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NUMERICAL SIMULATION OF THE PROCESS OF DIRECTED TRANSFORMATION OF A REGULAR HINGE-ROD SYSTEM

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Abstract. The process of forming new architectural solutions in the field of regular frame-rod systems necessitates the development of the concept of creating original spatial structures through the directed transformation of kinematically changeable truss-type objects. The article presents a numerical study of kinematic parameters during the gradual shaping of a rod system, which in its initial state is a flat hinge-rod network of repeating fragments in the form of equilateral triangles. The controlled kinematic effect on the object was modeled using actuators that were placed on the peripheral sections of the studied grids.
The wide variability of the hinge-rod forms, the economical installation process using the principle of "self-extension" allow us to speak about the relevance of research in this direction.

Keywords: hinge-rod structures, finite element method, matrix stiffness, the stress-strain state, actuators

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССА НАПРАВЛЕННОЙ ТРАНСФОРМАЦИИ РЕГУЛЯРНОЙ ШАРНИРНО СТЕРЖНЕВОЙ СИСТЕМЫ

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Аннотация. Процесс формирования новых архитектурных решений в области регулярных каркасно-стержневых систем обуславливает необходимость разработки концепции создания оригинальных пространственных структур путем направленной трансформации кинематически изменяемых объектов ферменного типа. В статье выполнено численное исследование кинематических параметров при постепенном формоизменении стержневой системы, представляющей в исходном состоянии плоскую шарнирно-стержневую сеть из повторяющихся фрагментов в форме равносторонних треугольников. Управляемое кинематическое воздействие на объект моделировалось с помощью актуаторов, которые размещались на периферийных участках исследуемых сеток.
Широкая вариативность шарнирно-стержневых форм, экономичный процесс монтажа с использованием принципа «самовыдвижения» позволяют говорить об актуальности исследований в данном направлении.

Ключевые слова: шарнирно-стержневая система, метод конечных элементов, матрица жесткости, напряженно-деформированное состояние, актуаторы.

INTRODUCTION

The process of forming new architectural solutions in the field of regular frame-rod systems necessitates the development of the concept of creating original spatial structures through the directed transformation of kinematically changeable truss-type objects.

Currently, folding in two directions have become widespread (S_x, S_y) cover formed from hinge-rod kinematic pairs (Fig. 1).

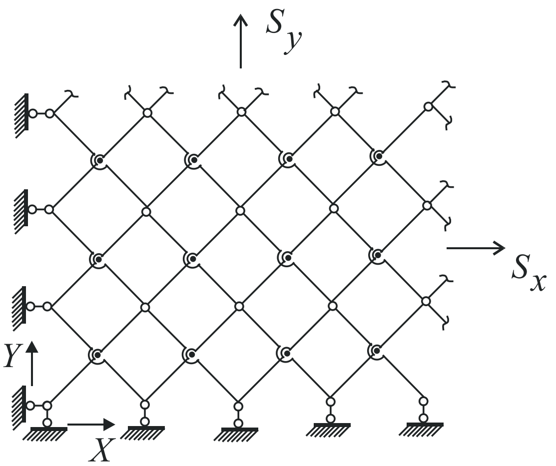

Figure 1. Kinematic scheme of a collapsible covering

A separate category consists of hinge-rod systems (HRS) of large-sized transformable space structures, the disclosure of which occurs automatically in zero gravity [1].

Works [2, 3] are devoted to the problem of finite element analysis of the stress-strain state of hinge-rod systems taking into account large displacements. In particular, in [2] a two-rod instantaneously kinematically variable HRS is considered, the design scheme of which is shown in Fig.2. For numerical simulation of the behavior of the HRS in a geometrically nonlinear formulation, the authors have developed an algorithm based on a step-by-step loading scheme and the formation at each step of a mixed system of equations in the form of the displacement method and the force method. The configuration of this HRS corresponding to a statically unchangeable state (the rightmost position of the second link) is shown in Fig. 3. In order to verify the algorithm proposed in [2, 3] we will perform the calculation of the two-rod HRS for the initial position A, B, C and configuration of the system in the position A', B', C (Fig. 3). Figures 4 and 5 show the patterns of vertical displacement distribution $u_y^{(A)}$ and longitudinal forces N in rods, derived using a nonlinear solver of the software package ANSYS Mechanical. Comparing these data with the results of [2], we establish that the value of $u_{y\,max}^{(A)}$ corresponding to the calculation of an instantaneously changeable system (Fig. 4) is in both calculations -4,97 m. when geometrically nonlinear calculation of HRS in position $\alpha = 90^0$ также получены the results are similar [2]. The coincidence of the results is also observed when comparing the longitudinal forces in the rods for the two positions of the system.

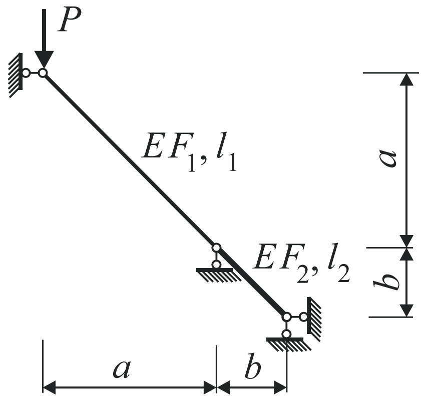

Figure 2. Two - rod HRS

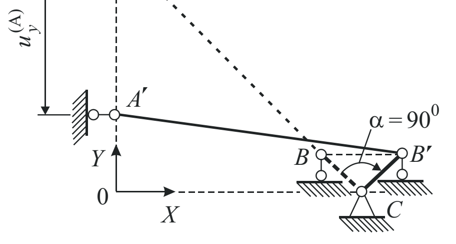

Figure 3. Configuration HRS

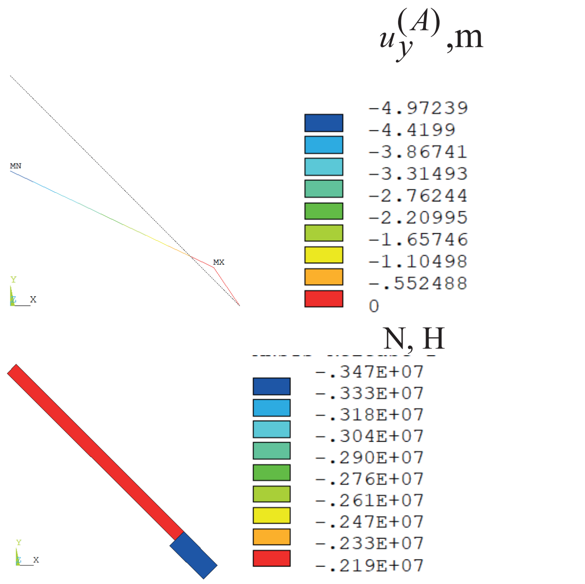

Figure 4. Distribution patterns $u_y^{(A)}$ u N for the initial instantaneously changeable state HRS

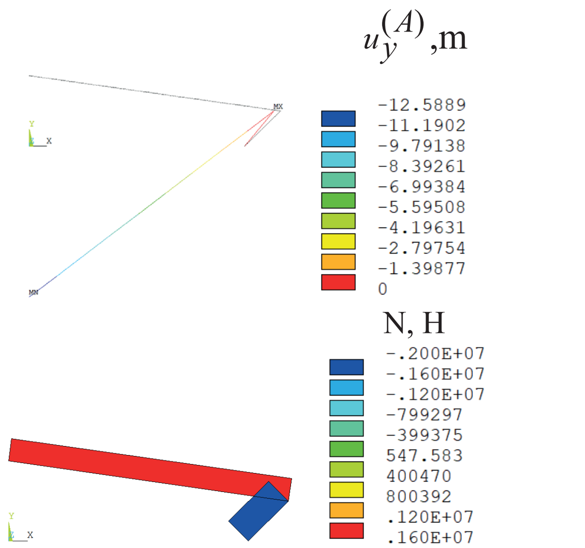

Figure 5. Distribution patterns $u_y^{(A)}$ u N for a statically immutable state HRS

Thus, it can be argued that the ANSYS software package allows for the simulation of HRS with sufficient accuracy, taking into account large displacements.

The article presents a numerical study of the kinematic parameters of the rod system with its gradual formalization. In its initial state, the system is a flat hinge-rod network of repeating fragments in the form of equilateral triangles. The controlled kinematic effect on the object was modeled using actuators that were placed on the peripheral sections of the studied grids. The wide variability of hinge-rod forms, the economical installation process using the principle of "self-extension" allow us to speak about the relevance of research in this direction.

MATERIALS AND METHODS

As an object of research, we consider a hinge-rod system (HRS), the initial state of which (before transformation) is shown in Figure 6. Each rod of the SHSS is modeled by one three-dimensional truss finite element [4]. We set the geometry of the SHSS in the global axes X, Y, Z. We believe that the stiffness of all the rods of the system is the same.

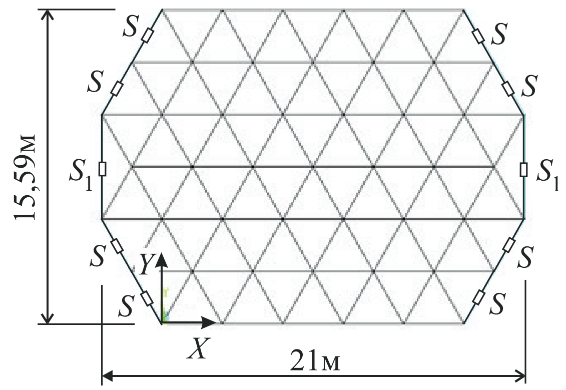

Figure 6. Hinge-rod system in the initial state

In Fig. 6, the links with actuators are marked with rectangles and marked with the letters *S* и *S*1. Synchronous axial movements can be created on the hinges of the actuators, causing shortening / elongation of the links. We model the actuators with combined finite elements [3]. Figure 7 shows a repeating fragment of the HRS. In the initial state, the positive direction of the normals $\overline{n}$ of all fragments coincides with the orientation of the Z axis. For each rod of a repeating fragment, we introduce a local system of axes so that the axis $\overline{x}, \overline{y}, \overline{z}$ so that the direction of the axis $\overline{z}$ coincided with normal $\overline{n}$, and the axis $\overline{x}$ was directed from the node

i to the node k provided that the node numbers are arranged in this sequence $j > k > i$. Axle $\overline{y}$ are pointing away from the center of the fragment.

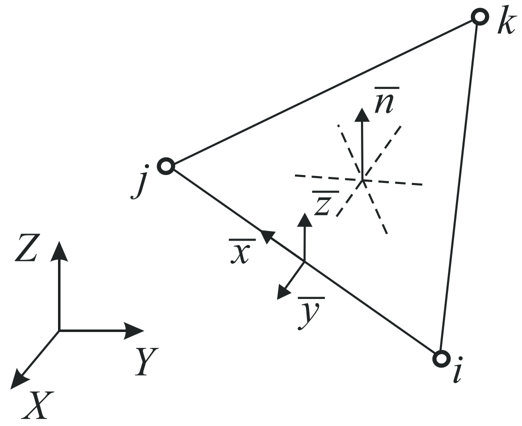

Figure 7. A repeating fragment of the hinge-rod system

The calculation scheme for modeling the process of transformation of the HRS is shown in Fig. 8. In this drawing, the symbols «+», «Δ», «▷» the connections prohibiting movement are marked, respectively, in the direction of the axes *Z*, *Y*, *X*. Letters *a* and *b* denote nodes, movements u_z which will be observed during directed transformation HRS. The letter *e* denotes an element, the kinematic parameters of which will also be investigated in the process of shaping the HRS.

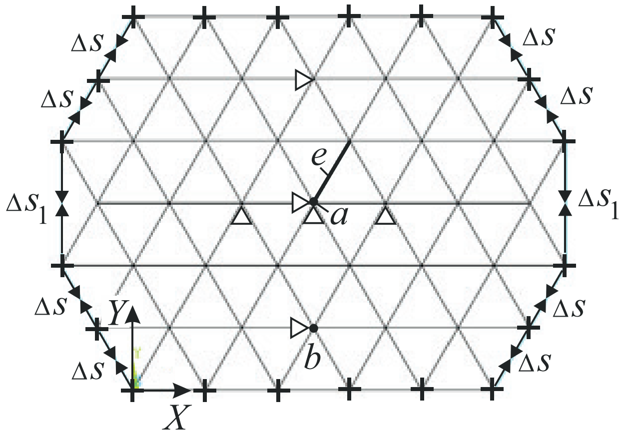

Figure 8. Calculation scheme for modeling the process of shaping HRS

We accept the following assumptions [5, 6, 7]:

- the process of transformation of the structure is a quasi-static sequence of steps $k = 1, 2, ..., n$ discrete changes in the lengths of combined finite elements by small values Δs, Δs_1 (Fig. 8);
- in the process of transformation of the structure, the achieved level of stress state of the rods is inherited.

We emphasize that the transition from the current position of the rod k to the subsequent provision $k+1$ it is accompanied by small increments of the values of the nodal coordinates. Based on this, the calculation of the stress-strain state at each step of the transformation of the HRS is carried out within the framework of the linear theory of elasticity.

For the software implementation of the proposed concept of the transformation of the HRS, we use the programming language APDL [8], built into the ANSYS Mechanical software package [4]. An application macro created on the basis of this language is entered into the command window, after which each line of the macro is processed by the APDL interpreter and, in case of a positive result, it is immediately launched for execution. Thus, the macro allows you to automatically create the geometry of the structure, build a finite element grid, set boundary conditions and load, run the solver to perform calculations, as well as perform intermediate operations related to extracting information from the ANSYS database at the current loading step and forming working arrays by performing the necessary algebraic procedures. In addition to the listed actions, the macro contains commands to delete and rebuild the finite element model at each step of the calculation.

RESULTS OF FINITE ELEMENT MODELING

First of all, it should be noted that the design scheme of the HRS (Fig. 8) is geometrically changeable. Therefore, the process of transformation of the HRS from the position when the coordinates of all nodes $z_i = 0$, it will not lead to the expected rise of repeating fragments, i.e. it is necessary to start (begin transformation) with a pre-prepared dome-shaped geometry of the HRS (Fig. 9).

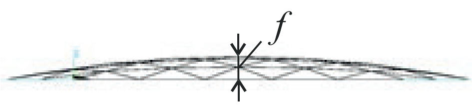

Figure 9. Pre - launch domed shape HRS

In this connection, the question arises: at what minimum value of the lifting boom f the arch effect occurs and how to make the transition from a flat configuration of the HRS ($f = 0$) to a domed shape ($f > 0$) with the preservation of the original lengths of the rods?

To transition from the initial flat shape of the SHSS to the starting dome-shaped configuration, we use kinematic boundary conditions, which are reduced to setting displacements in the direction of the axis Z in the non-support nodes of the grid:

$$u^*_{zi} = f \varphi_i(\xi,\eta),$$

marked: $\varphi_i(\xi,\eta) = 1 - \xi^2 - \eta^2 + \xi^2\eta^2$ – approximating polyquadratic polynomial; $\xi = \dfrac{2(x_i - 7{,}5)}{21}$; $\eta = \dfrac{2(y_i - 7{,}794)}{15{,}59}$ – normalized coordinates that take into account the dimensions HRS; x_i, y_i – coordinates of nodes truss finite element in global axes.

Based on the accepted kinematic boundary conditions, the stiffness matrix is adjusted according to standard technology and the corresponding vector of the right part of the resulting system of equations is formed. To solve the corrected system of equations, we use the nonlinear solver of the ANSYS complex, i.e. we perform the calculation taking into account large (finite) displacements. The obtained data on the new geometry of the nodes and the corresponding topology of the model are recorded in intermediate files.

In order to test the proposed approach to obtaining the domed shape of the HRS, a computational experiment was conducted for the values of the parameter f equals 0,1m, 0,25m, 0,5m, 1,0m, 1,5m. The calculations were carried out taking into account geometric nonlinearity (large displacements). As an evaluation criterion, we used control over the immutability of the lengths of the rods of the model during the transition from the initial (flat) shape to the domed shape of the HRS. It was found that the iterative process in the investigated range of the parameter f converges and the lengths of the rods before and after the calculation coincide.

The next step was to study the obtained dome-shaped shapes of the HRS for the presence of an arched effect under the boundary conditions shown in Fig. 5 and the action of only the own weight of the rods. As a result, it was found that the iterative process does not diverge, starting with f = 1 m. Visualization of the picture of the deformed state of the SSS and the distribution of the corresponding displacements u_z shown in Fig. 10.

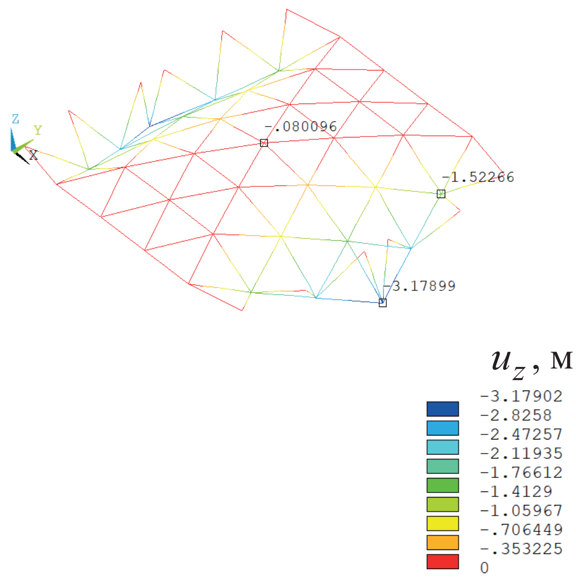

Figure 10. The picture of the distribution of movements in HRS u_z when f = 1m

Next, a simulation of the process of kinematic shaping of the HRS was performed using a specially developed step algorithm. Fig. 11 shows the results of modeling this process for the

SHSS with the initial boom of the dome $f = 0{,}1$ m, with the same movements Δs in all actuators. The following parameters were taken into account in the calculation: the course at each step of the transformation $\Delta s = 0{,}01$ m; number of transformation steps $n = 80$. Visualization of vertical movements u_z at points a and b, the HRS is shown in Fig. 12. As can be seen for the accepted parameter value Δs there is a rise of peripheral repeating fragments and a deflection of the central part HRS.

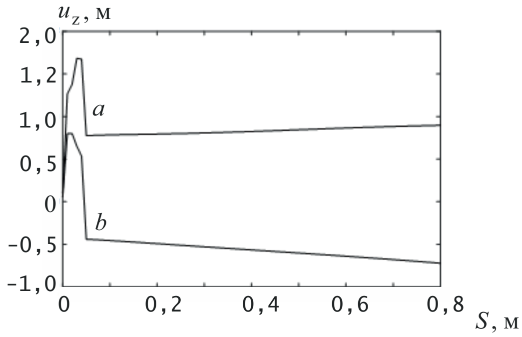

Figure 12. Charts $u_z \sim s$ at point a and b when $f = 0{,}1$ m; $\Delta s = 0{,}01$ m; $n = 80$

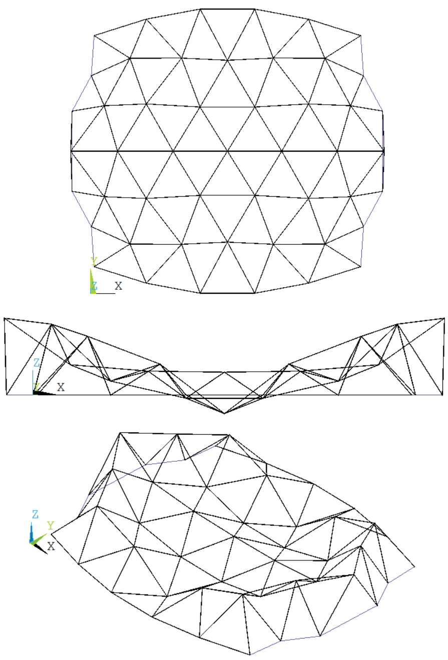

Figure 11. The result of modeling the shape change HRS when $f = 0{,}1$ m; $\Delta s = 0{,}01$ m; $n = 80$

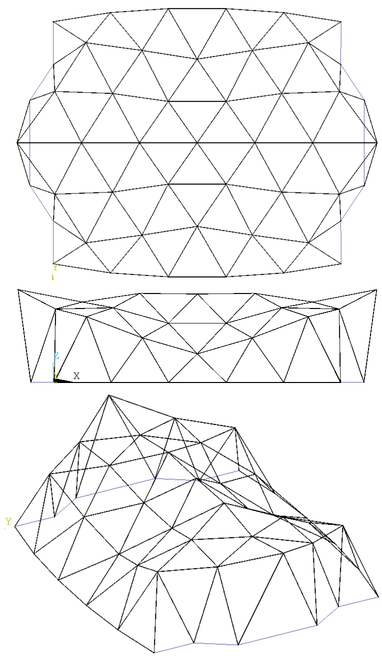

Figure 13. The result of modeling the shape change HRS when $f = 0{,}1$ m; $\Delta s = 0{,}02$ m; $n = 40$

To achieve the lifting of the rods in the center of the SHSS, it was necessary to double the parameter Δs. Figure 13 shows the model of the HRS in the transformed state obtained for the variant with $\Delta s = 0{,}02$ m и $n = 40$. Graphs of vertical movements in nodes *a* and *b* of the grid are shown in Fig. 14. From the presented graphs it can be seen that the dependencies $u_z \sim s$ at points *a* and *b* have clearly defined three sections. Moreover, in the last section, the displacement at point a continues to monotonically increase, and the displacement at point *b* monotonically decreases.

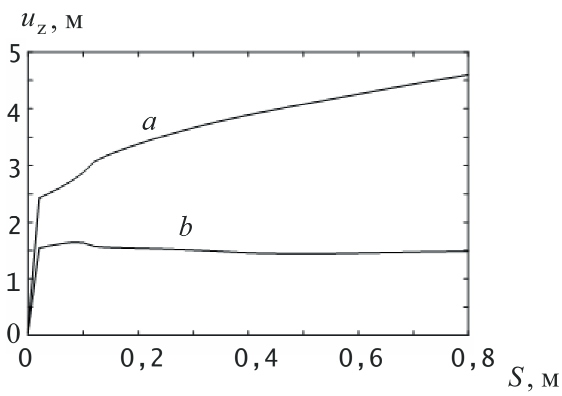

Figure 14. Charts $u_z \sim s$ at point a and b when $f = 0{,}1$ m; $\Delta s = 0{,}02$ m; $n = 40$

Based on the simulation data of the transformation process with variable stroke of the actuators $S_1 = 1,2S$ it is established that the final form of the HRS in this case differs little from the result of the previous calculation $(S_1 = S)$.

Important for the practical implementation of the concept of the shape of the HRS is the information about the kinematics of angular displacements of rods. In this regard, a study of the behavior of the rod was carried out *e*, adjacent to the node *a* in the process of transformation (Fig. 8). Figure 15 shows graphs of changes in the guiding cosines $cos(y\overline{x})$, $cos(z\overline{x})$, $cos(x\overline{x})$ the observed rod depending on the stroke *S* actuators. Visualization of plume projections of rod positions *e* during the transformation, the HRS is shown in Fig. 16.

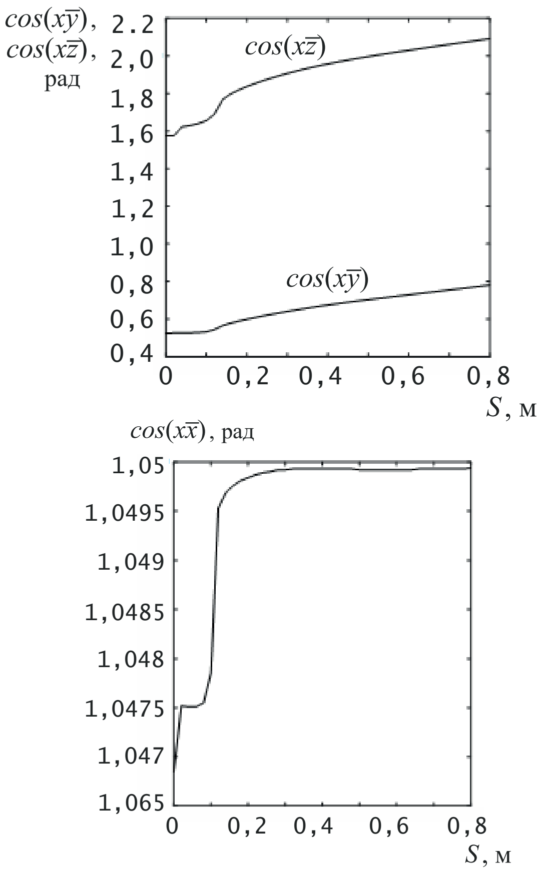

Figure 15. Charts $cos(x\overline{x})$, $cos(y\overline{x})$, $cos(z\overline{x})$ of rod e to option f = 0,1 m; Δs = 0,02 m; n = 40

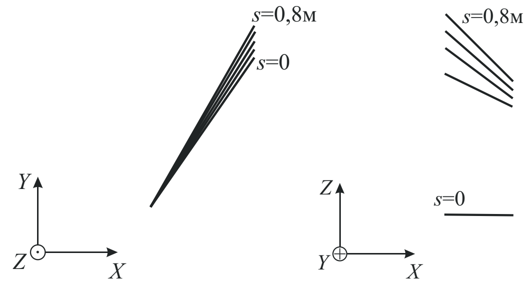

Figure 16. Visualization of plume projections of rod positions e

It follows from the presented data that the design of the hinge assembly should provide rotations relative to global axes. Naturally, this circumstance complicates the design of the hinge assembly. In the works [9,10,11], the design of a universal node providing the transformation of the HRS is proposed.

Let's consider a variant of the modified design scheme of the HRS, which differs from the previous scheme in that its rods located along the extreme rectilinear sides are replaced with actuators (Fig. 17). This arrangement of actuators allows for comprehensive compression of the structure. The boundary conditions are similar to those introduced earlier.

Visualization of a finite element model of a modified HRS circuit having an initial bend *f* = 0,1 m, after the transformation is shown in Fig. 18. The values of the stroke at each step of the transformation in all actuators were assumed to be the same $\Delta S_1 = \Delta S$. The result of the corresponding calculation in the form of graphs of the dependence of vertical movements at points *a* and *b* from the stroke of the actuators for the parameters, Δs =0,02 m; *n* = 30 presented in fig. 18.

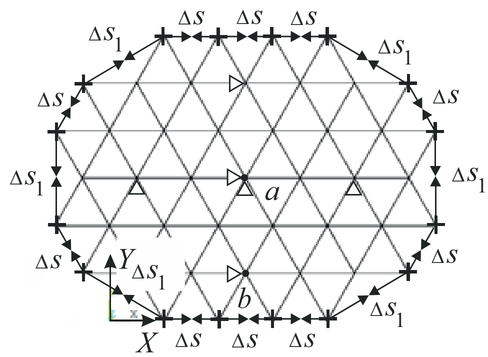

Figure 17. A modified calculation scheme for modeling the process of shaping HRS

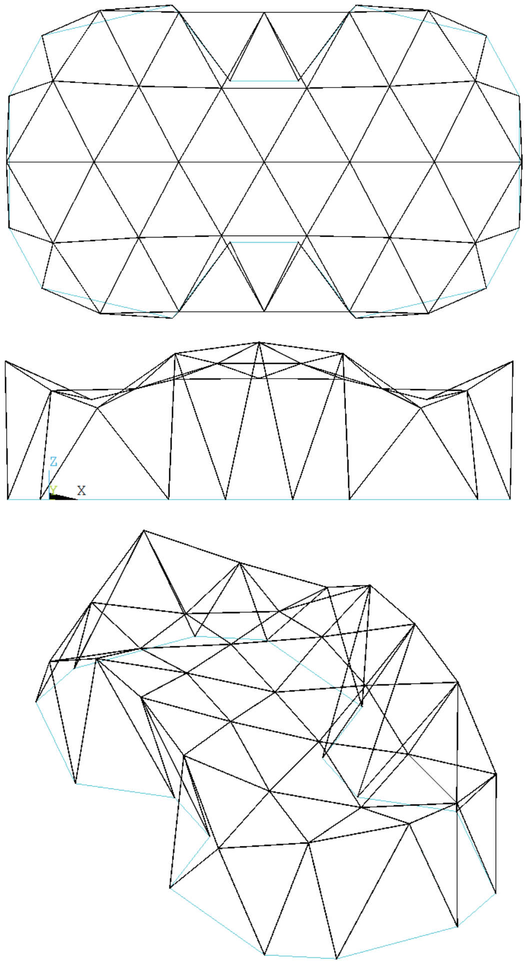

Figure 18. The result of modeling the shape change HRS when f = 0,1 m; Δs =0,02 m; n = 30

From the graphs of Fig. 19 it can be seen that the greatest rise $u_{z\ max}$= 4,8m observed in a section of a repeating fragment adjacent to the node *b*.

Visualization of the modified HRS circuit after transformation in the case of variable stroke values $\Delta S_1 = 1,2\Delta S$ is presented in Fig. 20. The corresponding graphs $u_z \sim s$ shown in Fig. 21.

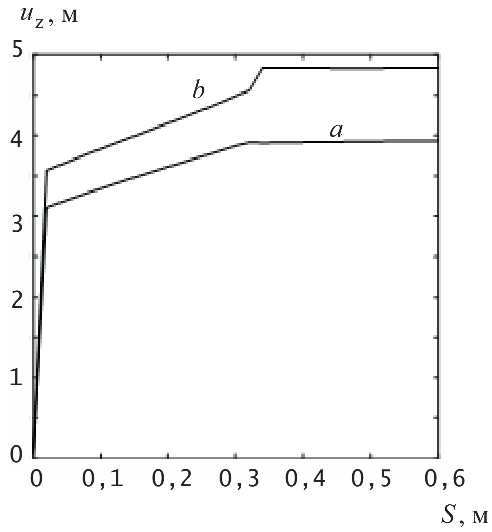

Figure 19. Charts $u_z \sim s$ at point a and b when f = 0,1 m; Δs =0,02 m; n = 30

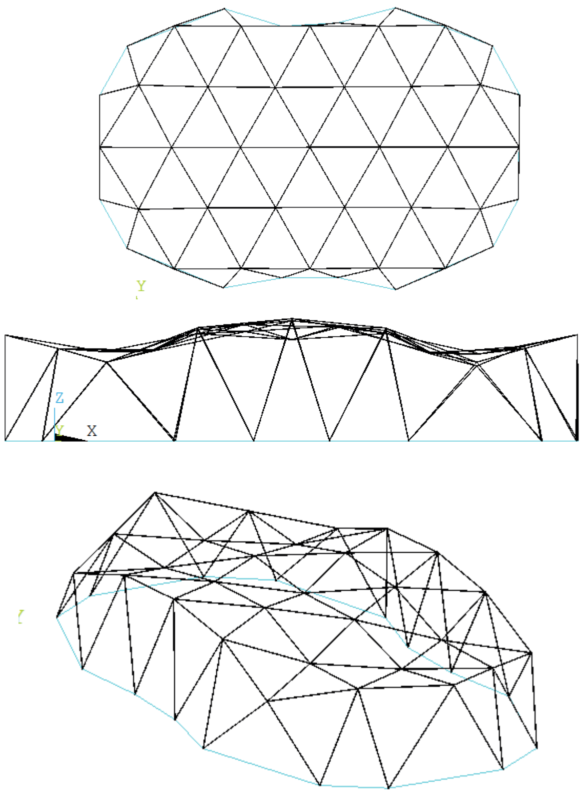

Figure 20. The result of modeling the shape change HRS when f = 0,1 m; Δs = 0,02 m; $\Delta S_1 = 1,2\Delta S$; n = 30

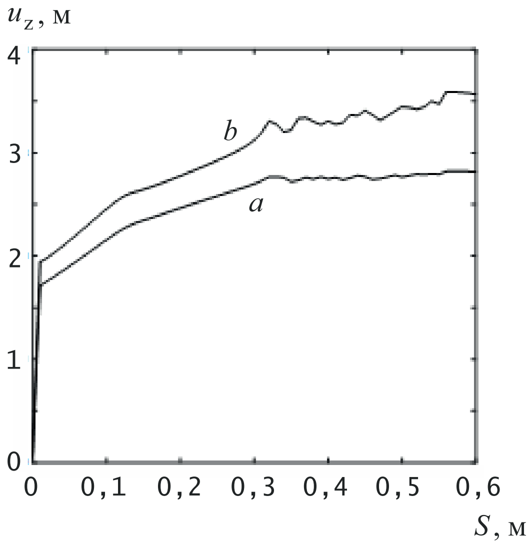

Figure 21. Charts $u_z \sim s$ *at point a and b when f = 0,1 m;* $\Delta s = 0{,}02$ *m;* $\Delta S_1 = 1{,}2\Delta S$ *; n = 30*

Analyzing displacement curves u_z in Fig. 20, we conclude that starting from $S > 0{,}3$m there is a zone of unstable transformation HRS.

CONCLUSIONS

1. A method of step-by-step modeling of the transformation process of a regular hinge-rod system formed by flat equilateral triangular fragments of the truss type has been developed and tested on test examples.
2. The range of geometric and kinematic parameters providing vertical lifting of the rods of the structure is established.

REFERENCES

1. **Usyukin V.I.** Stroitel'naya mekhanika konstrukcij kosmicheskoj tekhniki [Construction mechanics. of space technology constructions]. Moscow: Mashinostroenie Publ., 1988. 392 pages (in Russian).
2. **Ignatiev A.V., Ignatiev V.A. and Onishchenko E.V.** The possibility of using the finite element method in the form of a classical mixed method for geometrically nonlinear analysis of hinge-rod systems. Vestnik MGSU, No. 12, 2015, pp. 47-58. (in Russian).
3. **Ignatiev A.V., Ignatiev V.A. and Onishchenko E.V.** Solution of geometrically nonlinear static problems of hinge-rod systems based on the finite element method in the form of a classical mixed method. Vestnik MGSU, 2016, No. 2, pp. 20-33 (in Russian).
4. **Basov K.A.** ANSYS: user's guide. – M.: DMK Press, 2012. 248 pages (in Russian).
5. **Gaydzhurov, P.P., Iskhakova E.R., Tsaritova N.G.** Study of Stress-Strain States of a Regular Hinge-Rod Constructions with Kinematically Oriented Shape Change. International Journal for Computational Civil and Structural Engineering. 2020. Vol. 16. No 1. pp. 38-47 (in Russian).
6. **Gaydzhurov, P.P.** Finite element modeling of the formation process of a hinge-rod system under controlled kinematic action / P. P. Gaydzhurov, E. R. Iskhakova, N. A. Savelyeva, N. G. Tsaritova // News of higher educational institutions. The North Caucasus region. Technical sciences. 2020, № 3(207), pp. 5-12 (in Russian).
7. **Gaydzhurov, P.P**. Modeling of the process of directed transformation of regular hinge-rod systems / P. P. Gaydzhurov, N. G. Tsaritova // News of higher educational institutions. The North Caucasus region. Technical sciences. 2021, № 1(209). pp. 5-11 (in Russian).
8. **Morozov E.M., Muizemnek A.Yu., Shadsky A.S**. ANSYS in the hands of an engineer: Mechanics of Destruction. M.: LENAND, 2008, 456 pages (in Russian).
9. The regular hinged structure: The patent of Russia № 2586351: IPC E04B 1/58 / **N.G. Tsaritova, N.A. Buzalo**; applicant and patentee of Platov South-Russian State Polytechnic University – № 2015100939/03; declare 01.12.15; publ. 06.10.16, Bulletin № 16 (in Russian).

10. **Buzalo, N.A., Alekseev, S., & Tsaritova, N.** Numerical Analysis of Spatial Structural Node Bearing Capacity in the View of the Geometrical and Physical Nonlinearity. 2016, Procedia Engineering, 150, pp.748-1753.
11. **Tsaritova N., Buzalo N.** Creating a solid model of the spatial structure node with application of solidworks complex. 2015. Construction and Architecture, 3, pp. 1-6 (in Russian).

СПИСОК ЛИТЕРАТУРЫ

1. **Усюкин В.И.** Строительная механика конструкций космической техники. М.: Машиностроение, 1988. 392 с.
2. **Игнатьев А.В., Игнатьев В.А., Онищенко Е.В.** Возможность использования метода конечных элементов в форме классического смешанного метода для геометрически нелинейного анализа шарнирно-стержневых систем // Вестник МГСУ. 2015. № 12. С. 47-58.
3. **Игнатьев А.В**. Решение геометрически нелинейных задач статики шарнирно-стержневых систем на основе метода конечных элементов в форме классического смешанного метода / А. В. Игнатьев, В. А. Игнатьев, Е. В. Онищенко // Вестник МГСУ. – 2016. – № 2. – С. 20-33.
4. **Басов К.А**. ANSYS для конструкторов.-М.:ДМК Пресс,2012.-248 с.
5. **Гайджуров P., Исхакова E., & Царитова N.** Исследование напряженно-деформированного состояния регулярной шарнирно-стержневой конструкции при кинематически ориентированном изменении формы. International Journal for Computational Civil and Structural Engineering, 2020, 16(1), 38–47.
6. **Гайджуров П.П.** Конечно-элементное моделирование процесса формоизменения шарнирно-стержневой системы при управляемом кинематическом воздействии / П.П. Гайджуров, Э.Р. Исхакова, Н.А. Савельева, Н.Г. Царитова // Известия высших учебных заведений. Северо-Кавказский регион. Технические науки. – 2020. – № 3(207). – С. 5-12.
7. **Гайджуров, П.П.** Моделирование процесса направленной трансформации регулярных шарнирно-стержневых систем / П. П. Гайджуров, Н. Г. Царитова // Известия высших учебных заведений. Северо-Кавказский регион. Технические науки. – 2021. – № 1(209). – С. 5-11.
8. **Морозов Е.М., Муйземнек А.Ю., Шадский А.С.** ANSYS в руках инженера // Механика разрушения. М.: ЛЕНАНД, 2008. 456 с.
9. Патент № 2586351 C1 Российская Федерация, МПК E04B 1/58. Шарнирный узел пространственной стержневой конструкции регулярной структуры : № 2015100939/03 : заявл. 12.01.2015 : опубл. 10.06.2016 / **Н.Г. Царитова, Н.А. Бузало** ; заявитель федеральное государственное бюджетное образовательное учреждение высшего профессионального образования "Южно-Российский государственный политехнический университет (НПИ) имени М.И. Платова".
10. **Buzalo, N. A.** Numerical Analysis of Spatial Structural Node Bearing Capacity in the View of the Geometrical and Physical Nonlinearity / **N. A. Buzalo, S. A. Alekseev, N. G. Tsaritova** // Procedia Engineering, Chelyabinsk, 19–20 мая 2016 года. – Chelyabinsk: Elsevier Ltd, 2016. – P. 1748-1753.
11. **Бузало, Н.А.** Создание твердотельной модели узла пространственной стержневой системы с использованием комплекса SolidWorks / **Н. А. Бузало, Н. Г. Царитова** // Строительство и архитектура. – 2015. – Т. 3. – № 1. – С. 1-6.

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