APEM journal

Advances in Production Engineering & Management
Volume 16 | Number 1 | March 2021 | pp 67–81
https://doi.org/10.14743/apem2021.1.385

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Study of load-bearing timber-wall elements using experimental testing and mathematical modelling

Premrov, M.[a], **Ber, B.**[b], **Kozem Šilih, E.**[a,*]

[a]University of Maribor, Faculty of Civil Engineering, Transportation Engineering and Architecture, Maribor, Slovenia
[b]Jelovica hiše d.o.o., Preddvor, Slovenia

A B S T R A C T

Combining timber and glass in the wall elements of the building envelope with the proper orientation of such transparent façade elements enables the utilization of solar energy for heating and internal illumination of the building. However, the asymmetrical layout of timber-glass wall elements in such buildings can result in problems with the horizontal stability of the structure, so their participation to load-bearing capacity of the structure is usually neglected. The study deals with solutions for such elements as horizontal load-bearing members with proper connection details. First, specifically developed timber-glass wall elements were experimentally tested under monotonic and cyclic horizontal point load, and further in combination with classical timber-framed wall elements implemented into special single and two-storey box-house models, which were further experimentally tested on the shaking table. In the second part as the main goal of the study, a quite simple mathematical model of the box-house prototypes is developed using a fictive diagonal element for simulating the racking stiffness of the bracing timber-glass wall element. The calculated results for the 1st vibration period are compared with the previously measured experimental results to prove an accuracy of the developed model. Finally, a linear time-history calculation is done as a sample presentation of the developed mathematical model using Landers acceleration spectrum. The developed mathematical model enables a simple and effective seismic response calculation of timber buildings considering the developed timber-glass wall elements as load-bearing bracing elements against horizontal load actions. The model can also be recommended for using in further parametric numerical academic studies analysing the influence of various parameters.

A R T I C L E I N F O

Keywords:
Wall elements;
Timber;
Timber-glass building;
Stiffness;
Vibrations;
Experiments;
Modelling;
Landers accelerogram

**Corresponding author:*
erika.kozem@um.si
(Kozem Šilih, E.)

Article history:
Received 6 October 2020
Revised 26 February 2021
Accepted 7 March 2021

1. Introduction

Climate changes of the last few decades do not only encourage research 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 [1]. Therefore, the domain of energy consumption is witnessing a worldwide trend whose aim is to reduce primary energy consumption and greenhouse gas emissions. Consequently, many investigations have been carried out towards 100 % renewable and sustainable energy solutions in many different areas [2-5]. 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 requests of the hosing stock [6].

Moreover, the time of significant climate changes demands active search for energy efficient structural systems with as low CO_2 emissions as possible in the phases of object construction, its exploitation, and its decomposition. As a natural raw material requiring minimal energy input into the process of becoming construction material, timber shows indisputable environmental excellence with very low CO_2 emissions. Therefore, the prefabricated timber buildings are suitable for building the energy saving objects of different standards.

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. Manufacturers have improved thermal insulation and strength of the glass over years [7] and the factor of energy transmission of solar radiation which enabled not only the internal illumination of the building with big glass surfaces, primarily oriented toward the south, but also the solar energy heating.

Nowadays, timber construction combined with the usage of suitable and properly oriented glass surfaces represents a huge potential in residential and public building construction. The fact that location of Slovenia on the southern side of the Alpine range enables considerably high portion of the solar potential in the time of heating season results in high portions of solar gains with the proper installation of bigger glass surfaces in the southern side of the building envelope [8-10]. Consequently, so-called timber-glass buildings have been developed in order to provide the highest possible solar potential and internal natural illumination. In that way, fixed glass surfaces are installed besides windows primary in the southern part of the building envelope (Fig. 1). Such wall elements were earlier not considered as load - bearing to horizontal loads because of the extremely brittle behaviour of the glass. Only conventional prefabricated frame-panel wall elements with classical OSB or fibre-plaster boards were mostly installed on other three sides of the building envelope.

However, it is important to emphasize that consecutive asymmetrical installation of load-bearing wall elements of the building envelope, if timber-glass elements are considered as completely non load bearing, leads to the phenomenon of torsion in single floors due to the seismic load. As schematically presented in Fig. 2, the position of the mass floor centre (M) in such case can significantly deviate from the centre of stiffness (R) of the load-bearing elements.

Namely, the possible phenomenon in the mentioned case can be the so-called soft floor, which should be avoided when designing multi-storey buildings in seismic areas [11]. This phenomenon can be constructionally solved in two known and in engineering practice common used methods:

- Inner conventional prefabricated frame-panel wall elements can be additionally installed; however, this is not in line with contemporary architecture of residential buildings aiming to enlarge natural illumination and general living comfort.
- Special additional load-bearing diagonal elements can be installed in timber-glass wall elements of the building envelope, which are evidently visible (Fig. 3). Still, this practice is mostly used in public buildings only.

Subsequently, lots of researchers deal with the solution of the problem by means of load-bearing timber-glass wall elements. In this case, studies of non-linear seismic response of the buildings on object classes should be done, and accordingly such design methods should be developed that are reliable enough for introduction in construction. Importantly, the basic standard condition [12] – life safety should be met.

Fig. 1 Timber-glass houses with south-oriented fixed glazing

Fig. 2 Phenomenon of torsion on the floor due to deviation of mass (M), and centre of stiffness (R), randomly chosen case

Fig. 3 Detached house with fixed glazing with south-oriented and additionally installed visible diagonals; designed and photographed by Architekturbüro Reinberg ZT GmbH Vienna

The timber-glass wall elements are formed as alternative load-bearing members on horizontal weight which can significantly contribute to additional horizontal load-bearing capacity and stiffness of the whole building. Moreover, they reduce the torsion impact on single floors and at the same time the installation of the visible diagonals can be avoided. This requires the failure not to run at the glass panel, which is as a very un-ductile structural element, but on the joint surface between the glass and timber frame or on the steel corner joint inter-storey elements which can ensure high level of ductility of such load-bearing wall elements. An interesting alternative method of the development of timber-glass wall panels without any adhesive is shown in [13]. In [14] innovative hybrid structural components composed of cross-laminated timber frame and laminated glass infill without using any adhesive to examine their response on the reverse-cyclic loading. As a result, in the case of specimens with low vertical load, the strength degradation demonstrated on average twice higher than in the cases of specimens with high vertical load. The stiffness degradation was not influenced either by the intensity of vertical load or by the number of glazing panels. Therefore, it was possible to formulate this phenomenon with a common equation, which is important for the development of future mathematical model of the tested type of structural components.

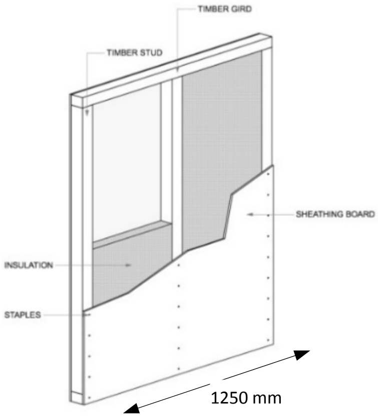
The goal of the study analysis in this contribution aims to find a solution to change a conventional board (plaster-fibre, OSB) of framed-panel wall elements with fixed thermal-insolation glazing. Importantly, by the right procedure of connection details in the connecting plane of the timber-glass frames, these can be considered as additional load-bearing vertical elements on known horizontal strain with proper level of ductility. This is briefly presented in the form of experimental study in Section 3. So-called timber-glass wall elements were developed and experimentally analysed in detail on numerous specimens in the frame of international research project WoodWisdom LBTGC [15]. However, it has to be emphasized that the costs of such experiments are too high to be recognized as useful in engineering practice using also various types of un-tested walls and box-house models. There are also many various parameters, such the adhesive and glass type and thickness, the bonding connection type, etc., which significantly affect racking stiffness of timber-glass wall elements and have to be very carefully analysed, [15-18]. On the other case, the group of authors widely investigated a case where the glass panes were completely not bonded to the timber frame, [19, 14].

Therefore, the second part in Section 4 as the main and final goal of the presented study, a quite simple mathematical model of the box-house prototypes is developed using a fictive diagonal element for simulating the racking stiffness of the bracing timber-glass wall element. It enables designers its application in a quite simple calculaculation software in order to determine the horizontal load-bearing capacity and stiffness of such timber-glass wall element and further also the calculation of oscillating form of the whole timber-glass building model. Such mathematical model can be later used for determination of complete seismic response of such buildings. A simple example performed on previously experimental box-house model is presented at the end of the study. However, the behaviour factor (q) should be determined first in that case. Only then such design methods can be finally developed that are reliable enough to be introduced in common engineering practice for a complete seismic calculation analysis of such timber-glass structures.

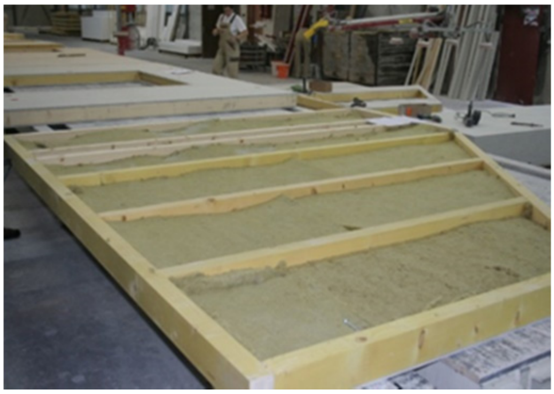
However, it should be especially finally emphasized that these topics are not yet included in European standards such as [11] or [12], since they are the first such implementing European guidelines in terms of glass construction as support and implementation of existing Eurocodes [20]. Nevertheless, studies are already mentioned in these guidelines which explicitly state that they are still in the stage of an academic level only. Generally, each object is unique, so a designer should provide sufficiently high resistance to all expected load cases, as determined by European standard. All presented and developed timber-glass wall elements from our article, separately listed in [20], can only increase this kind of calculated loads on request and at suitable constructor knowledge who does not need to use only known load-bearing wall elements or other strengthening methods (e. g. diagonals) in order to ensure sufficiently high resistance to expected horizontal loads (wind, earthquake), which are not the topics of this study. Hereby the problem of the so-called soft floor can be avoided, and all parameters of modern energy efficient prefabricated timber building can also be taken into consideration.

2. Materials and methods

Prefabricated framed-panel wall elements are made of timber frames composed by studs and longitudinal posts and sheathing boards (fibre-plaster or OSB), which may be unilateral or bilateral with nails or staples attached to the timber frame. The soft thermal insulation is installed in the space between the frame structure which together with outer stiff thermal insulation provides sufficient thermal insulation of the outer wall elements. Such prefabricated elements were in their original form technologically manufactured only as single-panel elements (Fig. 4a) with the standard length 1250 mm which was the standard length of sheathing boards. In 1990s, the single-panel system became a macro-panel system (Fig. 4b) for technological requirements after faster manufacture, so the entire wall systems were manufactured in one piece of 12500 mm length with mostly built-in window and doors openings. In terms of horizontal loads, a macro-panel system is statically considered as the sum of separate single panel wall elements. However, the method A in Eurocode 5 [12] requires only the consideration for the contribution of the single-panel elements without any window and doors openings.



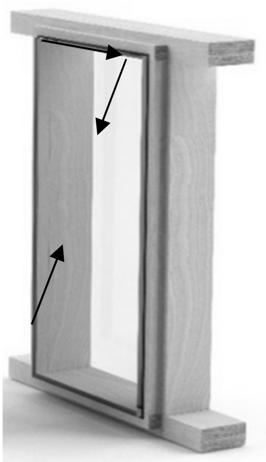
a)



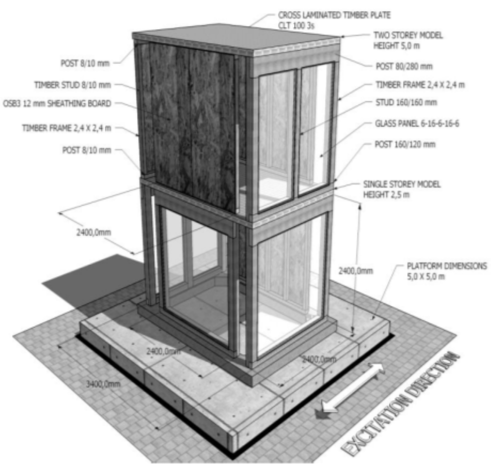
b)

Fig. 4 a) Single-panel, and b) macro-panel wall system

Several studies [21-24] in the known literature prove that elements with window and doors openings can contribute to a certain extend to horizontal load-bearing capacity and stiffness of such wall elements. Therefore, timber-glass elements, where conventional sheathing is replaced by insulation glazing (Fig. 5a), can be considered as load-bearing to horizontal loads to a certain extend. Obviously, horizontal force transfer should be assured both over connecting plane glass-timber with the help of the suitable adhesive and over fictive tensile diagonal of the glass panel, as schematically shown in Fig. 5a [25-27]. Furthermore, it should be emphasized that such load-bearing timber-glass wall elements should be then incorporated in a load-bearing wall system of prefabricated frame-panel macro-wall systems and used in the models of timber-glass prefabricated objects, presented in the shape of the simplified *box-house* models in Fig. 5b, which were experimentally tested in the frame of the project [15] on the shaking table of IZIIS in Skopje [28].



a)



b)

Fig. 5 a) Type single panel wall element with fixed glazing and schematic presentation of horizontal load transfer, b) *Box-house* model of a timber glass building

3. Results and discussion

3.1 Experimental analysis

Experimental analysis of timber-glass wall elements

Prefabricated single frame panel wall elements with fixed three-layered insulation glazing panel were first tested for monotonous static load according to the standard EN 594:2011, [29]. The vertical static load was constant and scaled up to 25 kN/m. The tests were then resumed with cyclic horizontal point load under the same load. In addition, the Niedermaier *end-joint* type 1 [30] was used to provide the joint between glass panel and timber frame. Two-component polyurethane adhesive of 5mm thickness and the annealed glass of 3x6 mm thickness were used, and the space between glazing was 16 mm thick. Two types of specimens were tested; they are schematically shown in Fig. 6:

- wall elements with insulating glass unit (IGU) in one piece (TGWE-1),
- wall elements of equal dimensions with a glass panel in two pieces (TGWE-2).

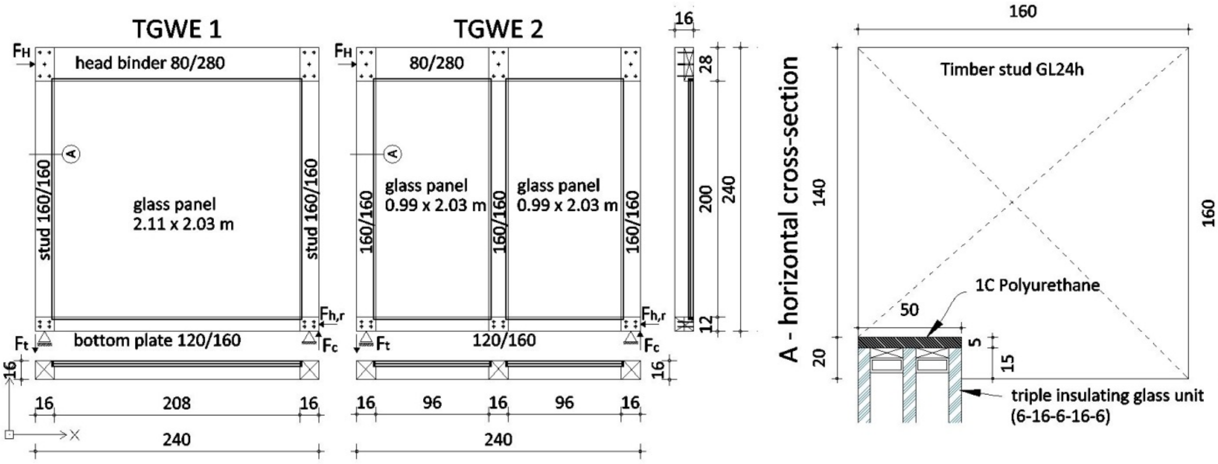


Fig. 6 Geometry of tested timber-glass wall specimens

The results for all obtained hysteresis of cyclic tests for both types of all tested specimens with drawn first envelopes of hysteresis curves are shown in Fig. 7.

It can be observed that the test samples with glazing in one piece (TGWE-1) notably prove slightly higher horizontal load-bearing capacity and especially higher stiffness. However, hysteresis curves show that the ductility for TGWE-1 is significantly lower, which could significantly influence on seismic resistance of such type of load-bearing timber-glass wall elements. The average ductility calculated according to EN 12512 [31] amounts for d = 2.8 for TGWE-1 and d = 3.1 for TGWE-2. The detailed presentation of the results under static horizontal load, calculated values for horizontal stiffness and detailed analysis of measured values with additional recommendations for practical usage can be found in detail in [15] and [28].

The reduction in load capacity in repetitive cycles is presented in Figure 8, where the force-displacement diagram shows the envelopes of the first, second and third cycles for all tested samples. The curves are markedly antisymmetric, and a cyclic decrease in stiffness is also observed. Additionally, the calculated mean values of the racking stiffness with the stiffness reduction chart for the first three envelopes are also presented for TGWE-1 and TGWE-2 test samples.

The stiffness diagram in Fig. 8 shows a slightly larger decrease in stiffness from the first to the second cycle for TGWE-2 type (16.3 %). From the second to the third cycle, the decrease in stiffness is more pronounced in the TGWE-1 type (8.6 %). The total decrease in stiffness, i.e., difference between the first and third cycle ranges from 19.1 % (TGWE-2) to 21.2 % (TGWE-1), respectively.

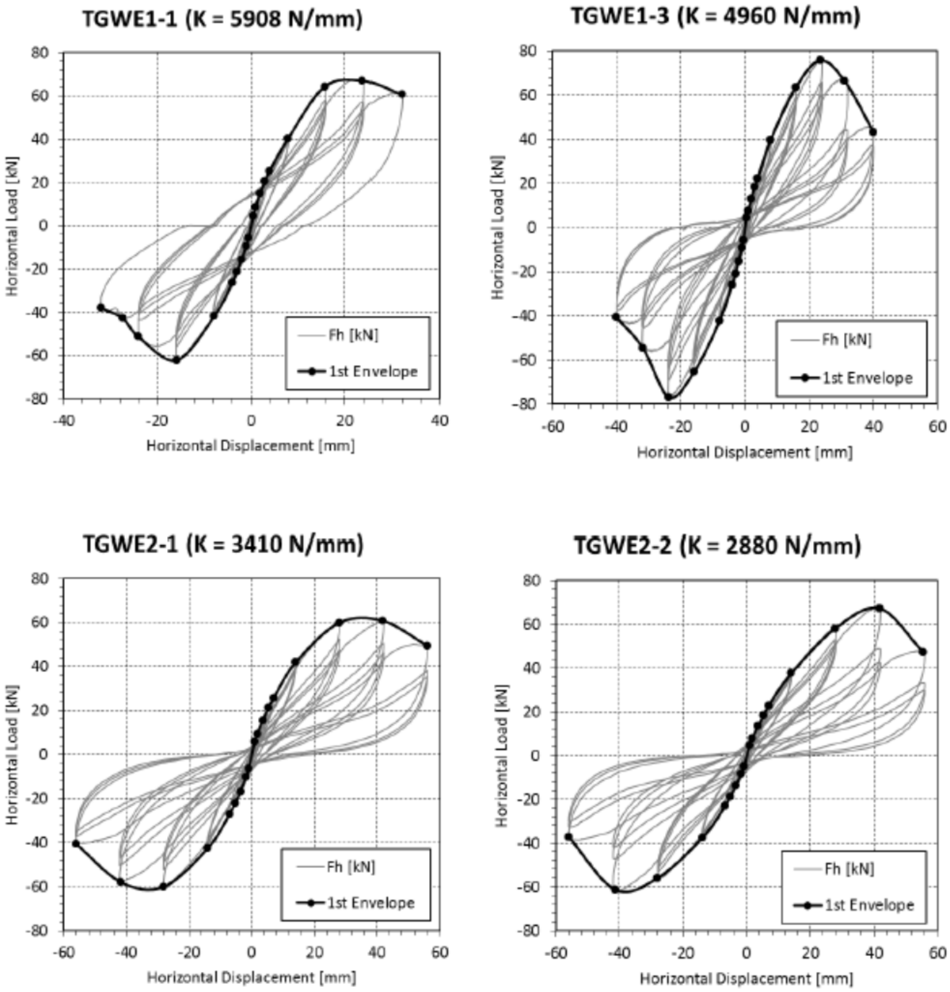


Fig. 7 Presentation of the response to horizontal cyclic load for both groups of specimens and calculated stiffness

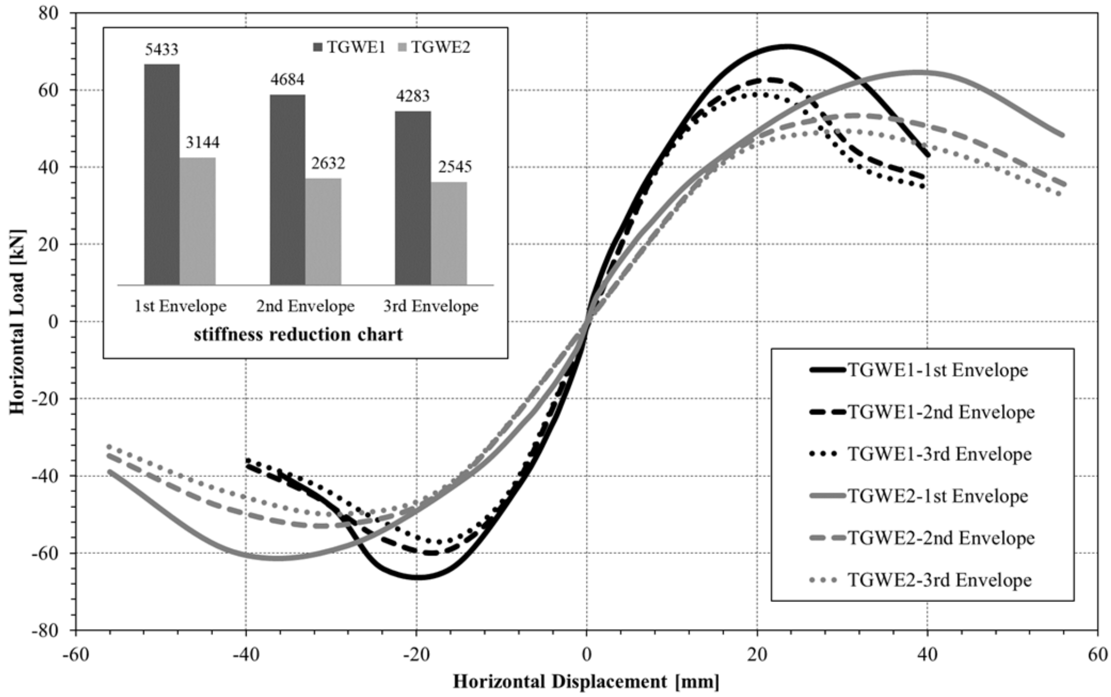


Fig. 8 Presentation of the response to horizontal cyclic load for both groups of specimens and calculated stiffness

Experimental analysis of box-house timber-glass specimens

The further analysis connects together the previously experimentally tested TGWE-1 and TGWE-2 timber-glass wall elements in different ways by conventional timber-framed wall elements sheathed with OSB (TFWE-1) boards. Consequently, as the final product so-called *box-house* timber-glass building models are developed, schematically presented in Figure 5b, and tested on the shaking table IZIIS in the Skopje institute. Single and two-storey composed *box-house* models with different settings of TGWE and TFWE wall elements are photographically presented in Figure 9. It should be mentioned that insulating three-layered glass panels from non-laminate glass were used just for the economic reasons, while laminate glass should be used in practice for safety reasons because it significantly increases the glass ductility. Anyway, failure mechanism should be created in order to generate the failure along ductile steel inter-storey hold-downs or at least along adhesive in connecting plane glass-timber, and by no means the failure along the glazing, which would lead to the instant brittle fracture.

Four single-storey and four two-storey objects with ground plan 2.4 × 3.4 m and height 2.5 and 5.0 m, were constructed from wall elements, type TGWE-1, TGWE-2 and TFWE-1. Three-layered cross glued panel of dimension 2.4 m × 3.4 m and thickness 100 mm served for the connection of wall elements. The additional mass of 1600 kg was applied to the panel which simulated the impact of its own weight and live load in the floor element. Due to the higher stiffness in shorter direction, the panel transferred the majority of vertical loads onto wall elements, installed perpendicularly to the direction of excitation. The wall elements that were seismically loaded in their planes received only a minor portion of vertical load. This is an important boundary condition which affects the behaviour of these wall elements. The wall elements were attached to the AB foundation with WKR-285 type of angle brackets and with additional M12 anchors along the length of the bottom sill. The ceiling panels were joint to the wall elements by self-tapping wood screws 8/180 mm on mutual distance of 150 mm. Upper and lower walls were joint together in corners by metal angle brackets and M12 screws. In addition, dynamic tests were divided into two basic modules: i) lower intensity testing without failure in the structure or in the so-called elastic state (together with all joints) and ii) higher intensity testing, where the ground acceleration was scaled up enough to cause failure in the structure.

After the structure was loaded with recorded *Petrovac* and *Landers* accelerograms, the structure did not exhibit visible damages. In order to intensify the response of the structure, randomly generated ground motion in frequency range 2.0 - 15 Hz and ground acceleration from 0.1 to 0.4 g was applied, as shown in Table 1.

Fig. 9 Photo of tested single- and two-storey *box-house* timber-glass models

Table 1 Protocol of GLS model loading

Low-intensity testing		**High-intensity testing**			
GLS1 - GLS4 and GLS6 - GLS9		GLS5		GLS10	
Modified Landers	0.15 g	modified Landers	0.50 g	modified Landers	0.50 g
Modified Landers	0.25 g	modified Landers	0.75 g	modified Landers	0.75 g
Petrovac	0.22 g	sine-beat 9.856 Hz	0.10 g	random 2-15 Hz	0.25 g
		sine-beat 9.856 Hz	0.50 g	random 2-15 Hz	0.35 g
		sine-beat 9.856 Hz	1.00 g		
		random 2-15 Hz	0.10 g		
		random 2-15 Hz	0.25 g		
		random 2-15 Hz	0.40 g		

Deformations can be noticed in the glue line between the glass panel and timber frame, shear drift and corner uplifting. Fig. 10 (left) shows the values of these deformations for the GLS5 model at random excitation (2.0-15 Hz) with acceleration 0.4 g. The vertical displacement of the corner was 1.0 mm, however, shear wall drift (1.9 mm) and deformations of the glue line in the size of 1.2 mm were also noticed.

The tests of structure excitation or the so-called *sweep tests* were carried out in the frequency area 1.0-32 Hz and the intensity acceleration 0.01 g. Based on these, vibration periods of the structure were calculated; this could serve also for the evaluation of the reduction level of the structural stiffness and damage levels. The measured values before and after high intensity excitation are graphically presented in Fig. 11.

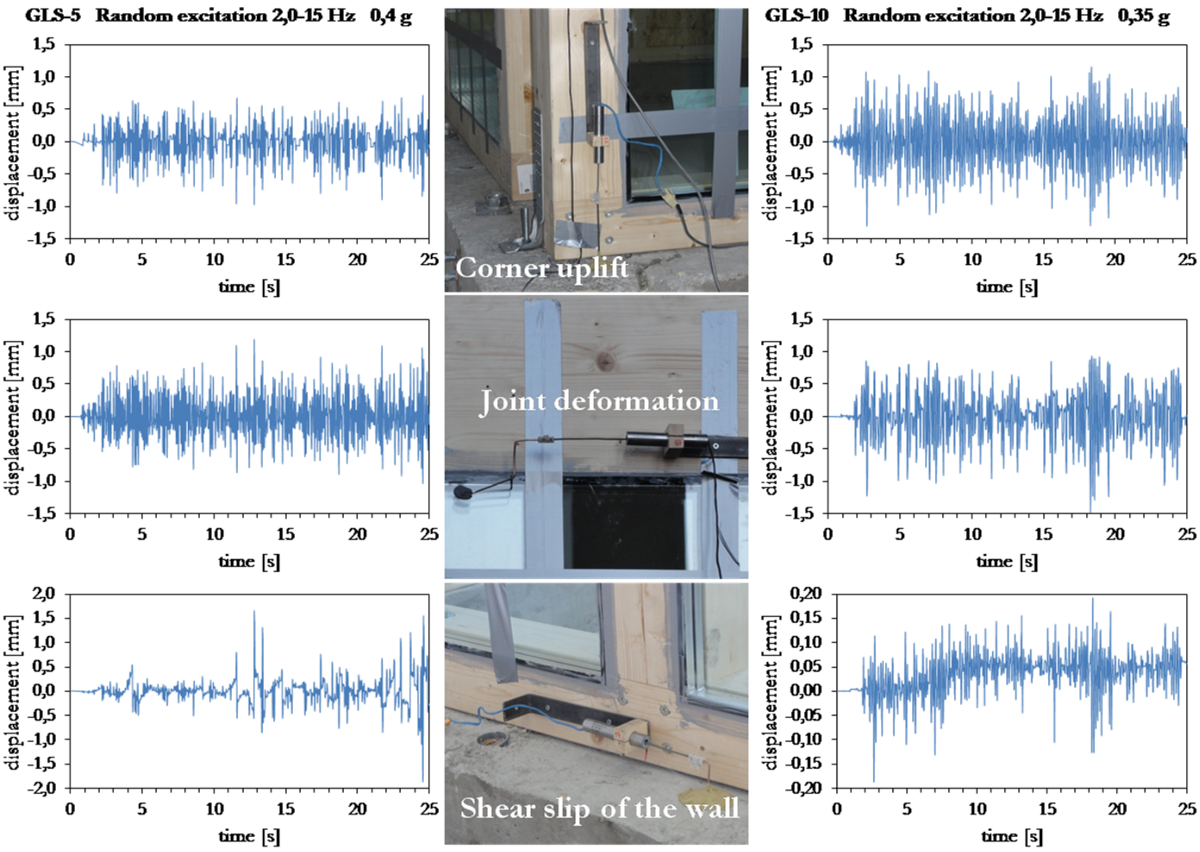
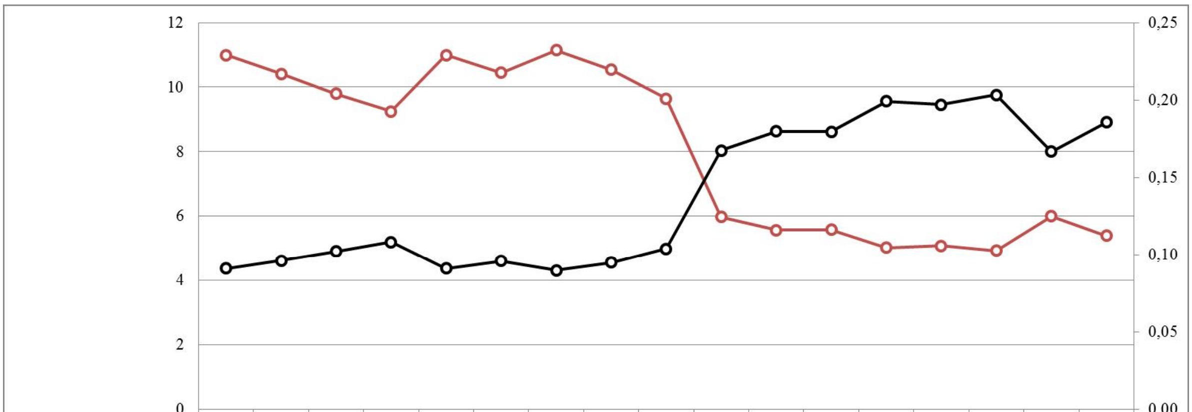


Fig. 10 Values of displacements and deformations of the GLS5 and GLS10 models for a high intensity dynamic test



	GLS1 before	GLS1 after	GLS2 before	GLS2 after	GLS3 before	GLS3 after	GLS4 before	GLS4 after	GLS5 after	GLS6 before	GLS6 after	GLS7 before	GLS7 after	GLS8 before	GLS8 after	GLS9 before	GLS10 after
1st frequency [Hz]	10,99	10,41	9,79	9,25	10,99	10,45	11,15	10,54	9,64	5,97	5,56	5,57	5,02	5,08	4,92	6,00	5,39
1st period [s]	0,09	0,10	0,10	0,11	0,09	0,10	0,09	0,09	0,10	0,17	0,18	0,18	0,20	0,20	0,20	0,17	0,19

Fig. 11 Measured values of basic vibration periods of the before and after high intensity testing

A detailed analysis of all results can be found in [15] and [28], however, it should be mentioned that the high intensity excitation did not result in any visible deformation in glazing, yet ductile failure mechanism with yielding of steel hold-downs between floors, the so-called rocking mechanism was generated at all test specimens. The majority of seismic energy was absorbed in the steel corner fasteners which function as ductile protectors of wall elements. In fact, this was also one of the goals of this study. The measured values of vibration periods before and after excitation (Fig. 11) also prove that there was no significant decrease in structure stiffness. The slight increase in the measured 1st time periods can result only from the yielding process in steel corner fasteners.

3.2 Mathematical modelling and numerical analysis of the single and two-storey box-house model

First, in order to perform the numerical analysis, it was necessary to define a suitable mathematical model of the structure. For this purpose, the previously introduced mathematical model with a fictive diagonal for determination of the racking stiffness of timber-framed wall elements with classical OSB or fibre-plaster (FPB) sheathing material [32] was applied and further developed for the timber-glass wall elements stiffness simulation. Following the expressions presented in [32], the fictive diagonal diameter for classical sheathing boards (OSB or FPB) is determined in the way that horizontal displacement of the actual wall element is the same as a horizontal displacement of the simplified model with a fictive diagonal, as schematically presented in Fig. 12. Lastly, the fictive diagonal diameter (d_{fic}) is expressed in the final form of:

$$A_{d,fic} = \frac{k_p \cdot L_d}{E_D \cdot cos^2 \alpha} \tag{1a}$$

$$k_p = \frac{1}{D_p} = \left(\frac{H^3}{3 \cdot EI_{eff}} + \frac{H}{GA_s} \right)^{-1} \tag{1b}$$

$$d_{fic} = 2 \cdot \sqrt{\frac{A_{d,fic}}{\pi}} \tag{1c}$$

with E_D being the modulus of elasticity of the diagonal, $A_{d,fic}$ the fictive cross-section of the diagonal and L_d the length of the diagonal.

However, it is important to point out that the already developed mathematical model by [32] can be used only for sheets which are mechanically fastened to the timber frame by staples or nails. The effective stiffness EI_{eff} is namely calculated using the gamma-method following the Eurocode 5 [12] expressions.

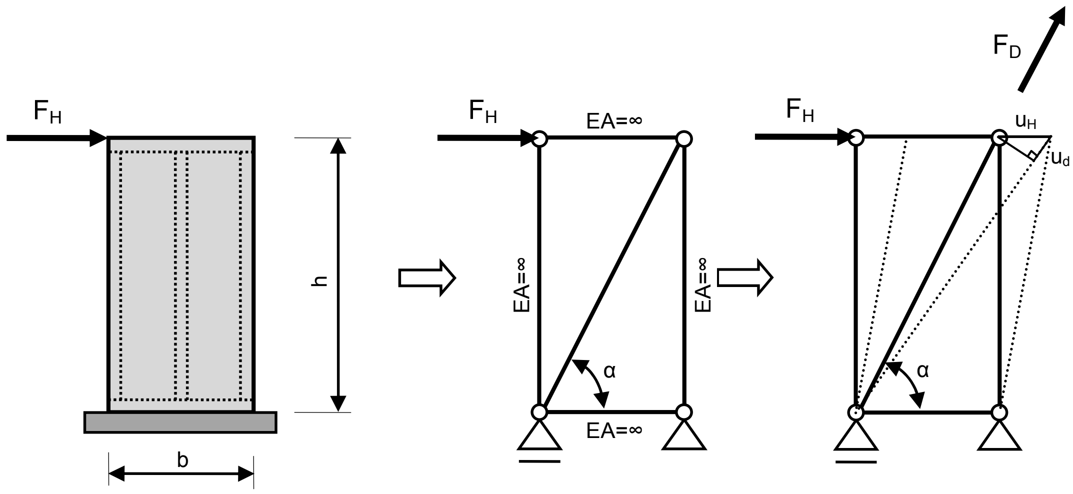


Fig. 12 Schematically presented transformation of a frame-panel wall modelled with truss members and a fictive diagonal

However, in case of timber-glass wall elements, where the glass pane is continuously bonded to the timber frame, it is not possible to determine the gamma coefficient and the effective stiffness EI_{eff} in Eq. 1b directly with the known expressions from the Eurocodes. Some already developed mathematical models with spring elements simulate the flexibility of the bonding line between the glass pane and the timber frame [25], followed by an extensive numerical parametric study [27], albeit the calculation time is too long to be implemented into the whole box-house building model. Therefore, for timber-glass wall elements the diameter of the fictive diagonal d_{fic} can be determined using experimental results from Subsection 3.1 upon derived equation only:

$$d_{fic} = \sqrt{\frac{4 \cdot F_{cr} \cdot L_d}{w_{cr} \cdot \ (\cos a)^2 \cdot \pi \cdot E_D}} \tag{2}$$

where F_{cr} represents the force upon appearance of the first crack and w_{cr} represents the corresponding displacement upon appearance of the first crack. The values for F_{cr} and w_{cr} can be determined only according to experimental testing.

The diameters of the diagonals were calculated in this way for each type of wall panel. As the box-house model is composed as a combination of classical timber-framed wall elements with OSB sheathing boards (TFWE-1) and the timber-glass wall elements (TGWE-1 and TGWE-2), the diameter of the substitutional fictive diagonal is determined for the OSB wall elements in semi-analytical final expressions using Eq. 1 and for the timber-glass TGWE-1 and TGWE-2 wall elements from the experimental results using Eq. 2. The results for d_{fic} are presented in Table 2. According to the results presented in Table 2, the horizontal stiffness of TGWE-2 and conventional TFWE-1 wall panels are practically equal, the stiffness of the TGWE-1 does not differ much as well. It also means that stiffness centre (R) and mass centre (M) of the box-house model coincide relatively well. Basically, this was one of the goals of our study, because consecutive high torsion loads along the building floor can be avoided in the case of an earthquake. Steel with the elasticity module E = 210 GPa was considered as material for diagonals.

Table 2 The diameter of the fictive diagonal for different wall elements

Wall elements	R (N/mm)	$\boldsymbol{d_{fic}}$ (mm)
TGWE-1	6704	16.60
TGWE-2	3595	12.16
TFWE-1	3636	12.23

In the mathematical model of the box-house are considered as rigid. Also, the timber frame elements are considered as axially rigid in order to eliminate the frame flexibility and only the flexibility of the diagonals is taken into account [32]. However, they are already further developed in [33] an upgraded mathematical approach for classical timber-framed wall buildings by including different contributions to the stiffness of the timber-framed walls, such as floor bending flexibility and flexibility in all floor to walls connections, which are not included in this study.

The mathematical model defined by this method was then used for the numerical analysis of the single-storey GLS5 and two-storey model GLS10. The numerical analyses were performed using the structural analysis software SAP 2000 v.17. Timber columns were modelled as axially rigid, while the timber cross-glued floor panels were considered as isotropic thin slabs ~~board~~. The floor slabs were subjected to a surface load of 2.0 kN/m^2. Fig. 13 shows the numerical models of the one-storey and the two-storey box-house using the fictive diagonals, while Table 3 presents the calculated fundamental vibration periods for both models and comparison with the measured fundamental periods as obtained from the experimental analysis (see Subsection titled *Experimental analysis of box-house timber-glass specimens*).

Table 3 shows that the results of the numerical analysis coincide well with the measured ones. Minor differences can be observed due to the fact that rigid supports were used in numerical models, while anchor elements in the experimental models have a certain flexibility which gives rise to a higher deformability of the structure and consequently slightly longer vibration periods. Subsequently, with the application of the developed mathematical models time-history analyses can be further performed using the Landers accelerogram, Fig. 13. The calculated horizontal displacements of the top of the structures as a function of time are shown in Fig. 14 for the single-storey models GLS5 and two-storey GLS10, respectively. The maximal horizontal displacement amounted to 2.67 mm for the model GLS5 and 11.86 mm for the model GLS10.

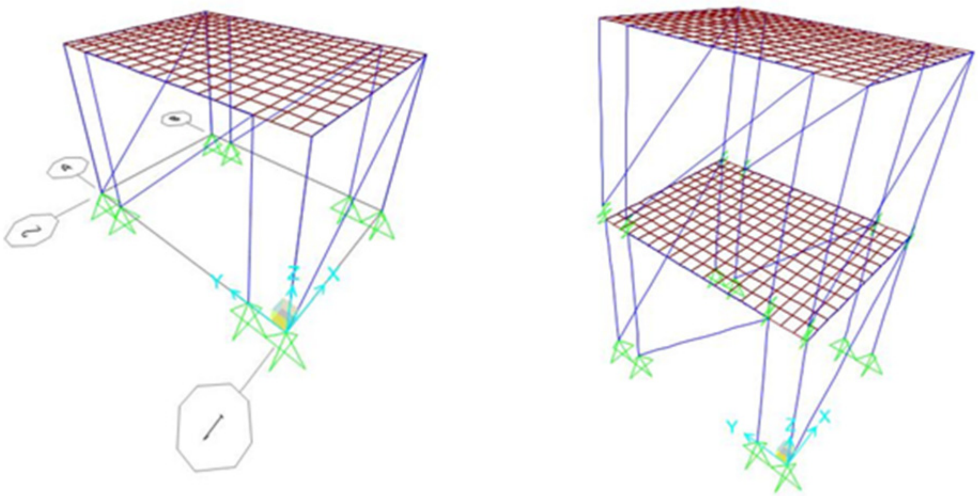


Fig. 13 Simplified numerical model of single-storey and two-storey model with a fictive diagonal (presentation of fundamental vibration forms)

Table 3 Review of fundamental vibration period of experimentally and numerically tested models

Model	Fundamental vibration period T_1 (s)	
	Experimental	Numerical
Single-storey GLS5	0.095	0.096
Two-storey GLS10	0.167	0.173

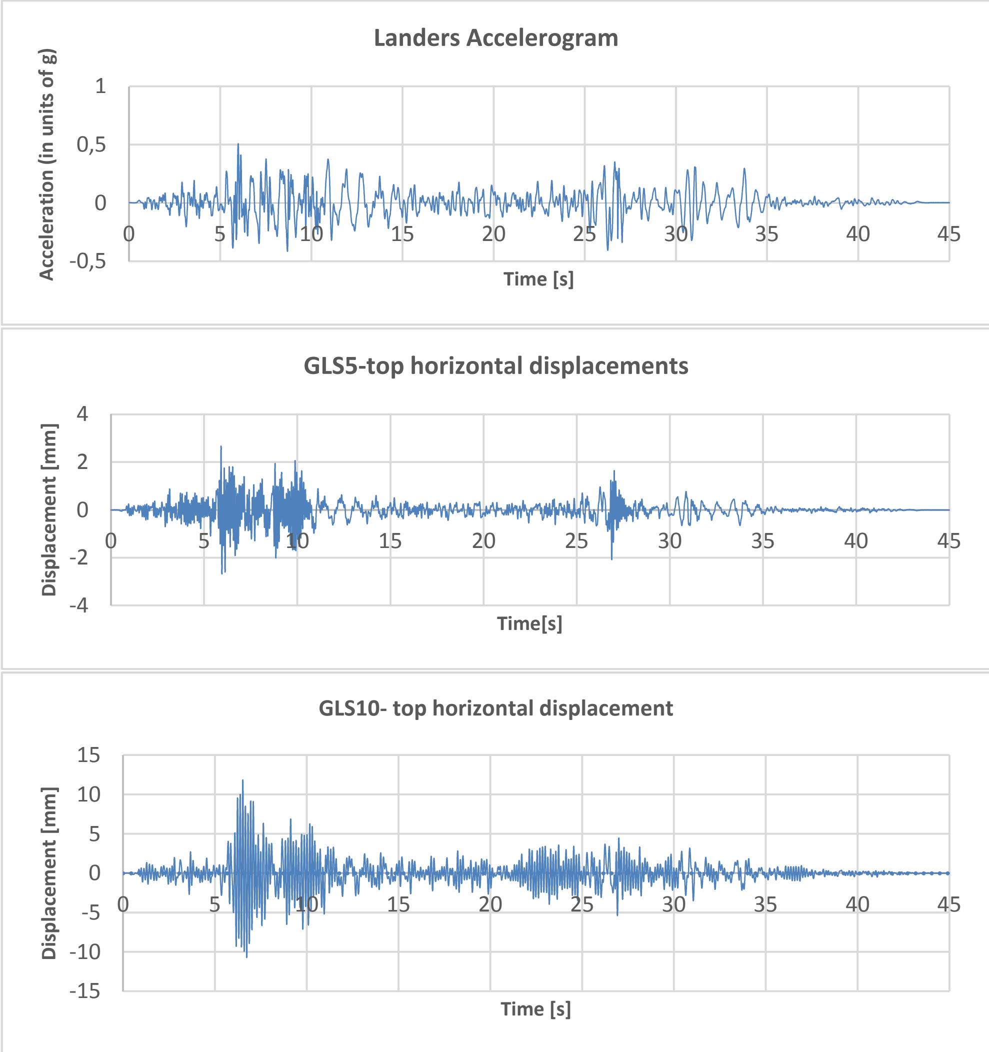


Fig. 14 Numerical values of the top horizontal displacements of the GLS5 and GLS10 models as the result of the time history analyses using the Landers accelerogram

4. Conclusion

The usage of enlarged portion of glass surfaces in modern timber objects provides solar thermal gains and impacts living comfort positively. However, large non-load-bearing glass surfaces under wind and seismic forces cause structural problems, above all in terms of uneven distribution of the horizontal force due to irregularity of the structure in its ground plan. Therefore, it is reasonable to ensure that such wall elements can provide certain horizontal load capacity and stiffness and also certain level of ductility in seismic active areas.

Firstly, discussed timber-glass elements were experimentally tested. Secondly, timber-glass wall elements were studied with combination of conventional frame wall elements which were used in the test box models of single-storey and two-storey objects. The timber-glass wall elements, used in the box models and subjected to highly intensive seismic impact showed sufficiently high level of robustness because the energy absorption was noted in uplifted and shear steel corner fasteners, whereas the wall panel remained in elastic area without any visible signs of deformation of the glue line. In Subsection 3.2, special mathematical models using fictive diagonal elements for prefabricated timber-glass wall elements are developed and upgraded from the already known study in [32], however, they are applicable for timber-framed wall elements with classical sheathing boards only. Consequently, previously experimentally developed load-bearing timber-glass wall elements with insulating three-layered glass pane are implemented into the linear seismic analysis of the whole timber-frame building by using a fictive diagonal approach for the first time in this study.

The developed new models for timber-glass elements however enable numerical simulation of seismic behaviour of single and two-storey timber-glass box-house models and demonstrated very good agreement with the previously experimentally measured results. Therefore, the models can be recommended for further parametric numerical academic studies analysing the influence of many various parameters.

Our further work will base on existing experimental results and expand numerical models in terms of actual nonlinear behaviour of single-wall and anchorage elements and determination of the factor for structural behaviour. Only then numerical analyses could simulate real structural behaviour as a whole and develop reliable design methods which could be introduced in practice. It is important to highlight once more that the basic requirement of the standard [11] should be fulfilled – that is life safety.

Finally, discussed timber-glass panels are in the development phase and at the level of implementing guidelines [20] in European standardization, even though some companies have started to use them in practice as additional panels after they were awarded international patent [34]. In fact, the usage of developed models should be implemented in practice after further seismic studies and proper certification of timber-glass wall element with CE marking.

References

[1] Diakaki, C., Grigoroudis, E., Kabelis, N., Kolokotsa, D., Kalaitzakis, K., Stavrakakis, G. (2010). A multi-objective decision model for the improvement of energy efficiency in buildings, *Energy*, Vol. 35, No.12, 5483-5496, doi: 10.1016/j.energy.2010.05.012.

[2] Olabi, A.G. (2013). State of the art on renewable and sustainable energy, *Energy*, Vol. 61, 2-5, doi: 10.1016/j.energy.2013.10.013.

[3] Olabi, A.G. (2014). 100% sustainable energy, *Energy*, Vol. 77, 1-5, doi: 10.1016/j.energy.2014.10.083.

[4] Lund, H., Mathiesen, BV. (2009). Energy system analysis of 100% renewable energy systems – The case of Denmark in years 2030 and 2050, *Energy*, Vol. 34, No. 5, 524-531, doi: 10.1016/j.energy.2008.04.003.

[5] Lund, H., Möller, B., Mathiesen, B.V., Dyrelund, A. (2010). The role of district heating in future renewable energy systems, *Energy*, Vol. 35, No. 3, 1381-1390, doi: 10.1016/j.energy.2009.11.023.

[6] Itard, L.C.M., Meijer, F. (2008). *Towards a sustainable Northern European housing stock: Figures, facts and future*, The series Sustainable Urban Areas, IOS Press, Vol. 22, Amsterdam, The Netherlands.

[7] Wurm, J. (2007). *Glass structures – Design and construction of self-supporting skins*, Birkhäuser Verlag AG, Basel, Boston, Berlin, doi: 10.1007/978-3-7643-8317-6.

[8] Žegarac Leskovar, V., Premrov, M. (2013). *Energy-efficient timber-glass houses*, Springer, London, Heidelberg, New York, Dordrecht, doi: 10.1007/978-1-4471-5511-9.

[9] Premrov, M., Žegarac Leskovar, V., Mihalič, K. (2016). Influence of the building shape on the energy performance of timber-glass buildings in different climatic conditions, *Energy*, Vol. 108, 201-211, doi: 10.1016/j.energy.2015.05.027.

[10] Žegarac Leskovar, V., Premrov, M. (2011). An approach in architectural design of energy-efficient timber buildings with a focus on the optimal glazing size in the south-oriented façade, *Energy and Buildings*, Vol. 43, No. 12, 3410-3418, doi: 10.1016/j.enbuild.2011.09.003.

[11] European Committe for Standardization CEN/TC 250 (2005). EN 1998-1:2005 Eurocode 8: Design of Structures for Earthquake Resistance – Part 1, General rules, seismic actions and rules for buildings, Brussels.

[12] European Committe for Standardization CEN/TC 250/SC5 N173 (2005). EN 1995-1-1:2005 Eurocode 5: Design of Timber Structures – Part 1-1, General rules and rules for buildings, Brussels.

[13] Antolinc, D., Rajčić, V., Žarnić, R. (2014). Analysis of hysteretic response of glass infilled wooden frames, *Journal of Civil Engineering & Management*, Vol. 20, No. 4, 600-608, doi: 10.3846/13923730.2014.899265.

[14] Žarnić, R., Rajčić, V., Kržan, M. (2020). Response of laminated glass-CLT structural components to reverse lateral loading, *Construction and Building Materials*, Vol. 235, 1-17, doi: 10.1016/j.conbuildmat.2019.117509.

[15] Premrov, M., Serrano, E., Winter, W., Fadai, A., Nicklisch, F., Dujič, B., Šušteršič, I., Brank, B., Štrukelj, A., Držečnik, M., Buyuktaskin, H.A., Erol, G., Ber, B. (2012-2014). Workshop report "WP 6: Testing on life-size specimen components: shear walls, beams and columns including long-term behaviour". Woodwisdom-net, research project, load bearning timber-glass-composites, *https://plus.si.cobiss.net/opac7/bib/18802454*.

[16] Blyberg, L. (2011). Timber/glass adhesive bonds for structural applications, Licentiate thesis, Linnaeus University, School of Engineering, Sweden, *http://www.diva-portal.org/smash/get/diva2:447937/FULLTEXT01.pdf*.

[17] Blyberg, L., Serrano, E., Enquist, B., Sterley, M. (2012). Adhesive joints for structural timber/glass applications: Experimental testing and evaluation methods, *International Journal of Adhesion and Adhesives*, Vol. 35, 76-87, doi: 10.1016/j.ijadhadh.2012.02.008.

[18] Cruz, P.J.S., Pacheco, J.A.L., Pequeno, J.M.B. (2007). Experimental studies on structural timber glass adhesive bonding, In: *COST E34, Bonding of Timber, 4th Workshop "Practical Solutions for Furniture & Structural Bonding"*, Golden Bay Beach Hotel, Larnaca, Cyprus, *https://sigarra.up.pt/feup/pt/conteudos_service.conteudos_cont?pct_id=30543&pv_cod=41slaqqt89ra*.

[19] Stepinac, M., Rajčić, V., Žarnić R. (2016). Timber-structural glass composite systems in earthquake environment, *Gradjevinar*, Vol. 68, No. 3, 211-219, doi: 10.14256/JCE.1505.2015.

[20] Dimona, S., Pinto, A., Feldmann, M., Denton, S. (2014). European Comission JCR Scientific and Policy Reports. Guidance for European Structural Design of Glass Components, Support to the implementation, harmonization and further development of the Eurocodes, Report EUR 26439 EN, Luxemburg, Publications Office of the European Union.

[21] Kozem Šilih, E., Premrov, M., Šilih, S. (2012). Numerical analysis of timber-framed wall elements coated with single fibre-plaster boards, *Engineering Structures*, Vol. 41, 118-125, doi: 10.1016/j.engstruct.2012.03.044.

[22] Šupek, S., Dujič, B., Žarnić, R. (2008). Influence of openings on shear capacity of KLH walls, In: *Zbornik 30. zborovanja gradbenih konstrukterjev*, Bled, Ljubljana: Slovensko društvo gradbenih konstruktorjev, Slovenia, 145-154.

[23] Kozłowski, M., Dorn, M., Serrano, E. (2015). Experimental testing of load-bearing timber–glass composite shear walls and beams. *Wood Material Science & Engineering*, Vol. 10, No. 3 (Special issue), 276-286, doi: 10.1080/17480272.2015.1061595.

[24] Dorn, M., Kozłowski, M., Serrano, E., Enquist, B. (2014). Development of large-scale load-bearing timber-glass structural elements, In: Salenikovich, A. (ed.), *World Conference on Timber Engineering, WCTE 2014*, Quebec City, Canada.

[25] Hochhauser, W. (2011). Ein Beitrag zur Berechnung und Bemessung von geklebten und geklotzten Holz-Glas-Verbundscheiben, Doctoral thesis, Vienna University of Technology, Austria, *https://www.ub.tuwien.ac.at/diss/AC07810717.pdf*.

[26] Štrukelj, A., Ber, B., Premrov, M. (2015). Racking resistance of timber-glass wall elements using different types of adhesives, *Construction and Building Materials*, Vol. 93, 130-143, doi: 10.1016/j.conbuildmat.2015.05.112.

[27] Ber, B., Finžgar, G., Premrov, M., Štrukelj A. (2018). On parameters affecting the racking stiffness of timber-glass walls, *Glass Structures and Engineering*, Vol. 4, No. 1, 69-82, doi: 10.1007/s40940-018-0086-5.

[28] Ber, B., Šušteršič, I., Premrov, M., Štrukelj, A., Dujič, B. (2015). Testing of timber-glass composite walls, *Proceedings of the Institution of Civil Engineers – Structures and Buildings*, Vol. 168, No.7, 500-513, doi: 10.1680/stbu.13.00105.

[29] European Committe for Standardization CEN/TC 250/SC5 N173 (2011). EN 594:2011 Timber structures. Test methods. Racking strength and stiffness of timber frame wall panels, BSI, London, UK.

[30] Niedermaier, P. (2003). Shear-strength of glass panel elements in combination with timber frame constructions, In: *Proceedings of the 8th International Conference on Architectural and Automotive Glass (GPD)*, Tampere, Finland, 262-264.

[31] European Committe for Standardization (2002). EN 12512:2002 Timber structures – Test methods – Cyclic testing of joints made with mechanical fasteners, *https://standards.iteh.ai/catalog/standards/sist/82e23cd2-e11c-40ad-8ca0-384618804f92/sist-en-12512-2002*.

[32] Pintarič, K., Premrov, M. (2013). Mathematical modelling of timber-framed walls using fictive diagonal elements, *Applied Mathematical Modelling*, Vol. 37, No. 16-17, 8051-8059, doi: 10.1016/j.apm.2013.02.050.

[33] Vogrinec, K., Premrov, M. (2018). Influence of the design approach on the behaviour of timber-frame panel buildings under horizontal forces, *Engineering structures*, Vol. 175, 1-12, doi: 10.1016/j.engstruct.2018.08.014.

[34] Ber, B. (2015). *Tragendes Glaswandelement für leichte Holzbauten*: CH707540 (B1), 2015-01-15. Bern: EPO, SI P-201300028, 2013-02-06; CH707540 (A2), 2014-08-15; SI23931 (A), 2013-05-31; DE102013217209 (A1), 2014-08-07; ITRM20130609 (A1), 2014-08-07.