Systematic Monitoring of the Deformed State of Long-Span Operated Structures with an Assessment of Their Reliability

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Abstract. The article shows the procedure for conducting systematic monitoring of the stress-strain state of reinforced concrete structures covering one of the operated public railway stations. The historical data of the building construction and its design features are described. The description of large-span structures of the building, their defects and damages acquired in the course of operation is given. The article describes the procedure and methods used for a long-term, more than 2 years, continuous monitoring of the deformed state of the coating structures that are in operation. The most damaged structures, which are installed on a measuring apparatus. The features of measurements in different time periods are described. Based on the results of the obtained measurements of the stress-strain state of the building coating structures, the possibility of their further operation is predicted, taking into account the defects and damages found during the survey.

1. Introduction

When operating public buildings with large-span structures, there is a need to monitor the state of the structures. This is especially true for modern buildings with large spans of coating structures and their complex cross-section. These types of buildings include, for example, waiting rooms at suburban train stations. These buildings usually have a unique configuration of some structures, for example, because of their architectural features. In this regard, during their design and manufacture, preliminary tests of these unique structures are performed. With successful results of these tests, the designs are allowed to be produced. But, over time, destructive processes occur in the structure itself. For example, if it is a reinforced concrete prestressed structure that works for bending, these processes include damage to the protective layer of concrete, cracks, corrosion of the reinforcement, loss of prestressed reinforcement, which in turn leads to increased deflections of the structure itself. The processes that take place in the structure itself during its operation will depend on many factors over time, such as the quality of project documentation, construction, installation, operating conditions, etc. In this regard, there is a need to monitor the operation of the structure under real conditions of its operation for a long time. There is also a question of assessing their reliability and suitability for use in the future.

As an example of a solution to this problem, this article discusses the construction of the coating of one of the stations.

Kursky railway station is one of the largest railway stations in the Russian Federation. The main building of the station consists of two parts: a historical building built in 1896 by the architect N. Orlov, and a new building attached to the existing one in 1972 by The «mosgiprotrans Institute» (chief
architect of the project G. Voloshin). The diagram of the modern building of the Kursk railway station is shown in Fig. 1.

![Diagram of the modern building of the Kursk railway station.](image)

**Figure 1.** Diagram of the modern building of the Kursk railway station.

The new station building in axes 5-25/A-G is a one-story building with a basement and mezzanines at the 1st floor level, rectangular in shape with a roof area of 195x45m. The supporting structures of the building are reinforced concrete. The first floor is an architectural volume formed by a roof of U-shaped precast concrete elements, glass stained-glass Windows and an adjacent wall of the old station building (Fig. 1).

![General view of the load-bearing structures of the station building at the 1st floor level.](image)

**Figure 2.** General view of the load-bearing structures of the station building at the 1st floor level.

The main supporting structures of the first floor are two reinforced concrete multi-span frames located along the longitudinal axes (A and G) of the building, and reinforced concrete U-shaped
coating elements laid on top of the frame crossbars in the transverse direction. The frame of the building is divided by two expansion joints (along the axes 11, 19) into three temperature blocks (Fig. 3-5).

![Figure 3](image1.png)

**Figure 3.** Diagram of the supporting frame of the frame in axes 5-11.

![Figure 4](image2.png)

**Figure 4.** Diagram of the supporting frame of the frame in the axes 11-19.

![Figure 5](image3.png)

**Figure 5.** Diagram of the supporting frame of the frame in the axes 19-25.

The foundations under the supporting columns of the temple are piled with monolithic grillwork. Piles are precast reinforced concrete. Monolithic columnar grillage, combined with a cruciform column support.

The columns of the frames are cast-in-place reinforced concrete, of a complex, geometrically variable cross-section in height, with a metal core made of rolled profile. Each frame has 11 columns set in 18 m increments. The connection of columns and crossbars is rigid, with the establishment of
the metal core of the column to the top of the crossbar. The height of the columns from the floor level of the first floor is 10.9 m along the main facade of the building (axis A) and 10.2 m in the part adjacent to the old building (axis G).

Frame crossbars are cast-in-place reinforced concrete, trapezoidal section, 2.3 m high. The reach of the crossbar consoles from the extreme axes 5 and 25 is 7.5 m.

U-shaped coating elements (66 pieces in total) of open trapezoidal cross-section (h=1.48 m) are made of pre-stressed reinforced concrete in the form of a beam structure (Fig.6). The design scheme of the U-shaped elements of the coating is a single-span double-console with a hinged support. Length pleats a - 45 m, length of the span part - 27 m, length of cantilever parts on the main facade of the building is 12 m, on the side adjacent to the old building is 6 m. To increase the rigidity of the coating, the U-shaped elements are connected to each other along the top with monolithic reinforced concrete dowels. According to the project, U-shaped coating elements were manufactured on the construction site. After manufacturing, The U-shaped coating element was loosened along the length by metal ties, raised on the crossbar and moved to the installation site on special rollers. Dismantling of metal ties according to the project was to be carried out after the set of 70% strength of concrete dowels.

![Figure 6. Cross section of the U-shaped element of the coating structure.](image)

During the operation of the building since 1972, The u-shaped elements of the coating structures have accumulated the following defects and damages: traces of concrete wetting and damage to the finishing layers on the lower edges of the coating due to leaks from the roof; surface corrosion of steel prestressed reinforcement at the ends of the coating in the bottom and walls; wetting and damage to the protective layer of concrete of the bottom of the coating with the formation of moss on their surfaces due to regular leaks from the roof; chipped, damaged the protective layer of concrete, exposure and corrosion of the rods of the mesh additional reinforcement of the bottom and walls of the covering resulting from regular wet; chips of the protective layer of concrete covering the inside of the building, traces of leaks, damage and finishing layers; cracks opening width of 0.1÷0.15 mm for protective layer of concrete in the bottom of the coating due to wetting as a result of regular leaks from the roof; the deflections of the individual U-shaped elements cover above acceptable regulatory values.

Based on the results of the engineering survey, it was decided to conduct systematic monitoring of the deformed state of the coating structures and assess their reliability.
2. Materials and methods

Due to the fact that it was supposed to perform long-term, for 2 years, observations of the deformed state of damaged elements, it was decided to use non-volatile mechanical devices. In the course of scientific research, hour-type indicators were installed in their design sections to monitor the deformations of the most damaged u-shaped coating elements. Two indicators with a division price of 0.001 mm were installed on the bottom of element № 18 under the lower row of fittings at the point of passage of cracks with the maximum opening width and height of development. One indicator with a division price of 0.002 mm was installed on the bottom of element № 21 under the extreme armature at the right wall, also at the point where the most developed crack passes. On the bottom of element №43, which has no cracks, strictly in the section with the maximum span moment under the extreme armature at the left wall, one indicator was also installed with a division price of 0.002 mm.

Under the accepted device installation scheme, the strain increments measured in elements №18 and №21 practically correspond to the increments of the crack opening width, and those measured in element №43 correspond to the absolute deformations of the prestressed reinforcement.

The method of collecting primary data used in this work included:
- systematic observation of the deformation of the folds for the instruments previously installed in the elements n of 18, 21 and 43;
- fixing the outdoor air temperature and snow cover height;
- periodic monitoring of the parameters of cracks on the side and bottom surfaces of elements in the places where the devices are installed;
- periodic monitoring of the condition of devices installed on elements 18, 21 and 43.

Readings from the devices installed on the most damaged elements were systematically taken during the entire observation period for 2 years. Special attention was paid to the readings of devices during heavy snowfalls. Readings on the instruments were taken either directly, for which the corresponding tower was used, or indirectly using binoculars from the floor level of the hall. In the latter case, due to the trembling of the binoculars in the hands, the counts were taken approximately, with an accuracy of several divisions. During the removal of readings using the tower, the condition of the devices was also checked, and in necessary cases, they were lubricated. In cases where the readings on the devices were different from zero, during the inspection of the devices, the readings were usually set to zero.

The daily outdoor temperature was recorded in the shade by a thermometer at 13-15 o'clock in the afternoon.

The thickness of the snow cover on the horizontal surface of the earth was determined mainly by direct measurements (up to 12 measurements at a time).

In some cases, the thickness of the snow cover on the horizontal surface of the earth was determined by corresponding recalculation of the thickness of the snow cover recorded directly on the studied elements of the coating.

In cases where the readings on the devices were taken directly with the help of the tower, the cracks located on the bottom and walls of the folds at the location of the devices were simultaneously examined. Such inspections were carried out once every three months.

No increase in the width of crack opening (Δa.crc) and the height of their development (Δh.crc) was recorded during the performed inspections.

To assess the reliability of damaged coating structures and analyze the obtained experimental data, we assume the most unfavorable case, in which the 0.046 mm tensile strain recorded in element 21 fully corresponds to an increment in the crack opening width and, consequently, an increase in deformations and stresses in the prestressed reinforcement of the bottom of the element. As the root cause of the marked increase in deformations and stresses, we hypothetically assume the development of destructive processes predetermined by the influence of the risk factors mentioned earlier and not eliminated to date. In this case, the coefficient of safety margin of the fold over the normal span section will decrease. Let's make a quantitative assessment of this decrease.
In the beginning, we estimate the increment of deformations of the armature of the fold №21 in the section with the crack ($\Delta \varepsilon_{\text{sp}}$) for this particular case as:

- for short-term load action ($a_{\text{crc}}$) = $195.7$ $\Delta \varepsilon_{\text{sp}}$ 
- for long-term load ($a_{\text{crc}}$) = $307.4$ $\Delta \varepsilon_{\text{sp}}$

where ($a_{\text{crc}}$) is the opening width of normal cracks.

Since the increase in deformations on the bottom of element 21 corresponding to an increase in the crack opening width by 0.046 mm has been recorded for a long period of time, use the formula (2).

In this case

$$\Delta \varepsilon_{\text{sp}} = a_{\text{crc}}/307.4 = 0.046/307.4 = 15 \cdot 10^{-5}$$

Corresponding to this value of the increment of deformation ($\Delta \varepsilon_{\text{sp}}$) the increment of stress ($\Delta \sigma_{\text{sp}}$) will be

$$\Delta \sigma_{\text{sp}} = E_{\text{sp}} \Delta \varepsilon_{\text{sp}} = 1.853 \cdot 10^5 \cdot 15 \cdot 10^{-5} = 27.8 \text{ MPa}$$

The constructions are shown in figure (7).

![Figure 7](image.png)

Figure 7. Determination of the calculated breaking moment $M_{u2,\text{cal}}$ taking into account the stress increment $\Delta \sigma_{\text{sp}}$ = 27.8 MPa.

### 3. Results

From the results of the calculations, it follows that the stress increment in the prestressed armature of the bottom of element 21 reduces its calculated load-bearing capacity in the span normal section ($M_{u2,\text{cal}}$) to the value of 1490 kNm. The minimum value of the margin coefficient in this case is

$$M_{u2,\text{cal}} / M^* = 1490 / 1050.7 = 1.42$$

where $M^*$ is the maximum span moment for the calculated value of constant and temporary loads acting on the coating elements.

The resulting value of the reserve coefficient is greater than the regulated GOST 8829-2018 and equal to 1.3.
Thus, even in the most unfavorable case, the minimum value of the reserve coefficient of element № 21 is not lower than the normalized value. At the same time, the reserves of increment of deformations and stresses in the pre-armature of the bottom for a long period of time practically did not remain.

4. Conclusion

During this research work, a complex of observations of the stress-strain state of reinforced concrete U-shaped elements of the coating of the main passenger building of the Kursky railway station in Moscow was performed under snow loads of various intensity and changes in the outdoor air temperature in the range of + 30°C to -25°C. The analysis and synthesis of the obtained data covering the observation period of 2 years and 1 month was carried out. Based on the research performed, the following main conclusions can be made:

1. in conditions where the main risk factors identified during previous work continue to have a negative impact on the reinforced concrete u-shaped elements of the coating. Systematic instrumental and visual monitoring of their condition is a fairly reliable guarantee against the occurrence of pre-emergency situations.

2. Despite the continuing negative impact of risk factors, the minimum safety factor of u-shaped coating elements in the span of normal cross-sections as a result of the study was not lower than the normalized value.

5. References

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