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Robustness of the combined arch system with radial ties

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Abstract. To ensure the safety of buildings and structures, it is necessary to analyze the structural integrity (robustness). The results of various studies show that arches with radial ties make it possible to create an architecturally expressive, cost-effective material consumption solution to the problem of girders bridging in public buildings, but the robustness of these systems is poorly studied. This article presents the results of the failure analysis of the coating elements in the form of combined steel arches with radial ties under various failure scenarios, the robustness of the n-th level in a static formulation is investigated, considering the geometrically nonlinear nature of the system operation, constructive measures are proposed to increase the robustness of a combined arch system with radial ties. The calculations were performed in the SCAD Office software 21.1.9.11. For the considered fragment of the scheme in both scenarios, the robustness index $I_{rob} > 98.5\%$ corresponds to the local nature of the excess of the load-carrying ability, $I_{rob} \leq 98.5\%$ - to disproportional. As soon as the asymmetric prestressing of the arch by ties disappears, which occurs when the most loaded ties are turned off step by step, the system either satisfies the strength and stability tests, or the number of elements in which the load-carrying ability is exceeded significantly decreases. Increasing the structural integrity of the structure by introducing chordal ties into the scheme contributes to increasing the robustness of the considered arch system.

1 Introduction

Among the priority tasks of the development of building sciences, one can note the development of methods and foundations for ensuring the safety and robustness of buildings and structures, conducting experimental researches of new types of large-span structures, reducing material consumption [1,2]. One of the ways to achieve the required level of reliability and safety in design is to analyze the degree of structural integrity (robustness) [3].

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Among the arch-cable-stayed systems, arches with radial and fan ties work better under nonuniform loads, can significantly reduce metal consumption [4-9], however, the robustness of these systems is poorly studied.

This article presents the analysis results of the coating system elements failure in the form of arches with radial ties under various failure scenarios, the robustness of the n-th level in a static formulation is researched, considering the geometrically nonlinear nature of the system operation, constructive measures are proposed to increase the survivability of a combined arch system with radial ties.

2 Methods

2.1 Initial data for the calculation

To study the robustness of the coating with load-bearing structures in the form of a combined arch system with radial ties, the following parameters were taken as initial data: loads were taken for the III snow and I wind regions as for the most common areas in the territory of the Russian Federation according to the maps in Appendix E [10]; the weight of the roof q = 100 (kg/m^2); span L=30 (m); arch rise f/L= 1/4 [11,12]; type of arches – two-hinged; sections 200x6; 250x8; 120x4 were selected for the arch belt, girders and cross ties according to GOST 30245-2012 [13]; the cross section of the radial ties Ø14 according to GOST 3064-80 [14]; the ties are prestressed (Fig. 1).

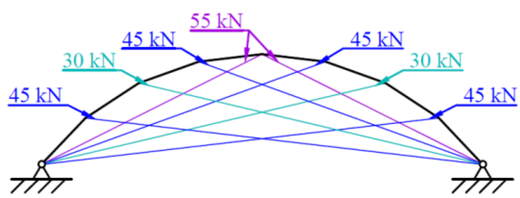

Fig. 1. Design scheme and prestressing of ties.

2.2 Modeling and calculation

Of the 9 main approaches to calculation models for the calculation of progressive collapse, given in paragraph 3.2.1 [15], an approach was adopted to assess the survivability of a combined arch system with radial ties, in which a fragment is allocated from the complete spatial calculation model of the entire building (Fig. 2) as follows: everything is discarded except the spatial section of the object, which includes structures that can receive and are able to redistribute the loads due to the removal of the load-bearing element from the structural drawing. Modeling and calculations of the arch-cable-stayed coating fragment were performed in the SCAD Office 21.1.9.11 software package, which implements the finite elements method. The arches belts, girders and connections are modeled by a finite element of type 305 (a spatial rod considering the geometrically nonlinear work nature), the tightening and prestressing in them are modeled by a cable–stayed element - type 308. The operation of the arch-cable system is considered with the two most unfavorable combinations of loads (Fig. 3) [12] the loads are determined according to the requirements [10] and are transmitted to arches with radial ties through girders. The calculation was performed according to the requirements of modern regulatory documents by a static method, considering the geometrically nonlinear nature of the coating fragment work [16-19].

Criteria for ensuring robustness:

- The forces in the structural elements or their connections according to the calculation results do not exceed their bearing capacity [16];
- The deformations of the element from the external load do not exceed the value of the maximum permissible deformations of the element [16].

In the calculations performed, if, after removing the coating bearing element, the forces in the structural elements exceed the bearing capacity only in the arch in which the element is removed, then the excess nature is local. If the excess of the bearing capacity occurs outside the arch in which the element is removed, then this nature is disproportionate.

A quantitative assessment of the structural system robustness was carried out using the I^{n}_{rob} robustness coefficient: the ratio of the number of intact structural elements $N_{undamaged}$ to the total number N [20,21]:

$$I^{n}_{rob} = N_{undamagedx} : N \cdot 100\% \tag{1}$$

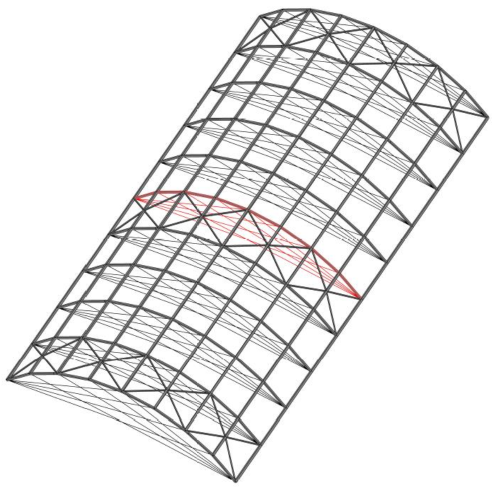

Fig. 2. Calculation model. The most loaded arch is marked in red.

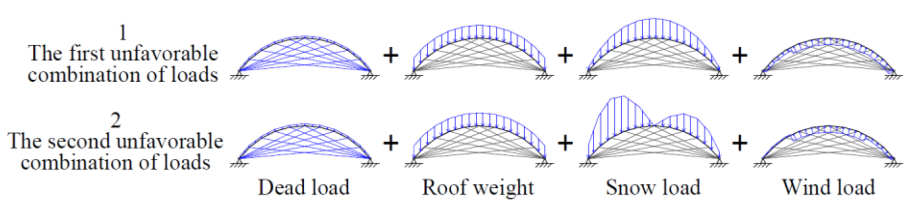

Fig. 3. Unfavorable load combinations.

2.3 Destruction scenarios

Since the probability of temporary loads calculated values agreement with the moment of the accident is very small, when checking for robustness, the normative values of permanent and temporary loads and the reduced value of short-term loads are considered [10,16,22]. However, the probability of failure of the coating elements is higher at the calculated values of loads. In this regard, in the considered scenarios (Table1), 3 load cases are considered: normative values with reduced snow load, design loads, calculated loads.

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Table 1. Numbering of destruction scenarios.

№ scenario	**№ of unfavorable load combination**	**Scenario sub-item**	**The value of loads**
1	1	1.1.1	Design loads with a reduced value of snow
		1.1.2	Design loads
		1.1.3	Calculated loads
	2	1.2.4	Design loads with a reduced value of snow
		1.2.5	Design loads
		1.2.6	Calculated loads
2	1	2.1.1	Design loads with a reduced value of snow
		2.1.2	Design loads
		2.1.3	Calculated loads
	2	2.2.4	Design loads with a reduced value of snow
		2.2.5	Design loads
		2.2.6	Calculated loads

Scenario No. 1 considers a step-by-step exclusion from the work of ties in the most loaded arch (Fig. 2). Fig. 4 shows the sequence of ties removing in the most loaded arch for various sub-items of the scenario, the ties with the maximal effort in the considered unfavorable combination are indicated in red, which are excluded at the next step. In scenario No. 2, a step-by-step exclusion of the most loaded ties in the scheme is considered (Fig. 5).

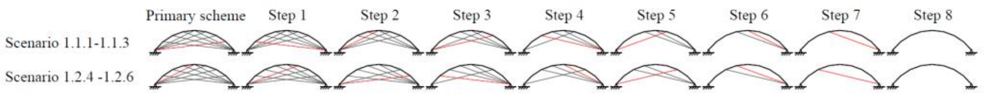

Fig. 4. Scenario 1. The sequence of ties removing in the most loaded arch.

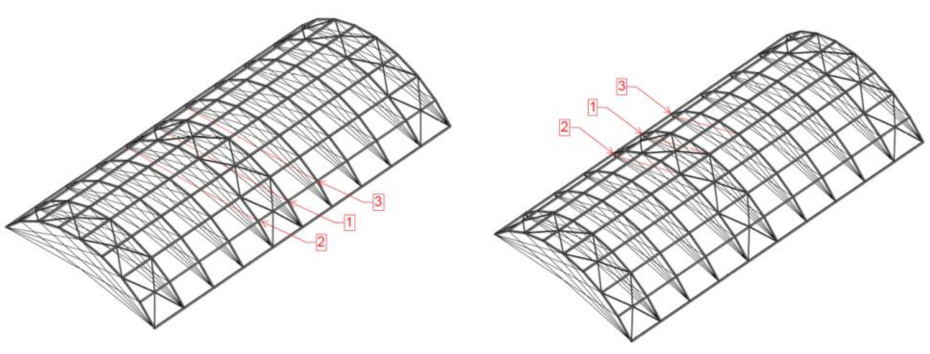

Fig. 5. Scenario 2. The sequence of the most loaded ties removing.

3 Results

3.1 Scenario 1

3.1.1 Sub-paragraph 1.1.1

The forces in the belt of the most loaded arch exceeded the bearing capacity only after removing all the ties in the most loaded arch and the most loaded ties in neighboring arches. The nature of the excess load–bearing capacity is local, in the belts of arches in which the ties are removed. The minimal I_{rob} = 99.3% is achieved at the 4th and 6th steps.

3.1.2 Sub-paragraph 1.1.2

The excess of the bearing capacity in the belt of the most loaded arch occurs at 1-6 steps, moreover, at 1-3,5 steps it is local, at 4 and 6 - disproportionate. At steps 7 and 8, the system satisfies the strength and stability tests. The minimal I_{rob} = 96.2% is achieved at the 6th step.

3.1.3 Sub-paragraph 1.1.3

The excess of the bearing capacity in the belt of the most loaded arch occurs at 1-8 steps, moreover, at 1-3,8 steps, it is local, at 4-7 - disproportionate. The minimal I_{rob} = 92.1% is achieved at the 6th step.

3.1.4 Sub-paragraph 1.2.4

The excess of the bearing capacity in the belt of the most loaded arch occurs at 1-6 steps, the nature is disproportionate. At steps 7 and 8, the system satisfies the strength and stability tests. The minimal I_{rob} = 91% is achieved at the 3rd step.

3.1.5 Sub-paragraph 1.2.5

The excess of the bearing capacity in the belt of the most loaded arch occurs at 2-6,10 steps, it is disproportionate. At steps 1,7 and 8, the system satisfies the strength and stability tests. The minimal I_{rob} = 92.9% is achieved at the 3rd step.

3.1.6 Sub-paragraph 1.2.6

The excess of the load-bearing capacity in the belt of the most loaded arch occurs at 1-8 steps, it is local and disproportionate. With a 2-8 step in the adjacent one, due to the redistribution of forces, the longitudinal force in the most loaded tightening exceeds the maximum permissible value, but the breaking force has not been achieved.
The minimal I_{rob} = 87.2% is achieved at the 3rd step.

3.2 Scenario 2

3.2.1 Sub-paragraph 2.1.1

The excess of the bearing capacity occurs in the belts of the arches at the fixing points of the remote ties at 2-4 steps, the character is local. The system shows robustness in case of a single failure. The minimal I_{rob} = 97.7% is achieved at the 3rd step.

3.2.2 Sub-paragraph 2.1.2

The excess of the bearing capacity occurs in the arches belts at the fixing points of the remote ties at 1-3 steps, at step 1 the character is local, at the subsequent ones it is disproportionate. The minimal I_{rob} = 94.7% is achieved at the 3rd step.

3.2.3 Sub-paragraph 2.1.3

The excess of the bearing capacity occurs in the arch belts at 1-3 steps, at step 1 the character is local, at the subsequent ones it is disproportionate. The minimal I_{rob} = 91.7% is achieved at the 3rd step.

3.2.4 Sub-paragraph 2.2.4

The excess of the bearing capacity occurs in the belts of the arches at 1-3 steps, the nature is disproportionate. The minimal I_{rob} = 90.6% is achieved at the 3rd step.

3.2.5 Sub-paragraph 2.2.5

The excess of the bearing capacity occurs in the belts of the arches at 2.3 steps, the nature is disproportionate. The system shows robustness in case of a single failure.
The minimal I_{rob} = 91% is achieved at the 3rd step.

3.2.6 Подпункт 2.2.6

The excess of the bearing capacity occurs in the belts of the arches at 1-3 steps, the nature is disproportionate. The minimal I_{rob} = 88% is achieved at the 3rd step (out of 3).

4 Discussion

In the scientific, technical and regulatory literature, there are various interpretations of the terms "robustness" and "avalanche-like (progressive) collapse" [3,16,17,19,26,27], however, in all definitions, the robustness of a building structure is characterized by the ability of the structural system to redistribute the load between the remaining load-bearing elements in the event of a local failure; the absence of damage that is not proportional to the local failure; the ability to maintain the bearing capacity (at least for some time) in the event of local destruction due to natural or man-made impacts. The term "avalanche-like (progressive) collapse" means the spread of initial local destruction, leading to the collapse of the entire structure or a disproportionately large part of it.

Among the methods of ensuring the robustness of buildings and structures, the most common and appropriate are the methods of the system principle [17]: performing calculations to analyze the adaptation of the work of the structure when modeling the removing of the load-bearing element [23]; considering the possibility of local destruction during design, consideration of various stress states due to the failure of one of the system elements [16,24]; increase in the strength of key elements, calculation of key elements for established emergency impacts [3,20,23].

Increasing the structural integrity (connectivity) of the structure by introducing connections that increase the continuous of the structure; increasing the degree of static indeterminability of the structure also contributes to increased robustness.

5 Conclusions

According to the results of performed calculations, it was revealed that with the exclusion of ties in the most loaded arch according to scenario 1 and the most loaded ties in the scheme according to scenario 2, efforts are redistributed to the bearing elements of neighboring arches, in particular, the efforts in ties increase. For the considered fragment of the scheme in both scenarios, the robustness index Irob > 98.5% corresponds to the local nature of the excess of the load-bearing capacity, Irob ≤ 98.5% - disproportionate.

For scenarios 1.1.1-1.1.3, the most dangerous situation is reached at the 6th step (Fig. 4), when two ties remain in the arch, connecting the arch belt with the left support. For scenarios 1.2.4-1.2.6, the most dangerous situation is reached at the 3rd step (Fig. 4), when 5 ties remain in the arch, of which 4 connect the arch belt with the left arch bearing; and 1 connects the arch belt with the right arch bearing. As soon as the asymmetric prestressing of the arch by ties disappears, which occurs when the most loaded ties are removed step by step, then, depending on the scenario subparagraph, the system either satisfies the strength and stability tests, or the number of elements in which the bearing capacity is exceeded significantly decreases.

Scenario 2 is more aggressive in comparison with scenario 1. The considered system shows a robustness feature in the case of a single failure in scenarios 1.1.1, 1.2.5, 2.1.1, 2.2.5.

Increasing the structural integrity (connectivity) of the structure by introducing chordal ties into the scheme increases the robustness of the considered arch system [8].

The combined arch system with radial ties allows you to create an architecturally expressive, cost-effective metal consumption solution to the problem of spans cover in public buildings (shopping galleries, exhibition halls, etc.), ensuring compliance with the requirements of strength and safety of structures.

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