Acta Polytechnica **64**(6):511–518, 2024
`https://doi.org/10.14311/AP.2024.64.0511`

ANALYSIS OF RETICULATED DOME WITH UNIVERSAL CONNECTOR

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Abstract. In order to investigate the stress-strain state of a 4 m diameter reticulated dome model, four series of glued wooden rods were prepared for centric and eccentric compression tests. The tests were carried out in the laboratory of the Department of Metal Wood and Plastic Structures. The stresses at the specific points of the elements were determined through the deformations using the strain gauges. The feature of the prismatic specimens was the stress concentrators in the bearing areas in the form of holes for the arrangement of universal connectors. These areas were also reinforced with steel sleeves. The general conclusion of the study is the high load bearing capacity of the tested samples. The destruction of the samples occurred in the bearing zone due to wood crushing. The next research tasks will be to optimise the dimensions of the elements and test the dome model. The cross-section of the elements, in addition to providing the load-bearing capacity, is also influenced by the need to obtain certain thermal characteristics of the enclosure, i.e. the dome elements should have dimensions that allow placing a layer of an effective insulation in their plane. A special task is to choose a roofing that can be considered only as a part of the constant load on the load-bearing system or as a continuous shell that unbinds the frame.

Keywords: Glued wood, reticulated dome, centric compression, eccentric compression, connector.

1. Introduction

Domes are one of the most cost-effective spatial structures. Domes have significant architectural expressiveness and uniqueness. Their use in urban environments improves the appearance of massive developments. The main problem limiting the use of domes is the lack of domestic research. We are not even talking about the material and type of the construction. Our architects and designers are limited to small-diameter steel domes on the roofs of multi-story buildings as an architectural decoration. An additional obstacle to the introduction of domes into widespread construction practice is the lack of a reliable and simple design solution for the nodal connection. The problem has a general nature, since the experimental studies are labour intensive and require the appropriate equipment and qualified specialists. Therefore, the research of a dome made of glued wood with the corresponding tests of its elements and the analytical calculation with a modern software package is a task of an utmost importance. We have proposed a universal connector for connecting the dome elements at the required angle [1]. The research subject was a digital model of the dome and its elements tested for the static load. The different types of domes were analysed to select the most effective one for the proposed universal connector.

Domes have their dimensions characterised by a diameter, rising height, and thickness of the working surface. The ratio of these values to each other is also extremely important to the dome dimensions. If we take the diameter as a basis, the ratio of the rising height to the diameter can be in the range from $\frac{1}{10}$ to 2–3, while the variation of the ratio of the coating thickness to the diameter is possible in the range from $\frac{1}{1\,000}$ to $\frac{1}{4}$. These limiting ratios limit the concept of the dome roof shape in construction. According to the diameter value, it is necessary to identify small domes, from 4 to 10 m, medium ones – from 10 to 30 m, and large ones – over 30 m. According to the size of the rising height, the domes are divided into the following groups: with a reduced height, when $f < \frac{1}{2}$ diameter, with a normal height, when $f = \frac{1}{2}$ diameter, with an increased height, when $f > \frac{1}{2}$ diameter, and with a pointed shape, when f is greater than the diameter. According to the thickness of the working construction, there are domes with a small thickness of the construction, which is $\frac{1}{1\,000}$–$\frac{1}{200}$ of its diameter, domes with a normal thickness, with a ratio to the diameter of $\frac{1}{200}$–$\frac{1}{40}$, and domes with a high thickness of the working load-bearing construction, which is $\frac{1}{40}$ of the diameter and more.

According to the surface type, the domes can have a curved surface, most often they are spherical domes, but they can also be parabolic, hyperbolic, elliptical, and with a faceted surface. According to the type of the basic dome shape, we can define full domes and cut domes, which form different shapes of dome cross-sections. Only a part of the dome contours can be cut. Basically, the dome divisions formed by the vertical and inclined planes of the cross sections reproduce only the external scheme of the dome part, and in terms of construction, they often consist of separate frames, arches, and vaults. Depending on the stresses in the dome elements, the envelopes can be compressed and the frames can be compressed and bent. The most characteristic type of the dome structure behaviour is compression, which appears both in the meridional direction and in the horizontal direction.

In the direction of the thrust, there are domes that transfer the thrust to the ground through the foundations and transfer the thrust to the elements of the coatings or vertical walls of the structure, and the domes that take the thrust with a supporting ring beam. According to the nature of the work, it is possible to distinguish between solid domes, where the shell has the function of a working and enclosing structure, and through ones with a rigid spatial framework, in which the bearing function of the shell is transferred to the individual rods. Through-dome shapes are most typical for the materials that behave well in transverse bending and longitudinal forces. And false domes, which create only the external architectural form, with radially arranged beam, frame, and arch structures [2]. We are interested in the domes in the form of a reticulated spatial frame made of a single renewable material – wood.

A sphere is known to be able to cover a given volume with the smallest surface area. Therefore, a hemisphere is the most efficient shape for covering a given area. If the hemisphere is reshaped into a parallelepiped, it turns out that up to 30 % of the interior space is lost. Since most traditional houses are a combination of rectangular shapes, the average loss of interior space compared to a dome structure can reach 60 %. The shape of a building is the number one factor in its energy efficiency. The amount of heat loss depends primarily on the total surface area of the envelope. For our research, we took a hemisphere with a diameter of 4 m. Such a dome can be considered not only a model but also a small structure. The comparison of a dome with a radius of 2 m with a traditional parallelepiped house, measuring 3 × 4 m in plan, of similar area and volume, shows the significant savings in the wall surface area. The dome has volume $V_k = \frac{\frac{4}{3}\pi r^3}{2} = 16.75\,\mathrm{m}^3$ and lateral surface area $S = \frac{4\pi r^2}{2} = 25.12\,\mathrm{m}^2$. The parallelepiped has a volume $V_n = a \cdot b \cdot h = 16.8\,\mathrm{m}^3$ and a side surface area $S = a\cdot b + a\cdot h\cdot 2 + b\cdot h\cdot 2 = 31.6\,\mathrm{m}^2$. In other words, the savings are 21 %, and an additional advantage is that the height of the room in a domed building is much higher. In terms of calculations, reticulated domes are a complex, trussed, spatial, statically indeterminate system. This architectural and structural form creates a multifaceted surface that can be transformed into a completely smooth and plain dome at its limit. The main disadvantages of this form include the complexity of calculation and the difficulty of designing nodal connections. The availability of a design solution of a simple universal nodal connector will allow the maximum use of wood in such domes, which behaves well in transverse bending and compression. Additional advantages of this design are the uniformity of the frame nodal connections, the possibility of their serial production and ease of installation.

The calculation of compressed and bending elements based on the stability theory is described rather extensively in the publications by S. P. Tymoshenko, E. A. Dmytrenko, A. R. Rzhanitsyn, etc. [3–5]. The calculation of eccentrically compressed and compressed-bending elements is carried out using the formulas based on the deformation method. The influence of longitudinal forces on the bending moment is considered by the separate coefficients specified in the standards and regulations.

Compressive and bending elements operating as a part of a dome roof have a number of specific characteristics, such as: elastic clamping on the supports, in the contact areas with the nodal part, and the resulting supporting bending moments. Interesting research data on the stress-strain state of glued wooden shells are given in the works of B. Miryayev, E. Shchepetkina, H. Khunagov, K. Pyatikrestovsky, H. Rebelo, B. Misztal, and Mehdi H. K. Ying Gao [6–13]. The researches and works of A. Guriev, D. Mykhaylovsky, Ye. Bakulin, and A. Turkov focus on the problems of including the real characteristics of the deformability of the joints in the calculation of building structures [14–17]. The spatial nature of the behaviour of rod structures with cyclic symmetry is thoroughly investigated in the works of V. Lebedev and D. Vainberg [18, 19], devoted to the development of a method for calculating cyclic rod systems. In these publications, a rod structure is considered as a spatial rod system under the influence of a complex spatial system of forces. In the strength calculation, the force method and the displacement method are used to calculate the strength of the cyclic symmetric systems. The nodes of the structure are "laid" on the surface of rotation at the intersection of meridians and parallels. The humidity level has a significant impact on the behaviour of a spatial structure made of wood, which was analysed by S. Gomon and T. Janiak [20, 21].

The aim of the work is to carry out an experimental and computational analysis of the stress-strain state of the elements of a reticulated dome made of glued wood under centric and eccentric compression, in order to determine their load bearing capacity under the influence of static loading.

2. Materials and methods

A dome model element with a diameter of 4 m was chosen as the object of study – two types of glued wooden beams with a cross section of 40 × 150 mm, with holes at the ends for placing a universal connector. Each type was tested for the centric and eccentric compression. The material used for the samples was second-grade pine glued wood. Four batches of samples were produced, three samples in each: two series with free holes, two with reinforced steel sleeves (Figure 1). In

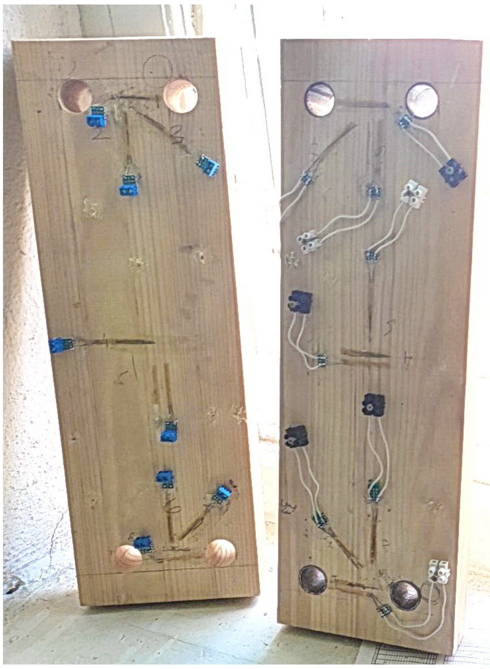

Figure 1. Samples with and without sleeves.

Markings	Marking of the samples	Sample size [mm]	Quantity	Test method	Purpose of the study
SERIES 1 with free holes	C1	800 × 150 × 40	3	Centric compression	Ultimate load-bearing capacity
SERIES 2 with free holes	C2		3	Eccentric compression	
SERIES 3 with the holes strengthened with steel sleeves	C3		3	Centric compression	
SERIES 4 with the holes strengthened with steel sleeves	C4		3	Eccentric compression	

Table 1. Description of experimental samples.

accordance with the research tasks, a programme of experimental testing of the prototypes was developed (Table 1).

The compression tests were carried out in the laboratory of the Department of Metal, Wooden and Plastic Structures of the Odesa State Academy of Civil Engineering and Architecture. The tests were carried out on a test bench using a hydraulic jack with a maximum possible load of 20 tonnes. The test bench is a steel frame fixed to the power floor. The design scheme of the rod was accepted as freely supported. The load value was monitored by a pressure gauge based on the divisions of the built-in indicator. To study the stress-strain state, the strain gauges made of the constant wire on a film base with a base of 30 mm were used. To record the data, a strain gauge station was used to measure the output voltage of the strain gauges and transmit the information to an external control computer. The diagram of the strain gauge arrangement is shown in Figure 2.

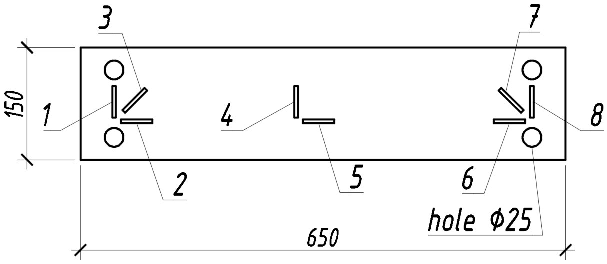

Figure 2. Diagram of the arrangement of the resistive strain gauge.

Figure 3. Compression test bench for glued wood samples.

The eight strain gauges used to measure the relative strains were placed mirror-symmetrical to the horizontal axis of the sample to allow verification of equally placed devices (Figure 3). The samples were loaded in equal increments of 10 % of the total calculated load. The full cycle of one loading stage was 10–15 minutes. The loading time at each stage was 1 minute and the load holding time was 15 minutes. Strain measurements were taken after loading and immediately before a new loading stage. During the tests, the state of the test structure was constantly monitored to detect any possible damage. Before starting the tests, a "zero" stage was created, followed by a zero load. The purpose of the test load was to bypass the steel gaskets between the sample and the jack.

3. Results

The calculation of the static loads was carried out using the multifunctional software package "PC LIRA-SAPR", designed for the design and calculation of building structures. It has a large library of finite elements, multifunctional processors, and product ranges. This allows to calculate the structures of any type of complexity for different types of static and dynamic actions. The calculation is based on the finite element displacement method. The structure is modelled as a frame structure located on the surface of a truncated sphere. The lattice elements are universal spatial rod, type 10. During the numerical experiment, it was planned to determine the strains of the nodes and the values of the forces in the elements of the dome model with a diameter of 4 m. The load was concentrated and applied to the nodes in increments of 10 kg up to a maximum of 50 kg. Thus, the total load on the dome nodes was 1 tonne. Under such a load, the growth of the strains and forces can be assumed to be linear; the influence of the elements' defects was not taken into account, since the significant plastic properties of wood at this load level can be considered insignificant. The nodal joints were considered to be rigid, operating by friction forces. To analyse the stress-strain state of the structure, two loadings were used: the first was evenly distributed, with the nodal load applied to all the nodes (Figure 4), and the second was asymmetrical, with the load applied to only one half of the dome (Figure 5). The values of the bending moments in the elements were very small, so the analysis was carried out on the longitudinal forces and deflections of the nodes at a maximum load of 50 kg per node. For a uniformly distributed load, it was expected that the maximum force values would be obtained in the reference contour, with a slight difference in their values in the individual elements. They mixed in pairs, two adjacent support elements, with a higher and a lower value of the longitudinal force. This distribution is explained by the hexagonal dome cell pattern with a pentagonal upper central cell. The forces from the corners of the pentagon are transferred through the elements adjacent to them to the two nearest elements of the reference contour. In these elements, the forces are slightly higher than in the two adjacent support elements (Figure 5). If only one half of the dome is loaded, the longitudinal elements of the loaded part will experience less stress, while the elements of the free part will experience significantly less stress. There were no fundamental changes in the behaviour of the dome, all the rods are acting in compression. There is no danger of total loss of stability. This distribution of forces is confirmed by the strain-deflection curves (Figures 6 and 7). There is a uniform decrease from the top nodes to the bottom nodes under continuous loading and an increase in the deflections in the central part of the dome under half surface loading. However, the absolute values of the strains relative to the diameter are insignificant, which allows the geometric dimensions of the elements to be optimised when designing larger structures.

Based on the test results, the experimental dependencies of compressive forces and strains were plotted

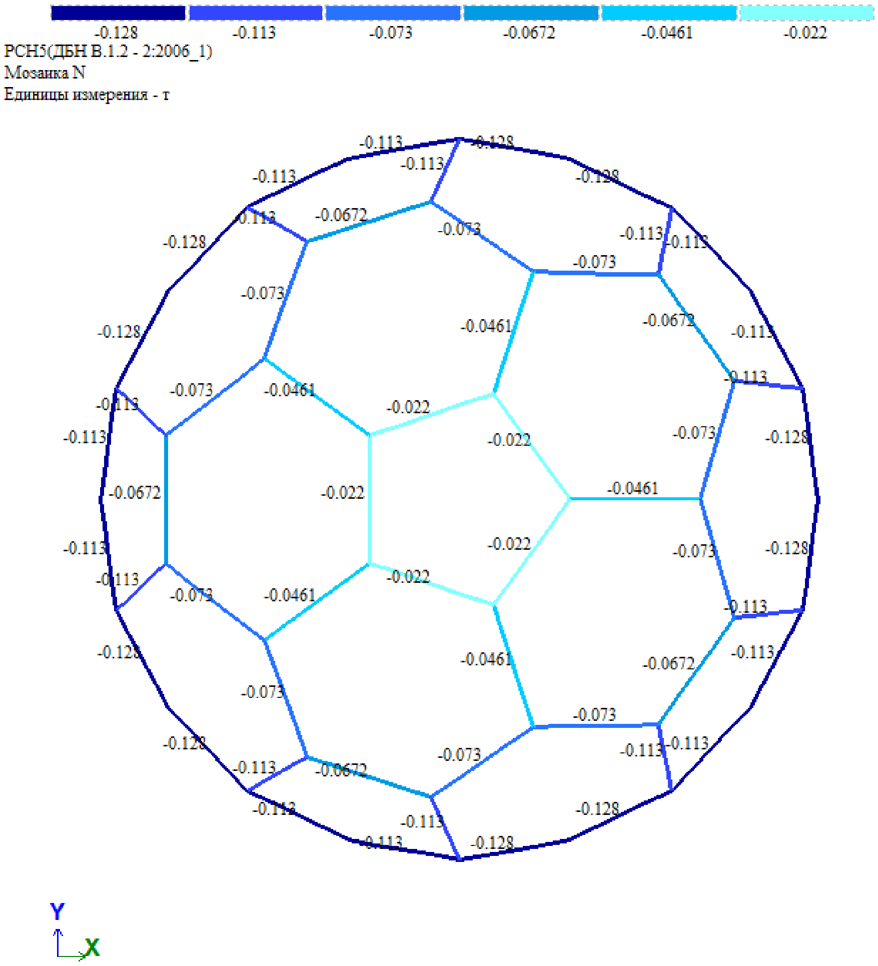

Figure 4. Longitudinal forces in the dome elements under the uniformly distributed load, *t*.

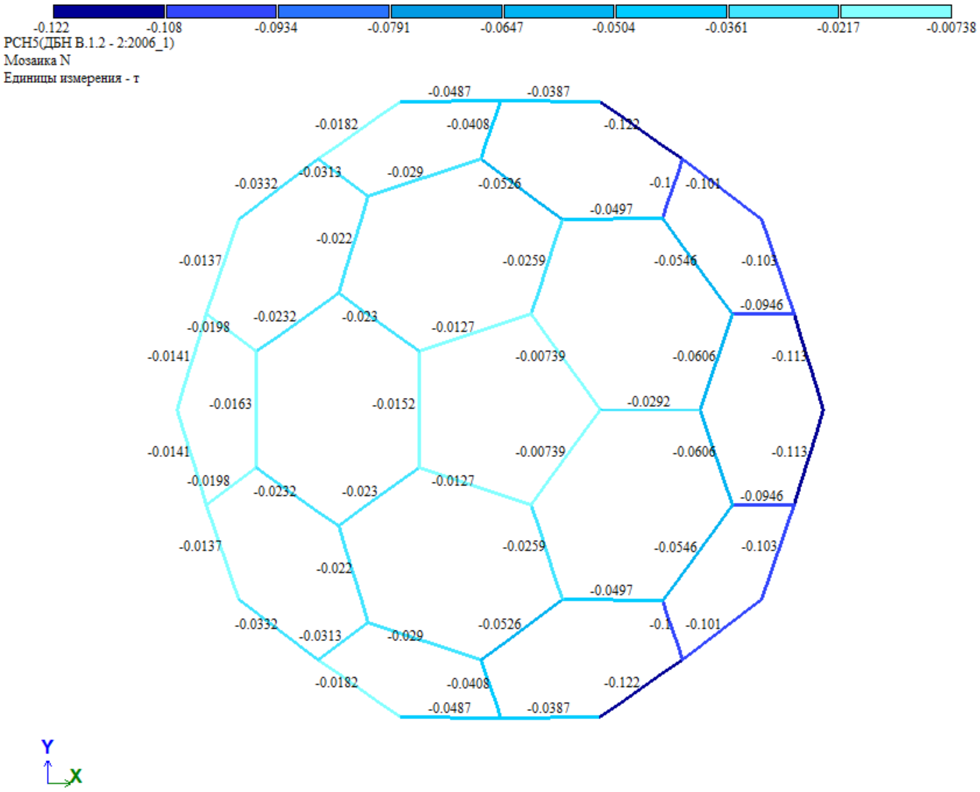

Figure 5. Longitudinal forces in the dome elements when $\frac{1}{2}$ of the dome is loaded, *t*.

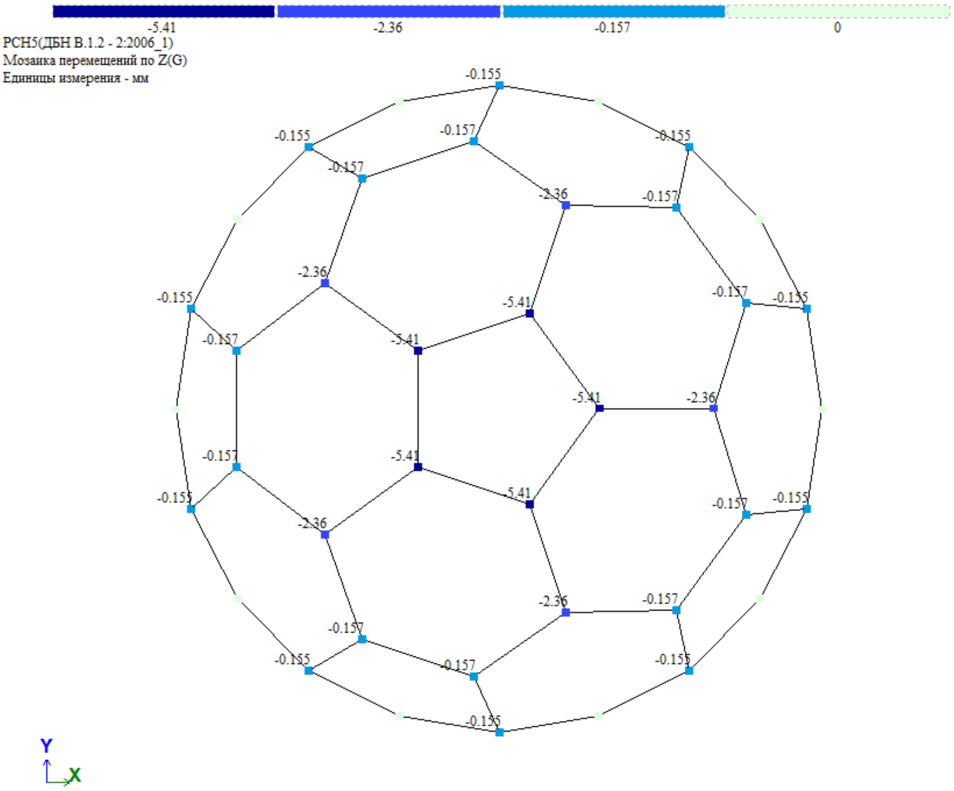

Figure 6. Strains in the dome nodes under the uniformly distributed load, mm.

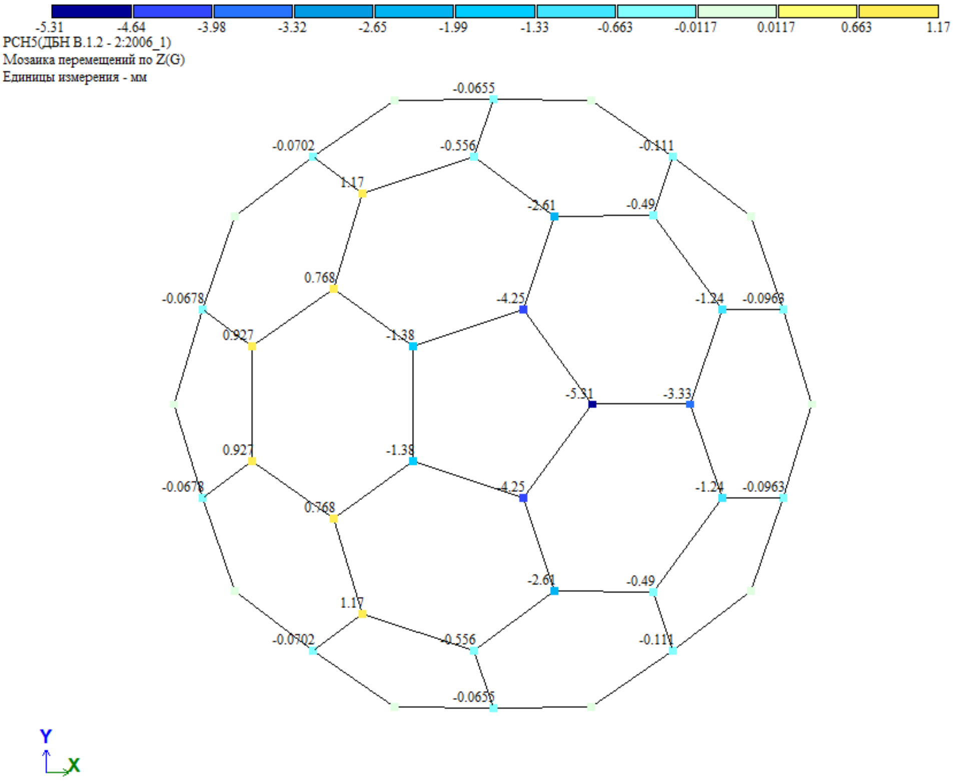

Figure 7. Strains in the dome nodes at $\frac{1}{2}$ dome load, mm.

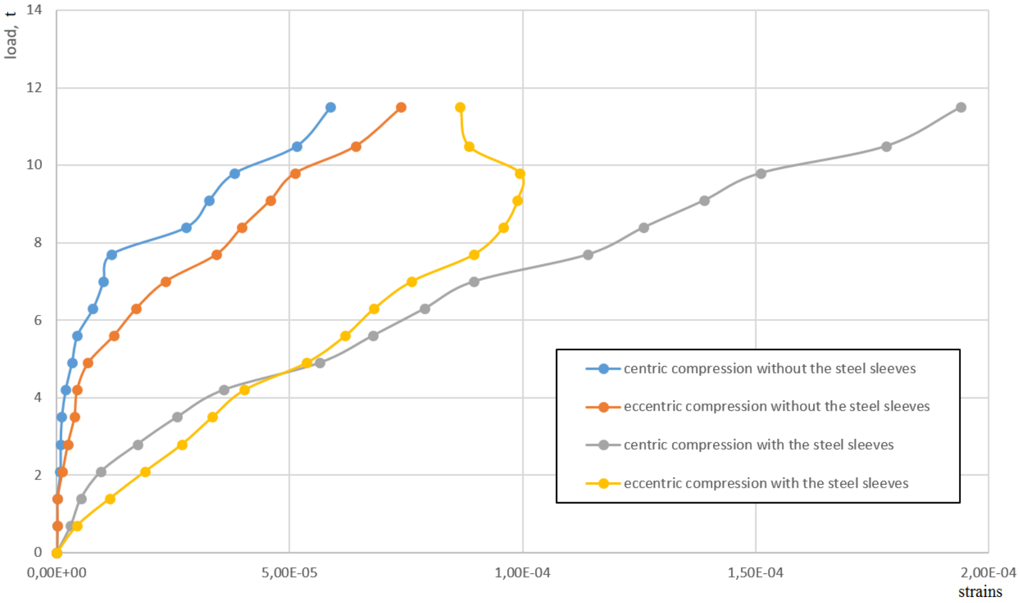

Figure 8. Average compression strains (ε_2, ε_6) at the ends of the sample, near the connector holes.

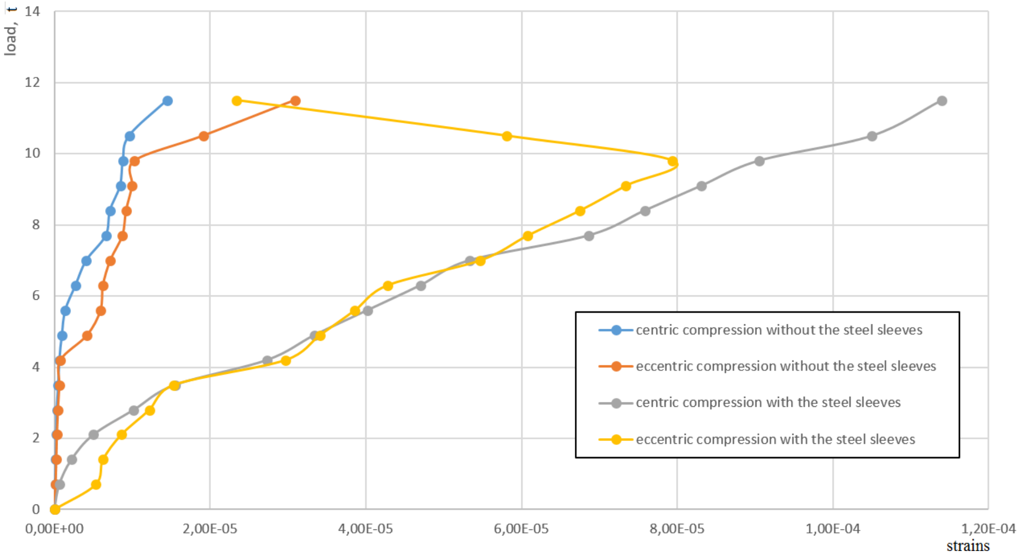

Figure 9. Compressive strains (ε_5) in the centre of the samples.

for two areas of the test samples: the support zone near the holes for the connector (strain gauges No. 2 and 6, Figure 3) shown in Figure 8, and the centre of the sample (strain gauge No. 5) shown in Figure 9. Each of the variants includes 4 graphs: the centric compression without the steel sleeves, the eccentric compression without the steel sleeves, the centric compression with the steel sleeves, and the eccentric compression with the steel sleeves. Obviously, the strains were higher for the eccentric compression. However, the main result was obtained from the effect of the steel sleeve on the stress-strain state of the sample. Instead of distributing the stresses along the cross-section and increasing the crush resistance in the hole area, the stresses in both areas increased under both the centric and eccentric compression.

Therefore, the use of steel sleeves can be considered detrimental, and their influence on the behaviour of the nodal joint and the rod can be considered as the influence of a stress concentrator. Such results are probably due to the large difference between the elastic moduli of steel and wood. It is easy to not use the sleeves, but impossible to not use the connector nuts in the holes. The solution may be to use nuts made of hardwood. The following tests will provide the answer to this question.

4. Conclusion

According to the test results obtained, the following was found:

(1.) The results of the numerical experiment showed a high load-bearing capacity of the dome, both under the action of a uniformly distributed load and under the action of a load applied to one half of the dome.

(2.) The load-bearing capacity of the samples under the different loads was quite high. The nature of the work can be considered elastic.

(3.) The use of steel sleeves in the holes for the connector is detrimental, and their effect on the operation of the nodal joint and the rod is the influence of a stress concentrator.

(4.) In order to increase the load-bearing capacity of the nodal joint between the dome elements, it is worth carrying out some experimental studies with the nuts for the connector bolts made of hardwood.

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