The numerical geometry optimization of the spatial structures’ nodal connector made of a massive part

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Abstract. Many elements of spatial trussed structures are converged at the nodes. The structural assembly operates in a difficult stress state. It is possible to study the distribution of stresses inside the nodal connector, which is a massive part, using the calculated software systems. The authors performed a study of the MARKHI system node’s stress-strain state, analyzed the surface stresses level and stresses inside the nodal connector.

1. Introduction
At the spatial trussed structures’ (STS) nodes many elements are converged. The peculiarity of STS is that each element is involved in the work of perceiving the external load and its further transfer to the foundations [1–5]. Each STS element has an internal force, transmitted to the nodal connection. The nodal connection perceives a lot of multidirectional, diverse forces from the elements adjacent to it. A node in such a situation operates in a difficult stress state [2, 4–13].

2. Materials and methods
Traditionally, the study of the stress-strain state (SSS) of nodal nodes was performed by the experimental methods. The most common method is electro strain measurement. A feature of the experimental methods is the stresses level assessment only on the test element’s surface. It is difficult to evaluate the internal stresses by the experimental methods. In practice, the internal stresses in the test element are determined based on the stresses measured along its surface. For the thin-walled elements, this method gives the acceptable results, for the massive bodies - internal stresses are calculated very approximately. For massive bodies with complex internal geometry, for example, cavities and holes, it is practically impossible to calculate the internal stresses by the surface stresses’ magnitude.

Modern computational software systems (CSS) make it possible to evaluate the internal stresses in models of almost any complexity. When analyzing the SSS, the computer models of CSS give a possibility to “look” inside, build any section with a distribution of the internal stresses level [6, 8, 9].

The well-known method of material concentration in the places with high levels of stress and in the places requiring increased reliability is widely used in the STS design. The STS nodes are often massive, steel of high strength is use for this kind of nodes. Thus, in practice, the goal is to increase the reliability of the chargeable nodes and, in particular, to lay a reserve for the of internal stresses’ “uncertainty”.

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The well-known nodes of spatial structures - Mero, Orona, Cubotto, Weimar, MARKHI, Kislovodsk are based on a solid ball or polyhedron with the holes [1, 2, 4, 9]. In these systems, up to 16 rods can be converged simultaneously. According to the research of R.I. Khisamov mass of nodes in the total STS mass can be up to 40% [11]. Moreover, in terms of the structures’ optimal design theory, the nodal elements refer to auxiliary elements, unlike the rods, related to the main elements [14, 15]. One of the generally accepted ways to optimize the structures is to reduce the size and number of auxiliary elements. As an example of this principle’s successful implementation, it is possible to cite the prefabricated trusses’ construction of bent-welded sections. They principle of the nodal connectors’ (auxiliary elements) rejection is implemented to the maximum extent, that is why the weight of such trusses is much less than of the trusses with nodal shapes. Thus, the reduction in the STS nodal connectors’ mass can save steel up to 40% in the limit.

The authors of this article see the possibility of reducing the material consumption of STS with the nodes made on the solid part basis, such as MARKHI, in the study of the node connectors’ bearing capacity reserves using computer simulation methods. The aim of the authors’ studies is to study the internal stresses distribution in the nodal connection of MARKHI, to find the ways to reduce its material consumption. To achieve this goal, the reference node of the MARKHI system spatial design implemented in practice was taken as an object of research (Figure 1).

![Figure 1. Initial design data for the studied node](image)

The necessary initial data for the study were taken from the corresponding project. The reference site was chosen for the research for a number of reasons. Firstly, this assembly is the most loaded in the design, secondly, fixing this assembly to the column is most understandable for describing the boundary conditions of fixing, thirdly, the requirements for the maximum reliability should be presented to the supporting elements due to the possible maximum damage during the progressive fracture’s development [16, 17].

Node geometry modeling was performed in the SolidWorks software package (Figure 2). When creating the node model, the authors sought to take into account the essential features of its design, such as: external and internal geometry of the node connector, adjacent couplings (nuts) and bolts, the difference in the physical and mechanical characteristics of the elements’ materials (due to the use of various steels). Some features of the nodal connection had to be neglected due to the complexity of their consideration in the model and the lack of influence principle on the final result. In particular, they
underwent the following simplification: threaded connection and the conditions for supporting the connector on the column. The threaded connection was replaced by a solid contact on the surfaces of the bolt and connector (contact task).

3. Results and discussions
The support of the connector in practice is relatively “free” (Figure 1), implemented through a centralizer and the safety angles’ installation. Vertical forces from the connector to the column are transmitted along the lower edge of the connector. Horizontal loads are perceived by the friction forces, and in case of emergency safety thrust angles are used. In the studied node model, there was no column with its structural elements - a centralizer, thrust angles, etc. The support of the node was modeled by rigidly fixing the surface of the connector’s lower edge. This corresponds to the situation in which the friction forces on the surface of the connector’s lower edge hold possible horizontal forces, i.e. normal operating situation.

Figure 2. Node design model

Figure 3. Design stresses on the node

As a result of calculating the nodal connection model in the CosmosWorks environment, the stresses were obtained both on the surface of the connector and inside it. The complex makes it possible to perform the arbitrary sections according to the model with the iso fields stress display. The complex allows to visualize the sections of the model with voltages exceeding the level set by the user. The latter function is convenient for isolating and analyzing the model sections with stresses reaching the plastic level. The results of stress analysis in the nodal connector are presented in Figures 3, 4.

As expected, the stresses on the connector’s surface do not exceed the conditional yield strength for the material - Steel 45, which means that the external connector is almost completely in the elastic stage of operation. An exception is the areas under the adjacent nuts. In the assembled node, these sections are hidden and therefore should be attributed to the internal sections for the node in the assembly.
Inside the connector, the small sections with stresses exceeding the conditional yield strength of steel and even the small sections with stresses exceeding the tensile strength of steel were found (Fig. 4). The latter should be attributed to the so-called “outliers”, characteristic for calculating the models using the software systems operating on the finite element method’s basis. These sites are affected by the well-known fact that there are the sections with peak values of the calculation results at the places of the nodal (point) load application and at the places of nodal fastenings (boundary conditions), which should be neglected, determining empirically the area of a reliable solution. The sections with peak stresses are observed along the edge of the connector’s supporting surface, along the edge of the nut and along the contact surfaces of the connector-bolt. Discarding the indicated sections from the analyzed geometry of the connector, it can be concluded that the entire volume of the connector’s massive body is in the region of stresses not exceeding the tensile strength, but inside the volume there are limited sections with stresses exceeding the conditional yield strength of steel, taking into account the worst design load combinations accepted in the draft under consideration.

For the studied geometry of the connector, the distribution of material by its volume turned out to be rational, to reduce its mass, i.e. to optimize by simply reducing its size was impossible.

The distribution of internal stresses in a massive body with internal voids in the form of “intersection of holes” for bolts has a characteristic form for the crystalline structures. Stresses are concentrated from the efforts’ application places and are distributed over the shortest distances to the support. The existing vacuum of the massive body in its upper part (the place of installation of the bolts) causes stress concentration in the “narrow” places. In the lower part of the connector’s massive body (closer to the reference plane), where there is more material and less vacuum, the tension level decreases. The connector’s surface portions located at a distance of the connector-nut and connector-bolt contacts’ boundaries are relatively little involved in the assembly power operation. We are talking about the connector polyhedron outer faces edges sections. In these places, the material can be completely removed, as a result of which the polyhedron connector outwardly turns into a ball, specific for the Mero node (Figure 4).

It is possible to reduce the steel consumption on a massive nodal connector by changing its basic design, for example, by considering the node’s formation in the form of a hollow spherical shell made of high strength steels. With this approach, the internal stresses characteristic of the described massive connectors will be absent altogether [18–20]. In this case, the force lines will pass along the surface of the shell, causing the appearance of only surface stresses that can be easily verified using the electro strain measurement method. The systems SDC, Nodus, NS, Oktaplatta, Vestrut, etc. are the examples of such nodes.
4. Summary
Based on the studies performed, the following conclusions are made:

1. The stresses on the connector’s surface from the combination of the calculated loads generally do not exceed the conditional yield strength of steel.
2. The maximum stresses on the connector’s surface are observed on the reference plane and at the contact points of the nut and the connector, i.e. under the nuts.
3. The small sections with stresses exceeding the yield strength of steel were found inside the connector.
4. The areas with high internal stresses are located at the points of the bolt and connector contact (threaded connection area) and inside the connector at the “holes’ intersection” for the bolts.
5. For the studied geometry of the connector, the material’s distribution turned out to be rational; it is impossible to reduce its mass by simply reducing its size.
6. It is possible to reduce the steel consumption on a nodal connector by changing its basic design, for example, by considering the nodal formation from a hollow shell.

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