1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.103

Seismic and energy renovation of masonry or RC framed buildings with timber or composite timber panels

Vlatka Rjačić[1], Jure Barbalić[2], Nikola Perković[3]
[1] *Professor*, University of Zagreb, Croatia, *vrajcic@grad.hr*
[2] *PhD. Student*, University of Zagreb, Croatia, *jbarbalic@grad.hr*
[3] *PhD. Student*, University of Zagreb, Croatia, *nikola.perkovic@grad.unizg.hr*

Abstract

In seismic European countries, most of the residential building stock is earthquake-prone and highly energy-intensive because it was built before the enforcement of the recent seismic and energy codes. Furthermore, this stock often shows a low architectural quality due to poor maintenance and/or construction and design deficiencies. For all these reasons, it needs deep renovation. The use of common seismic and energy upgrading techniques however is often unsustainable in terms of costs, work duration, and occupants' disturbance. Therefore, new integrated, affordable, fast, and low-disruptive renovation actions are strongly needed. This study proposes a seismic, energy-efficient renovation solution for masonry or reinforced concrete (RC) framed buildings, based on the addition of cross-laminated timber (CLT) panels to the outer walls, in combination with wooden-framed hybrid panels made from the wooden frame and structural glass. Moreover, the CLT panels can be connected to the existing masonry structure or RC frame through innovative seismic energy dissipation devices. In case of an earthquake, these devices in combination with the CLT panels reduce the drift demand of the building, preventing, or reducing structural damages and consequent repair costs. Furthermore, strengthening of the old timber floor system is proposed also by CLT or LVL panels, coupled with existing floor timber beams, in a composite floor system that forms a stiff diaphragm. Another proposed solution is based on the complete demolition of the inner structure leaving only facades under the cultural protection and rebuilding the inner structure using CLT as a material of high strength, stiffness, and dimensional stability, good insulating performance, a renewable material with characteristics of quick installation (prefabricated systems built with high accuracy), cost-effectiveness, low-disruption, reversibility, and low-carbon or zero carbon emission.

Key words: seismic, timber, glass, façade, panels CLT, masonry, prefabricated

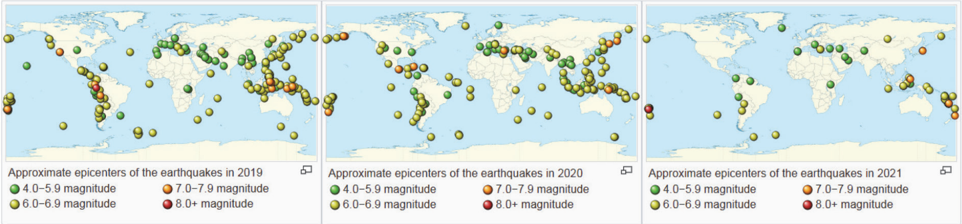
1 Introduction

1.1 Catastrophic earthquakes in the last years and their consequences on building stock

After having experienced a catastrophic natural disaster in March 2020, an earthquake in Zagreb and a close environment, measuring 5.2 on the Richter scale, and an earthquake in Petrinja and the wider environment (Banovina) on the 28th and 29th December 2020. (First day 5,3 and second one 6,3 on the Richter scale with further also rather intensive earthquakes following the strongest one) left 10 people killed and lots of injured. As a result of a devastating earthquake measuring 5,5 on the Richter scale that hit Zagreb, Krapina-Zagorje, and Zagreb counties on March 22, 2020 the quake caused damage to 25.000 buildings and caused damage estimated at a whopping 11,5 billion Euro. Additionally, damage in Banovina is still in the estimation phase. About 35.000 buildings are reported for damage assessment. Besides buildings, extensive changes are in the soil. Bearing capacity is changed with a variety of soil failure events, like deep cracks, big holes, liquefaction, landslides, etc. That means additional problems because those soil failures are near houses and make reconstruction plans more complicated.

According to European-Mediterranean Seismological Centre (EMSC), an earthquake with an epicenter in Petrinja is categorized as level VII based on the EMS-98 and given definition "destroying". An earthquake with epicenter Kašina near Zagreb is categorized as level V based on the EMS-98 and given definition "largely felt". Although it shouldn't have so many consequences, the earthquake in Zagreb made very large damages because of the large number of old buildings built before building law took into account seismic actions on the buildings.

There are continuous earthquake events all around the world every day: in 2019 strongest (8,0 Mw) in Peru and deadliest (6,4 Mw) in Albania (51 deaths), in 2020 strongest (7,8 Mw) in USA and deadliest (7,0 Mw) in Turkey/Greece (119 deaths); in 2021 strongest (8,1 Mw) in New Zealand and deadliest (6,2 Mw) in Indonesia (105 deaths). The list of devastating earthquakes and their tragic consequences for the residential population and buildings seem to be endless (Figure 1).



magnitude	2019	2020	2021
8,0 – 9,9	1	0	1
7,0 – 7,9	9	9	5
6,0 – 6,9	135	112	38
5,0 – 5,9	1.484	1.315	549
4,0 – 4,9	11.897	12.216	2.080
total	13.530	13.654	2.673
fatalities	288	205	110

Figure 1. Review of earthquakes in the period of last three year (https://m.emsc.eu/; https://en.wikipedia.org/)

1.2 Possibility of the seismic and energy renovation of masonry buildings or RC framed buildings in the Zagreb disaster area

1.2.1 Possibility of the renovation with prefabricated timber-based panels

All further actions regarding the reconstruction of the disaster area will be according to the laws of the Republic of Croatia. According to the Law on Reconstruction of Earthquake Damaged Buildings in the City of Zagreb, Krapina-Zagorje County, and Zagreb County (Official Gazette, NN 102/2020). This Act regulates the manner and procedure of reconstruction or removal of buildings damaged or destroyed in a natural disaster declared in the City of Zagreb, Krapina-Zagorje County, and Zagreb County affected by the earthquake on March 22, 2020, construction of replacement family houses and housing for those affected. In the event of an accident, the competent authorities, deadlines for action, and other related issues shall be determined to protect human life and health, protect animals, protect property, protect the environment, nature, and cultural heritage and create conditions for normal life in the affected area.

According to the above-mentioned law, Ways to restore damaged buildings depending on the degree of damage, shall be restored in the following ways: 1) by repairing non-structural elements, 2) by repairing the structure, 3) by reinforcing the structure, 4) complete restoration of the structure and 5) complete renovation of the building.

When thinking about the restoration of structures or repairing the structures in the center of Zagreb there are lots of advantages of using prefabricated timber or composite timber panels. High criteria such as lasting value, earthquake resistance, energy efficiency, environmental non-pollution, short construction time, no possibility of heavy machinery in the old part of town.

In seismic regions, energy and seismic renovation actions must be combined. To do this, we have two options: to retrofit or to demolish and reconstruct the building. Generally, the first option entails lower embodied energy, global warming potential and economic impact, and shorter relocation time, thus proving to be more sustainable. However, many barriers currently hinder the combined use of current energy and seismic retrofitting techniques, such as excessive costs, long time for implementation, and high occupants' disturbance. making these interventions poorly accessible to the owners, especially to the low-income families. Moreover, most combined renovation interventions require the occupants' relocation during the works, thus resulting in additional costs and disruption for temporary accommodation. In this framework, this paper proposes and analyses an innovative integrated renovation solution for RC framed buildings based on the use of prefabricated timber panels. Specifically, the technical feasibility, the energy efficiency, and the structural enhancement potential of the proposed solution are here investigated.

A recently integrated approach to building renovation (Figure 2, right) is based on the use of cross-laminated timber (CLT) prefabricated panels [1, 2]. CLT is an engineered wood product with high strength, stiffness, and dimensional stability due to the crosswise build-up [3]. It is also a good insulating material thanks to its low thermal conductivity (0,13 $Wm^{-1}K^{-1}$). CLT panels coupled with a further insulation layer and finishing materials have been investigated in replacement of the existing masonry infill walls of RC framed buildings, with the main purpose of increasing the overall lateral stiffness of the structure, thus reducing the story drift demand [2]. The same integrated system has been also proposed in addition to the external walls, realizing the connection to the structure through special dissipative devices [1]. The external arrangement of CLT-based integrated systems well meets the current renovation requirements of quick installation, cost-effectiveness, low-disruption, use of low-carbon materials, and reversibility [4] (Figure 2, left).

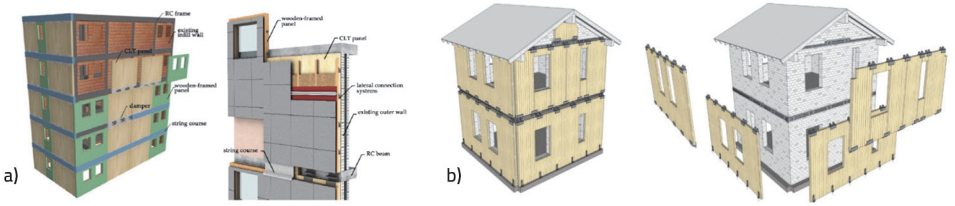


Figure 2. a) Components of the proposed retrofitting system and external installation of prefabricated timber panels with ventilated façade system [4]; b) Retrofitting with CLT panels proposed by [1]

1.2.2 Possibility of renovation with prefabricated hybrid timber-structural glass panels

For the external and internal walls, especially if we need light and transparency, the same results can be obtained using hybrid panels CLT- structural glass instead of whole CLT panels. Besides the need for optimal structural performances for these innovative hybrid solutions, moreover, a facade element as a whole should fulfill a multitude of performance requirements, including the thermal response, energy efficiency, waterproofness, airtightness, etc.

One successful solution is a hybrid multi-purpose panel composed of a CLT frame and two double sheets of laminated glass, where wood and glass contact is achieved only through friction interactions. The panel was developed inside the Croatian science fund VETROLIGNUM project (www.grad.unizg.hr/vetrolignum). A series of tests whose results are published in [6-9] have demonstrated good load-bearing capacity for static and dynamic loads, good stability, serviceability, earthquake resistance, and excellent ability to dissipate seismic energy by friction and ductile behavior of connector in the corner of the CLT frame.

As could be seen in Figure 3, panels were made of CLT frames (with the cross-section dimension b/h = 90/160 mm). Laminated glass sheets are installed in the frame without sealant along with the glass-to-timber contact. The glass infill was made of two-ply, laminated semi-tempered layers bonded by Ethylene Vinyl Acetate (EVA®) foils. The thickness of each glass sheet was set at 10mm, while the thickness of the Bridgestone EVASAFE adhesive bond was 1,6 mm. A continuous, flexible rubber edge trim was used to seal the interposed air cavity, with its thickness of 12,8 mm. The edges of the tested glass sheets were trapezoidal polished, to remove all those micro-cracks and potential weak regions where glass damage could initiate during the mechanical loading stage.

The VETROLIGNUM system takes the best characteristics of two breaking and rather new building materials, Cross-Laminated Timber and bearing laminated glass, by optimizing the interaction between them. It is daily recognized that wooden buildings whether designing for the light frame or mass timber structural systems (panel or frame systems, etc.), can benefit from the material's versatility, benefits to occupants, as well as thermal, acoustic, seismic, and fire performances. CLT is a relatively new structural engineered wood panel system that is gaining popularity all over the world. Typical applications for CLT in buildings include floors, walls, and roofing. The panels' ability to resist high racking and compressive forces makes them especially cost-effective for multi-storey and long-span diaphragm applications. CLT is the basis of tall wood movements, as the material's high strength, dimensional stability and rigidity allow it to be used in mid-and high-rise construction [10]. Additionally, it has favourable aesthetic, energy and environmental, properties that enhance its intrinsic qualities [11]. Also, structural glass has recently been more widely used as the structural material for transfer various types of loads and being used under different boundary conditions.

Glass products are well covered by European norms. [12, 13], Harmonised European norms for the comprehensive structural design of load-bearing glass elements are in preparation and should be presented to designers in 2021 [14-16]. Meanwhile, there are many national documents (technical regulations or technical guidelines) for verification of glass elements (see for example [17-19]).

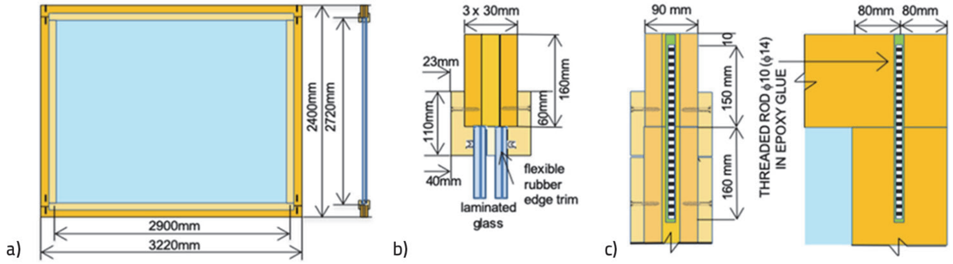


Figure 3. a) Full-scale CLT-glass facade element (front view); b) CLT-to-glass frame connection detail (cross-section); c) Timber frame corner joint

Conclusion regarding load-bearing capacity and serviceability on the performance of 20 tested specimens (3 bare frames, 6 frames with single glazing, and 11 frames with double glazing) in terms of deformation capacity, lateral strength, stiffness degradation, strength degradation and energy dissipation capacity which has been analysed, are following:

- Glass infills radically increase the lateral load-bearing capacity/resistance of the frame because frame joints are loaded in pure shear due to vertical support of frame lintel provided by infill. In the case of glazed frames, the intensity of vertical load increases the lateral strength of specimens by 40% due to the activation of friction between frame lintels and glass sheets.
- The number of glass sheets (single vs. double glazing) does not influence the lateral strength. The reason is in approximately equal fiction force acting along the horizontal edges of the glass sheathing. The reason is in approximately equal fiction force acting along the horizontal edges of the glass sheathing; in the case of double glazing the normal force, which is approximately the same for both cases, is distributed to two sheets (half of the force to double thickness) while in case of single sheathing the entire normal force acts on one sheet.
- The thicker frame joint glued-in rod (d = 14 mm vs. d = 10 mm) increases the lateral strength by 20 %.
- The drift capacity of single-glazed frames was almost 70% lower in comparison with the drift capacity of double-glazed frames. The intensity of vertical load and the thickness of the glued-in rod did not influence the drift capacity. The friction effect highly influenced ductility. In the case of specimens with low vertical load (self-weight only), the ductility of double-glazed frames was 60 % higher than that of single-glazed frames. In the case of high vertical load (25 kN/m), the ductility of double-glazed

frames was 2,4-times higher than that of single-glazed frames. The ductility of the specimen having thicker glued-in rods was 10% higher than that of the specimen with the thinner rod.

- The intensity of vertical load influenced the strength degradation. In the case of specimens with low vertical load, the strength degradation was on average twice higher than in the cases of specimens with a high vertical load. The stiffness degradation was not influenced either by the intensity of vertical load or by the number of glazing panels. Therefore, it was possible to formulate this phenomenon with a common equation, which is important for the development of the future mathematical model of the tested type of structural components.
- High energy dissipative properties of glass infilled CLT frame are confirmed by the values of the equivalent viscous damping coefficient. Due to the effect of plastic deformation of glued-in-steel rods, the thinner ones contribute to the higher amount of dissipated energy in the range of low damages of timber in which the rods are embedded. In the range of larger story drifts, the effect of glass-to-timber friction plays a major role in energy dissipation. The investigation provided the necessary data for the development of design procedures, computational models, and design guidance for the new codes.

In the current codes and standards, glass panels are considered as secondary elements and their beneficial influence is not properly considered. Therefore, the newly developed structural components have to be tested to obtain information on their load-bearing capacity, deformability and durability. The limitation of code-demanded 0,3 % story drift is usually achievable in the case of shear walls and facade panels. However, in the case of buildings located in earthquake prone areas, the story drift limits are more demanding. EN 1998-1 establishes the limits to the inter-story drift due to frequent earthquakes, related to the serviceability seismic action, from 0,5 % to 1,0 %. The idea behind the herein described research was to develop a novel type of attractive, durable, and repairable structural component that would meet the requirements of the code. Structural components presented in this paper do meet these requirements. Table 2 of [6] presents the basic data that illustrate the differences in strength for lateral load and deformability of the tested specimens. The coordinates of four characteristic points of hysteresis response are depicted in Fig. 7 of [6] . The set of data (F_{min}, D_{Fmin}, F_{max}, D_{Fmax}) refers to the strength for lateral load of specimens in both directions of loading, while the set of data (F_{Dmin}, D_{min}, F_{Dmax}, D_{max}) refers to the extremes of story drifts, where F denotes lateral force and D lateral drift of the panel.

However, there are still several open questions regarding the design of load-bearing glass. Among others, one of the challenging issues that will be partly addressed in this paper is related to the increased thermal exposure of glass in facades, and its effects on the mechanical properties of load-bearing glass systems.

1.2.3 Thermal and energy efficiency assessment of facade components

The thermal strategic role of facades is a crucial step in research and design [20], especially in the case of non-traditional envelopes that propose the use of new constructional details, and various literature studies can be found in [21-24]. Even more, extended calculation efforts may be required in the case of the so-called "adaptive" dynamic systems that are subjected to continuous variations in their boundary conditions and performances [25]. Among other things, the use of timber in facades has been explored both in the form of secondary, non-structural cladding elements [31], or load-bearing frames.

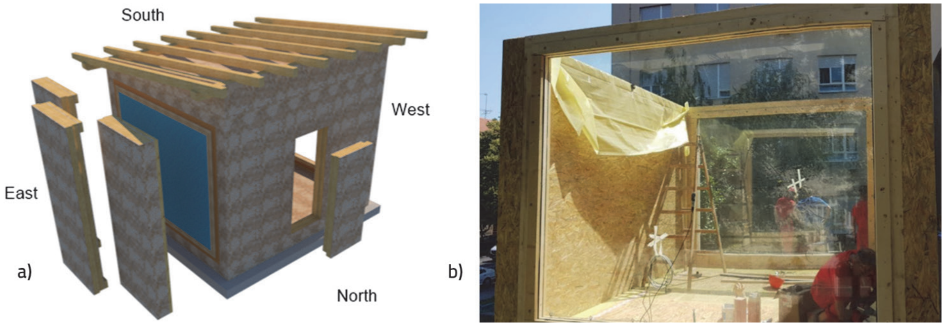


Figure 4. a) Assembly process for the Live-Lab facility at the University of Zagreb - general concept; b) CLT-glass facade elements on Live-Lab

The experimental measurements for the 3D building prototype in Figure 4 were derived from the collection of one-year cyclic records, hereafter referred to as "Cycle 1" (September 2018–August 2019), and so on. These included: indoor Relative Humidity (RH) and temperature, outdoor RH and temperature, RH and temperature data within the cavity of the double insulated glass (for limited time intervals only) and preliminary measurements of the energy consumption for the 3D building system.

Alongside the ambient measurements, a thermographic camera was used to capture possible critical details of the Live-Lab assembly, paying special attention to the area of the corner joints [26].

In the first stage of this study, a series of numerical simulations were carried out with the EnCert-HR computer software (www.encert.hr) to calculate - as accurately as possible - the expected overall energy consumption for the 3D Live-Lab facility (Figure 4). Accordingly, the whole calculation process was developed concerning the Croatian Technical Regulations on energy economy and heat retention in buildings (Official Gazette, NN 128/2015 [27]).

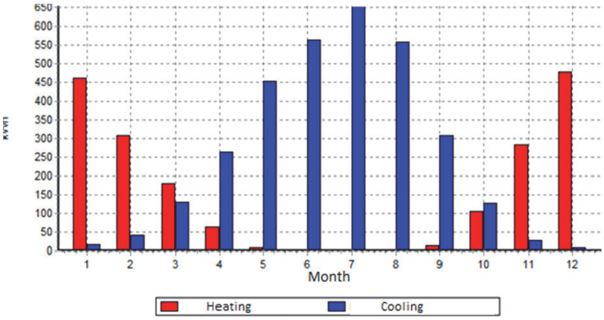


Figure 5. Calculation of required heating and cooling energy (EnCert-HR)

Table 1. Numerical prediction of the critical temperature factor for the hybrid CLT-glass facade element (ABAQUS)

		Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Glass (minimum)	$T_{si,FE}$ [°C]	14,4	15,0	16,2	17,6	19,1	-	-	-	18,9	17,5	18,1	14,6
	$f_{Rsi,FE}$	0,706	0,708	0,708	0,708	0,709	-	-	-	0,708	0,709	0,859	0,705
Glass (edge average)	$T_{si,FE}$ [°C]	16,4	16,7	17,5	18,4	19,4	-	-	-	19,3	18,4	18,8	16,4
	$f_{Rsi,FE}$	0,809	0,809	0,808	0,809	0,810	-	-	-	0,810	0,814	0,908	0,809
CLT frame	$T_{si,FE}$ [°C]	13,8	14,5	15,9	17,4	18,9	-	-	-	18,7	17,1	17,9	13,9
	$f_{Rsi,FE}$	0,674	0,678	0,676	0,682	0,675	-	-	-	0,673	0,663	0,843	0,674

First, besides the simplified geometrical description of the envelope details for the full-sized numerical model of the Live-Lab prototype, the required energy for heating and cooling the facility was calculated (Figure 5, Table 1). The expected cooling energy was found to reach the highest values from April to September, with QC = 260-650 kWh. Similarly, the maximum energy required for heating was expected from November to February, with QH = 300–460 kWh. The annual energy for heating and cooling was thus estimated as QH, nd = 1906 kWh/year and Qc, nd = 3155 kWh/year, respectively, with a relatively higher cooling consumption. Significant energy losses, as expected, were observed to derive especially from the linear thermal bridges due to the different properties of the materials used, as well as from relevant geometrical variations.

2. Conclusion

This paper presents and describes an innovative and versatile renovation solution for RC framed buildings in terms of a technical-feasibility, energy-efficiency, and architectural-enhancement potential. The proposed solution consists of cladding the building envelope with a new tailorable skin based on prefabricated timber panels or hybrid timber-structural glass prefabricated panels, which improve the energy and seismic performance as well as the architectural quality of the renovated buildings. The use of pre-assembled timber-based components and the external dry-installation allow reducing implementation costs and time, embodied energy, and occupants' disruption, resulting in a sustainable system from a social, economic, and environmental point of view.

Dynamic thermal simulations performed on the parametric model of a typical RC framed apartment in Zagreb, both pre-and post-renovation, confirmed that the proposed solution significantly reduces the energy demand. In particular, the overall annual energy needs for heating and cooling were decreased up to 56 %. The comparison between the suggested integrated retrofitting intervention and a traditional solution based on an ETICS application showed that the two solutions were similar in terms of energy savings, while the dynamic thermal performance of the outer walls improved considerably with the addition of prefabricated timber as well as hybrid timber-structural glass panels.

Regarding the seismic behaviour, the described CLT structural panels and CLT-structural glass panels were conceived to overcome the typical deficiencies of most existing RC framed buildings located in earthquake-prone areas. Indeed, these panels, which are specifically equipped with friction dampers, can provide the existing structure with additional stiffness, strength, and energy dissipation capacity.

This research is we can say in the middle stage and more research project and experimental investigations are currently ongoing to optimize the industrial replicability, structural efficiency, and durability of the presented friction damper, while numerical simulations will evaluate the heat transfer through the thermal bridges and the seismic performance of buildings upgraded with the proposed techniques.

Acknowledgements

The herein reported research work is funded by The Croatian Science Foundation (Project no.: IP-2016-06-3811 VETROLIGNUM: Prototype of multipurpose timber - structural glass composite panel) and by the Slovenian Research Agency core funding no.: P2-0185, 2009-2018 (Earthquake Engineering). Their contributions are gratefully acknowledged.

References

[1] Šušteršič, I., Dujič, B. (2014): Seismic shaking table testing of a reinforced concrete frame with masonry infill strengthened with cross-laminated timber panels, World Conference on Timber Engineering 2014, Quebec City, Canada, 6 pages.

[2] Stazi, F., Serpilli, M., Maracchini, G., Pavone, A. (2019): An experimental and numerical study on CLT panels used as infill shear walls for RC buildings retrofit, Construction and Building Materials, 211, 605–616, doi: 10.1016/j.conbuildmat.2019.03.196

[3] Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., Thiel, A. (2016): Cross laminated timber (CLT) - Overview and development, European Journal of Wood and Wood Products,74, 331–351, doi: 10.1007/s00107-015-0999-5

[4] La Greca, P., Margani, G. (2018): Seismic and energy renovation measures for sustainable cities - A critical analysis of the Italian Scenario, Sustainability, 10 (1), 254, 1-19, doi: 10.3390/su10010254

[5] Stepinac, M., Šušteršič, I.; Gavrić, I.; Rajčić, V. (2020): Seismic design of timber buildings - Highlighted challenges and future trends, Applied Sciences - Basel, 10 (4), 1380, 1-14, doi:10.3390/app10041380

[6] Žarnić, R., Rajčić, V., Kržan, M. (2020): Response of laminated glass - CLT structural components to reverse-cyclic lateral loading, Construction and building materials, 235 (117509), 1-17, doi: 10.1016/j.conbuildmat.2019.117509

[7] Žarnić, R., Rajčić, V. (2017): Laminated glass - timber panel as a dissipative bracing structural component for existing frame structures, 16th World Conference on Earthquake Engineering, Santiago, Chile, 12 pages.

[8] Rajčić, V., Žarnić, R. (2012): Seismic response of timber frames with laminated glass infill, Meeting forty-five of International council for Research and Innovation in Building and Construction Working Commission W18 – Timber Structures (CIB – W18), Växjo, Sweden, 12 pages.

[9] Rajčić, V., Žarnić, R., Perković, N., Barbalić, J. (2019): Optimisation test study of connections and joints between elements of the hybrid timber - structural glass panel, World Construction Forum 2019: Buildings and Infrastructure Resilience, Ljubljana, Slovenia, 1 page.

[10] Jeleč, M., Varevac, D., Rajčić, V. (2018): Cross Laminated Timber (CLT) - A state of the art report, Građevinar, 70 (2), 75-95, doi: 10.14256/jce.2071.2017

[11] Bejtka, I. (2011): Cross (CLT) and diagonal (DLT) laminated timber as innovative material for beam elements, KIT Scientific Publishing, Karlsruhe, Germany.

[12] CEN - European Committee for Standardization (2011): EN ISO 12543-2 Glass in building - Laminated glass and laminated safety glass - Part 2: Laminated safety glass, European Standards, Brussels, Belgium.

[13] CEN - European Committee for Standardization (2000): prEN 13474-2 Glass in building - Design of glass panes – Part 2: Design for uniformly distributed loads, European Standards, Brussels, Belgium.

[14] Feldmann, M., Di Biase, P. (2018): The CEN-TS "Structural Glass - Design and Construction Rules" as pre-standard for the Eurocode, ce/papers (Special Issue: Engineered Transparency 2018 - Glass in Architectural and Structural Engineering), 2 (5-6), 71-80, doi: 10.1002/cepa.911

[15] CEN - European Committee for Standardization, CEN/TC 250 (2019): prCEN/TS xxxx-1: 2019 - In-plane loaded glass components (December 2019), European Standards, Brussels, Belgium.

[16] CEN - European Committee for Standardization, CEN/TC 250 (2019): prCEN/TS xxxx-2:2019 - Out of-plane loaded glass components (December 2019), European Standards, Brussels, Belgium.

[17] CNR - Consiglio Nazionale delle Ricerche (2013): CNR-DT 210/2013 Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di costruzioni con Elementi Strutturali in Vetro, Ente Nazionale Italiano di Unificazione, Roma, Italy.

[18] Buildings Department (2018): Code of practice for the structural use of glass, The Government of the Hong Konsg Special Administrative Region Standards, Hong Kong, People's Republic of China.

[19] Feldmann, M., Kasper, R., et al. (2014): Guidance for European structural design of glass components - support to the implementation, harmonization and further development of the Eurocodes, Joint Research Centre - Institute for the Protection and Security of the Citizen - Report EUR 2643, Luxembourg City, Luxemburg.

[20] European Commission (2010): Directive 2010/31/EU of the European Parliament and of the Council, Official Journal of the European Union, Brussels, Belgium.

[21] Zobec, M., Colombari, M., Peron, F., Romagnoni, P. (2002): Hot-box tests for building envelope condensation assessment, 23rd AIVC and EPIC 2002 Conference (in conjunction with 3rd European Conference on Energy Performance and Indoor Climate in Buildings) - Energy efficient and healthy buildings in sustainable cities, Lyon, France, 6 pages.

[22] Aldawoud, A. (2017). Assessing the energy performance of modern glass facade systems, International Conference on Advances in Sustainable Construction Materials & Civil Engineering Systems 2017, Sharjah City, Sharjah, United Arab Emirates, 7 pages.

[23] Bedon, C., Pascual, C., Navarro, A.L., Overend, M. (2018): Thermo-mechanical investigation of novel GFRP-glass sandwich façade components, Challenging Glass 6, Delft, Netherlands, 12 pages.

[24] Planas, C., Cuerva, E., Alavedra, P. (2018): Effects of the type of façade on the energy performance of office buildings representative of the city of Barcelona. Ains Shams Engineering Journal, 9 (4), 3325-3334, doi: 10.1016/j.asej.2017.04.009

[25] Favoino, F., Loonen, R.C.G.M., Doya, M., Goia, F., Bedon, C., Babich, F. (2018): Building performance simulation and characterisation of adaptive façades – Adaptive Façade Network, TU Delft Open for the COST Action 1403 - Adaptive Facade Network, Delft, Netherlands.

[26] Rajčić, V.; Perković, N., Bedon, C., Barbalić, J., Žarnić, R. (2020): Thermal and energy-efficiency assessment of hybrid CLT-glass façade elements, Applied Sciences - Basel, 10 (9), 3071, 1-22, doi:10.3390/app10093071

[27] Ministry of Environmental Protection and Energy: OG 88/17 Ordinance on energy audits and energy certification of buildings (with call on OG 128/15 Technical regulation on energy economy and heat retention in buildings, and OG 69/06Technical regulation for windows and doors), Official Gazette, Zagreb, Croatia