On potentiality and practicability of installing flooring suspended in geodesic domes by means of cable system

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Abstract. The article considers the potentiality and practicability of installing flooring suspended in the geodesic domes by means of a cable system. Such design consideration will allow using the interior space of the geodesic domes more rationally and ramp up the rentable area of the building dramatically. The literature review revealed that the question of the possibility of embedding a flooring in a geodesic dome remains unexplored at present. The stress-strain state of the geodesic dome with worked in flooring was studied in the course of the investigation. Further, the authors conducted comparative analysis of the investigated structure with a test version has been carried out. The efficiency of the investigated test model was confirmed. Solutions for the elimination of stress and strain raisers in the model elements were proposed. Reliability of the results of the obtained data for the analysis of the investigated model was ensured by the accuracy of the finite element method. The practical significance of the paper lies in the development of methods for calculating and constructing geodesic domes with the worked in flooring.

1. Introduction
At the present time there is a global trend towards the use of the light space structures in the construction engineering sector. The search for an optimal engineering solution is an important criterion when choosing a structural system of a building [1].

Geodesic dome is a shell built on the basis of a system of geodesic lines marking out a surface of a sphere into polyhedra in various ways [2,3].

Geodesic dome has many advantages: lightness of the construction, large bearing capacity, speed of the frame construction etc. The surface of the lateral sides of the domed building is extremely minimized. The architectural properties of the domes allow to create a unique architectural space [4-7].

These days the development of the computer-aided design systems allows to select the optimal design diagram [8-11], to design [12-16], to perform calculations for all elements of the geodesic dome and to perform analysis of the stress-strain state of structures [17-23].

The strength calculation for the geodesic domes can be: approximate — an analytical solution for a smooth spherical shell [24]; numerical- using the general-purpose programs of the strength calculation [25]; numerical- using specialized computer programs aimed at determining the stress-strain state of the geodetic shells [26-28]. Modern software solutions allow to exchange data between graphical and calculation programs [29-31].
Analysis of the world research experience has shown that the issue related to incorporating the flooring into the geodesic dome is still unexplored. The experience in designing these types of domes is extremely small. There are no manuals and systematic recommendations for calculating and designing geodesic domes with flooring on external suspenders. The choice of the research topic has been determined by this shortage.

Flooring suspended by means of a cable system will make it possible to use the interior space of the geodesic domes more rationally, to apply not only horizontal but also vertical functional zoning and to increase the effective area of the building several times. That is why the search for the rational solutions of the dome systems is currently a topical question in the development of construction and architecture. Unification of decisions on the investigated topic will help to make a big step in the application and use of the light space structures.

The purpose of the investigation is to study the potentiality and practicability of installing flooring suspended in geodesic domes with the help of a cable system.

Research objectives: elaboration and development of the design model, investigation of the stress-strain state of the studied model; comparison of technical and economic indexes of the structural model with the studied one.

The object of the investigation is a building designed in the form of a geodesic dome with flooring suspended on a cable system, the layout of which is applicable to exhibitory installations without being bound to any particular location. The subject of the research is the stress-strain state of the shell.

2. Methodology

The methodology of the conducted investigation involves the review of the up-to-date experience in calculating and designing geodesic domes, selection of the best possible design diagrams, machine computation and analysis of the resulting data. Machine computation anticipates the following steps:

1. calculation of a geodesic dome with an worked in flooring suspended by means of a cable system (the first model);
2. calculation of the geodesic dome with an worked in flooring suspended by means of a cable system, arranged with due account for the analysis of the first model (the second model);
3. calculation of the geodesic dome check sample.

In this investigation the geodesic dome has been considered as a discrete truss structure and has been calculated using the structural theory method of the spatial truss structure. This approach has been implemented using a PC and the static calculation program of the spatial systems LIRA-SAPR PC.

A geodesic dome in the form of a hemisphere with a diameter base of 60 m and a boom lift of 30 m has been selected as an investigated model. Flooring on the external suspenders has been designated at a height of 13.4 m.

The investigated geodesic dome has been developed on the basis of the icosahedron. Steel tubes of 114x5mm circular cross section have been preliminarily taken as the material for the dome lattice elements. The flooring on metal beams has been of the reinforced concrete(broad-flanged beams 50SH2, 60SH3, 60SH4). The material for the flooring suspension elements ahave been steel ropes of hot rolled round steel of 30 mm in diameter. The foundation has been conditionally selected as a monolithic reinforced concrete ring for the dome supports. The dome coating has been an ethylene tetrafluoroethylene translucent film. Cross sections of the elements have been assigned on the basis of the design experience.

The automated technological chain for creating a design model based on a linear processor in LIRA-CAD software has been as follows: the design model — static calculation — RFC (rated force combination) - ILC (intended load combination)—the design system — the result output.

The physical model of the investigated object is shown in Fig. 1.
8 loadings have been formed during the calculation: the dome frame self-weight; the reinforced concrete slab self-weight including beams; the dome cover self-weight; the short-term load on the floor due to the people weight; long load on the floor due to the weight of the partitions and equipment; symmetrical and asymmetrical snow loads; short load due to the wind pressure. The calculated values of the ground snow load and the standard value of the wind pressure are accepted for the conditions of the town of Vladimir, the Russian Federation.

Selection and examination of the steel cross-sections in regards to the most hazardous combinations of loads have been made in accordance with the building codes. Calculation of the rated force combination has been made upon the criterion of extreme stress values at the characteristic points of the elements cross sections with reference to the rules established by regulatory documents. Stages of the calculation have been as follows: static calculation, rated force combination (hereinafter RFC), intended load combination (hereinafter ILC), stability according to (RCN) Regional construction norms.

3. Results
Before analyzing the results, the dome elements cross-sections according to the RSN in the LIRA-SAPR mode “Results on steel structures” have been selected and the cross section of the elements in the form of a tube of 152x10 mm has been made for the further calculation.

Analysis of the deformations and displacements of the dome nodes has been carried out according to the calculated combination of loads. The dome nodes have the maximum displacements along the lines of the loads action due to the flooring, namely in the nodes of the stress application from the external suspenders (see Figure 2).

Having analyzed the data of the displacements calculation it has been concluded that the nodal load has a negative effect on the operation of the structure that the loss of stability form proves (see Figure 3). It requires the development of solutions for the force distribution between the the dome nodes because non-uniform deformations take place due to the current load case. However, these displacement have been accepted as permissible since according to the calculation of the LIRA-SAPR module the structural stability has been ensured with the reserve of 2.78.
To determine the main criteria for the stress state of the dome (the longitudinal forces $N$, the shear forces $Q_y$ and $Q_z$, the bending moments $M_y$ and $M_z$, the torques $M_x$), the RFC has been calculated. Extreme values of normal and tangential stresses, calculated at characteristic points of the given rectangular section, as well as the extreme values of forces in the cross sections have been taken as the criteria for the hazard of the RFC for the bar elements.

![Figure 2. The original scheme with the overlapping of the deformed dome due to the action of RFC (the first version of the model).](image)

![Figure 3. The form of the loss of stability on the RFC (the first version of the model).](image)

In the course of the structure deformability analysis it has been found out that the node connections possess certain deformability which has been reflected in the results of the nodes movements. The deformability of the dome node connections affects the stress-strain state of the dome as a whole including the forces in the bars.

The meridional forces from the constant loads and the snow loads compress the shell throughout the height but at the same time their value from the apex to the supports increases. Ring strength from the same loads vary from the maximum value of compression at the apex of the shell to zero and then to the maximum value of tension at the support ring.

Having analyzed the stress-strain state of the investigated structure it has been deduced that the structure has been stable and its load-carrying ability has allowed to erect the flooring on the external suspender. However large values of effort arise in the most loaded elements. Hence it has been necessary to develop solutions for the loads distribution. In view of the above said a load dilute system has been developed. In the new model the cables have also been attached to the main beams of the...
covering with the same pitch and in the same quantity but at a distance of 1.0 m from the dome shell they have had an embranchment which has allowed to fix the suspension at several points (see Figures 4.5).

Figure 4. Layout of the external suspenders (the second version of the model). Side-view.

Figure 5. Geodesic shell with the flooring on the external suspenders (the second version of the model). View from above.

Subsequent to the results of the calculation, under the new version of the suspenders lattices, the same sections of the elements as in the first version, the welded pipe of 152x10 mm, have been selected. But the nature of the stress-strain state has changed.

Comparing the model with a load point application (in the 1st node) and a model with a distributed load (at several points) it has been determined that the second version of the cable system unloads the structure in the most loaded elements and nodes. Thus the maximum displacements along the X axis in the first version have been 11.3 mm and in the second version they’ve been 6.1 mm.

A scheme with a system of cables with the load distribution (the second model) with several nodes has been adopted for the further analysis.

The effectiveness of the dome construction solution has been estimated by the comparison with the control model. A geodesic dome with the same geometrical characteristics as the investigated design model has been selected but it didn have a worked in flooring. The cross sections of the design model elements have been solid seamless tubes of 25x5 mm. The deformed diagram of the test model is shown in Figure 6.
Analysis of the calculation results has shown that the strain-stress state of the geodesic dome with a worked in flooring, as in the 2nd design variant, is more closely approximated to the nature of the stress-strain state of the test model.

![Deformed diagram of the test model](image)

**Figure 6.** The deformed diagram of the test model.

Comparison of technical and economic indicators of the investigated and test models has been conducted to determine the practicability of designing geodesic domes with a worked in flooring.

| Table 1. Technical and economic indicators |
|-------------------------------------------|
| Cross sections of the dome bars | Stability | Effective area of the building with the same built-up area | Gross building volume | Steel intensity per 1 m² of the rentable area | Steel intensity square per 1 m³ of the building volume |
|------------------------------------------|-----------|------------------------------------------------|-------------------------|---------------------------------------------|------------------------------------------------|
| The test model                           | 25x5 mm   | enabled                                      | 2862 m²                  | 113040 m³                                    | 41 kg/m²                              |
| The investigated model                   | 152x10 mm | enabled                                      | 5117 m²                  | 113040 m³                                    | 9 kg/m²                               |

Steel intensity of 1 m³ of the geodesic dome building volume with a worked in flooring has been 0.4 kg / m³ while the metal intensity of 1 m³ of the geodesic dome building volume without the flooring has been 1.0 kg / m³. Comparison of the technical and economic indicators of the test model with a geodesic dome with an incorporated flooring has shown that the investigated variant is an advanced design possessing good technical-and-economic indexes and high architectural distinctiveness.

4. Conclusions

According to the results of the conducted work the efficiency of the investigated design model has been confirmed and the solutions for the elimination of the stress and strain concentrators in the model elements have been proposed. Economic expediency of the proposed structure has been identified by comparing the investigated model with the test model.

Practical significance of the investigation lies in the development of the methodology for structural analysis and construction of the geodesic domes with a worked in flooring.

Additional investigations on the geodesic domes operation with the bars of different cross-sections as well as with different variants of the lattice of the external suspenders for the a worked in flooring to reduce the structure steel consumption and to stabilize the strain in the dome lattice nodes are needed.
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