Modeling the Construction Stages of Large Span Spatial Unique Buildings of Complex Geometry

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Abstract. The results of experimental-theoretical studies of precast-monolithic reinforced concrete shells of complex geometry, assembled from enlarged elements at the assembly stage, are presented. The studies were carried out on full-scale composite shells 116 m, 96x88, 48x48 m and 18x36 m, its enlarged elements 3x18 m and 3x24 m, as well as on a shell model at a scale of 1:15, 1:10 and 1:4. The stress-strain state of composite shells was investigated for different versions of mounting and uncoiling. Recommendations are given on rational methods of erection and incineration of shells from enlarged elements for public buildings.

1. Introduction
The use of large-span unique buildings of complex geometry is associated with the tasks of improving the methods of their installation and unburdening (Fig. 1). Installation of these shells can be carried out using continuous scaffolding and conductors or pre-enlarged arched mounting sections, hinged method [1-6, 10, 12]. For shallow shells at the present time, the optimal installation method is the use of enlarged mounting elements up to 24 m long [3, 5-8]. In this case, each enlarged prefabricated element represents a vaulted-type structure with a temporary assembly tightening [4, 7, 11].

2. Objectives of the study
Study of the possibility of using the method of enlarged mounting elements for the installation of compound and conjugated shells with a square or arbitrary plan (Fig. 1). Investigation of the stress-strain state of precast-monolithic composite shells in the stages of installation, unloading, and transition to the stage of operation. [14-16]. The results of the analysis of tests of composite shells with side elements of negative and positive curvature of the polygonal shell with dimensions of 4.8x4.8 m, Ø 7.7 m and 12x12 m; and 18x36m. [5, 7, 9,11,13,15].

3. Method of physical modeling of shells operation
To identify a rational method for unloading composite shells, the removal of the forces in the puffs was carried out with the mounting racks lowered and raised. The sequences of their influence on the work of the spatial coverage were studied. The static work of the shell at the stage of installation and operation was analyzed in two types of geometric shapes of the central and side shells:
On models of composite standing shells in the area of linear operation, loaded with a uniformly distributed load equal to 1.7 kN / m², the stress-strain state of the coating was determined at the assembly stage. After that, two main methods of uncoiling were studied. In the first method, the mounting beams were first lowered, then the forces in the mounting straps were removed, in the second, the mounting braces were first removed, then the mounting beams were lowered. The uncircular variants were repeated three times [14,16,18,19].

Figure 1. Structural diagrams of shells of complex geometry investigated in the editing stage.

4. Studies of work in the process if dismantling a composite shell
In the first method, the uncoiling of the composite shell of the sediment of all racks was carried out simultaneously [11, 17] in steps of 5 mm. The detachment of the mounting hardware from the covering occurred first at the edges of the mounting beams with a settlement of the racks by 4 mm, then in the middle zone of the shell at a settlement of the racks by 15 mm. The separation of all mounting hardware from the shell occurred when the racks were upset by 20 mm. The initial efforts in tightening the central and side shells when lowering the mounting beams decreased by 20-35%. This made it much easier to dismantle the puffs. In this case, a more favorable character of the stress state was observed in the ribs of panels of composite shells.
In Fig. 2 shows diagrams of shell deflections in the process of lowering the mounting beams, removing the tension in the puffs and applying pretension in the mounting puffs to restore the primary to dismantling state of the shells.

When the mounting beams were lowered, the greatest deflection in the central shell was 2.85 mm, or 1/1174 of the span, and in the side shell, 2.2 mm, or 1/1542 of the span. Further removal of the forces in the assembly tightenings led to an increase in the initial deflections of the central and side shells, respectively, by 1.2 and 1.15 times.

To reduce the deflection of the shell in the operational stage, prior to unloading, the assembly ties were tensioned with control of the forces and bending of the shell. This led to a decrease in the maximum deflections of the central and lateral shells by 1.4 and 1.23 times. With an increase in the tension force in the puffs, the deflections of the shells decreased up to 2 times. It should also be noted that when the puffs were removed, the horizontal displacements in the contour girders of the shells increased up to 15%.

In the second method, uncoiling the coating shell at the beginning of the effort was removed in 24 puffs of the central shells and then remaining in 28 puffs in four side shells. The effort was removed sequentially, as in the first method, after which the mounting beams were lowered, which led to a slight change in the stress-strain state of the shell. [9,20]. The diagrams of deflections and forces were smoother (Fig. 2).

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**Figure 2.** Scheme of arrangement in the composite shell model of 4.8x4.8 m of mounting ties and beams: **a** - the sequence of their removal (1-16); **b-c** deflections along when loading the model with a load of 1.7 kN / m²; **d** - for various types of connections of the central and side shells; 1 - when lowering the mounting beams; 2 - when removing puffs; (1), (2) - means options for uncoiling; 3 - when tightening the assembly tightening; 4 - for monolithic connections; 5 - with for connection by discrete connections; 6 - for free-standing casings.

The maximum deflection values for the central and side shells were 0.45 and 0.43 mm, respectively. Lowering the mounting beams led to an increase in deflections by 9.14 and 6.8 times. In this case, the diagrams of forces and deflections are uneven.
Comparison of the deflections of the shell with two methods of unloading showed that the use of the first method led to a decrease in the deflections of the central and side shells, respectively, by 1.35 and 1.3 times. This confirms the advisability of using the first method of uncoiling.

Analysis of studies on two variants of uncoiling of composite shells showed that when using the first variant of uncoiling, the deflections for the middle of the span of the shell and diaphragm decreased by 1.7 and 1.5 times, respectively. A similar phenomenon was observed for horizontal displacements of the shell, which decreased by 1.14-1.3 times for different sides of the contour structures.

The smallest value of longitudinal forces and bending moments was obtained according to the first version of uncoiling, which creates a favorable nature of the stress state of the shell, which indicates the expediency of its use. [9,11,18,19].

In composite shells with side elements of negative and positive curvature of 12x12 m in size, their stress-strain state was investigated in the stages of installation, long-term operation and the transition from the installation stage to the operational stage (Fig. 3,4). The installation of the shell was carried out from enlarged arched elements. Before the monolithing of the seams, the enlarged elements worked as structures that were not connected with each other.

![Image](image.png)

Figure 3. Deflections of the diaphragm of the composite shell 12x12 m with negative and positive curvature at the stage of installation: a, c - diaphragms loaded with mounting arched elements; b, d - the same, not loaded; 1, 3 - experimentally for a shell of negative and positive curvature; 2.4 - the same as calculated.

After embedding the seams between the panels, the shell was transformed into a single spatial system, in which subsequent efforts were perceived by the shell as a whole.
Deflections of a composite shell 12x12m of negative and positive curvatures at the stage of installation \( a, b \) - deflections of the shell; 1,3 - experiment for the shell with negative and positive curvatures; 2.4 - the same, by calculation without taking into account, 5.6 taking into account mounting conditions.

Before the removal of the tightening forces, the load on the shell was 2.9 kN / m\(^2\). There was no snow load during the test. In the process of uncoiling the shell, efforts were retained, and the efforts that arose in the shell due to the removal of temporary puffs and ties were added to them.

**Table 1** shows data on the change in the forces in the puffs in the process of their removal for a composite shell with side elements of negative and positive curvature. When removing the efforts in the puffs, an additional increase in the forces in the remaining puffs was recorded. This is especially true for edge ties. The efforts in the extreme tightening of the side and central shells increased by 1.16 and 1.23 times, respectively. The nature of the diagrams, the values of forces and displacements in the shell (Fig. 3) are close to those of the equivalent distributed load. However, the efforts in the middle diaphragms when removing the puffs differ sharply, while in the parallel diaphragms the forces increased, and in the perpendicularly located ones, there were no significant changes.

Thus, at the stage of installation in the two middle diaphragms, forces arose from the own mass of the arched enlarged elements, and after monolithing of the joints in the process of unloading in these diaphragms, the forces remained without significant changes. In the other two diaphragms, efforts arose from the expansion of the tightening of the enlarged arched elements. The redistribution of efforts in the diaphragms occurred mainly in the process of unloading the shell.

The research results were compared with the calculation data using a specially developed program (Fig. 4). Comparison of deflections and forces showed that the maximum calculated values differ from the experiment by 2 times. This is due to the fact that during the installation stage, the calculations of the shell did not take into account the installation state and compliance of the contour diaphragms.

**Figure 4.** Deflections of a composite shell 12x12m of negative and positive curvatures at the stage of installation \( a, b \) - deflections of the shell; 1,3 - experiment for the shell with negative and positive curvatures; 2.4 - the same, by calculation without taking into account, 5.6 taking into account mounting conditions.
Table 1. Changes in the process of unloading the force in the mounting ties of a 12x12 m compound shell with side elements of negative (in the numerator) and positive curvature (in the denominator).

| Sequence removal puffs | Efforts to unroll, [kN] | Change of forces in puffs in the process of their removal (uncoiling), [kN] |
|------------------------|--------------------------|--------------------------------------------------------------------------------|
| In the central shell   |                          |                                                                                |
| 1                      | 4.56                     | 5.18                                                                           |
|                        | 5.00                     | 5.34                                                                           |
|                        | 4.78                     | 4.78 5.00                                                                     |
|                        | 5.02                     | 5.11 5.20                                                                     |
| 4…                    | …                        | …                                                                               |
| 11                     | 5.10                     | 5.28 5.09 5.80 5.69 5.96 6.04 6.14 6.33 6.44 6.44                            |
| In the side shell      | 1.99                     | 2.00                                                                           |
|                        | 2.01                     | 2.03                                                                           |
|                        | 2.04                     | 2.09 2.16                                                                      |
|                        | 2.14                     | 2.26 2.31                                                                      |
|                        | 2.35                     | 2.41 2.46 2.55                                                                 |
|                        | 2.55                     | 2.60 2.65 2.73                                                                 |
| 16                     | 4.11                     | 4.34 4.46 4.55 4.67                                                           |
|                        | 4.24                     | 4.33 3.41 4.62 4.81                                                           |

Thus, the assessment of the stress-strain state of spatial systems only during the operation stage, without taking into account the installation conditions, gives underestimated results.

A numerical study was carried out on the possibility of using the results of these studies for the construction of buildings with shells of coatings 18x36m and evaluating the work of shells of various geometric shapes, for unique large-span buildings with spans of 18-116 m showed the feasibility and developed method for wide application.

5. Conclusion
Experimental and theoretical research on modeling the staging of construction of large-span spatial unique buildings of complex geometry allows us to formulate the following conclusions:

- Rational types of coatings for public buildings are prefabricated monolithic reinforced concrete shells, outlined along various geometric surfaces and consisting of unified cylindrical panels, the geometric dimensions of which are assigned from the condition of staging and rationality of the accepted installation methods.
- Installation of these shells is recommended to be carried out without continuous scaffolding by the method of preliminary enlarged assembly of panels into vaulted mounting elements with temporary puffs with a span of 18-24 m, which are installed on the shell contour and one or two lines of mounting trusses and supports. At the same time, labor costs for installation are significantly reduced (up to 20-25%) compared to using the method of installation on assembly conductors.
- The stress-strain state of a composite shell made of enlarged elements has features at the stage of unloading, which must be taken into account when determining the normal forces and bending moments in the edges of the panels parallel to the mounting tightenings.
– Experimental and theoretical studies made it possible to analyze various installation options and identify a rational method for uncoiling composite shells. It was found that lowering the mounting beams (trusses) at the beginning, and then removing the forces in temporary tightening of the enlarged mounting vaulted blocks, leads to a decrease in the tightening forces by an average of 30%, which greatly facilitates their dismantling.

When designing composite shells, the installation state must be taken into account. Otherwise, it is possible to underestimate the values of forces and deflections by 1.7-2 times, therefore, the operational safety of unique structures will not be ensured.

6. References
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