Analysis of Stress-Strain State of Spherical Roof Shell

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Abstract - This paper contains the results of experimental and theoretical research of the stress-strain state (SSS) of reinforced concrete spherical roof shell with complex internal and external geometries. The loading was carried out by hydrostatic method, which correctly represents the snow load on the roof.

Keywords – spherical shell, snow load, shotcreting.

I. INTRODUCTION

Technological processes and techniques of modern cast-in-situ buildings, as well as the current state of the theory of analysis of reinforced concrete structures in general, allow to create arbitrary curved shape structures, then design and implement buildings and facilities with unique architectural features, and with different plans, large spans, etc. However, bold and unusual architectural solutions often are implemented by structural elements of complicated configuration which leads to sky-high cost of construction due to increased consumption of materials as well as necessity to develop individual construction techniques and to make disposable formwork.

In this connection it was offered a new structural system Monofant (monolithic fantasy) to solve the above described problem [1]. The peculiarity of this system is application of non-extractable void-forming inserts inside of the cast-in-situ reinforced concrete element (Fig. 1). Inserts may be made of any easily available lightweight material of construction, such as foam polystyrene, foam plastic, foam polyurethane, etc. Inserts introduced within a reinforced concrete shell transform the cross-section of flexural member from rectangular to I-shaped so that one of the flanges sustains tension stress, whereas the other one is under compression. On the basis of the designed cross-section of the reinforced concrete I-beams the dimensions of insert are determined.

II. MONOLITH STRUCTURE BY SHOTCRETING PROCESS

Recently shotcreting process has become widely used in installation of cast-in-situ reinforced concrete structures, which consists of concrete mortar placed under pressure to a rigid surface. In this way a compacted layer of air-placed concrete was formed, which in some cases has better properties than vibroconcrete.

Air-placed concrete possesses higher compression and tensile strength, water permeability, reliable cohesion with
surface of coated structure, accelerated strength gain at equal service conditions.

Two shotcreting methods exist – wet and dry. The wet shotcreting process has some advantages as compared to dry process: low dusting, uniform composition of placed concrete, applicability in tight environment, negligible concrete mortar rebound in the course of placing, low cost of working for site protection.

Using the wet shotcreting technique in the above-described Monofant system opens way to make structural elements for a cast-in-situ reinforced concrete frame with actually arbitrary geometry. Thus, it was made, and subject to experimental study, a structural element having a complicated external and internal geometry. The process was tested at the laboratory site of Kharkov National University of Municipal Engineering-Beketov, where was created a fragment of roof spherical shell of 2200x2200mm in plan, with dimensions and reinforcement shown in Fig.2. Fabricated the external and internal concrete casings of 50mm thick each and placed between them the extruded foam polystyrene of 160mm thick void-forming insert. Both casings are equally reinforced with 200x200mm BRC mesh Ø6mm. Along two diagonal directions of shell installed ribs of 100mm width to ensure cooperative work of casings, and reinforced them with the Ø10mm cages. Curvilinear reinforcement cages and foam polystyrene inserts were prepared in fabrication conditions. The geometric topology and exact dimensions of inserts are achieved by using special jigs. In turn, necessary shape of inserts was maintained due to special templates in the course of polystyrene sheets cutting. The combination of reinforcement and inserts formed a skeleton, which works as formwork during the concreting of shell (Fig.3a).

This research showed that ready-made spatial blanks have substantial rigidity needed for concrete placing. The next step was application of concrete mortar to the prepared elements by shotcreting. General view of the ready concrete structure in the form of the fragment of roof spherical shell is shown in Fig. 3b.

![Fig.3. Roof shell tested fragment: a- reinforcement cage with non-extractable inserts; b- ready structure.](image)

### III. THEORETICAL ANALYSIS OF STRESS-STRAIN STATE OF SPHERICAL SHELL

The developed Monofant structural system together with applied wet shotcrete technology always needs to analysis of SSS of designed and manufactured fragment of roof spherical shell. In the whole Northern Europe, including Ukraine, and in major mountain regions of Kurdistan, the snow load is the most significant type of load on the elements of roof of the buildings and structures. Both European and national specifications regulate the consideration of snow load effect [2, 3], roof surface configuration is the most influencing factor affecting on the magnitude and distribution of snow load [4]. Issuing from this, within the presented study, performed a finite-elements structural model of the created in laboratory shell in ANSYS software environment (Fig. 4). The capabilities of this software complex permit automatic triangulation of complicated shapes of finite elements using automatic import from auxiliary 3D modeling software package (in this case Autodesk Inventor package is used). This finite-elements model consisted of 459061 elements and 261791 nodes. The FEM model is built by using a universal 3D finite elements (concrete, reinforcement, and polystyrene foam - all the
elements are the same). Then, for each material entered the physical and mechanical properties (modulus of elasticity $E$, tensile strength, $R$). The connection between the concrete and rebar, by default assumed absolutely rigid.

The pin supporting is suggested at four corners of the shell, and load was applied to shell surface in four different patterns as shown in Fig. 5. The value of uniformly distributed applied load is $10\, \text{kN/m}^2$.

Fig. 4. Shell finite-elements model.

Fig. 5. Load patterns: 
a- whole surface; b- 1/2 of surface; c- 1/4 of surface; 
d- 1/8 of surface.

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a- whole surface; b- 1/2 of surface; c- 1/4 of surface; 
d- 1/8 of surface.

Fig. 6 shows the displacement of the shell bottom surface along $Z$ axis for each of four load patterns.

Fig. 6. Shell vertical displacement due to various load patterns: 
a- total surface; b- 1/2 of surface; c- 1/4 of surface; d- 
1/8 of surface.

IV. EXPERIMENTAL INVESTIGATION

Having finished the theoretical analysis of SSS of the roof spherical shell, performed experimental studies of the manufactured fragment.

Object of study: a fragment of Monofant system of roof spherical shell.

Purpose of study: search of the mode of deformation of the object.

In the experimental study, described above, shell was installed on a specially manufactured frame made of 100x6mm square-section pipe. The frame provided shell pin supporting of the shell at 4 corners. The height of
experimental supporting frame ensured easy access to bottom surface of shell where measuring instruments were installed.

**Measurement system.** To determine a qualitative and quantitative mode of deformation of the tested shell, the vertical component of the displacement was measured at 25 points (Fig. 7a). Substantial rigidity of the tested structure, which, in turn, caused small values of expected displacement, it was decided to use the 2µm-20mm measurement dial gauge (Fig. 7b). Dial gauges were fixed at specified points with specially manufactured fasteners made of 40x3mm square-section pipe and 10x10mm steel rods which, in turn, were welded to the basic experimental frame.

**Loading system.** A hydrostatic load was applied to the tested shell fragment, which can exactly represents the effect of uniformly distributed snow load on structure surface [5]. According to this method, a special basin was made above the tested structure and filled with liquid exerting hydrostatic pressure on basin bottom which actually is the top surface of the shell. Considering the complicated configuration of the loaded surface, and in order to ensure uniformly distribution of water column pressure, installed additional longitudinal and transverse baffles inside the basin. Thus, the basin installed above the shell was a cellular structure of 121 cells of 200x200mm, and 1200mm high (Fig. 8).

Fig. 7. Measurement system: a)-arrangement of dial gauges; b)-general view of dial gauges.

Fig. 8. Cellular basin of loading system: a)-general view; b)-gap between basin and shell.

Basin walls and internal baffles were made of seven-layer plywood, external walls being 20mm and internal baffles 10mm thick. The basin external walls were supported by experimental basic frame, whereas internal baffles were
rigidly fastened to external walls with drive screws and glue. The existed gap (Fig. 8b) between basin internal baffles and shell was filled with insulation foam in the course of basin installation, thus, basin self-weight was distributed only to supporting frame. Each formed cell was installed specially using polyethylene cases, thus ensuring total basin sealing. The loading was carried out by four schemes similar to the theoretical analysis of the shell (Fig. 5). For each of the four independent load pattern was 6 cycles of load/unload as shown in Table 1 and Fig. 9. Also, the table shows the deviation \( \Delta \) of experimental values of vertical deflection from the theoretical for each of the four loadings. Fig. 10 shows the results of experiments in graphical form.

**Table 1.** Averaged experimental displacement and deviation \( \Delta \) of experimental deflection from the theoretical for each of the four loadings patterns.

<table>
<thead>
<tr>
<th>Dial Gauge No.</th>
<th>Vertical Displacement, mm, due to load pattern (10kN/m²)</th>
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<tbody>
<tr>
<td></td>
<td>whole</td>
</tr>
<tr>
<td>1</td>
<td>0.275</td>
</tr>
<tr>
<td>2</td>
<td>0.382</td>
</tr>
<tr>
<td>3</td>
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<tr>
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<tr>
<td>5</td>
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<td>6</td>
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<td>7</td>
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<tr>
<td>8</td>
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<td>9</td>
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<td>25</td>
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</table>

Fig.9. Averaged displacement for different load patterns.

Fig.10. Shell vertical displacement due to various load patterns.
CONCLUSION

The comparison of the experimental data with the theoretical demonstrates the correctness of the analysis modelling of shell, as well as the purity of the experiment. This research showed that structural elements created according to the developed technology possess all necessary strength and rigidity attributes for load bearing member of cast-in-situ concrete buildings.

In general, it should be noted that the performed investigations confirm representativeness of Monofant system which opens fundamentally new horizons in construction of cast-in-situ concrete buildings. It is proved by the design of hotel complex in Kharkov which may be built soon (Fig. 11).

![Fig. 11. Hotel design (Monofant system): a- plan view; b- section; c, d- visualization.](image)

References


