OPERATIONAL EXPERIENCE WITH THE TUBULAR-SPACE STRUCTURE DESIGNED BY THE MOSCOW ARCHITECTURAL INSTITUTE FOR THE MACHINE GALLERY AT THE SAYANO-SHUSHENSKOE HYDROELECTRIC POWER PLANT

V. I. Bryzgalov and A. A. Klyukach

The crossed-tube space design developed by the Moscow Architectural Institute (hereinafter called MARCHI) was first used as a large-scale continuous frame at the Sayano-Shushenskoe hydroelectric power plant for the ceilings and walls of the machine gallery. The design consists of unified metallic elements (Fig. 1). Nowhere in the world has there been experience with the use of such a design for a hydroelectric power plant under a continuous vibratory load induced by turbine operation and (rather frequently) discharge flows and passage of high water and spring floods. The maximum power generated by a discharge flow is more than $25 \times 10^6$ kW.

The frame of the machine gallery is built in the form of 13 independently standing single-span space frames of widely varying heights with rigid nodes for supports and cross beams; the frames fan out one after the other, repeating the curvilinear planform configuration of the machine gallery. A frame cross beam has a 2-percent slope in the direction of the upper pool to insure that water runs off from the roof. The tubes in a section are connected at nodal metallic hemispherical or spherical elements of the MARCHI system (Fig. 1). The tubular elements are joined at the nodes by high-strength bolts that can be screwed into the nodal elements. It was proposed in design that the required strength of the joints should be ensured by prestressing the bolts in tension with a force of no more than $15 \times 10^3$ N. Tensioning should be automatically limited by the shearing of a control pin by a special bushing at the moment that the bolt is tightened. The section and material of the pin were selected so that its shearing would occur under a given force.

The space frames are supported on a reinforced-concrete subcrane trestle from the upper pool and a wall from the lower pool, and are rigidly connected to the base. The roof is placed on girders, which are supported at the nodal elements of the MARCHI system. The ceiling and walls of the machine gallery serve to enclose the equipment and personnel from the external medium, and are designed for a snow and wind load and a seven-point earthquake. On visiting the Sayano-Shushenskoe hydroelectric plant, both domestic and foreign specialists have noted the architecturally artistic expressiveness and elegance of the machine gallery, which are defined largely by the external form of the tubular-spatial design of the MARCHI system.

As profoundly as the architectural portion of the design of the superstructure to the machine gallery was developed, insufficient attention was given to the technical solution. To this should be added the fact that production rules and procedures, as well as technical control, which are included in the practice of assembling conventional metal structures, could not ensure that quality of assembly that would correspond to the design first employed in the practice of constructing hydroelectric plants. It was found that the prestress required in the bolts was ensured on shearing of the pins, but at the same time, did not ensure the density of element continuity at the nodes. Among other things, gaps that exceed design clearances between coupled components of the nodal elements occur in many areas of the structure. For certain tubular elements, the support surface of the special bushings is reduced during their fabrication; this, in turn, lowers the bearing capacity of these elements. There were no requirements for rejection of components with similar deviations. According to assumptions made by the design organization, the defect may lead to a significant redistribution of forces in the tubes of this structure right up to their overloading.

The above-noted drawbacks have placed rather rigid requirements on the maintenance of the MARCHI structure in its normal condition. After each idle discharge through the dam, it is necessary to inspect the thousands of nodal points of the design, measuring the clearances in the butt joints and prohibiting the existence of a snow cover more than 0.2 m thick on the roof. During one of the similar inspections of the MARCHI design, which revealed many weakened special bushings, it was concluded that warping of the ends of the special bushings will occur when the roof is loaded by the design snow load (2330 N/m$^2$), and this may result in a change in the geometry of the structure.
nodes of the structure in the zone where frame bending moments act and the distribution of forces in the tubes is significant. Based on the results of the inspection, the design organization has reduced the allowable temporary static loads on the roof to 22% and proposed to strengthen the special bushings in all nodal elements. Considering that this work will require extensive outlays of time and facilities, the operating service has performed special testing of the weakest bushings at maximum loads [1]. The tests indicated that under the design load, the weakest special bushings behave elastically. As a result of their deformations, the top of the wall section has settled by 1.2-1.8 mm. This deformation of the crossed-tube design may not exert a significant effect on its stressed state, if we consider the large dimensions of the frame with a height of 17 m and a span of 34 m.

In 1997, operating personnel took alternate measurements of the vibrations of the elements of the tubular space design. The test results made it possible to evaluate the level of the dynamic influence exerted by operation of the hydraulic units and spillways and to compare the results with initial measurements taken by the Lengidroproekt in 1984. At that time, the ceilings (floors) of the machine gallery had not been concreted for units 9 and 10. Maximum peak-to-peak oscillations of the midpoint of the MARCHI ceiling span, which amounted to 2340 μm (point 1 in Fig. 1) were measured in this zone. This is explained by the insufficient stiffness of the newly monolithized unit block. It is assumed that in the future, the peak-to-peak vibrations would be appreciably reduced on full completion of the structural portion of the powerhouse, and level off over the length of the machine gallery.

The 1997 tests were conducted for a different combination of the two spillway openings and operation of the units under a constant load. The structural portion of the powerhouse was fully completed in conformity with the design. The points of sensor installation for vibration measurements are shown in Figs. 1 and 2. The measurements indicated that basically, the vibrations correspond to nearly harmonic oscillations called wobble.

Diagrams of the vertical oscillations of the midpoint of the ceiling of the machine gallery for different spillway openings in section 40 and simultaneously fully opened sections 40 and 43 are shown in Fig. 3. It is apparent on the plots that the oscillations of the ceiling depend to a certain degree only on the flow rate of water through the spillway. Operation of the units at the hydroelectric plant does not exert a noticeable influence on peak oscillations of the ceiling of the machine gallery. It is also apparent in Fig. 3 that the ceiling oscillations for different unit blocks of the machine gallery differ from one another with the spillway in operation. The maximum displacement is recorded for the ceiling of unit 10 and is 1064 μm for a 100% simultaneous opening of the two spillway gates. The characteristic frequencies of the vertical ceiling oscillation of all structures is within the 0.8-0.9-Hz band with the gates closed (Fig. 4a), and within the 2.6-3.8-Hz band with the spillways open (Fig. 4b).

The peak oscillations of the wall of the machine gallery on the side of the upper pool are lower than those for the ceiling, but also depend on the operating regime of the spillway. As compared with the 1984 measurements, increases in oscillations were recorded in the middle section of the machine gallery. The characteristic frequencies of these oscillations with a closed and open spillway range from 0.5 to 2.7 Hz. The oscillations of the wall on the tailrace side of the machine gallery are also more dependent on the operating mode of the spillway. Maximum wall oscillations of 628 μm are recorded for unit 8 with the two spillways 100% open. The level of oscillations has remained the same as compared with the 1984 measurements. The characteristic frequencies of the oscillations have two bands:

![Fig. 1. Schematic diagram of tubular-space frame designed by MARCHI for superstructure of machine gallery at Sayano-Shushenskoe hydroelectric power plant: 1, 2, 3, 4, 5) points of installation of vibration sensors; 6) tube; 7) special bolt; 8) pin; 9) nodal element; 10) special bushing.](image)