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ON THE POSSIBILITY OF USING TIMBER STRUCTURES IN THE CONSTRUCTION OF HIGH-RISE BUILDINGS IN SEISMIC AREAS

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Abstract

Introduction: Part of the territory of Russia is located in a seismically dangerous area. In recent years, glued laminated wood has been gaining popularity in private housing construction as well as other construction sectors. However, Russian standards lack design and structural requirements for buildings and structures made of glued laminated wood**. Methods:** The paper reviews the foreign experience in construction with the use of glued laminated wood and presents seismic design for a multi-story building made of wood and materials based on it. **Results:** We considered the seismic design of a multi-story timber building and reviewed foreign experience in the construction of buildings made of glued laminated wood. Besides, we analyzed how the choice of the material for individual load-bearing structures affects seismic resistance.

Keywords: glued laminated wood, seismic resistance, earthquakes, multi-story buildings.

Introduction

Climate changes on our planet are forcing the population and the governments of various countries to pay more attention to environmental issues directly related to human construction activities. The increase in temperature is largely due to anthropogenic emissions of greenhouse gases into the atmosphere. Compared with concrete and steel, the use of wood as a building material is the most preferable since it reduces carbon dioxide emissions into the atmosphere. Wood production waste is environmentally friendly and can be used in the future as biofuel or for other industrial purposes. All this testifies to the relevance of using wood in the construction of buildings for various purposes. Besides, due to its high performance characteristics, wood has a huge potential in the field of building construction in specific climatic and seismic conditions, reducing the risks of structural collapse and minimizing economic costs of restoration after potential natural disasters, e.g., after violent earthquakes (Black et al., 2010; Goda and Yoshikawa, 2013; Goda et al., 2011; Şahin Güçhan, 2007).

Centuries of experience in the operation of timber buildings show that they can last for hundreds of years. Modern studies on the fire resistance of timber constructions allow us to consider timber buildings quite fire-resistant. This is mainly due to the moisture content in the wood, including the most dried samples. As the research results show, glued laminated wood is characterized by the greatest resistance.

Despite the positive experience of using wood in civil engineering, its use in multi-story or high-rise construction is still quite problematic. This is related to one of the significant disadvantages of wood, i.e., limited choice of geometric dimensions of structures, which increases the cost of wood harvesting and processing. Among other disadvantages of timber structures, the following can be mentioned: changes in the geometric shape as a consequence of shrinkage or swelling, persisting during the operation of structures. As known, additional stresses occur in the nodal joints as a result of shrinkage and settlement, which significantly increase throughout the height of the building. These negative factors are mainly typical for solid wood. They can be largely overcome by using a wide range of wood composite materials, which are quite popular abroad. These include glulam (glued laminated wood), CLT (cross laminated timber) plates, plate materials capable of withstanding loads in loaded structures (OSB plywood), parallel strand lumber (PSL), etc. The main feature of the developed wood composite materials is the possibility of their use in the construction of multi-story and high-rise buildings due to their high performance characteristics, which primarily include strength, rot resistance, corrosion resistance, high vapor permeability, fire resistance, unlimited cross-section sizes, and low specific weight compared with reinforced concrete and steel. Products made of wood composite materials can be used as load-bearing and enclosing structures.

As an example, we considered the multi-story Brock Commons Tallwood House consisting mainly of timber structures, shown in Fig. 1. The building has a hybrid structure consisting of PSL beams, CLT floors, and reinforced concrete stiffening cores where escape routes and elevator shafts are located.

The first floor is also made of reinforced concrete. The structural system is frame, post-and-beam. The used PSL material is isotropic, so it can be used in structures without preferred load direction. Wood fibers in the longitudinal direction are characterized by the best strength indicators at tension and bending. Besides, these products have increased moisture resistance.

Glued laminated wood (glulam) (Fig. 2) is a structural material made by linking individual wood segments glued together using special industrial adhesives, e.g., polyurethane adhesives.

The obtained products are characterized by high strength, fire and moisture resistance. These segments can be used to create construction facilities of various shapes and sizes. One of the main advantages of this type of materials is that it is light and easy to assemble. The joints between various elements can be made not only with adhesives but also with steel dowel pins. An important property of this material is its stable behavior; shrinkage and swelling are minimized.

Another popular wood composite material is cross laminated timber (multilayer cross laminated wooden panels), better known as CLT. This technology was first developed and used in the early 1990s in Germany and Austria and became widespread in the 2000s.

CLT is a wooden panel made of timber layers glued together, with each layer oriented perpendicular to adjacent layers. Panels are made from layers of wood dried to optimum moisture content. The cross arrangement of the longitudinal and transverse layers reduces the shrinkage and swelling of wood in the panel plane to insignificant values, which increases the bearing capacity and minimizes changes in the geometric sizes of the elements. CLT panels can be used as load-bearing and enclosing structures. Due to stiffness and the absence of residual deformations, structures made of this material also found their use in seismic areas. In Japan, a 7-story building made of CLT panels was tested on special equipment simulating earthquake conditions. The results showed high seismic resistance of CLT elements at 7–8 earthquake magnitudes (Porcu et al., 2018; Shen et al., 2013).

Fig. 3 shows the Mjøstårnet building. It is the 18-story building built in Norway, with a total height of 84.5 m. To erect this large object, load-bearing columns, beams, and massive diagonal members made of glued laminated wood were used.

The total area of living space in the building is ca. 11,300 m^2. The building is based on the post-and-beam structural scheme. The posts and beams are made of glued laminated timber and reinforced with additional braces. The floor slabs are made of CLT panels. However, reinforced concrete structures were also used in the construction. Up to the 12th floor, wooden beams are covered with laminated veneer and a 50 mm concrete layer to improve acoustic properties and reduce oscillations. From the 12th to the 18th floor, the floor slabs are reinforced concrete. Thanks to this structural solution, it is possible to erect a building with such a height and ensure optimal wind load resistance. The semi-basement floor, the foundation, and the slab of the first floor are also made of reinforced concrete. The building has a stiffening core made of CLT panels, where a staircase and an elevator shaft are located. Fig. 4 shows the general view of the load-bearing structures.

Another example of using CLT is the Via Cenni residential complex in Milan. It is based on the technology for the construction of high-rise buildings with the use of CLT panels. The residential complex consists of four 9-story towers, each 28 m high, connected by two-story buildings. The structural scheme used in the design is panel-wall. This technology made it possible to erect the residential complex in just 14 weeks. The construction area is located in a 7-magnitude seismic zone. The building (except for the semi-basement floor, the floor of the first story, and the foundation) is completely made of CLT panels. To ensure the required horizontal

Fig. 1. Brock Commons Tallwood House

Fig. 2. Glued laminated wood

Fig. 3. Mjøstårnet Tower, Norway

stiffness, each panel has at least 5 layers. Reinforced concrete stiffening cores play an important role in the seismic vulnerability of the building since they resist horizontal loads transmitted from the CLT floor panel through steel joints (resistance bars), thus ensuring the frame resistance to loads of this nature. To avoid the transmission of vertical loads in the bearing areas of the columns to the CLT panels, a steel bond is provided, directly connecting the upper and lower columns, thereby preventing the deformation of the floor panels due to the pressure from the columns. The enclosing structures of the building consist of CLT-based prefabricated panels finished with refractory materials. The erection of the building took only 70 days. As of today, the seismic resistance of buildings made of reinforced concrete and steel is most extensively studied, and those studies are systemic and reflected in Russian and foreign standards. The studies addressing the seismic resistance of timber buildings are either local or deal with local issues of wooden house construction (Belash and Ivanova, 2006, 2019; Belash et al., 2010, Kirkham et al., 2014). Those studies also do not provide the specifics of structural engineering with regard to buildings made of glued laminated wood: methods for accounting the anisotropic properties of wood or methods for accounting the mutual arrangement of fibers. Based on the aforesaid, we aimed to study the seismic resistance of a multi-story building with load-bearing structures made of glued laminated wood and determine the possibility of using this material in large-scale construction at the current level of science and technology development.

Subject, methods and materials

To assess the load-bearing capacity of the analyzed structural solutions under seismic impacts, we performed calculations and theoretical studies. The subject of the study is an 18-story building with load-bearing structures made of glued laminated wood (Fig. 5). The floors of the building are made of CLT panels consisting of 5 layers of 40 mm each.

The vertical load-bearing structures (with the transmission of vertical loads as the main function) are columns made of glued laminated wood of first grade with a cross-section of 600x600 mm.

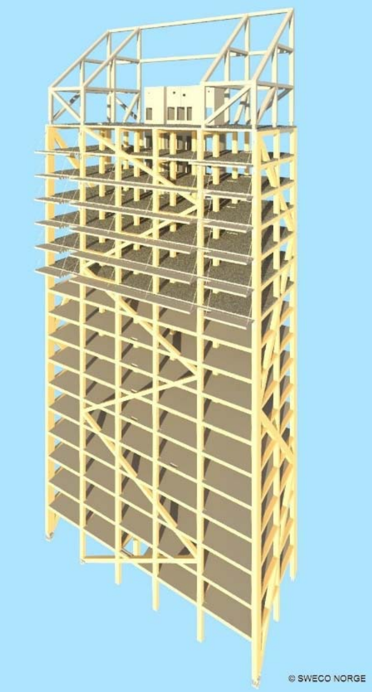


Fig. 4. Mjøstårnet Tower, general view of the load-bearing structures

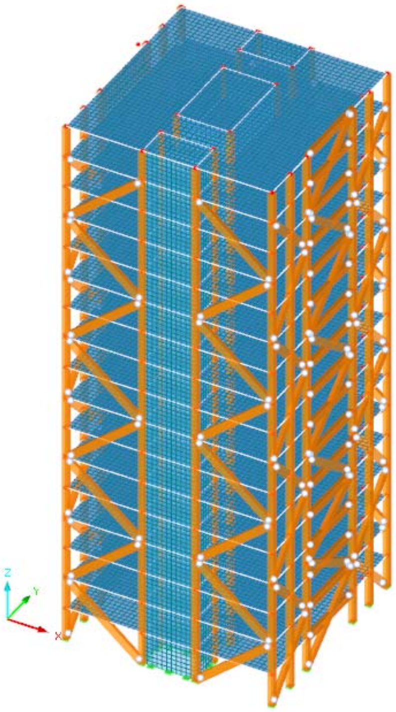


Fig. 5. Building under consideration. General view

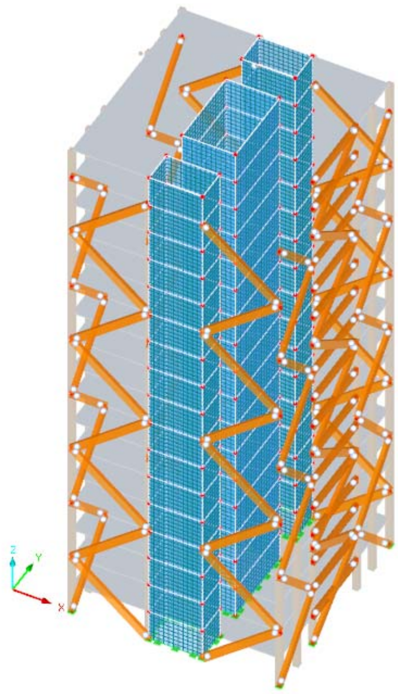


Fig. 6. Horizontal load resistance system

To increase the stiffness of the building as a whole to horizontal loads as well as to increase its seismic resistance, it is necessary to provide a transverse load resistance system in the building (hereinafter — the TLRS). In this building, the TLRS elements are the walls of the elevator shafts made of CLT panels as well as external diagonal members forming vertical trusses (Fig. 6). For comparison, a design scheme was developed where only reinforced concrete stiffening cores act as the TLRS, and the walls of the elevator shafts are made of reinforced concrete with a thickness of 200 mm.

The design model does not take into account the ductility of the element joints, which can affect the stress-strain state of individual elements (Astakhova et al., 2022). The design model adopts completely hinged and completely rigid joints. The braces in the bases of the columns are rigid. To simulate the seismic impact, we used the accelerogram for Friuli, Italy (Finetti et al., 1979). Based on this accelerogram, the response spectrum of the system was generated (Fig. 7).

Based on the given response spectrum, equivalent loads were formed, which were applied to the joints of the finite elements. The design scheme of the adopted structural system was analyzed using the finite element method. The design scheme was built by replacing horizontal and vertical elements modeled in the academic version of Autodesk Revit with rods, and flat structures — with flat elements, and assigning to them stiffness characteristics in accordance with design solutions for each type of load-bearing elements (Chernykh et al., 2020). The calculations were performed using the academic version of DLUBAL RFEM software.

Results and discussion

An analysis of the existing materials in high-rise wooden housing construction shows that most developments were carried out abroad (Filiatrault et al., 2003; Leimke et al., 2017). This is primarily due to the fact that Russia has not yet developed the production of more innovative types of timber structures, and regulatory documents are still under development. Meanwhile, the interest of specialists in these products is quite high (Benin and Ivanova, 2000; Ivanova, 2005) since the use of timber structures is one of the most popular and priority directions in the field of building materials widely used in Russia.

Based on the calculation results, we determined horizontal displacements caused by a specific combination of loads (Fig. 8). We also determined stresses in the multilayer CLT panel of the floor (Fig. 9).

As the isofields of stresses in the slab show, the maximum stresses are observed only in the bearing areas of the columns (Fig. 10).

Let us consider the stress-strain state of the main vertical load-bearing structures as well as the elements of the transverse load resistance system. Figs. 11–13 show forces arising in the columns.

As can be seen, the columns of the multi-story building mainly act as a compressed-bent rod. Figs. 14–18 show forces in the elements of the vertical truss.

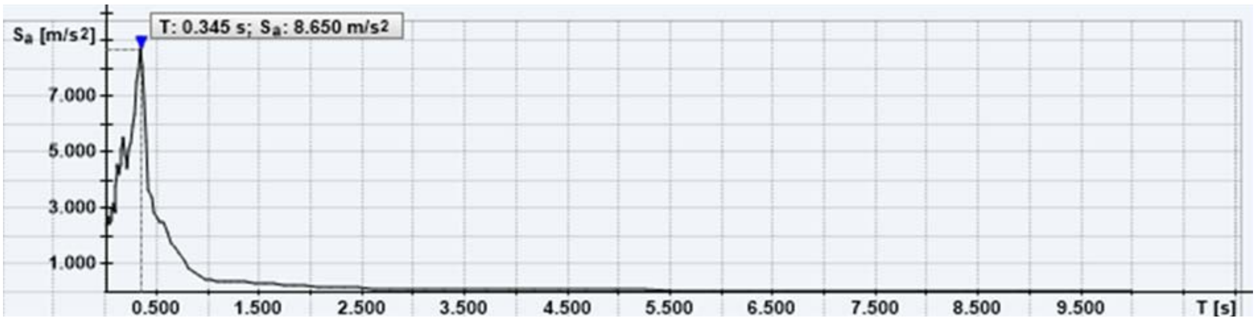


Fig. 7. Synthesized response spectrum from the seismogram

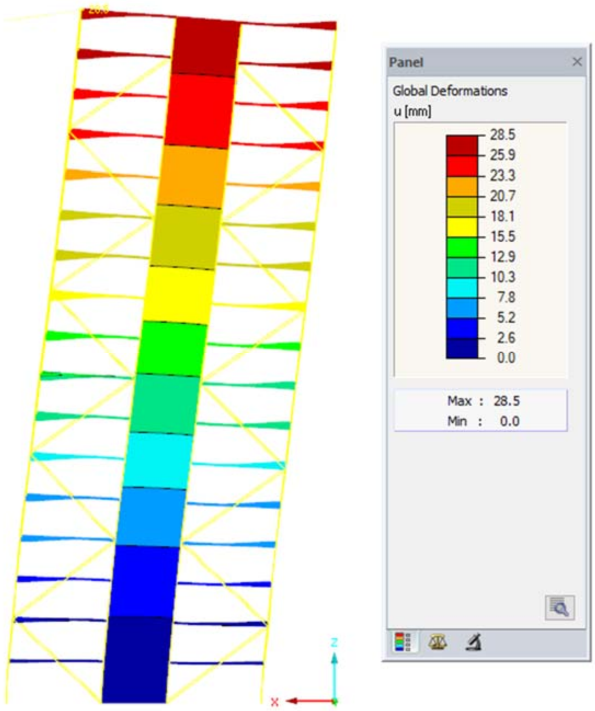


Fig. 8. Deformed scheme of the building as a result of a specific combination of loads

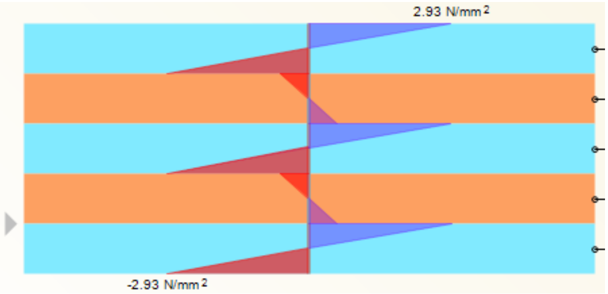


Fig. 9. Maximum normal stresses in the cross-section of the CLT panel of the floor

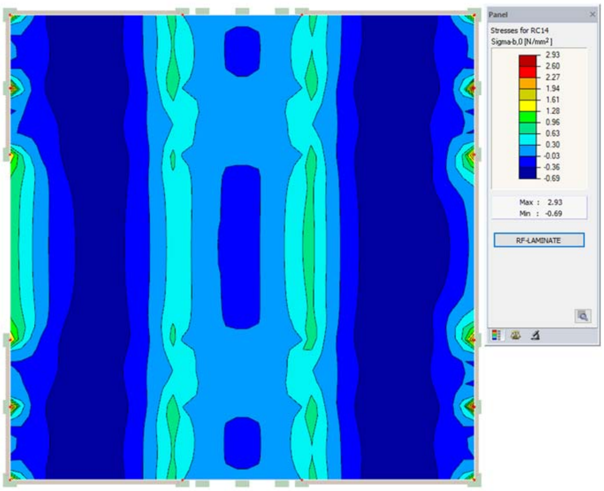


Fig. 10. Isofields of stresses in the CLT panel of the floor

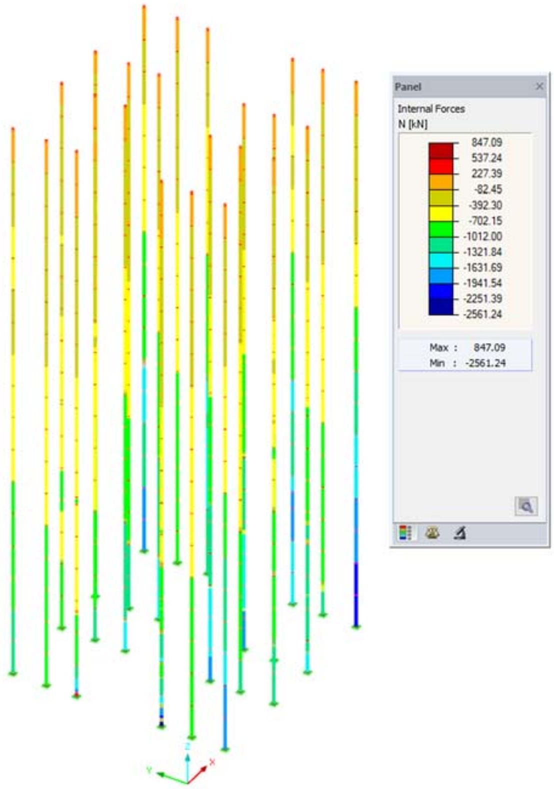


Fig. 11. Diagram of longitudinal force N in the columns of the building

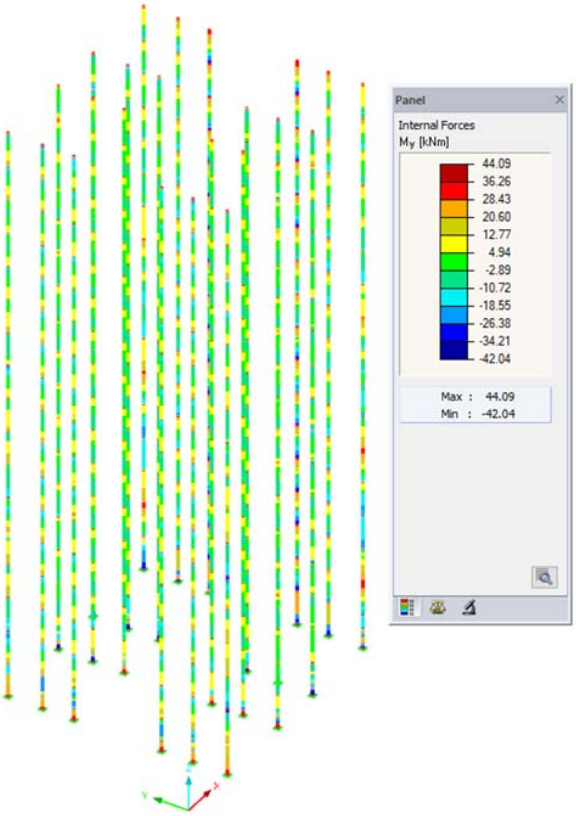


Fig. 12. Diagram of bending moments M_y of force in the columns of the building

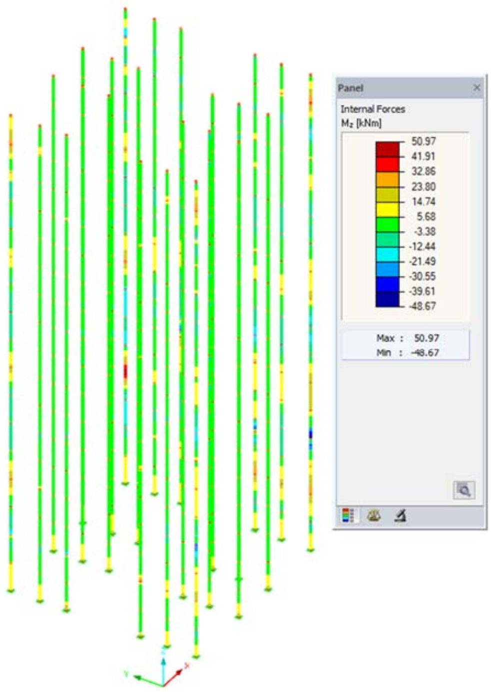


Fig. 13. Diagram of bending moments M_z of force in the columns of the building

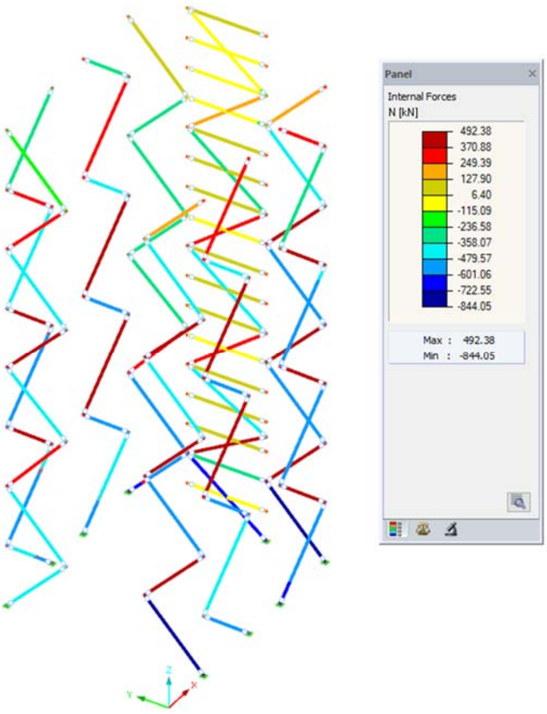


Fig. 14. Force N in the elements of the vertical truss of the building

Based on the presented values of internal forces arising in the mesh elements, we can conclude that the mesh elements act as a compressed-bent or stretched-bent element. The bending moment acts in two planes, being caused under the action of a load equivalent to seismic impact.

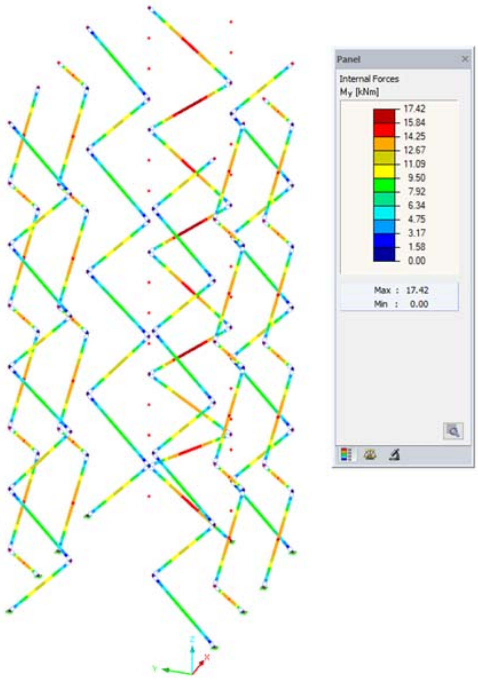


Fig. 15. Force My in the elements of the vertical truss of the building

Let us consider the modes of the building oscillations calculated during the intermediate modal analysis of the scheme. The first two modes of oscillations with the greatest contribution in dynamic analysis are shown in Figs. 19–20.

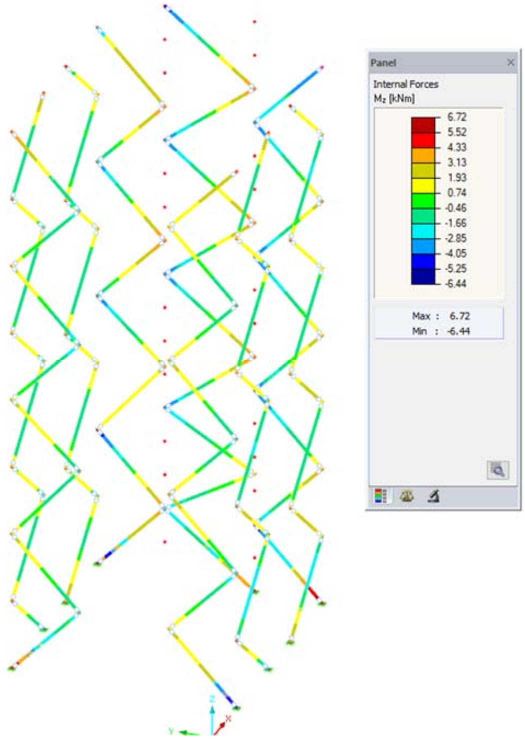


Fig. 16. Force M_z in the elements of the vertical truss of the building

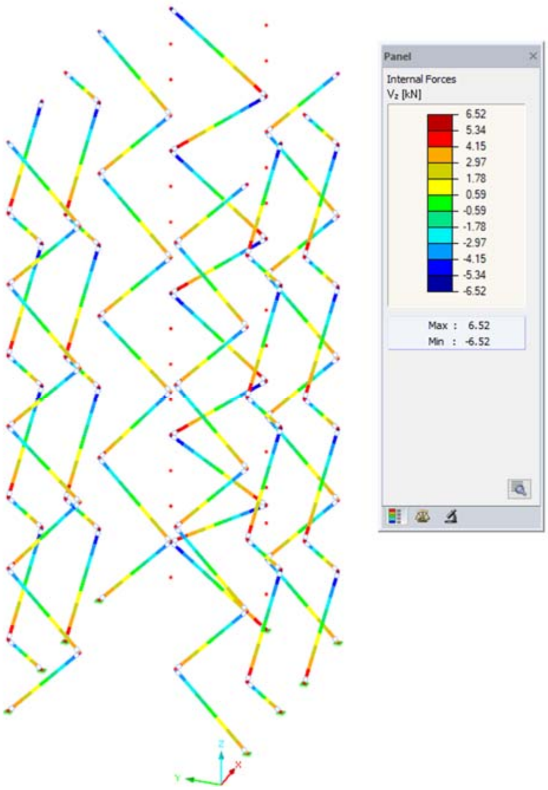


Fig. 17. Force Q_z in the elements of the vertical truss of the building

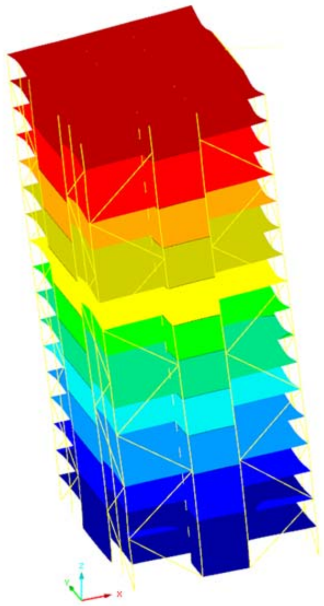


Fig. 19. The first mode of the building oscillations

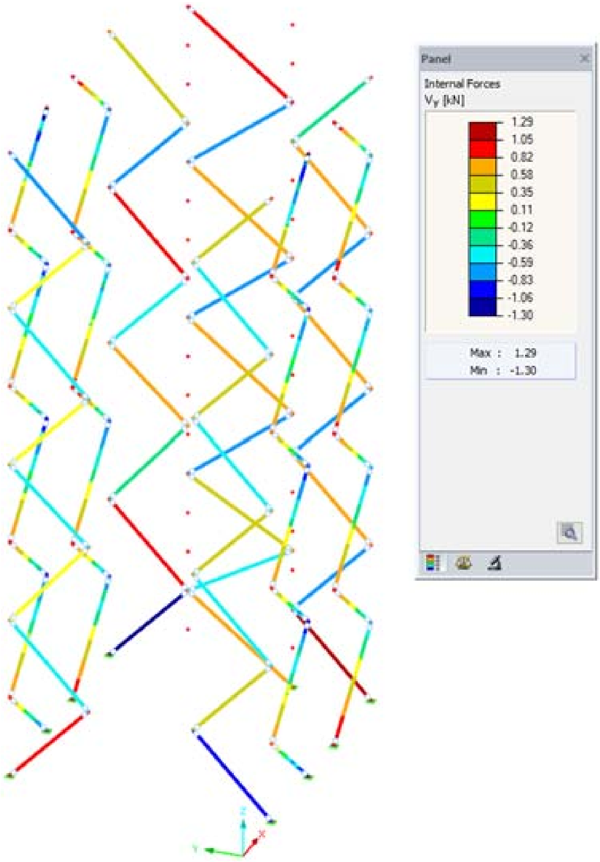


Fig. 18. Force Q_y in the elements of the vertical truss of the building

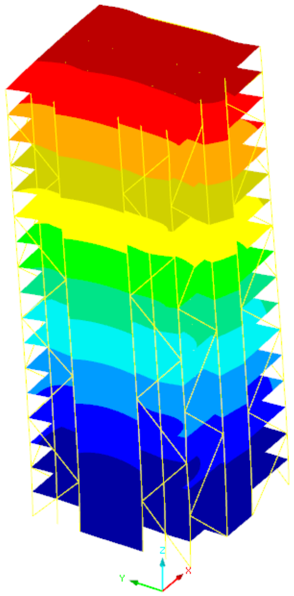


Fig. 20. The second mode of the building oscillations

The oscillation modes presented above represent bending-translational modes of possible oscillations in this building. It should be noted that in the third possible mode of oscillations, the oscillations are bending-torsional. This mode is shown in Fig. 21.

This mode does not affect the final stress-strain state in the elements, since the effective mass inclusion factor for this mode of oscillations is zero or has a near-zero value. Fig. 22 shows the values of the modal mass inclusion factor according to the modes of oscillations. The values in the frame correspond to the effective modal mass factors in the bending-torsional mode of oscillations.

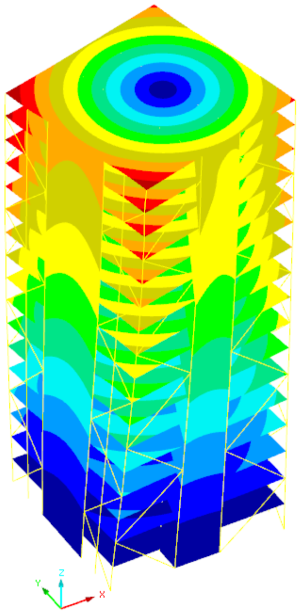


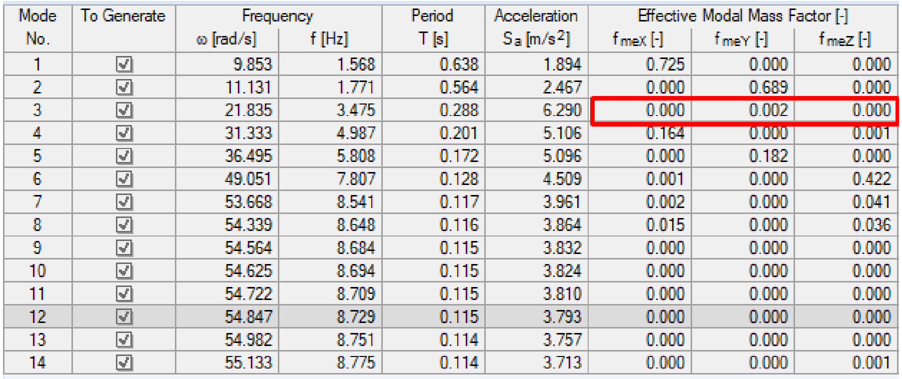
Fig. 21. The third mode of the building oscillations

It should be noted that bending-torsional modes of oscillations should be avoided in multi-story as well as high-rise buildings to prevent the occurrence of significant torsion forces, which are the cause of a significant increase in the cross-sections of the bearing elements of the building.

Let us consider the natural oscillations of a building with reinforced concrete stiffening cores. The first two modes of oscillations with the greatest contribution in dynamic analysis are shown in Figs. 23–24. The first two modes are bending-translational modes of oscillations.

The third mode of oscillations is bending-torsional. This mode does not affect the stress-strain state in the elements of the building, since the effective mass inclusion factor for this mode of oscillations is zero (Fig. 25). Figs. 26–28 show forces arising in the columns.

The horizontal displacements of the scheme with the reinforced concrete stiffening core amount to 25.7 mm (Fig. 29).



Mode No.	To Generate	Frequency ω [rad/s]	Frequency f [Hz]	Period T [s]	Acceleration S_a [m/s²]	Effective Modal Mass Factor [-] f_{meX} [-]	f_{meY} [-]	f_{meZ} [-]
1	☑	9.853	1.568	0.638	1.894	0.725	0.000	0.000
2	☑	11.131	1.771	0.564	2.467	0.000	0.689	0.000
3	☑	21.835	3.475	0.288	6.290	0.000	0.002	0.000
4	☑	31.333	4.987	0.201	5.106	0.164	0.000	0.001
5	☑	36.495	5.808	0.172	5.096	0.000	0.182	0.000
6	☑	49.051	7.807	0.128	4.509	0.001	0.000	0.422
7	☑	53.668	8.541	0.117	3.961	0.002	0.000	0.041
8	☑	54.339	8.648	0.116	3.864	0.015	0.000	0.036
9	☑	54.564	8.684	0.115	3.832	0.000	0.000	0.000
10	☑	54.625	8.694	0.115	3.824	0.000	0.000	0.000
11	☑	54.722	8.709	0.115	3.810	0.000	0.000	0.000
12	☑	54.847	8.729	0.115	3.793	0.000	0.000	0.000
13	☑	54.982	8.751	0.114	3.757	0.000	0.000	0.000
14	☑	55.133	8.775	0.114	3.713	0.000	0.000	0.001

Fig. 22. Effective modal mass inclusion factors according to the modes of oscillations

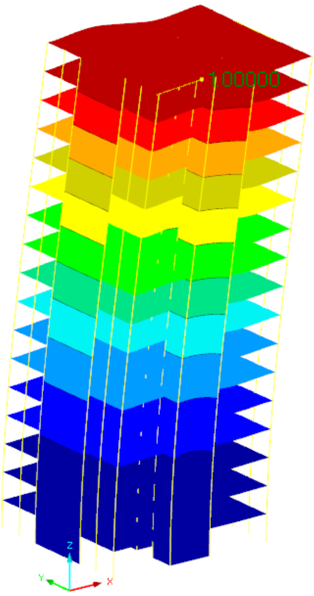


Fig. 23. The first mode of the building oscillations

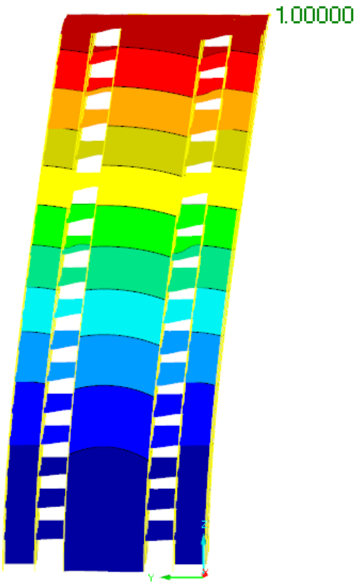
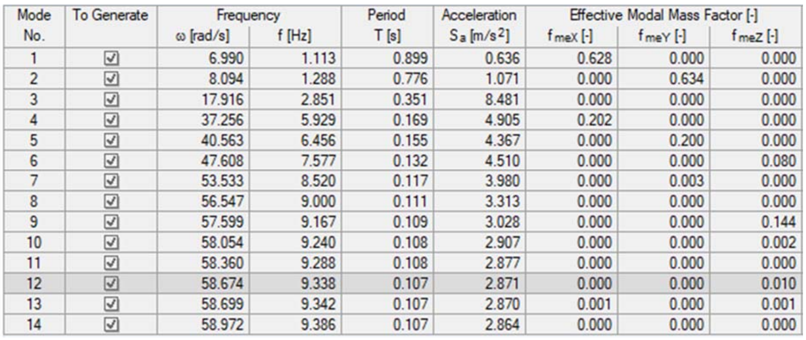


Fig. 24. The second mode of the building oscillations



Mode No.	To Generate	Frequency ω [rad/s]	Frequency f [Hz]	Period T [s]	Acceleration S_a [m/s²]	Effective Modal Mass Factor [-] f_{meX} [-]	f_{meY} [-]	f_{meZ} [-]
1	☑	6.990	1.113	0.899	0.636	0.628	0.000	0.000
2	☑	8.094	1.288	0.776	1.071	0.000	0.634	0.000
3	☑	17.916	2.851	0.351	8.481	0.000	0.000	0.000
4	☑	37.256	5.929	0.169	4.905	0.202	0.000	0.000
5	☑	40.563	6.456	0.155	4.367	0.000	0.200	0.000
6	☑	47.608	7.577	0.132	4.510	0.000	0.000	0.080
7	☑	53.533	8.520	0.117	3.980	0.000	0.003	0.000
8	☑	56.547	9.000	0.111	3.313	0.000	0.000	0.000
9	☑	57.599	9.167	0.109	3.028	0.000	0.000	0.144
10	☑	58.054	9.240	0.108	2.907	0.000	0.000	0.002
11	☑	58.360	9.288	0.108	2.877	0.000	0.000	0.000
12	☑	58.674	9.338	0.107	2.871	0.000	0.000	0.010
13	☑	58.699	9.342	0.107	2.870	0.001	0.000	0.001
14	☑	58.972	9.386	0.107	2.864	0.000	0.000	0.000

Fig. 25. Effective modal mass inclusion factors according to the modes of oscillations for buildings with reinforced concrete stiffening cores

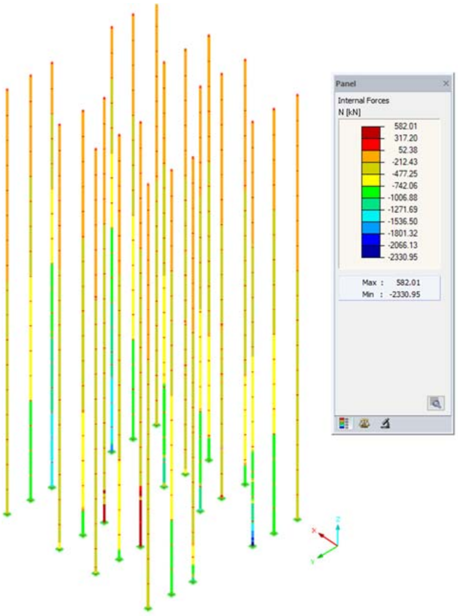


Fig. 26. Diagram of longitudinal force N in the columns of the building

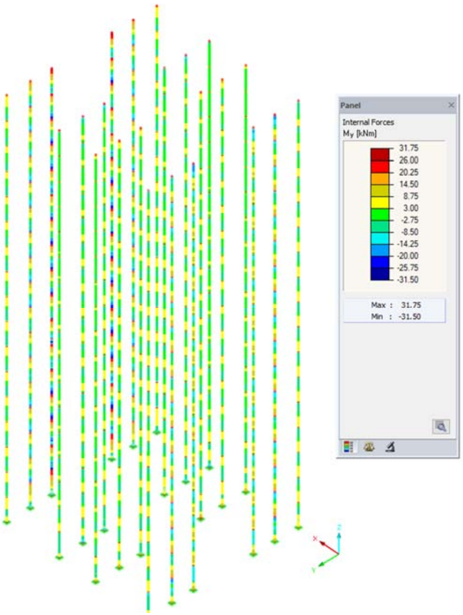


Fig. 27. Diagram of bending moments M_y of force in the columns of the building

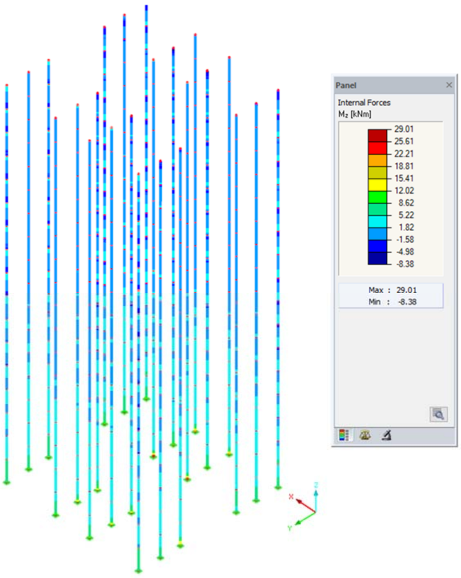


Fig. 28. Diagram of bending moments M_z of force in the columns of the building

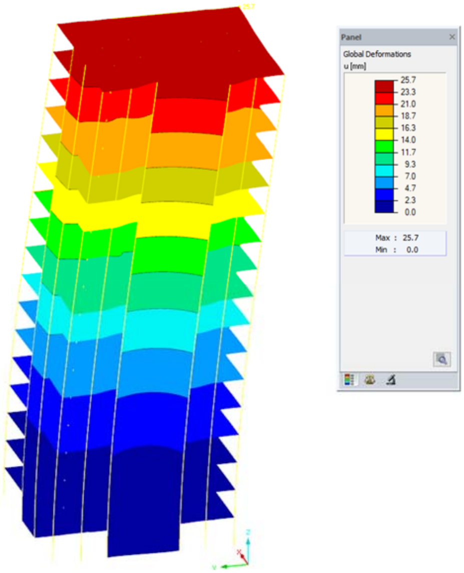


Fig. 29. Deformed scheme of the building with the reinforced concrete stiffening core

Conclusions

The studies performed confirm the possibility of using wood-composite systems for high-rise buildings without the use of concrete and reinforced concrete structures in the superstructure**.** Special attention should be paid to the selection and design of the horizontal load resistance systems, which withstand most of the seismic impact and reduce the possible oscillation amplitude.

During the comparative analysis of the two design schemes, we established the following:

- The first two modes of free oscillations are bending-translational in both cases;
- Bending-torsional modes of oscillations do not affect the stress-strain state in the elements for both the first and second design schemes, since the inclusion of masses in this mode of oscillations has a zero or near-zero value;
- The horizontal displacements of the building consisting entirely of wood composite materials amount to 28 mm, and the horizontal displacements of the building with the reinforced concrete stiffening core amount to 25.7 mm;
- The elements of the diagonal members in the first design scheme with load-bearing elements made of wood composite materials are characterized by a compressed-bent stress-strain state, while the forces of bending moments arise from loads equivalent to seismic impact**.**

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О ВОЗМОЖНОСТИ ИСПОЛЬЗОВАНИЯ ДЕРЕВЯННЫХ КОНСТРУКЦИЙ В СТРОИТЕЛЬСТВЕ ЗДАНИЙ ПОВЫШЕННОЙ ЭТАЖНОСТИ В СЕЙСМИЧЕСКИХ РАЙОНАХ

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Аннотация:
Введение: Часть территории России находится в сейсмически опасной зоне. В последнее время, большую популярность в частном домостроении, а так же в других секторах строительства набирает популярность клееная древесина. Но в отечественной нормативной базе отсутствуют расчетные и конструктивные требования по проектированию зданий и сооружений из клееной древесины**. Метод:** в данной статье производится обзор зарубежного опыта строительства с применением клееной древесины, а так же приводится расчет многоэтажного здания из древесины и материалов на ее основе на сейсмостойкость. **Результаты:** был рассмотрен расчет многоэтажного здания из древесины на сейсмостойкость, рассмотрен зарубежный опыт строительства зданий из клееной древесины. Рассмотрено влияние выбора материала отдельных несущих конструкций на сейсмостойкость.

Ключевые слова: клееная древесина, сейсмостойкость, землетрясения, многоэтажные здания.