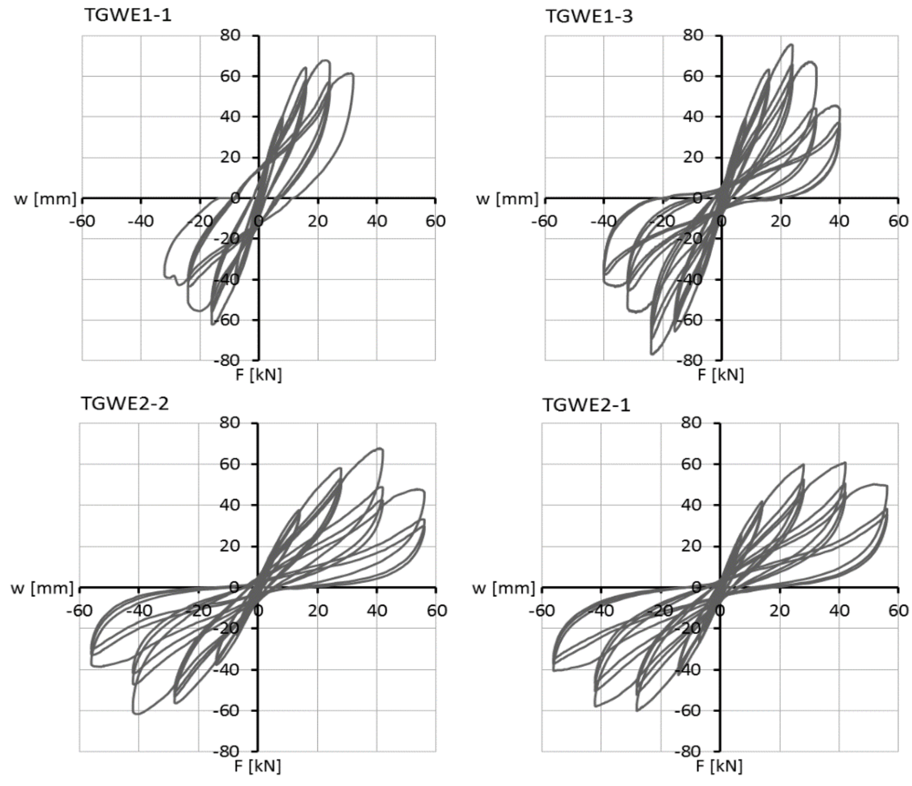

Figure 11: F-w Diagrams for the Cyclic Horizontal Point Loaded Test Samples; a.) TGWE-1 (glass pane in one piece), c.) TGWE-2 (glass pane in two pieces), Source: Ber et al. (2014)

Seismic resistance of timber-glass buildings

Finally, the box-house timber glass house models, schematically already presented in Figure 4c, were tested on the shaking table at IZIIS Institute in Skopje, Macedonia, under a common guidance of University of Maribor and companies CBD and Kager. The box model consists of already monotonic and cyclic tested timber-glass wall elements, as well as of the timber-framed

wall elements with classical OSB sheathing boards which proved essentially higher racking resistance and stiffness under the monotonic point load than the timber-glass wall elements.
Four single-storey and four two-storey box-house structural models (Figure 12) combining different types of wall elements with ground plane dimension of 2.4 x 3.4 m were tested on the shaking table. Single-storey setups had a total height of 2.5 m, two-storey setups reached exactly 5 m in height. Cross laminated timber floor slabs of 100 mm thickness were used to simulate rigid behaviour of floor diaphragms and an additional mass of 1600 kg was installed on each floor in order to simulate the dead load and 30% of the vertical live load in real structural design. According to the loading protocol the testing series were divided into two basic modules:

- Low-intensity testing where the structure remained undamaged and in an elastic state of the material behaviour (including all the connections) and
- High-intensity testing where the ground acceleration was scaled up enough to cause failure in the structure. Before and after each earthquake simulation a sine sweep test (frequencies in the range of 1-32 Hz, acceleration intensity of 0.01g) was performed in order to clearly calculate the vibration period of the structure.

Before and after each earthquake simulation sine sweep test with frequencies in the range of 1-32 Hz and intensity of 0.01g was applied in order to clearly calculate the vibration period of the structure and to record the response of the building.

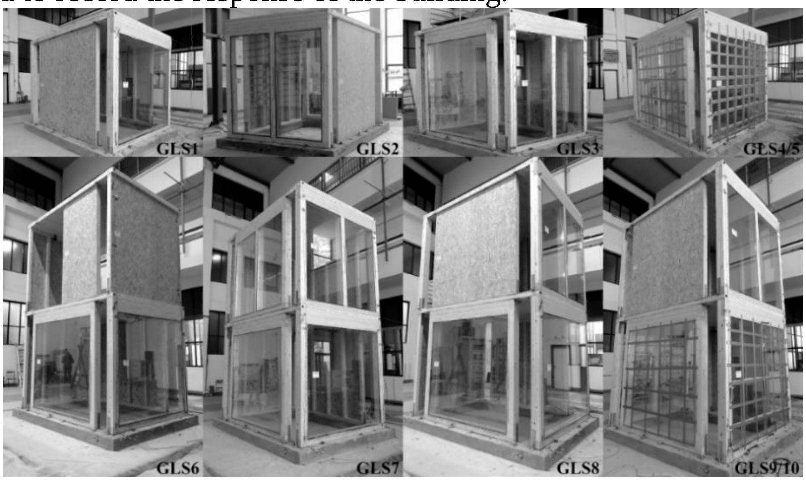

Figure 12: Configuration of One-Storey and Two-Storey Test Models, Source: Premrov et al. (2014)

It can be generally observed from the presented results that there was only a slight change in the measured 1st periods before and after excitation by all tested models. This can prove that there was only a small decrease in a horizontal stiffness of the tested models which can be the first indicator that the deformation range in the structural elements and connections was not essentially high. This statement can be supported with the fact that the timber-glass walls have generally five theoretically possible failure modes when loaded in-plane: (i) failure of corner hold-downs, (ii) failure of shear brackets, (iii) failure of the adhesive joint between glass and timber, (iv) failure of the glass panel and (v) failure of the columns, Figure 13. The tested walls demonstrated a desirable rocking-type of behaviour without any residual deformations in the adhesive joint and the timber frame. By all tested box-house models a ductile failure mechanism (i) was established in the steel hold-downs, Figure 13.

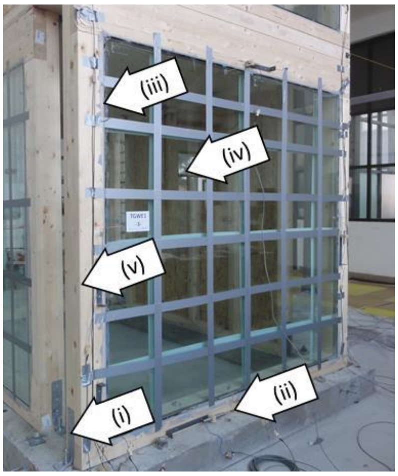

Figure 13: Theoretically Possible Failure Modes, Source: Premrov et al. (2014)

Conclusions

The development of quality glass products recently, both in terms of thermal insulation and load-bearing capacity, has enabled completely new architectural aspects in timber construction. By appropriate placing of glazing areas on the building envelope it is possible to optimally take an advantage of the available solar potential in the given location and consequently essentially reduce of necessary energy demand for heating. The so-called timber-glass buildings thus enable the highest standard of living comfort in a wide variety of climatic conditions, but on the other hand also produce many structural problems. An integrated architectural and structural approach presented in this paper is thus necessary to be considered to obtain the best product. Consequently, the need for the development of load-carrying prefabricated timber-glass wall elements recently widely appeared. Such resisting wall elements can significantly contribute to an essential increase of horizontal stability of the whole timber-glass building and can result in more attractive architectural design of multi-level timber-glass structures located on wind or earthquake-active areas in different climate conditions.

The article presents one of several possible approaches in developing of resisting timber-glass wall elements. The test specimens with the three-pane insulating glazing proved very good behaviour under monotonic and cyclic horizontal point load tests. Moreover, as integrated in the prefabricated timber box-house model tested on a shaking-table they also demonstrated an unexpected ductile failure procedure and consequent very good earthquake resistance. Further results and consequent conclusions on this experimental study can be found in final report of Work Package 6 of WoodWisdoom Research Project LBTGC, Premrov et al. (2014).

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