Research on survivability of mesh hyperboloid structures

Ivan Samokhvalov¹,² and Vladimir Erofeev³,⁴

¹Lobachevsky State University of Nizhny Novgorod - National Research University, 603950, Nizhny Novgorod, Russian Federation
²Nizhny Novgorod State University of Architecture, Building and Civil Engineering, 603109, Nizhny Novgorod, Russian Federation
³Institute of Problems of Mechanical Engineering of the Russian Academy of Sciences – Branch Federal research center Institute of Applied Physics of the Russian Academy of Science, 603024, Nizhny Novgorod, Russian Federation
⁴Research Institute of Mechanics of the Lobachevsky State University of Nizhny Novgorod - National Research University, 603950, Nizhny Novgorod, Russian Federation

i.a.samohvalov@yandex.ru

Abstract. The object of study is a mesh hyperboloid tower, which has a base diameter of 34 meters and a height of 128 meters, constructed by an engineer V.G. Shukov. The survivability property of the mesh hyperboloid tower was accepted as a subject of research. The aim of the work is to perform a numerical calculation of the mesh hyperboloid tower for survivability in a static setting, under conditions of failure of individual load-bearing elements of the system as a result of an accident. This calculation evaluates the survivability of the structure. The research methodology involves consideration of several options for the collapse of the bearing elements: 1. Collapse of the intermediate rings of the 1st and 2nd tiers and 16 racks of the mesh tower, excluding power transmission cables; 2. Collapse of the intermediate rings of the 1st and 2nd tiers and 16 racks of the mesh tower, taking into account the influence of the load from the power transmission cables during operation. As a result, the most dangerous destruction zones are identified, from the point of view of the survivability of the structure, the survivability coefficient of the mesh tower, as a whole is determined. As a result of the calculations, it was revealed that when the intermediate rings and 16 racks in the tower elements are removed, the efforts in the elements adjacent to the collapse zone increase by 2.6 times. The asymmetry of the load on the removed elements plays a significant role in changing the efforts. With the removal of the intermediate rings of the 1st and 2nd tiers and 16 racks, the zone of the 1st lower tier becomes the most loaded. Compression efforts in the remaining racks of this tier increase by 150%. In addition, the number of compressed-bendable elements of the tower shell increase. The results of this work can be used by designers to calculate structures’ survivability.

1. Introduction
Currently, predicting emergency situations (terrorist attacks, structural defects, accidents caused by heavy operation of structures, etc.), as a result of which the destruction of individual elements of the structure occurs, is not widely used. Under certain conditions, a single failure of the load-bearing elements of the structure can lead to a progressive collapse.
Vladimir Grigoryevich Shukhov (August 16 (28), 1853 – February 2, 1939) is the first engineer in the world who used steel mesh shells for the construction of buildings and towers. Subsequently, high-tech architects, the famous Buckminster Fuller and Norman Foster, finally implemented mesh shells into modern construction practice, and in the XXI century shells became one of the main means of shaping avant-garde buildings [1].

Mesh hyperboloid structure is a special class of building structures, which is an object in the form of a hyperboloid of revolution or a hyperbolic paraboloid (hypar). At the end of the XIX century, Vladimir Shukhov overtook engineering thought by inventing mesh-based structures for decades to come. He was the first engineer who came up with the idea of using a joint static operation of a system of metal rods that intersect in two directions. The coating with this design works as a whole, and all the rods bear approximately the same load, which allows them to be made from the same section. In case of failure of individual elements, this type of structures shows the greatest potential for safe operation and survivability of the entire system.

For research the Shukhov’s tower was selected, which had been built on the Oka river in 1929 and is recognized by Western experts as perfect and worthy of being included in the world heritage list.

Employees of the Nizhny Novgorod State University of Architecture and Construction were engaged in the survey of the tower. They carried out work to clarify the actual state of the tower, as well as analysis of the state of its individual elements, several of which were subjected to corrosion, and deformations associated, perhaps, with errors during installation.

According to the results of the survey, it was concluded that the tower is in satisfactory condition, and local deformations in the elements and corrosion did not affect the overall stability and strength characteristics of the tower/ the strength of the tower.

After carrying out repairs to restore the lost intermediate rings of the 1st and 2nd tiers and 16 racks and painting elements, the tower returned to its original state and overall load-bearing capacity.

Analysis of tower element failures shows that the supports are a fairly reliable element of such structures, and only 9-13% of failures are associated with damage to the support elements [2].

To improve the safety of the object's operation, it is proposed to provide it with such quality as survivability. The survivability property of the structure is only manifested as a result of an emergency impact, which leads to the failure of any element of the structure.

As noted in [3,4] the emergence of the term "progressive collapse", from which the concept of survivability was derived, is associated with a number of tragic events, common to which was the factor of disproportion between the cause (emergency event) and the magnitude of the final damage. So, the first of them was the collapse of the side facade of the building "Ronan Point" in England in 1968, caused by an explosion of household gas on the 18th floor, which led to the destruction of the outer panel, which served as a support for the overlying panels. After the tragedy, there were changes in the regulatory framework of England – in November 1968, "Standards for preventing SOFTWARE in large-panel structures" were published. The terms such as alternative load path, continuity, and random load, were first recorded in these standards.

Considering the achievements in the area of structural survivability, it is necessary to note the works [5-7], which provide methods for calculating against progressive collapse, strategies based on taking into account the established emergency loads, as well as limiting the size of localized destruction. Studies [8-10] indicate that structures must be designed so that they are not damaged when emergency events occur: explosion, impact, local defect, etc. In [11-13], methods of indirect, direct, alternative loading path, special local strength, as well as ways to reduce the probability of progressive collapse and case studies of the survivability of structures are given.

Generally, under the survivability of load-bearing structures, we will understand their ability to maintain for some time performance in the presence of developing defects and damages of various nature. Sources of survivability are: physical-mechanical properties of materials to resist destruction; strength reserves that determine the stress-strain state and the intensity of degradation; structural redundancy and redundancy of elements. Within the framework developing security theory of
technical systems, the process of forming a system of quantitative indicators of survivability and safety is currently underway.

Consider the survivability indicators for the following modes of operation of the structure beyond the nominal operating conditions:

1) the mode of initiation of an emergency. This is a short-term mode, during which the design parameters of the structure go beyond the acceptable values;

2) the mode of development of an emergency situation. This is a mode of arbitrary duration, during which the structure degrades to a complete loss of strength, load-bearing capacity, and structural integrity.

The most common survivability indicators for these two modes belong to one of the following groups:

1) the system reserves of strength;
2) compensation characteristics;
3) characteristics of degradation intensity.

If we consider a design that has a system safety margin, in the case when, due to structural redundancy, increased classical safety margins of individual elements, the design is weakly sensitive to the occurrence of local damage and destruction. In this case, the occurrence of damage and loss of load-bearing capacity of individual elements leads to such a redistribution of internal force factors that in all the remaining elements of the structure, the classic strength reserves are within acceptable limits, so that the emergency initiation mode simply does not occur.

Under the compensatory characteristics of survivability, it is proposed to understand the properties of the structure to resist the transition from the initiation mode to the emergency development mode. In fact, they characterize the stability of the set of parameters of the stress-strain state, deviations from which occur in the conditions of the emergency initiation mode. Compensation characteristics are most often functions of the system properties of the structure. Compensation characteristics are provided by the flexibility of the structure and its elements, redundancy, and boundary conditions.

Characteristics of degradation intensity as indicators of survivability can be characterized as follows: in the emergency development mode, the survivability indicators characterize both the rate of falling of the load-bearing capacity and its time derivative, that is, the conditions for accelerating or slowing down the ongoing degradation processes.

Thus, if the design has the ability to redistribute forces to neighboring elements when individual load-bearing elements (or nodes) fail, then it can be considered that it has potential survivability [14-16].

The most striking examples of modeling and calculating structures for survivability and progressive collapse, using modern computer technologies, are given in [17-22].

2. Methods

The object of the study is a mesh hyperboloid tower with a base diameter of 34 meters and a height of 128 meters (Fig. 1). As a subject of research, the survivability property of mesh hyperboloid towers was accepted. It is necessary to assess the range of distribution and redistribution of forces, and as a result to assess the survivability of the tower, as well as the predisposition of mesh structures to progressive destruction.
Figure 1. Model of the V. G. Shukhov’s mesh hyperboloid tower with a height of 128M

A static calculation of the V. G. Shukhov’s mesh hyperboloid tower with a base diameter of 34 meters and a height of 128 meters was performed according to the current standards for the I wind district. The calculation was performed using the finite element method, with the "SCAD Office" application package. As a coverage model, a spatial CE model is adopted that takes into account the geometric parameters and the nature of the load distribution (own weight, ice load, wind load). The snow load was not taken into account in this work due to the minimal impact on the calculation.

Then the supporting elements were removed from the structure: intermediate rings, racks. Then the picture of the distribution of forces in the tower elements and the picture of the resulting deformations of the nodes were studied.

When various groups of elements are removed from the model, internal forces are redistributed in the remaining structural elements. An increase in internal forces can lead to destruction, since initially the strength calculation is carried out with a minimum margin. Therefore, it is necessary to determine which version of the possible collapse is the greatest increase in internal forces in the structural elements, and which version of the collapse is the most dangerous for the strength and stability of the structural elements.

Based on the analysis, a combination of loads, consisting of the structure's own weight, ice load, and wind load, was identified.

3. Results and Discussion
On figures 2-5 the results of static calculation of a structure with different variants of deleted elements are presented on the example of the lower section. The pictures show that in the worst case scenario, when the intermediate rings of the 1st and 2nd tiers and 16 racks are removed, the tower elements which adjacent to the collapse zone increase in effort by 2.5 times, compared to the calculated ones.
Figure 2. Scheme 1. Option for distributing forces during normal operation of the tower

Figure 3. Scheme 2. Option for redistributing efforts with the destruction of the intermediate rings of the 1st and 2nd tiers

Figure 4. Scheme 3. Option for redistributing efforts with the destruction of 16 racks
Figure 5. Scheme 4. Option for redistributing efforts with the destruction of intermediate rings of the 1st and 2nd tiers and 16 racks.

![Diagram of scheme 4 showing redistribution efforts]

Table 1. Options for efforts in tower elements

| Scheme 1. Efforts, kN | Scheme 2. Efforts, kN | Scheme 3. Efforts, kN | Scheme 4. Efforts, kN |
|----------------------|----------------------|----------------------|----------------------|
| -162.02              | -161.36              | -325.44              | -404.53              |
| -146.36              | -145.73              | -292.75              | -371.65              |
| -130.69              | -130.11              | -260.05              | -338.77              |
| -115.03              | -114.49              | -227.36              | -305.88              |
| -99.36               | -98.86               | -194.67              | -273                 |
| -83.7                | -83.24               | -161.97              | -240.12              |
| -68.03               | -67.61               | -129.28              | -207.23              |
| -52.37               | -51.99               | -96.58               | -174.35              |
| -36.7                | -36.36               | -63.89               | -141.47              |
| -21.04               | -20.74               | -31.19               | -108.58              |
| -5.37                | -5.11                | 1.5                  | -75.7                |
| 10.3                 | 10.51                | 34.19                | -42.82               |
| 25.96                | 26.14                | 66.89                | -9.94                |
| 41.63                | 41.76                | 99.58                | 22.95                |
| 57.29                | 57.39                | 132.28               | 55.83                |
| 72.96                | 73.01                | 164.97               | 88.71                |
| 88.62                | 88.64                | 197.66               | 121.6                |

It is important to pay attention to which side, relatively to the asymmetric load, the removal (destruction) of a part of the tower shell occurs.

4. Conclusions
Based on the obtained results, we can conclude that there are a large number of options for redistributing efforts in the elements of the tower, depending on the emergency situation that caused...
this or that type of destruction. Analyzing the results obtained, namely, the increase in longitudinal forces, in emergency situations, we can conclude that when designing a structure, the selection of sections must be carried out with a multivariate statement of the problem. So, in our case, it was necessary to make an adjustment of the sections – to increase them by 2.5 times compared to the original ones. It is obvious that with the removal of the intermediate rings of the 1st and 2nd tiers and 16 racks, the zone of the 1st lower tier is the most loaded. Compression forces in the remaining racks of this tier increased by 150%.

At the comparison of the reallocation of efforts in schemes 1-4 (Fig. 2-5), it can be concluded that the most "destructive" influence is the removal of part of the struts between the support ring and the ring of the 3rd tier (scheme 3), which led to a large increase in the stretching and compression forces in the remaining struts (2 times). Further removal of the intermediate rings (scheme 4) cardinaly changed the forces in the tower elements (table 1) - the compression forces increased by 2.5 times, and the tensile forces decreased by 1.6 times. In addition, the number of compressed-bending elements of the tower shell has increased.

Graphical analysis of the geometric model of a mesh hyperboloid tower in SCAD reveals that the most loaded elements are the remaining racks between the support ring and the ring of the 3rd tier.

A fatal consequence, which can lead to the destruction of the entire structure of the tower, is the loss of stability of the remaining struts, the estimated lengths of which have increased due to the removal of intermediate rings.

The conclusions of this research can be used by practicing engineers to assess the survivability of other structures of a similar class and to find the most vulnerable areas during the facility operation.

Acknowledgements
The work was supported by the RFBR (projects 18-08-00715, 20-38-70158).

References
[1] Kurrer K E 2008 The History of the Theory of Structures: From Arch Analysis to Computational Mechanics (Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG)
[2] Samokhvalov I A 2018 The effect of defects in the supporting leg of a metal tower 72 meters high on the stress-strain state of its structure Proceedings of the section Mechanics and modeling of materials and technologies. «Gagarinskie chteniya» (Moscow: IPMekh RAN) 128 – 130 (in Russian)
[3] Crowder B 2005 Devil in details (Navfac) 12 p
[4] Crowder B 2005 Definition of progressive collapse (Navfac) 10 p
[5] General Services Administration Washington. DC Draft 2003 Progressive Collapse Analysis Draft, Progressive Collapse Analysis Office Buildings and Major Modernization Projects
[6] Starossek U 2009 Progressive collapse nomenclature Struct. Eng. Int. 1886–1895
[7] Haberland M 2007 Progressiver Kollaps und Robustheit (Progressive collapse and robustness). Hamburg University of Technology, Structural Analysis and Steel Structures Institute. Diploma the-sis.
[8] Pujol S and Smith-Pardo J P 2009 A new perspective on the effects of abrupt column removal Engineering Structures 31 869–874
[9] Wald F 2016 Benchmark cases for advanced design of structural steel connections Ceska technika 188
[10] Abruzzo J, Matta A and Panariello G 2006 Study of mitigation strategies for progressive collapse of a reinforced concrete commercial building Journal of Performance of Constructed Facilities 20(4) 384–390
[11] Ellingwood B R, Robert S, Dusenberry D O, Dat D and Lew H S 2007 Best Practices for Reducing the Potential for Progressive Collapse in Buildings, U.S. Department of Commerce, National Institute of Standards and Technology (William A. Jeffrey, Director) 214
[12] Agnew E and Marjanishvili S 2006 Dynamic analysis procedures for progressive collapse
Structure Magazine 24–27
[13] Vlassis A, Izzuddin B, Elghazouli A and Nethercot D 2009 Progressive collapse of multi-
storey buildings due to failed floor impact Engineering Structures 31(7) 1308–1318
[14] Testoedov P S and Tryanina N Yu 2014 Survey of hanging mesh survivability International
Scientific and Industrial Forum "Great Rivers - 2014". Congress proceedings (N. Novgorod:
NNGASU) 157–159 (in Russian)
[15] Canisius T D 2007 Robustness of structural systems – a new focus for the joint committee on
structural safety Applications of Statistics and Probability in Civil Engineering (London) 8 p
[16] Dusenberry D O and Hamburger R O 2006 Practical means for energy-based analyses of dis-
proportionate collapse potential Journal of Performance of Constructed Facilities 20(4) 336–
348
[17] Powell G 2005 Progressive collapse: case study using nonlinear analysis In: Proceedings of
the Structures Congress and Exposition (New York, NY, USA) 2185–2198
[18] Kim J and Kim T 2009 Assessment of progressive collapse-resisting capacity of steel moment
frames Journal of Constructional Steel Research 65(1) 169–179
[19] Gao S and Wang S 2018 Progressive Collapse Analysis of Latticed Telecommunication
Towers under Wind Loads Advances in Civil Engineering 3293506 1–13
https://doi.org/10.1155/2018/3293506
[20] Song B I, Girjunas K A and Sezen H 2014 Progressive collapse testing and analysis of a steel
frame building Journal of Constructional Steel Research 94 76–83
[21] Gerasimidis S and Sideri J 2016 A new partial-distributed damage method for progressive
collapse analysis of steel frames Journal of Constructional Steel Research 119 233–245
[22] Asgarian B, Eslamlou S D, Zaghi A E and Mehr M 2016 Progressive collapse analysis of
power transmission towers Journal of Constructional Steel Research 123 31–40