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Timber frame buildings with efficient junction designs for earthquake-prone areas

T.A. Belash*, Zh.V. Ivanova
Petersburg State Transport University, St. Petersburg, Russia
** E–mail: belashta@mail.ru*

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Abstract. The object of the study is a timber building of frame type, consisting of timber vertical posts, lower and upper binding, a system of connections (horizontal and vertical), elements of overlap and coating (roof). The impact of an earthquake of different intensity and frequency on the seismic resistance of a timber building is considered. Seismic stability was assessed on the basis of experimental and theoretical studies. Experimental methods were performed on laboratory facilities and large-scale models. Taking into account the experimental data obtained, the calculation and theoretical evaluation of the frame building on simple and complex models under the influence of different intensity and frequency composition was performed. It is established that the frequency composition of seismic impact significantly affects the seismic resistance of frame buildings. It is recommended when designing these buildings to assign their dynamic parameters (period of natural oscillations) depending on the forecast of the prevailing period of seismic oscillations of the construction area, which will more effectively solve the layout of the nodal joints of the frame. It is recommended to introduce additional materials and devices having pliability and high dissipative properties into nodal connections.

1. Introduction

Currently, the use of timber structures in earthquake-resistant buildings is getting more widespread in buildings for various purposes. This is primarily due to the specific properties of the material from which the building structures are made. As is known, the benefits of wood structures include: low weight, low coefficient of thermal expansion, resistance to chemical media, good transportability, cheaper than steel and reinforced concrete, and less labor-consuming than steel and reinforced concrete. However, their disadvantages include flammability, deformability and decay. These properties are usually taken into account in for the design and construction of timber buildings.

Today the range of timber building materials contains dozens of items. The most popular among them are frame products, which are embodied in various civil building designs. Popularity of this type of timber structures is mainly associated with more rational consumption of timber and ability to ensure high energy performance during building operation. In addition, no hoisting machinery is required for construction of such buildings. This is the reason why timber frame buildings have become widely spread in various climatic regions, including those with complicated geological and seismic conditions both in Russia and abroad. The fundamental constructive solution of this building is shown in Figure 1.

The short-term development program adopted in Russia is intended to increase the construction of lightweight frame structures by a factor of 4 times or more. In the USA, more than 80 % of newly built timber houses are of frame type. This type of timber buildings is widely accepted in such seismically active countries as China and Japan. Publications of many Russian and foreign professionals [1–4] describe the main reasons why these buildings are so popular in seismic areas. First of all, they include the following: potential development of plastic deformations in the considered structural solutions; significant yielding that allows to

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accommodate earthquake loads; structures of this type also have a good capability to damp arising vibrations, etc. Seismic resistant behavior of these buildings during earthquakes is confirmed by the survey of timber frame buildings after Kemino-Chui earthquake in 1938 [5], Fukuisk earthquake in 1948 [6], the Chkhaltinsky earthquake in 1963 [5] and others. It should be noted that the buildings examined after Chkhalta earthquake were erected on flexible posts from 1.5 m to 1.8 m high [5].

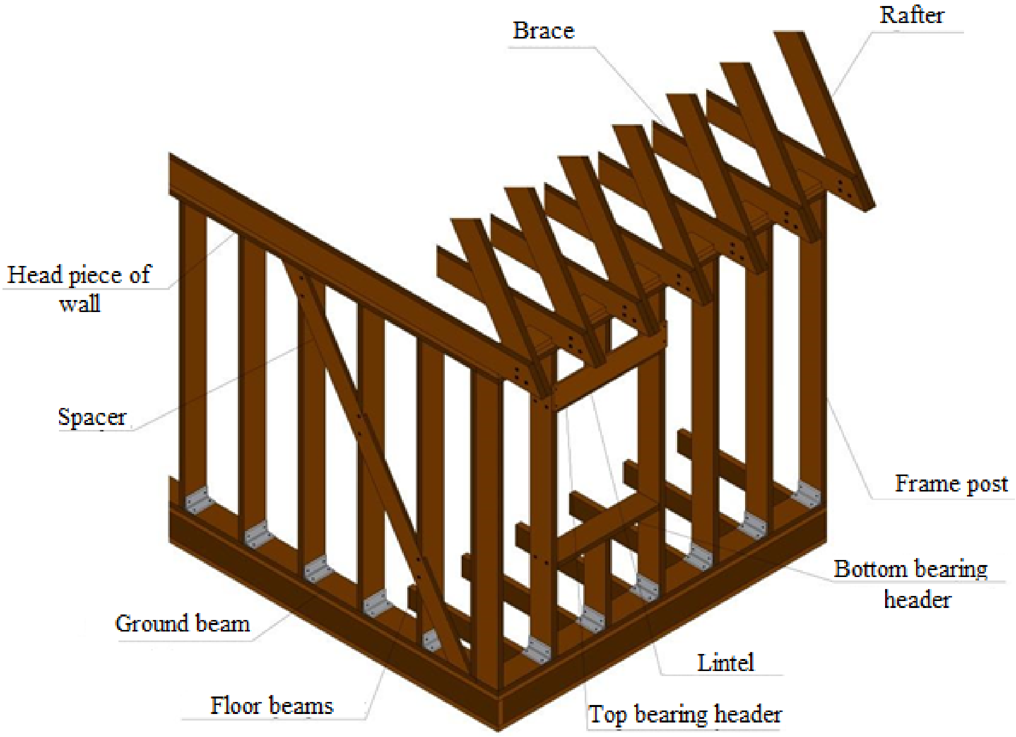

Figure 1. Timber framework arrangement.

In current earthquake-resistant timber frame construction industry, certain design approaches for these buildings are in place, including the following measures. The main frame studs and braces shall be secured to the ground beam using anchor bolts and metal plates (clamps) made of strip steel securely embedded in the foundation (Figure 2, a-c). Fastening to interfloor plates is made using drift bolts similar to fastening of interfloor beams to intermediate posts (Figure 2, d). Building stiffness is achieved using oblique siding of the frame wall structure. Nails, clamps and pads [3] shall be used to joint frame components in the nodes.

However, despite the set of the above listed structural measures, timber frame buildings can be severely damaged during earthquakes. This is primarily due to the fact that the seismic impact spectrum contains different frequency components, which, on the one hand, are not dangerous for this type of buildings that was confirmed by the investigation of strong earthquakes (examples of which are listed above), and on the other hand, seismic impacts may contain low-frequency components which cause serious oscillation buildup in the frame building.

Figure 3 shows examples of such destructive impacts caused mainly by the failure of frame nodes as result of large displacements of the foundation. As described in [7–10], in two-storey buildings, the weakened ground floors were damaged or completely destroyed, while the upper floors remained undamaged. A frequent type of damage in these buildings is the lack of a strong bracing between the timber portion and foundation. Significant damage and failure occur in stub-in and mortise joints.

The review of theoretical and experimental studies of timber frame buildings conducted in the recent years by many authors, including the authors of this publication, in Russia and abroad [11–64] shows their significance and scale. Meanwhile, to assess the real picture of the stress-strain condition of timber frame buildings based on the elastic and dissipative properties of nodes, as well as on the accumulated experience of behavior of these buildings during various types of earthquakes, additional studies and updates are required using new software packages and advanced experimental facilities.

On the basis of the above, the object of the study is a timber framework building of civil purpose, in which the main attention is paid to the structural work of node joints under seismic impacts taking into account the peculiarities of their manifestation, namely various effects of frequency character and its intensity. Various rigid and dissipative parameters of the timber frame are considered, taking into account which the complete assessment of seismic resistance of the building as a whole was carried out.

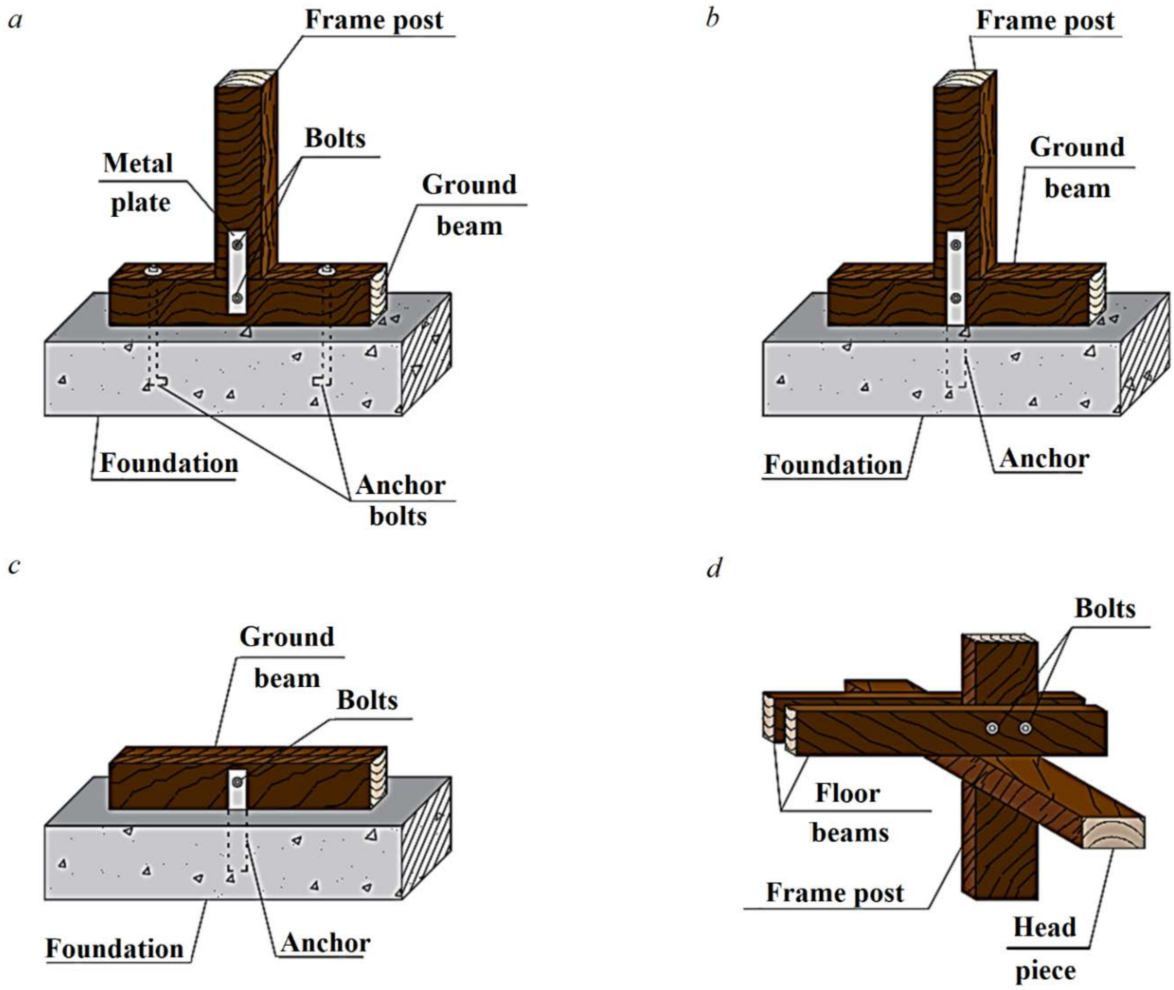

Figure 2. Connection options: between frame building studs and ground beam at the intersections of walls (a, b) and in intervals (c); floor beam-to-post joint (d).

It should be noted that earlier studies in Russia and abroad did not fully take into account the above-mentioned factors, both at seismic impacts and at various design solutions of timber frame buildings. In the normative practice, there are practically no recommendations on the design of timber frame buildings.

In this connection, the results of the studies presented in this article make it possible to estimate more objectively the seismic resistance of such buildings in seismic areas and thus to expand the possibility of their use.

2. Method

For real assessment of stress-strain condition of timber frame buildings, a set of experimental studies was carried out, which included two test stages.

At the first stage, mechanical and dissipative properties of the main members and nodes of a timber frame building were assessed. The test was carried out on various versions of frame post-to-beam nodes and on wall segments. The studies were carried out using dedicated laboratory facilities and included static and dynamic loading stages. Dynamic loading was applied using short-term and long-term cyclic load at forced oscillations with a frequency of 3Hz, 5Hz and 8Hz. Examples of the design versions of the "post – beam" test nodes with various dowel connection options are shown in Figure 4. A general view of the test facilities is shown in Figure 5. The wall was assumed with a post-to-post width of 1.2 m and a height of 3 m per floor (Figure 6). The wall test included the assessment of damping properties of the structure by logarithmic decrement and natural vibration frequency, and quasistatic bend test of the wall also performed. Bearing capacity of the structure was evaluated based on the test results.

Figure 3. Examples of timber frame building failures: a – March 1970 Geiz (Turkey) [8–9]; b – earthquake in San Francisco (USA) in 1989; c – earthquake in Norwich, California (USA), in 1994 [10]; d – earthquake in Kumamoto (Japan) in April, 2016 [7].

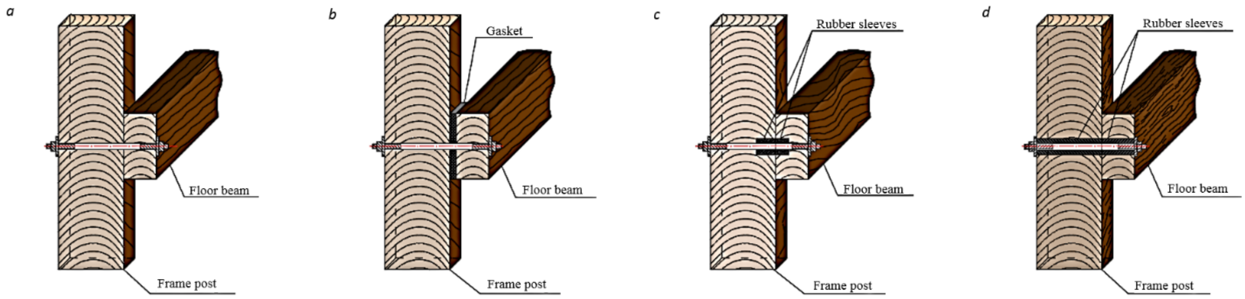

Figure 4. Versions of the test models of "post – beam" nodes: a – dowel connection version; b – gasket made various materials (steel, rubber) is installed between the post and a beam; c – using a rubber sleeve with a length equal to 1/3 length of the node components; d – using a rubber sleeve with a length equal to the entire length of the node components.

At the second stage, the obtained characteristics and parameters were checked, updated and used to develop final recommendations for evaluation of timber frame building performance. The study was carried out on a large-scale model of a frame building, a general view of which is shown in Figure 7. The tests were carried out on a specially designed bench capable of accommodating items with horizontal dimensions of 7.0 m x 2.5 m and a height up to 6.0 m. Cable sensors were used to record the movements of the model. Data collection, recording and control were carried out using a dedicated system with a capacity of 64 channels installed at the test bench.

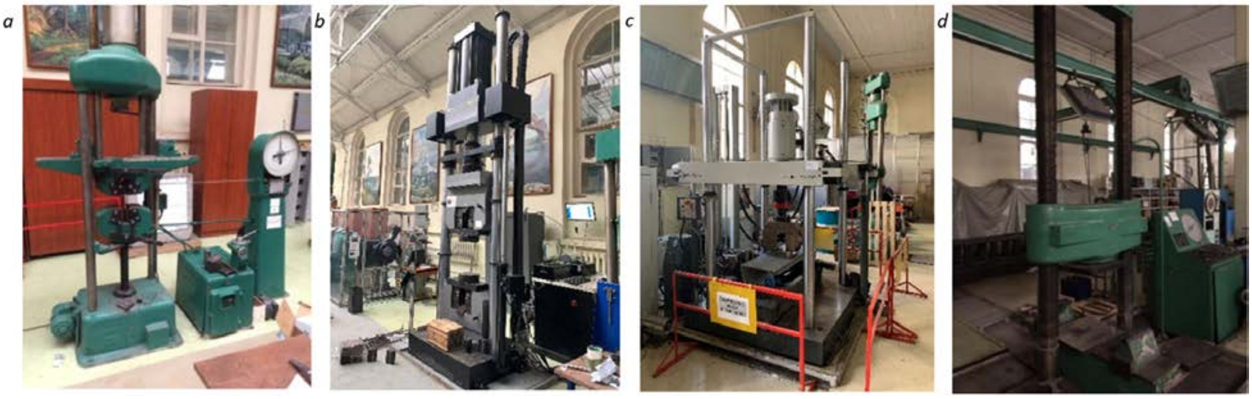

Figure 5. General view of the installations: a – TsDM-30 general-purpose machine (Germany); b – HB-250 testing machine (pulsator) (Germany); c – general-purpose static test machine with SATEC 1200KN-J3D hydraulic drive (USA); d – PPM-250 universal press (Russia).

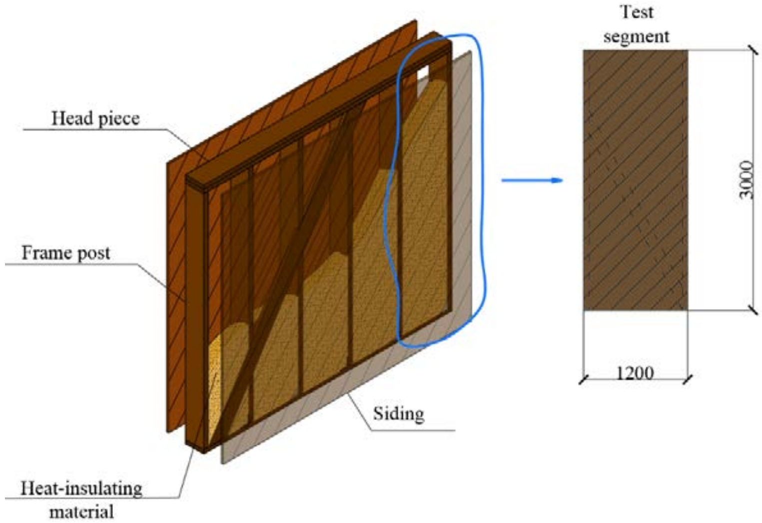

Figure 6. General view of the wall and test segment.

Figure 7. General view of the model mounted on the test bench.

The experimental studies were used to conduct a theoretical analysis of the behavior of this type of timber buildings. The studies were carried out according to the specified method using the spectral calculation and dynamic methods for actual earthquake accelerograms. Examples of calculation models used for the analysis are shown in Figure 8.

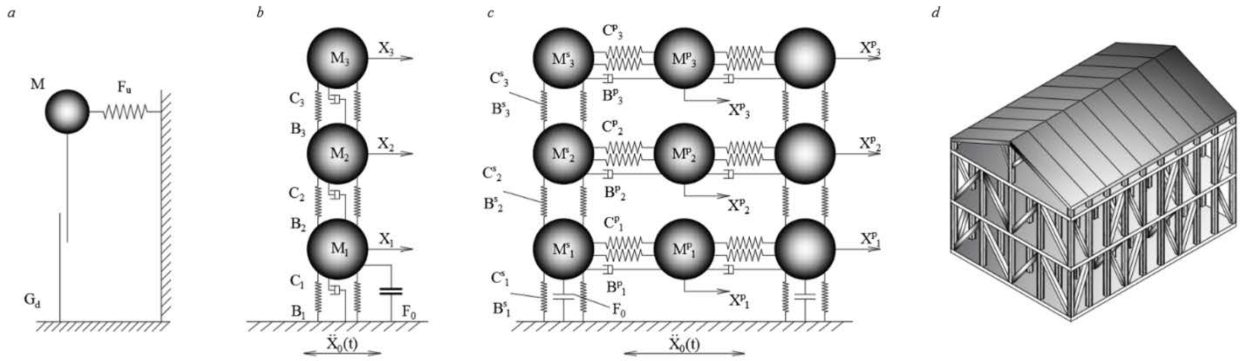

Figure 8. Design models of the building: a – single-mass nonlinear oscillator; b – basic linear model; c – building model with yielding bracing; d – three-dimensional finite element model.

As the initial object, a two-storey frame building was adopted with natural period of oscillations within 0.1 sec. During the study, the stiffness parameters of the building were varied. To consider foundation yielding, spring elements were included in the calculation model, stiffness factors of which corresponded to various soil conditions. In previous studies, the authors showed the need for yielding in frame nodes [4, 58, 60]. In this regard, when performing further studies, additional yielding parameters and damping factors were included in the elastic restraints between the floors and frame. To perform dynamic calculations, accelerograms of strong earthquakes with a fairly wide frequency range were selected. Dynamic calculations were performed by numerical integration according to the 4th order Runge-Kutta method. Three-dimensional performance test of the building was carried out by the finite element method using COSMOS V.2.9 software package.

3. Results and Discussions

The results of the studies are partially reflected in the publications by the authors [57–60]. It should be noted that the actual behavior of a timber frame building during earthquakes essentially depends on the design of all nodes which, on the one hand, must have a certain yielding and stiffness and, on the other hand, have sufficiently high potential dissipative properties that limit dangerous displacements during low-frequency impacts. Some results of experimental studies are shown in the form of diagrams in Figure 9.

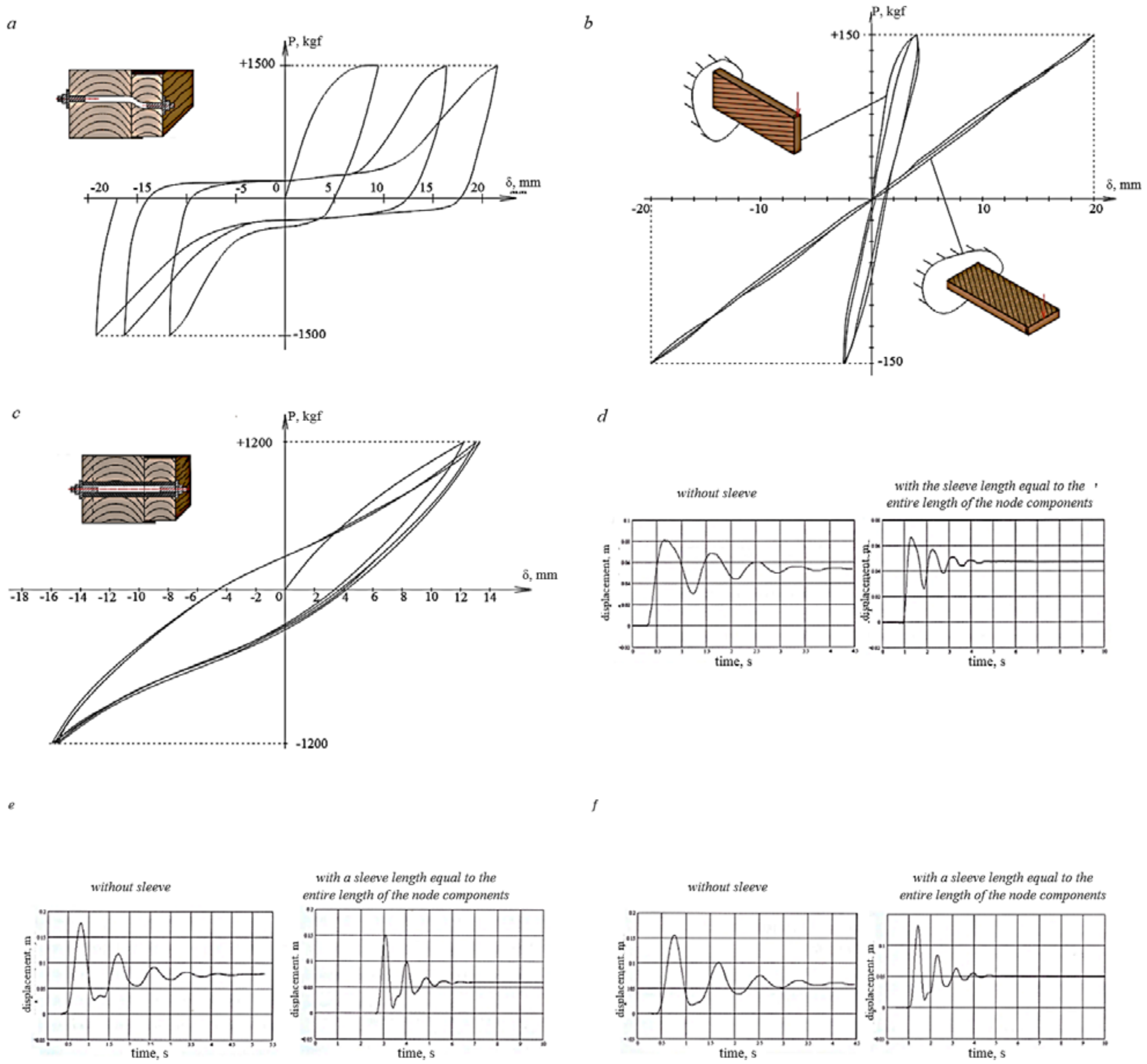

Figure 9. The results of experimental studies: a – «post – beam» node strain diagram; b – wall bending strain diagram; c – «post – beam» node strain diagram with a sleeve length equal to the entire length of the element; d – vibration mode (at the framing beam level) of the timber frame building foundation when exposed to magnitude 8; e – vibration mode of the upper part of the building when exposed to magnitude 8; f – vibration mode of the upper part of the building when exposed to magnitude 9.

During the experimental study, various designs of the main nodes such as «post – beam» nodes were used. The experimental studies have shown that rubber sleeves of various lengths inserted in the nodes changed the stress-strain condition of the node as compared to a traditional dowel joint. So, compression of timber in the initial hole without a rubber sleeve ranged from 2 mm to 3 mm, while no compression occurred when a rubber sleeve was inserted.

The results of the theoretical analysis of the seismic resistance of timber frame buildings confirm the results of the previous studies of the impact of yielding and dissipative properties of components materials on the stress-strain condition of timber structures under earthquake loads with various frequency content. For this, it is necessary to ensure a reasonable relationship between the period of natural vibration of the building and the prevailing period of earthquake when assigning certain parameters of vibration damping to the building structures. So, to reduce the earthquake load by a factor of 2 or more, it is necessary to ensure a natural vibration period of the building in the range from 0.8 s to 1 s, which is achieved by certain yielding of the attachment nodes of floors and frame posts. The introduction of additional elements, for example, the use of rubber sleeves, etc., allows you to achieve the desired result. At the same time, the deformability of the nodes shall be at least 6 cm to 10 cm.

The results obtained allow us to conclude that the proposed structural solutions of nodal connections are highly efficient compared with existing proposals presented in [62–64].

4. Conclusion

1. The stress-strain condition of timber frame buildings during earthquakes significantly depends on the nature of the seismic impact and its frequency content which has a significant influence on its seismic resistance.

2. For design of timber frame buildings in areas of seismic activity, it is recommended to assign the fundamental period the building depending on the predicted prevailing period of seismic vibrations in the construction area.

3. In the case of strongly pronounced high-frequency vibrations, the frame nodes shall include yielding components such as rubber gaskets. For low-frequency impacts, dangerous movements arising from these vibrations shall be preferably limited by the insertion of additional components with enhanced dissipative properties. For this special materials or damping devices may be used.

4. When data on the frequency content of seismic impacts to reduce seismic loads by a factor of 2 or more are not available, the yielding parameters of support anchors shall be assigned based on the natural vibration period of the building, which shall be in range from 0.5 s to 0.8 s, while the deformability of the nodes shall be at least 6 cm.

5. The performed studies confirmed the results previously obtained by the authors regarding the influence of design of timber frame building nodes and dissipative properties of building materials on the stress-strain condition of timber structures under seismic loads. In this regard, it is recommended that the most careful approach be used when designing frame nodes and selecting the best materials and products for them.

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Contacts:

Tatiana Belash, +7(921)9910115; belashta@mail.ru
Zhanna Ivanova, +7(921)9818419; syrmava@mail.ru

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Деревянные здания каркасного типа с эффективными конструкциями узловых соединений для сейсмически активных районов

Т.А. Белаш*, Ж.В. Иванова
Петербургский государственный университет путей сообщения Императора Александра I, Санкт-Петербург, Россия
** E–mail: belashta@mail.ru*

Ключевые слова: малоэтажное строительство, деревянные конструкции, сейсмостойкость, деревянные здания каркасного типа, расчетно-экспериментальные исследования

Аннотация. Объектом исследования является деревянное здание каркасного типа, состоящее из деревянных вертикальных стоек, нижней и верхней обвязки, системы связей (горизонтальных и вертикальных), элементов перекрытия и покрытия (крыша). Рассматривается воздействие землетрясения различной интенсивности и частотного характера на сейсмостойкость деревянного здания. Оценка сейсмостойкости произведена на основании экспериментальных и расчетно-теоретических исследований. Экспериментальные методы выполнялись на лабораторных установках и крупномасштабных моделях. С учетом полученных экспериментальных данных выполнена расчетно-теоретическая оценка каркасного здания на простых и сложных моделях при воздействии различной интенсивности и частотного состава. Установлено, что частотный состав сейсмического воздействия существенным образом влияет на сейсмостойкость каркасных зданий. Рекомендуется при проектировании этих зданий назначать их динамические параметры (период собственных колебаний) в зависимости от прогноза преобладающего периода сейсмических колебаний района строительства, что позволит более эффективно решать компоновку узловых соединений каркаса. Рекомендуется в узловые соединения вводить дополнительные материалы и устройства, обладающие податливостью и высокими диссипативными свойствами.

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Контактные данные:

Татьяна Александровна Белаш, +7(921)9910115; эл. почта: belashta@mail.ru
Жанна Васильевна Иванова, +7(921)9818419; эл. почта: syrmava@mail.ru