### Decisions for Ensuring Facility Safety

<table>
<thead>
<tr>
<th>№</th>
<th>Facility Structural Component</th>
<th>Condition Category</th>
<th>Decisions for Ensuring Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Roof</td>
<td>Designed</td>
<td>Continuous automated monitoring of the roof parameters generating emergency messages (signals) to the facility's OCD. Annual and quarterly monitoring with making conclusions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited operability</td>
<td>Continuous automated monitoring of the roof parameters generating emergency messages (signals) to the facility's OCD. Shift to weekly and/or daily monitoring with making conclusions. Examination. Identification and removal of the reasons for the change in the technical condition of the roof structures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Critical</td>
<td>Emergency monitoring measurements and examination. Identification of the reasons for the change in the roof structures' technical condition. Emergency engineering and technical activities. Calling rescue workers if needed.</td>
</tr>
<tr>
<td>2</td>
<td>Load-bearing ferroconcrete structures</td>
<td>Designed</td>
<td>Continuous automated monitoring of the ferroconcrete structures' parameters generating emergency messages (signals) to the facility's OCD. Annual and quarterly monitoring with making conclusions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited operability</td>
<td>Continuous automated monitoring of the ferroconcrete structures' parameters generating emergency messages (signals) to the facility's OCD. Shift to weekly and/or daily monitoring with making conclusions. Examination. Identification and removal of the reasons for the change in the ferroconcrete structures' technical condition.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Critical</td>
<td>Emergency monitoring measurements and examination. Identification of the reasons for the change in the ferroconcrete structures' technical condition. Emergency engineering and technical activities. Calling rescue workers if needed.</td>
</tr>
</tbody>
</table>
when the weather conditions change (heavy snow, heavy rain, etc.);
when storm warning is announced (based on the weather forecast).

The parameters listed below are continuously controlled and logged in an automated fashion to provide the data required for drawing conclusions concerning the monitoring stages of the facility structures’ technical condition:

- vertical movements of the roof threads and inner ring;
- horizontal movements of the outer bearing ring;
- horizontal and vertical movements of the building framework at the bearing points for the outer roof ring;
- building framework subsidence at the bearing points for the outer roof ring;
- snow load on the roof surface is measured at 60 points on the roof surface;
- water level on the roof is measured if the funnels are clogged and precipitation is heavy;
- roof weight throughout the facility exploitation;
- damping logarithmic decrement;
- lowest frequencies of characteristic oscillations.

The monitoring data gathered for a corresponding stage are sent to a dedicated Monitoring Center for preparing a conclusion on the condition of the facility load-bearing structures.

The condition of the facility load-bearing structures is assessed through the change in the real structure parameters and the calculated parameters.

The ready conclusions are sent to:
- the institution responsible for the facility exploitation;
- the institution supervising the facility.

The operating company makes decisions for ensuring the facility safe technical condition based on the conclusion on the condition of the facility load-bearing structures or based on the continuous automated monitoring data on the load-bearing structures parameters fed by the ESMS to the operations control desk (OCD).

The decisions for ensuring the facility safe technical condition are made according to the recommendations in Table 10.
In the latter case, snow layers slid to the center to make snow bags. The snow load increased by 60 kg/m² and the frequency (that is hardness) compared to the first day of tests increased by 4.1 % and 8.2 % accordingly.

This change in frequency can be reliably measured by the ESMS means. Thus, the experiments carried out justified the major approach to the selection of the roof construction continuous monitoring methodology.

The following findings are another positive outcome of the tests:

1. The ESMS sensitivity to the change in the roof condition, including the load-bearing capacity safety margin depending on the snow load, is ensured.

2. The current location scheme for the vibration sensors supports identification of the first shape of oscillations.

The data obtained became a foundation for designing the methods and localization features of the Monitoring Methodology.

### Table 9

<table>
<thead>
<tr>
<th>ISP Roof Mathematical Model Vibration-Based Diagnostics Results Compared to Experimental Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof mathematical model resonance oscillation frequencies (Hz) as of Figure 14</td>
</tr>
<tr>
<td>ISP Roof experimental data on resonance oscillation frequencies, experiment results as of February 20, 2007.</td>
</tr>
<tr>
<td>Difference between design and experimental oscillation frequencies, %</td>
</tr>
</tbody>
</table>

3.5. Load-bearing Structures Monitoring Methodology

The technical condition of the facility load-bearing structures is monitored to ensure safe exploitation. This includes automated control of the processes happening in the structures for timely and early identification of a negative change in the structures’ stress and strain state, which may cause the facility to acquire a limited operability or critical condition.

There are four stages for the facility load-bearing structures’ monitoring:
- annual;
- quarterly;
- weekly;
- daily.

Every monitoring stage results in drawing a conclusion on the condition of the building’s load-bearing structures:
- design;
- limited operability;
- critical.

If the conclusion is that the building’s load-bearing structures are in the ‘design’ condition, annual monitoring is performed.

The decision to start quarterly, weekly, or daily monitoring of the facility structures’ technical condition is to be taken:
- when the conclusion is limited operability or critical condition of the facility’s load-bearing structures;
- when a critical change in the controlled parameters of the load-bearing structures is identified by the continuous automated monitoring;
As a result, vibration-based diagnostics for the roof of the Ice Sports Palace on Khodynskoye Field was performed to generate a matrix of the complex transfer functions and identify the first oscillation shapes.

The active and passive types of vibration-based diagnostics were used.

They resulted in the vertical dynamic deflections in the roof construction as transfer functions of the force input.

The vibration-based diagnostics was used to obtain the actual values for the ISP roof transfer functions and the characteristic oscillation shapes (Figures 15 and 16).

The first two characteristic frequencies were identified (1.36 Hz and 1.79 Hz). The generalized damping factor is 0.019.

Table 9 shows the design and experimental data on resonance oscillations by frequency values. The table makes one conclude that the match between the design and experimental data is comparatively good. The average deviation is −5.2 % with the rage of +2.9 % to −8.7 %.

The ISP roof mathematical model vibration-based diagnostics results as analyzed above lead one to an assumption that the most reliable results are related to the first four frequencies of forced oscillations (considering symmetry – up to characteristic frequency eight). Average deviation here is −3.5 %. The frequencies may be recommended for intermittent monitoring control.

The following conclusions are based on the roof vibration-based diagnostics results and preliminary data analysis:

1. The first shape of roof oscillations has been identified at the frequency of 1.36 Hz. The system's damping factor is 0.019. This shape of oscillations can be effectively controlled by the ESMS.

2. The on-site experiments provided data on the resonance peaks for the first characteristic frequency with the controlled precipitation fall out indicators.
Table 8

| Calculated Data for ISP Roof Mathematical Model Vibration-Based Diagnostics Compared to Calculated Data for Characteristic Oscillation Frequencies |
| Resonance frequencies of roof oscillations (Hz) as of Figure 14 | 1.43 | 1.68 | 1.78 | 1.93 | 2.11 | 2.37 |
| Oscillation amplitudes (mm) | 5.37 | 9.15 | 7.70 | 6.70 | 8.35 | 5.96 |
| Number of half-waves of oscillations (pieces) | 2 | 4 | 6 | 8 | 6 | 6+(6) |
| Respective characteristic oscillation frequency (Hz) (as of Table 7) | 1.449 | 1.693 | 1.786 | 1.938 | - | (2.363) |
| Number of characteristic oscillation frequency (as of Table 7) | 2 | 4 | 5 | 8 | - | (15) |

This caused a multi-stage set up of the on-site experiment.

Stage one. Oscillation excitation and response signal registration.

This stage was defined to obtain real-time results of instrumental measurements required for further analysis of oscillations. The results comprised amplitude, phase, and frequency characteristics of dynamic deflections for the data-important points of the construction. The transfer functions of the construction response to the harmonic loading were determined the following way:

- the input and response signals were measured and registered;
- the Fourier analysis was performed;
- the construction response converted signals to the force impact input signal ratio was identified.

Stage two. This included secondary processing of the instrumental measurements, including animation of oscillation forms, identification of characteristic frequencies and damping factors, statistical analysis. This stage also included an examination designed to identify the reasons for the deviation in the construction response to the dynamic impact.

Stage three. This included: the construction condition assessment, summing up experimental data, comparison to the master (design or statistical) data; determination of the overall condition and assessment of the construction working capacity.

The exciter of the harmonic dynamic impact on the subject construction was a technical system answering the following criteria:

- smooth and continuous change of working frequency (slow sine) in the 0.6–30.0 Hz range;
- external control of forcing frequency and amplitude from an external signal source, including a personal computer;
- stability of output characteristics in terms of frequency and amplitude;
- high mobility and short deployment time;
- no need for the oscillation exciter anchoring on the facility under test;
- The exciter as a technical system was answer the following criteria:
- 0.6–30.0 frequency band;
- at least 2.5 accuracy rating;
- dynamic range of at least 90 dB;
- the range of measured movements (depends on the frequency) – 0.1 micron – 0.01 m;
- easy and reliable fixing on the structure under test;
- inertia principle movement measurement requiring no measurement base (ground surface, another construction elements of the structure) or any mechanical connection with it (wire, leash, etc.);
- interference resistance to stray currents;
- immunity to climate effects.

The minimal measurement accuracy of 2.5 % was maintained through the measurement system component certification, dedicated quick control tools, as well as a cut-through automated calibration of all the information and measurement system's measurement channels.
Since the most basic oscillation shapes and frequencies may be similar to the construction characteristic oscillation shapes and frequencies, then, if identified by an on-site experiment, they let one control the most representative characteristic oscillation shapes and frequencies of the construction via intermittent monitoring. Their change lets one understand the technical condition of the whole construction.

To predict and simplify the analysis of the on-site experiment outcomes, the vibration-based diagnostics was initially applied to a mathematical model of the construction. Besides, it is just as important to justify the mathematical model validity by comparing the design data to the on-site experimental data.

In the mathematical model, the virtual vibrator was applied to the junction between the radial thread and ring five counting from the outer ring. The 1.000 kgf exciting force oscillatory amplitude was used for the calculations, which is a standard for experimental data processing. The 1.4 to 2.4 Hz frequency band with the 0.01 Hz interval was used for the calculations to analyze the structure dynamic response within the range of the first 18 characteristic oscillation frequencies.

Figure 14 shows the amplitude and frequency characteristics of the ISP roof mathematical model when it is subject to harmonic excitation at the point mentioned above. The horizontal axis shows the oscillation frequencies, the vertical one shows the respective vertical movements (cm) of the point (a node of the end-element scheme). It is easy to notice that the transfer function has six distinct resonance peaks.

Table 8 shows the calculated data for the ISP roof mathematical model vibration-based diagnostics compared to the calculated data for the characteristic oscillation frequencies.

The comparative analysis of the mathematical model vibration-based diagnostics in Table 8 has shown that the shapes of forced oscillations may be considerably different from the shapes of characteristic oscillations, and that they may be quite unusual.
by the non-linear work of a complex suspended structure, which has kinematic movements apart from the ‘force-determined’ ones.

The frequencies and shapes of characteristic oscillations are calculated for the structure normal exploitation conditions in summer, that is for standard loads without considering the snow. This is a condition the construction has with slight deviations for the most part of the exploitation time.

Table 7 shows the values for the first twenty characteristic oscillation frequencies of the roof.

Figure 12 shows the shapes of the roof characteristic oscillation frequencies on frequency one.

Figure 13 shows the shapes of the roof characteristic oscillation frequencies on frequency 16.

Summing up, it is worth mentioning that due to the axial symmetry in the mass distribution on the roof, the shapes of the characteristic oscillation frequencies are grouped in pairs: 1+2, 3+4, 5+6, 7+8, 9+18, 10+11, 12+13, 14+17, 15+16, 19+20. If the mass distribution is asymmetrical, the situation will be different. This may happen in winter, when the snow on the roof may slide or distribute unevenly due to aerodynamic effects.

Vibration-based diagnostics was performed in order to identify the resonance oscillation frequencies for the construction under the stimulated harmonic force impacts in a given frequency band.
(200 kgf/m²) applied to half of the roof and all the surface inside the inner ring. The snow redistribution on the roof was caused by its gradual slide from the peripheral area to the center. It is obvious, that a snow distribution on the roof like that is not strictly justified and is used here with a certain safety margin given the lack of more precise data.

Regular instrumental monitoring of the distribution features and snow load values for the roof with statistical measurement results processing and criteria adjustment is to be set up for further exploitation of the ISP building.

Table 6 shows a comparison set of design data for an even snow distribution on the roof.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Meter Number} & \text{Normal Exploitation Thresholds} & \text{Unacceptable Exploitation Thresholds} \\
& \text{Movements (mm)} & \text{Rotation Angle (Radian)} & \text{Movements (mm)} & \text{Rotation Angle (Radian)} \\
\hline
1 & 0.0 & 40.7 \times 10^{-4} & 0.0 & 42.3 \times 10^{-4} \\
2 & 35.7 & 19.1 \times 10^{-4} & 37.4 & 20.2 \times 10^{-4} \\
3 & 46.4 & 3.4 \times 10^{-4} & 48.5 & 3.2 \times 10^{-4} \\
4 & 54.7 & 3.2 \times 10^{-4} & 55.5 & 2.9 \times 10^{-4} \\
\hline
\end{array}
\]

Table 4

Acceptable and Limit Values of Vertical Movements and Rotation Angles at the Meter Locations for the Summer Exploitation Period

Table 5

Acceptable and Limit Values for Vertical Movements and Rotation Angles at the Meter Location Points in Winter with Uneven Snow Distribution over the Roof

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Meter Number} & \text{Normal Exploitation Thresholds} & \text{Unacceptable Exploitation Thresholds} \\
& \text{Movements (mm)} & \text{Rotation Angle (Radian)} & \text{Movements (mm)} & \text{Rotation Angle (Radian)} \\
\hline
1 & 0.0 & 70.9 \times 10^{-4} & 0.0 & 85.5 \times 10^{-4} \\
2 & 70.8 & 45.4 \times 10^{-4} & 87.5 & 57.7 \times 10^{-4} \\
3 & 100.6 & 7.4 \times 10^{-4} & 126.0 & 8.9 \times 10^{-4} \\
4 & 93.9 & 12.2 \times 10^{-4} & 112.0 & 19.1 \times 10^{-4} \\
\hline
\end{array}
\]
3.4. Assessing the Stress and Strain State of the ISP Roof Load-Bearing Structures

The stress and strain state of the ISP roof load-bearing structures was assessed to define the criteria for the roof movements and rotation angles at the meter installation points.

Figure 9 shows the stress and strain state of the roof load-bearing framework with the design load coming from the load-bearing and enclosure structures gravity loads, technological loads and the snow, which are evenly distributed throughout the roof. The highest stress of 1.258 kg/cm² is generated in element № 4,850 of the hard thread. The highest vertical movement of 10.22 cm is observed in node № 10,517 located approximately in the middle of the hard thread, but not in the center of the roof.

Figure 9. Roof Stress and Strain State for Evenly Distributed Load

Figure 10 shows the same picture for a non-symmetric snow load. The snow is evenly located inside the central ring and on half of the rest of the roof. The highest stress of 1.649 kg/cm² is in element № 8,209, the diagonal rod, and the highest movement of 13.06 cm is in node № 10,365.

Figure 10. Stress and Strain State for Load-Bearing Structures with Snow Load on Half the Roof

The continuous monitoring criteria for movements and rotation angles should be independently established for the summer time without the snow load and for the winter time, when snow is possible and may be located in an asymmetric fashion, which increases the structure work.

The roof meter numbers are a leading index for the movements and rotation angles database. Figure 11 shows the meters location and numbers.

Table 4 gives the results of statistic calculations determining the thresholds for normal and unacceptable exploitation of the ISP roof in summer and winter.

The calculations shown in the table above are based on the standard gravity loads generated by the roof load-bearing and enclosure structures, technological loads from engineering networks, flying bridges, the technological platform and the mediacube.

Table 5 shows the acceptable and limit values for vertical movements and rotation angles at the meter location points in winter with uneven snow distribution over the roof.

The figures in Table are based on the design values of the permanent loads mentioned above, as well as the design snow load.
loads and sets of loads: the understressed elements for one set of loads become overstressed elements for another set of loads, and otherwise.

The abovementioned facts show that the SSS control is not acceptable for designing an ESMS concept for the ISP roof. Furthermore, an attempt to implement an idea like that may lead to a system for gathering technical information, which will mislead those taking important decisions.

It is obvious that the use of integral characteristics like movements, shapes and oscillation frequencies of the construction will be a more logical way to control the load-bearing framework of the ISP roof.

3.3. Criteria for Technical Condition of the ISP Roof Load-Bearing Structures

There are two major limit states defined for a construction design and exploitation:

The first limit state means a construction has lost all exploitation characteristics, e.g. it has collapsed, lost stability, overturned, etc. In this case the maximum possible (design) impact and minimum possible (design) resistance values for the construction materials are used for the design process. Nevertheless, it should not be taken literally, since the limit state methodology is, on one hand, based on the probability principles, and, on the other hand, the designer always has an opportunity to apply extra safety margins to compensate for the unaccounted impacts and adverse conditions. The service factors and reliability factors for the construction purpose can be used as an example.

The second limit state means the load-bearing capacity of a construction is maintained, whereas its normal exploitation is hampered, e.g. the structure movements (arching) lead to manufacturing equipment failures, structure oscillations cause uncomfortable feelings of those inside the building, etc. The construction facilities are then designed based on the so-called ‘standard values’, which are lower for the loads and higher for the material durability since the state is believed to be of short duration and removable by organic means. Then the construction will satisfy all the exploitation requirements, including the safety ones.

The technical condition criteria for the ISP roof load-bearing structures can be developed on the aforementioned basics to establish a conclusion-drawing procedure for a monitoring stage of the technical condition of the facility engineering structures and determine a decision-making procedure to ensure safe technical condition for the facility engineering structures.

The ‘traffic lights’ may be used as danger indicators and the integral characteristics like movements, shapes and oscillation frequencies of the construction may be considered to ‘switch on’:

– The green light, when the values monitored for these characteristics are within the standard impact scope. This is a normal exploitation condition for the construction.

– The red light, when the monitored values reach or exceed the limits for design impact. This condition bans further construction exploitation.

– The yellow light, when the monitored values are between the abovementioned ones. This condition warns about a significant danger forthcoming. It is expedient to discover the reason quickly, eliminate it if possible, or take preemptive measures.
frame fragment has the stresses, which are quite acceptable and do not cause concern (blue and green colors). The question is how to find the areas in the very complicated construction of the Ice Sports Palace (ISP) and get there with measurement tools to timely prevent possible issues? It is also noteworthy that the geometry of the load-bearing framework of the ISP does not compare to the example mentioned. It includes dozens of thousands of various junctions, crossings and other load concentrators.

Figure 7 illustrates the stress distribution in the elements of a three-dimensional, multiply redundant construction system designed based on a rod scheme. The horizontal axis shows stress values for the elements and the vertical axis shows the number of elements with corresponding stress. A construction like that is a direct analogy for the load-bearing framework of the ISP roof.

Figure 8 shows the stress distribution in the rods of a complex three-dimensional structure.

Figure 8 shows that stress is quite unevenly distributed between the elements. Most of the construction elements are underloaded (area around zero stress). There are few extensively loaded elements (on the tail of the distribution curve). The role the elements play in ensuring the load-bearing capacity of the whole framework changes when the structure is under various

Figure 7. Stress State of a Steel Frame Fragment

Figure 8. Stress Distribution in the Rods of a Complex Three-Dimensional Structure
### Table 3

<table>
<thead>
<tr>
<th># of node (load area)</th>
<th>PROP</th>
<th>Load area $A_i$ (m²)</th>
<th>Summer (no snow)</th>
<th>Winter (with snow)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$m = A_i/81$</td>
<td>$m = A_i/15/81$</td>
<td>$m = A_i/283/81$</td>
</tr>
<tr>
<td>1</td>
<td>22</td>
<td>19.45</td>
<td>1.487</td>
<td>4.263</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td>33.33</td>
<td>2.548</td>
<td>7.300</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>27.58</td>
<td>2.109</td>
<td>6.045</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>24.59</td>
<td>1.880</td>
<td>5.389</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>21.58</td>
<td>1.650</td>
<td>4.730</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>18.56</td>
<td>1.419</td>
<td>4.068</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>15.52</td>
<td>1.187</td>
<td>3.401</td>
</tr>
<tr>
<td>8</td>
<td>29</td>
<td>12.47</td>
<td>0.953</td>
<td>2.733</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>7.34</td>
<td>0.561</td>
<td>1.609</td>
</tr>
<tr>
<td>10</td>
<td>31</td>
<td>3.93</td>
<td>0.300</td>
<td>0.861</td>
</tr>
<tr>
<td>11</td>
<td>32</td>
<td>16.43</td>
<td>1.256</td>
<td>3.600</td>
</tr>
<tr>
<td>12</td>
<td>33</td>
<td>4.77</td>
<td>0.365</td>
<td>1.045</td>
</tr>
<tr>
<td>13</td>
<td>34</td>
<td>1.68</td>
<td>0.128</td>
<td>0.368</td>
</tr>
<tr>
<td>14</td>
<td>35</td>
<td>Technological platform with the weight of ~ 8 tf. $m = 8000/4/981 = 2.0387$ kgf·sec²/cm⁴</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>36</td>
<td>Mediacube with the weight of ~ 10 tf. $m = 10000/4/981 = 2.548$ kgf·sec²/cm⁴ (only for the Y axis)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thus, the mathematical model of the load-bearing structures of the Ice Palace roof was designed in accordance with the roof geometric layout considering the location of the end-elements as lump masses at the ring and radial elements' intersection nodes (Figure 6). The technological platform is four-point suspended to the top chords of the girders on the inner ring of the roof. The mediacube is likewise suspended to the bottom chords of the girders.

### 3.2. Selection of Controlled Parameters

Forces (loads) and movements are subject to measurement and control. The measurements can be used for calculating the stress and strain state (SSS) of a construction, for instance, by applying a mathematical model based on some hypotheses and assumptions. The results of the calculations will be dramatically dependent on the type of the model and the assumptions used. For instance, one cannot use the rod mathematical model to calculate the SSS at the load concentration points, which are the most dangerous points of the load-bearing framework and are, as a rule, ‘responsible for’ construction accidents.

Figure 7 shows an example of the stress state (Von Mises Stress) calculations for a steel frame fragment at the crossbar and column junction point. Here we can see that the largest stresses (3.521 kg/cm²) are observed at the small area at the reentering angle of the junction. A disastrous fracture may develop from this point and destroy the whole construction. The picture, though, implies that most of the...
profile shell, based on the geometric and physical features of the construction materials.

The loads coming from the insulating roof layers, technological equipment and snow are applied to the roof bearing mesh as lumped masses at the ring and radial element intersection nodes. The dedicated MASS end-element type is used for this purpose. Table 2 shows the calculation results for the load intensities.

Given the roof symmetry, the values of node masses located on one radial hard thread can be calculated. Figure 5 shows the sizes of load areas A(m²) related to corresponding nodes, where Num shows the numbering of the nodes on the hard thread, starting with the outer ring and going to the center.

Table 3 shows standard and design values of node masses.

The data in the table is based on the design materials specified according to the results of an on-site survey.
\( \nu = 0.3 \) – Poisson ratio,
\( \rho = C \cdot \gamma / g = 1.1 \cdot 2.5 \cdot 10^{-3} / 981 = 2.8 \cdot 10^{-6} \text{ kgf-sec}^2/\text{cm}^4 \) – density.

Nastran, the specialized component unit, was used for designing the geometric features of the cross-sections of the construction elements.

The lines and end elements are represented by corresponding groups of numbers, which are in their turn arranged by layers. A structure like that when used for designing a roof mathematical model ensures convenient application of large databases in the future.

The Rigid hard insertions are the end elements connecting the frames inside the central ring.

The 48 joints at the crossing of the outer ring and the hard threads have vertical hinged bearings. The three of them located at the main axes have horizontal hinged supports tangent to the ring.

To ensure the roof survivability if the outer ring fails (damaged), 96 extra horizontal bearings are employed if the ring moves inside about 20 mm. In the mathematical model, the elements are represented by the dedicated GAP type end elements with the gap of 20 mm and compressive stiffness of \( C_e = 2 \cdot 10^6 \) and tension stiffness of \( C_t = 1 \cdot 10^{-4} \) (Table 1).

In the roof design, there is solid roofing profile put on the hard threads. In the mathematical model, the roofing profile work is taken into consideration by a corresponding increase in the cross-sectional area of the ring elements (Figure 3).

Table 1

<table>
<thead>
<tr>
<th>Geometric features of the cross-sections of construction elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer ring, ferroconcrete filling</td>
</tr>
<tr>
<td>Prop. 1 (Grade KH1)</td>
</tr>
<tr>
<td>( A = 18.424 \text{ cm}^2 )</td>
</tr>
<tr>
<td>( I_z = 21.088.910 \text{ cm}^4 )</td>
</tr>
<tr>
<td>( I_y = 37.940.582 \text{ cm}^4 )</td>
</tr>
<tr>
<td>( I_{kp} = 459.17.907 \text{ cm}^4 )</td>
</tr>
<tr>
<td>Open safety supports</td>
</tr>
<tr>
<td>Prop. 3 (GAP – element)</td>
</tr>
<tr>
<td>( C_e = 2 \cdot 10^6 )</td>
</tr>
<tr>
<td>( C_t = 1 \cdot 10^{-4} )</td>
</tr>
<tr>
<td>( \Delta = 5 \text{ mm} )</td>
</tr>
<tr>
<td>Hard threads 2</td>
</tr>
<tr>
<td>Prop. 5 (Grade B2)</td>
</tr>
<tr>
<td>( A = 172 \text{ cm}^2 )</td>
</tr>
<tr>
<td>( I_z = 54.969 \text{ cm}^4 )</td>
</tr>
<tr>
<td>( I_y = 3.577 \text{ cm}^4 )</td>
</tr>
<tr>
<td>( I_{kp} = 235 \text{ cm}^4 )</td>
</tr>
<tr>
<td>Hard threads 4</td>
</tr>
<tr>
<td>Prop. 7 (Grade B4)</td>
</tr>
<tr>
<td>( A = 230 \text{ cm}^2 )</td>
</tr>
<tr>
<td>( I_z = 77.383 \text{ cm}^4 )</td>
</tr>
<tr>
<td>( I_y = 6.565 \text{ cm}^4 )</td>
</tr>
<tr>
<td>( I_{kp} = 496 \text{ cm}^4 )</td>
</tr>
</tbody>
</table>

Figure 4 shows the end-element view of the designed roof layout. The dots signify the mesh nods. The layout shows the BEAM type rod end elements, and the PLATE type flat elements, and the GAP type bearing elements.

The Nastran design software was used to calculate the gravity load of the roof load-bearing structures, including the roofing
The external bearing ring rests on a ferroconcrete slab crowning the load-bearing structures of the stalls. The main supports of the shell are ‘floating’ to prevent the thrust transfer from the shell to the stalls. The three supports on the major diameters of the roof prevent it from the horizontal shift.

The load-bearing element of the roof is roofing profile put in a circular fashion on the load-bearing threads and attached to them by tapping screws. The roofing profile makes an orthotropic shell working jointly with the major reticle shell.

The mathematical model has been designed on the Nastran calculation suite and includes a geometric layout of the structures, databases on the physical features of the construction materials and geometrical features of the cross-sections of the construction elements, databases on the loads and their design combinations.

All the construction elements of the roof mesh (rings, hard threads and bracings) were modelled by lines, and the plate elements framing the internal ring were modelled by flat surfaces.

The end element mesh was superimposed on the geometric layout: the BEAM type rod end elements were used for the lines, and the PLATE type elements were used for the surfaces.

The database on the physical features of the construction materials was generated based on the following data.

For steel:
\[ E = 2.1 \cdot 10^6 \text{ kgf/cm}^2 \] – modulus of elasticity,
\[ \nu = 0.3 \] – Poisson ratio,
\[ \rho = C \cdot \gamma / g = 1.2 \cdot 7.85 \cdot 10^{-3} / 981 = 9.6 \cdot 10^{-6} \text{ kgf} \cdot \text{sec}^2 / \text{cm}^4 \] – density,
where \( C = 1.2 \) – construction coefficient, \( \gamma = 7.85 \cdot 10^{-3} \text{ kgf/cm}^3 \) – bulk weight of steel, \( g = 981 \text{ cm/sec}^2 \) – free fall acceleration.

For concrete:
\[ E = 3 \cdot 10^5 \text{ kgf/cm}^2 \] – modulus of elasticity,
3. ESMS Establishment and Exploitation Basics

ESMS has unique features and thus requires dedicated scientific and technical research. Firstly, the system has to gather long-term, reliable and accurate information on the condition of load-bearing structures. This requirement stems from the fact that construction facilities, especially the unique ones, are designed for a long life totaling dozens and hundreds of years and the accident-causing events feature very low probability of tenths and even thousandths of percent.

It is advisable to highlight an important feature of the ESMS design calculations compared to the load-bearing structures design calculations. The design process has to ensure the structures reliability under the statistical uncertainty of the design parameters, which is often offset by establishing safety margins and redundancy of design models. While performing calculations for setting up an ESMS, including experimental research, one has to deal with a real structure and real loads, while the design models have to be adequate for a real construction operation. All the features mentioned require in-depth analysis of the results of theoretical and experimental research to project the behavior of structures in exploitation, which will help design a concept for a monitoring system and its technical implementation, design the parameters and criteria to assess the technical condition of the structures for decision-making concerning further exploitation.

The following tasks are to be performed to achieve the goal:
1. To create a mathematical model of the load-bearing structures.
2. To calibrate the model based on the on-site experimental data to ensure its adequacy.
3. To perform static calculations under normal exploitation conditions (based on standard loads) and extreme conditions (based on design loads) to identify and assess the parameters controlled by monitoring.
4. To perform dynamic calculations – modal analysis and vibration-based diagnostics – to predict and analyze corresponding experimental data.
5. To perform dynamic calculations to identify typical damage scenarios and corresponding changes in the controlled parameters of the structures.

3.1. Designing a Mathematical Model for the Load-Bearing Structures

Let’s consider a mathematical model for the roof of the Ice Sports Palace on the Khodynskoye Field in Moscow as an example for developing a mathematical model for load-bearing structures.

The load-bearing structure of the roof of the Ice Sports Palace on Khodynskoye Field is a one-layer, reticle, guy shell made of 48 radial flexural-hard I-section threads delineated on the 198 m radius, ring cells consisting of I-section beams and tubular connections filling virtually all the roof cells. In fact, this is an inverted Shvedler Cupola, which is a discreet analogue of a guy shell with the elements resisting tension, compression, bending, and shear in three dimensions (Figure 2).

The roof shell has a circular outline with the external diameter of around 110 m. The sag is 7.9 m, or 1/14 of the flight. The shell has a doubly connected contour comprised by an external composite ring with rectangular 1.200×1.600 mm cross-section, and an I-section central internal ring with 20 m diameter and 1.200 mm height.
2. Facilities for ESMS Installation

ESMS installation is advisable for the following types of facilities:

– facilities constituting nuclear and/or radiation hazard (nuclear power plants, research reactors, fuel cycle facilities, temporary and long-time warehouses for nuclear fuel and radioactive waste), facilities using nuclear energy;

– for production, use, processing, generation, storage, transportation and disposal of hazardous materials in the volumes exceeding the limits under then Law;

– for chemical and other hazardous waste disposal and burial;

– having large warehouses for storage of oil and oil products (over 20,000 tons) and isothermal storage facilities for liquefied gases;

– for production of melts of ferrous and nonferrous materials and alloys based on these melts;

– for mining, minerals processing, subsoil operations, including companies performing subsoil and open-pit (mining depth over 150 m) extraction and processing of solid minerals;

– using cableways and funiculars;

– for production, generation or processing of liquid or solid materials with explosive features or prone to spontaneous decomposition with a possible explosion energy equal to 4.5 tons of TNT;

– power transmission lines and other grid facilities with the voltage of 330 kilovolts or more;

– space infrastructure facilities;

– airports and their infrastructure facilities;

– public railway system facilities;

– metros,

– sea ports excluding specialized sea ports for sports and pleasure boats maintenance;

– thermal power plants with the capacity of 150 megawatts and more;

– offshore oilfield facilities;

– mainline gas, oil and product lines;

– gas distribution system facilities using, storing or transporting natural gas or liquefied hydrocarbon gas;

– waterworks of class 1.2 and 3;

– large industrial facilities with more than 10,000 workers;

– capital construction facilities with the design documentation comprising at least one of the following features: height over 100 meters; flights over 100 meters; console over 20 meters;

– with depth of the subsoil part (in full or in part) more than 10 meters below the grade (ground) elevation;

– with constructions and construction systems, which have unconventional design methods applied to them to consider physical or geometric non-linear features or have specialized design methods developed for them;

– facilities with maximum design capacity of 500 people and more: entertainment, sports facilities, multifunctional office centers and shopping malls, health facilities, hotels;

– life-supporting facilities: units, warehouses, storage facilities, waterworks and engineering protection facilities and communications whose destruction (damage to) may disrupt the life of people (stop water, gas, heat, power supply, cause flooding, damage residential communities, cause failure of waste water and sewage water treatment facilities) resulting in an emergency.
1. The Role of Engineering (Load-Bearing) Structures and Natural Hazards Monitoring Systems in Ensuring Safety of Buildings and Constructions

The ESMS is designed for:
- timely automated remote notification of the emergency and dispatching services on the condition of the facility’s load-bearing structures, using the following criteria: ‘normal condition’, ‘higher risk’, ‘emergency’;
- monitoring and documenting changes in the condition of the load-bearing structures caused by accumulated exploitation defects, which may lead the building or construction to an extreme condition mandating corresponding repairs or bringing the operation to a halt, throughout the whole facility operation period.

The ESMS structure is illustrated by Figure 1.

The ESMS is comprised by equipment for monitoring changes in the condition of foundations and engineering structures of buildings and constructions; engineering protection facilities, and also, if there is any corresponding hazard, for monitoring the areas of possible mudflows, mudslides and avalanches in the building or construction operation area. It includes:
- ESMS servers, local servers and controllers;
- ESMS automated workstations (AW);
- data gathering and transferring network equipment;
- sensors monitoring changes in the condition of foundations and engineering structures of buildings and constructions; engineering protection facilities, and also areas of possible mudflows, mudslides and avalanches.

The ESMS has the following functional subsystems:
1) the signaling monitoring subsystem, which continuously operates:
   - to monitor the integral characteristics of the facility load-bearing structures in an automated real-time mode;
   - to notify the facility operations control desk and CPSAP personnel on the critical changes in the condition (deformed condition) of the facility structures in an automated real-time mode;

2) the intermittent monitoring subsystem, which is launched by notifications (incident, accident) coming from the signaling monitoring subsystem or under a regulation. In an automated mode it:
   - assesses the technical condition of the facility load-bearing structures and issues recommendations for reinforcement (reconstruction);
   - controls and adjusts (if necessary) the signaling subsystem.

Figure 1. ESMS Structure
Terms and Definitions

Exploitation Safety is a condition bearing no unacceptable risk of damage to life and health of people, property of individuals and legal entities, governmental or municipal property, environment, life and health of animals and plants.

Destabilizing Factor is a deviation from the norm of technical parameters related to operation or supporting processes of buildings and constructions, as well as mudflows, mudslides, and avalanches having negative or destructive impact on buildings and constructions.

A City Public Safety Answering Point (CPSAP) is a day-to-day city governance body designed to coordinate the operation of the city emergency and dispatching services.

A Building is a construction system made of load-bearing and enclosure structures or combined (load-bearing and enclosure) structures creating an on-the-surface closed volume designed as a residence or a short-time stay place depending on the functional purpose (houses, industrial constructions, stadiums, shopping malls, hospitals, schools, cinemas, etc.).

Engineering Risk of Building (Construction) Collapse is a value depending on the damage extent and describing the probability of the building (construction) collapse for a given time interval, 1/year.

Engineering Safety of a Building (Construction) is a value describing the ability of a building (construction) to resist a possible collapse jeopardizing human life.

Emergency Prevention is a set of preventive activities designed for maximum possible emergency risk reduction and also for preserving human health, reducing damage to the environment and material damage in case of emergency.

Emergency Forecasting is an anticipatory description of an emergency occurrence probability and development based on the analysis of possible reasons for its occurrence and its origin in the past and the present.

Technogenic Emergency Forecasting is an anticipatory description of a technogenic emergency occurrence probability, development, and consequences based on the analysis of the risk of occurrence of fires, explosions, accidents, and disasters.

Emergency Risk is a probability or frequency of occurrence of an emergency origin determined by corresponding risk indicators.

Safety System is a hardware and software suite designed for emergency prevention including emergency warning.

Engineering (Load-Bearing) Structures and Natural Hazards Monitoring System (ESMS) is a hardware and software suite performing real-time control over the changes in the condition of foundations, engineering structures of buildings and constructions; engineering protection facilities, and mudflow, mudslide, and avalanche flow paths in the construction and operation area of the facility under monitoring for emergency prevention.

A Construction is the result of a construction process, which is a volumetric, flat or linear construction system with the on-the-surface, above-the-surface and/or below-the-surface parts made of load-bearing and sometimes enclosure structures and designed for various types of operations, product storage, temporary accommodation of people, movement of people and cargo.

A Building (Construction) Damage Extent is a value defining the loss of initial technical and exploitation qualities (durability, stability, reliability, etc.) due to the impact of natural and technogenic factors.
Summary

The load-bearing structures of buildings and constructions (further on referred to as ‘facilities’) are subject to wear-caused loss of operability. Exploitation of facilities with damaged construction elements may lead to emergencies, which are likely to cause loss of life. This is confirmed by unexpected collapses of facility construction elements in Russia, Germany, Poland, and other countries, which resulted in extensive casualties.

The methodology is designed for setting up an automated real-time system for monitoring load-bearing structures of buildings and constructions. This system will provide the respective services with remote real-time access to the information on the condition of the load-bearing structures of buildings and constructions, and therefore save the facility from collapsing unexpectedly.

The methodology is designed for the institutions providing scientific and technological support for development and exploitation of the systems for automated monitoring of load-bearing structures of buildings and constructions and also for the companies monitoring the facilities under exploitation.