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Influence of the size of the upper ring on the stressed state of the ribbed-ring metal dome

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Conflicts of interest

The author declares that there is no conflict of interest.

Abstract. Studies of several metal ribbed-ring large-span domes on computer models have been carried out. All elements of the dome frames are made of steel I-beams. The dome frames have the same number of ribs and rings, but they have different size of the upper ring. The frame elements cross-sections are oriented normally to the dome surfaces, with the exception of the upper ring. The joints of the frame elements with each other are assumed to be rigid in the normal direction and hinged in the tangential direction. The frames are mounted on support nodes at the level of the lower ring pivotally. All the domes are subjected to the same nodal loads from the weight of the enclosing structures and the weight of snow. The snow load is assumed to be asymmetrical, located only on one side of the dome. Under the combined action of these loads, the dimensions of the upper ring of the domes influence the stress-strain state of their frames. As a result of the research, graphs have been generated representing the stress level in the meridional ribs and in the upper rings of the domes. The conclusion has been made that the stress state of metal dome frames depends on the size of the upper ring. The necessity of increasing the cross-section of the upper ring with an increase in its size has been noted.

Keywords: ribbed-ring dome, meridional rib, upper ring, computer model, statical calculations, stress state

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Влияние размера верхнего кольца на напряженное состояние ребристо-кольцевого металлического купола

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Аннотация. Выполнены исследования нескольких ребристо-кольцевых металлических большепролетных куполов на компьютерных моделях. Все элементы купольных каркасов приняты из стальных двутавров. Купольные каркасы имеют одинаковое количество ребер и колец, но отличаются друг от друга размером верхнего кольца. Сечения элементов каркасов ориентированы нормально к купольным поверхностям, за исключением верхнего кольца. Сопряжения элементов каркаса друг с другом приняты жесткими в нормальном направлении и шарнирными в тангенциальном направлении. Каркасы установлены на опорные узлы в уровне нижнего кольца шарнирно. На все купола приложены одинаковые узловые нагрузки от веса ограждающих конструкций и веса снега. Снеговая нагрузка принята несимметричной, расположенной только с одной стороны купола. При совместном действии этих нагрузок размеры верхнего кольца куполов отражаются на напряженно-деформированном состоянии их каркасов. В результате исследований построены графики, отражающие уровень напряжений в меридиональных ребрах и в верхних кольцах куполов. Сделан вывод о зависимости напряженного состояния каркасов металлических куполов от размеров верхних колец. Отмечена необходимость увеличения сечения верхнего кольца с увеличением его размера.

Ключевые слова: ребристо-кольцевой купол, меридиональное ребро, верхнее кольцо, компьютерная модель, статический расчет, напряженное состояние

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1. Introduction

Domes are used as coverings of buildings and structures both because of the expressiveness of their geometric shape and reliability of their structural systems. Due to their spatial rigidity and cost-effective metal consumption, they occupy a leading position among spatial coverings [1–3].

Geometric schemes of metal dome frames are diverse, depending on the overlapping spans and the purpose of the structure [4; 5]. Also, there can be different geometrical schemes of frames in ribbed-ring domes, for example, related to the number of sectors or tiers. One of the essential features of this difference is the size of the upper ring. Although the size of the upper ring often depends on the aesthetic or technological concept of a designer.

Many publications considered various aspects of ribbed-ring domes by means of various computer programs. For example, stress state of the dome frame was analyzed with changing parameters of its geometric scheme [6], with different dome height-to-diameter ratios for different spans [7], when brick filling of the frame cells between steel ribs and rings [8], with different dome height ratios and different cross-sections of core elements [9], and with different heights compared to the span of the dome frame with connections [10]. However, there are no publications devoted to the study of ribbed-ring domes with relatively different sizes of the upper ring.

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Asymmetric load has the greatest influence on the stress-strain state of the frames of spatial structures. This load includes the second variant of the snow load on the dome cover[1]. It determines the required cross-sections of the main bearing elements of the dome frames.

Six frames of spherical ribbed-ring domes with a curvature radius of 23 m, a span of 39.3 m and a height of 11.0 m ($h/D = 0.28$) were considered as objects of the research. Domes' frames consisted of 24 ribs, had 6 tiers, and differed from each other by the size of the upper ring. The smallest ring had a diameter of 4 m ($d_{\min}$), the largest one had a diameter of 14 m ($d_{\max}$), and the step of changing the diameter of the upper ring was 2 m. Due to the increase in the diameter of the upper ring, the lengths of the meridional ribs elements between the rings varied from 3.42 m to 2.75 m. The length of the upper ring elements varied from 0.78 m to 1.81 m.

All elements of the dome frames were made of steel **I**-beams: the ribs are made of **I** 50Ш1, the upper ring was made of **I** 50Ш4, the remaining rings were made of **I** 20Ш1. The cross sections of the frame elements were oriented normally to the dome's surfaces, with the exception of the upper ring, a cross section of which was oriented vertically (Figure 1). It was assumed that the conjugations of the upper ring to the meridional ribs, as well as conjugations of the other rings to the ribs, are rigid in the normal direction and hinged in the tangential direction. The frames are pivotally mounted on the supporting nodes at the level of the lower ring.

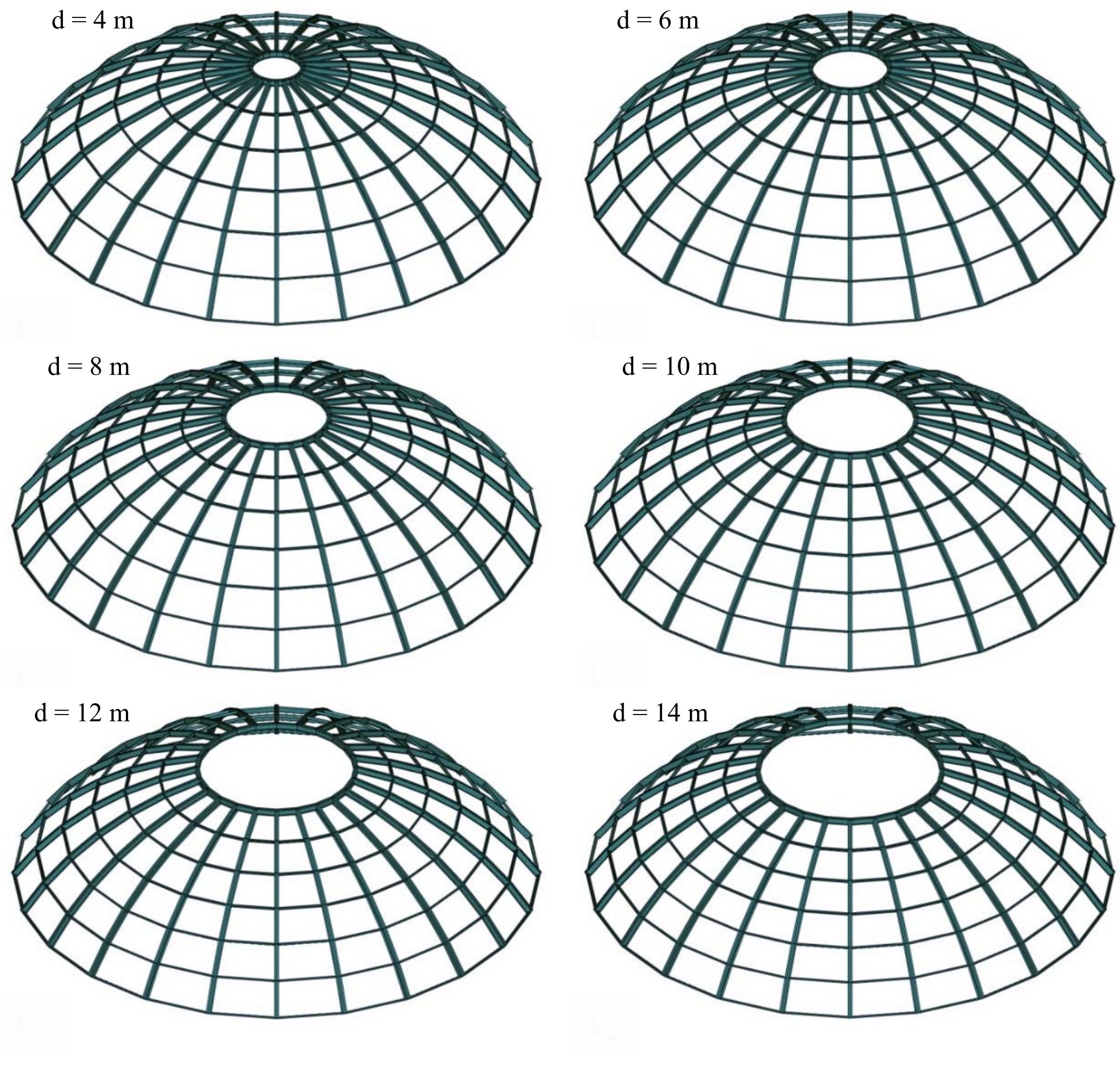

Figure 1. Investigated models of dome frames

[1] CR 20.13330.2016. Loads and impacts. Updated version of CNR 2.01.07–85*. Moscow: Ministry of Construction of Russia, 2016. (In Russ.) Available from: https://www.minstroyrf.gov.ru/docs/13673/

2. Methodology

The study of the stress state of the ribbed-ring dome's frame was carried out in the SCAD program [11] using computer models of spatial rod systems [12]. The study of dome type rod systems is usually carried out by scientists in various computer programs. Previously, the author performed a comparative study of ribbed-ring domes with various mounting methods [13; 14], as well as on the number of installed connections between meridional ribs [15]. The material presented in this paper has been obtained by the author in full compliance with the generally accepted principles of research for similar states in spatial rod systems.

Dome frames are spatial rod systems pivotally mounted on supports under the meridional ribs at the level of the lower ring. It is with such computational models that they were presented in these computer studies. All computer models of domes differed from each other only in the size of the upper ring. The same nodal loads were applied to all dome frames: from the weight of the enclosing structures, which was symmetrical relative to the axis of the domes; from the weight of snow, located only on one side of the domes and being asymmetrical (Figure 2).

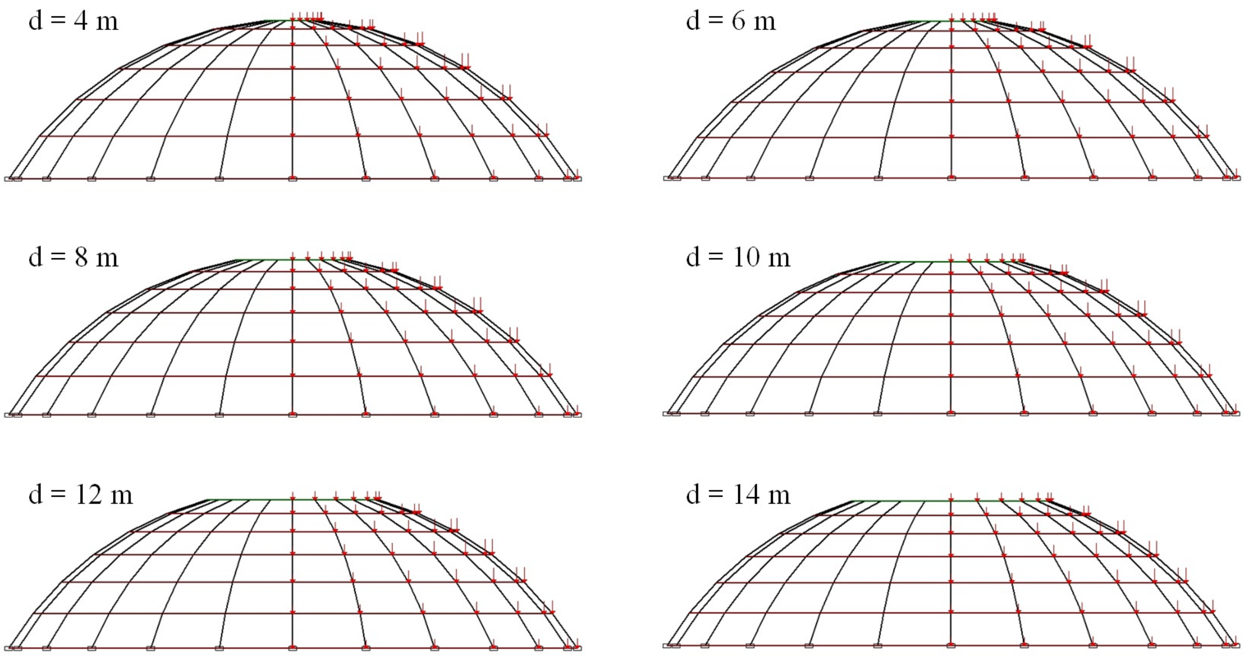

Figure 2. Asymmetric snow load on the dome frames

The combined effect of these loads creates a stress-strain state of the dome frames, which determine their bearing capacity. Despite the fact that the loads are the same, the stress-strain states in the elements of the dome frames with different sizes of the upper ring of the domes differ from each other.

The outlines of deformed schemes of dome frames with different sizes of the upper rings do not differ from each other, but the values of deformations are not the same. If the maximum deflection in the most loaded part of the dome with the smallest size of the upper ring ($d_{\min}$) is equal to $f = 9.5$ cm, then it increases by 1.6 times in the dome with the largest size of the upper ring ($d_{\max}$) (Figure 3).

The graphs of longitudinal forces N in the elements of dome frames with different sizes of the upper rings differ from each other insignificantly. And the diagrams of bending moments in the elements of dome frames with different sizes of upper rings show significant differences. These differences are associated with a change in the ratio between the values of moments M_x in the upper rings and those at the meridional ribs (Figure 4).

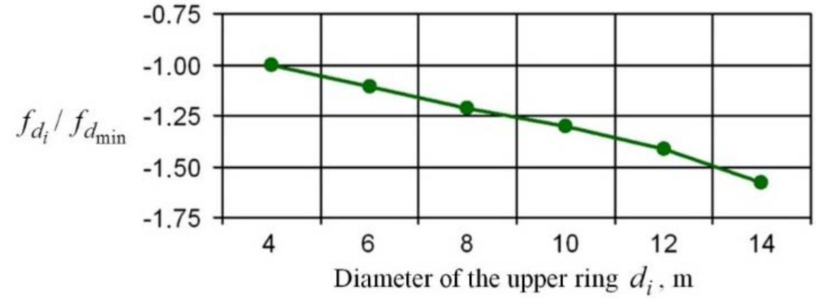

Figure 3. The ratio of the largest deflections $f_{d_i} / f_{d_{\min}}$ in the frame

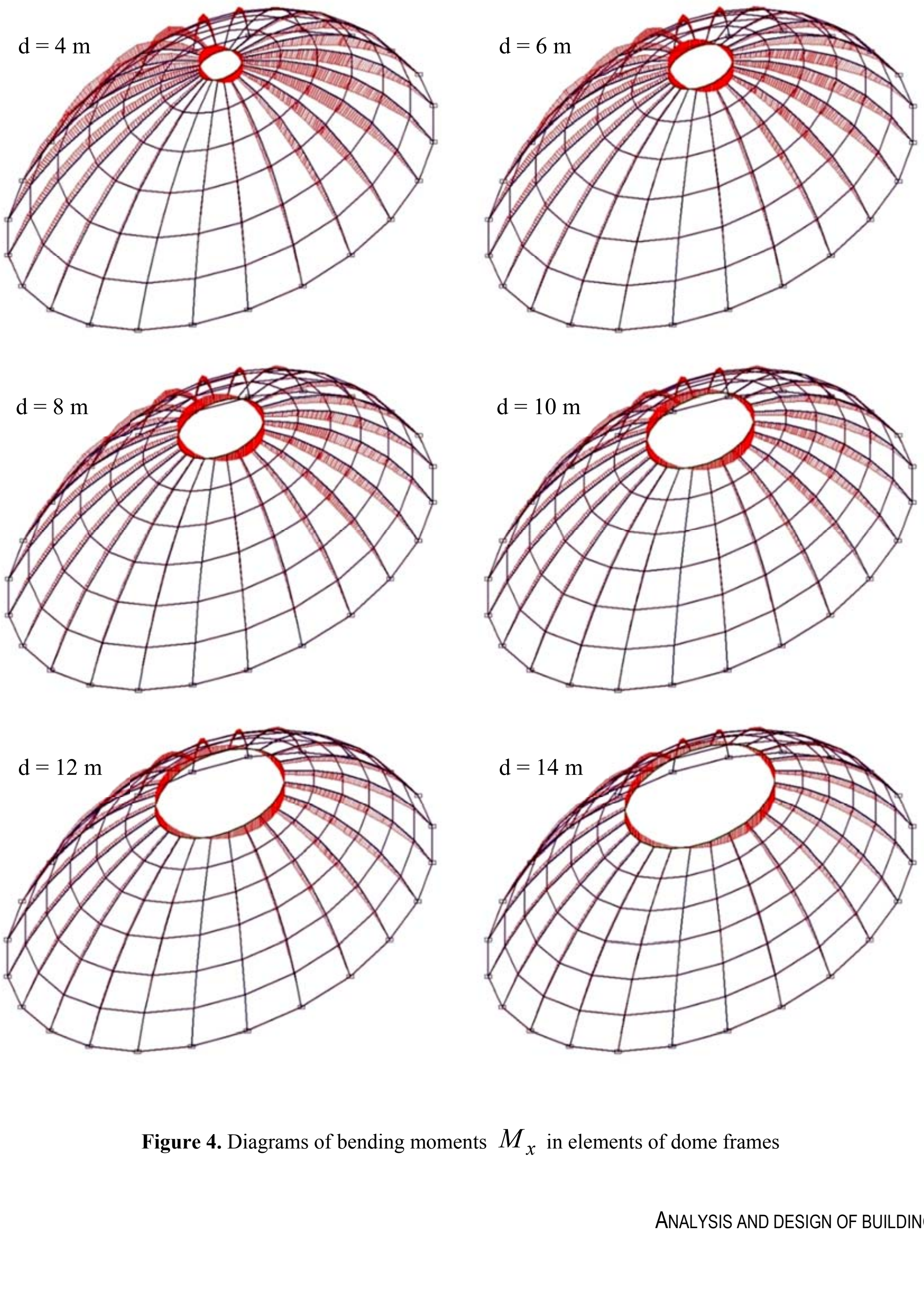

Figure 4. Diagrams of bending moments M_x in elements of dome frames

3. Example

With an increase in the size of the upper rings, the values of bending moments M_x and longitudinal forces N in the meridional ribs change, but these changes are different and insignificant in magnitude (Figure 5): M_x first increases within 11% of the initial value, then decreases; N first decreases, then stabilizes within 19%.

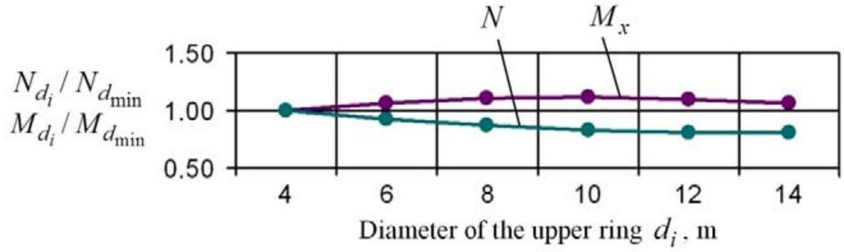

Figure 5. The ratio of forces $N_{d_i} / N_{d_{\min}}$ and $M_{d_i} / M_{d_{\min}}$ in the meridional ribs

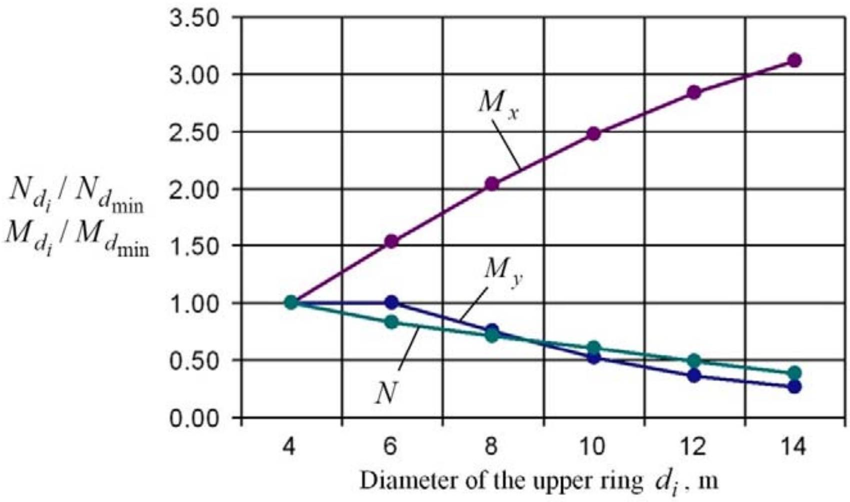

Figure 6. The ratio of forces $N_{d_i} / N_{d_{\min}}$ and $M_{d_i} / M_{d_{\min}}$ in the upper rings at $\beta = 0^{o}$

A different pattern of changes in bending moments $M_x$and longitudinal forces N, as well as in moments M_y, is observed in the upper ring. At the same time, the internal forces along the axis of the one-sided asymmetric snow load ($\beta = 0^{o}$) and in the direction perpendicular to this axis ($\beta = 90^{o}$) differ from each other. For $\beta = 0^{o}$ as the size of the upper rings increases, the bending moments M_x increase significantly, reaching the value that is 3.1 times more than the moments at $d_{\max}$ than the moments at $d_{\min}$ (Figure 6). At the same time, the longitudinal forces N and moments M_y decrease, reaching values of $0.38N$ and $0.26M_y$ compared to the forcesat $d_{\min}$. For $\beta = 90^{o}$ with an increase in the size of the upper rings, the bending moments M_x also increase significantly, reaching 2.7 times higher values at $d_{\max}$ compared to the moments at $d_{\min}$ (Figure 7). At the same time, the longitudinal forces N and moments M_y decrease, reaching values at $d_{\max}$ of $0.46N$ and $0.38M_y$ compared to the forces at d_{min}.

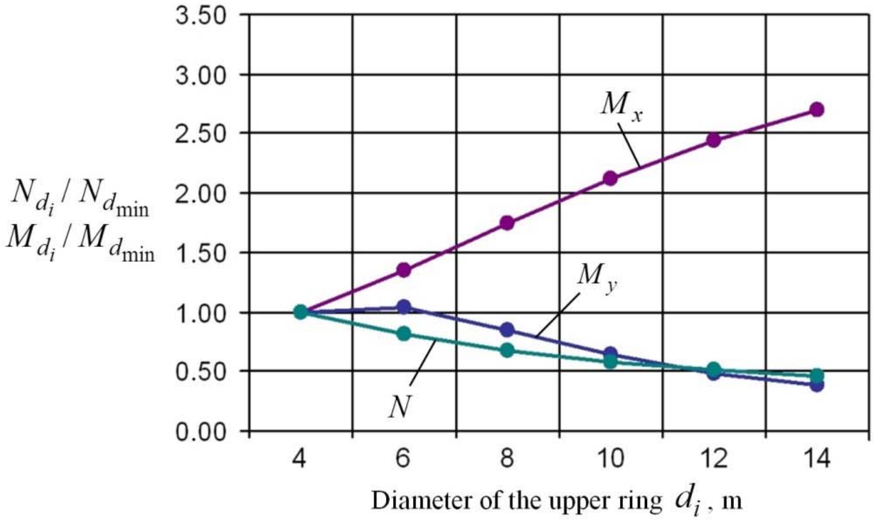

Figure 7. The ratio of forces $N_{d_i} / N_{d_{\min}}$ and $M_{d_i} / M_{d_{\min}}$ in the upper rings at $\beta = 90°$

Since the internal forces N, M_x, M_y in the meridional ribs and in the upper rings of the dome frames change differently when the size of the rings is changed, the studies of the normal stresses σ_i in them were carried out. The stress values were determined by the formula:

$$\sigma_i = \frac{N_i}{A_i} \pm \frac{M_{x,i}}{W_{x,i}} \pm \frac{M_{y,i}}{W_{y,i}} .$$

With an increase in the size of the upper rings in the dome frames, the initial stresses ($12.51\ \text{kN/cm}^2$) at $d_{\min}$ in the meridional ribs change insignificantly, within 9% with no tendency to rise (Figure 8). The initial stresses ($15.05\ \text{kN/cm}^2$) in the upper rings at $d_{\min}$ change significantly, within 26% and have a tendency to increase (see Figure 8).

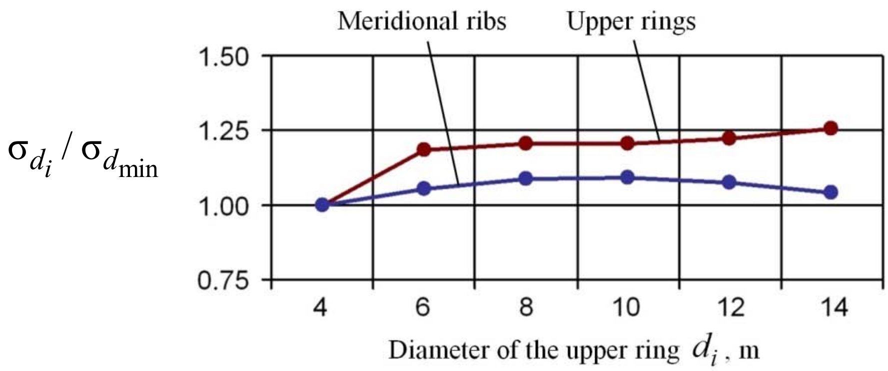

Figure 8. The ratio of the greatest stresses $\sigma_{d_i} / \sigma_{d_{\min}}$ in the elements of the dome frames

4. Conclusions

1. As a result of the research, it has been shown that with an increase in the size of the upper rings in the frames of ribbed-ring domes, the bending moments in the vertical plane in these rings increase several times, but the longitudinal forces and moments from the vertical plane decrease.

2. The normal stresses in the meridional ribs increase slightly at first, then decrease without reaching the initial values. The normal stresses in the upper rings increase significantly with an increase in their size, with a tendency to further increase.

3. With increasing the size of the upper rings in metal ribbed-ring domes, it is necessary to increase their cross-section. The reliability of metal domes mainly depends on calculations for a combination of loads considering asymmetric force influences.

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