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Dynamic parameters and aerodynamic pressure estimation of a long-span suspension cable roof

Robert Soltys[1], Michal Tomko[2], Stanislav Kmet[3], Christos T. Georgakis[4]

[1]Institute of Structural Engineering, Technical University of Kosice, Kosice, Slovak Republic, robert.soltys@tuke.sk
[2]Institute of Structural Engineering, Technical University of Kosice, Kosice, Slovak Republic, michal.tomko@tuke.sk
[3]Institute of Structural Engineering, Technical University of Kosice, Kosice, Slovak Republic, stanislav.kmet@tuke.sk
[4]Department of Civil and Architectural Engineering, Aarhus University, Aarhus, Denmark, cg@cae.au.dk

SUMMARY:

The dynamic parameters and aerodynamic pressure of long-span suspension cable roof are estimated in this paper. The hyperbolic-paraboloid shape of the roof is created using prestressed cable net with double curvature, which stiffens to the system leading to higher stability and lower deformations under static and dynamic loading. The most prominent loading imposing dynamic response is wind with its fluctuating components, whose interaction with the structure may produce resonance. Dynamic characteristics estimation of the full-scale structural system plays an important role in predicting the structural response and to verify preliminary assumptions with those obtained from field measurements. This paper focuses on the verification of identified modal parameters of the cable roof computed using the finite element method with those obtained from the field dynamic test. For extraction of the modal parameter the frequency domain decomposition method was applied. The second part of the paper provides computed aerodynamic pressures of the roof.

Keywords: suspension cable roof, dynamic test, modal identification

1. INTRODUCTION

Long-span suspension cable roofs are increasingly being constructed worldwide resulting from their graceful appearance and structural efficiency. These flexible and lightweight structures are predetermined to cover large areas without any internal supports. The hyperbolic-paraboloid shape of the cable nets supporting the roof is created using a prestressed cable net with double curvature, which stiffens the system leading to higher stability and lower deformations. The structural behaviour is strongly influenced by geometric nonlinearity, prestress, mass, flexibility of the circumferential supports, creep effects of cable members, stiffness and coupling of non-structural layers and cladding. Due to the complexity, it is important to include these effects during the design stage, usually using numerical models based on finite element method (FEM) for structural response estimation. On the other hand, full-scale field tests provide a most reliable approach of assessing the dynamic properties of structures (Chen et al., 2016). The cable roof might be prone to wind induced vibrations due to its lightweight.

Kim et al. (2011) extracted modal properties from long-term monitoring of wind-induced response using the system identification technique. Chen et al. (2016) used identified modal parameters to update the FEM model with artificial neural networks. Rizzo et al. (2023) carried out an extensive investigation of the eigenmodes of aeroelastic test models of flexible roofs in wind tunnel. Liu et al. (2016) investigated characteristics of dynamic pressure on a saddle type roof in various boundary layer turbulent flows.

2. CHARACTERISTICS OF THE CABLE ROOF

The analysed suspension cable structure is a roof covering of the Presov Ice Hockey Stadium (Slovak Republic), which was put into use in 1966. Its plan view dimensions are 92.0 x 77.64 m, which ranks it among the largest structural systems of this type in the world. Its visualisation is shown in Fig. 1. After 50 years of service the previous roof reached the end of its life cycle. The new cable roof (under construction shown in Fig. 2) was designed by our institute at the Technical University of Kosice and was finally constructed in 2020. The hyperbolic-paraboloid shape of the roof is created using prestressed cable net with double curvature and cables spacing of 1.0 m anchored into two monolithic reinforced concrete parabolic arches supported by hinges created between the arches and the columns.

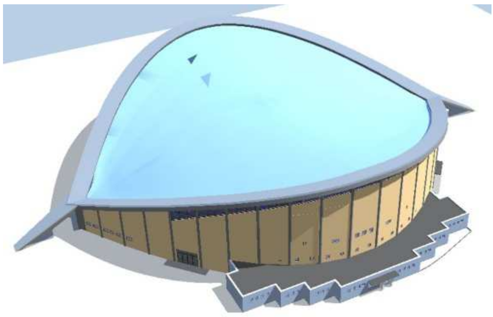

Figure 1. Visualisation of the ice hockey stadium.

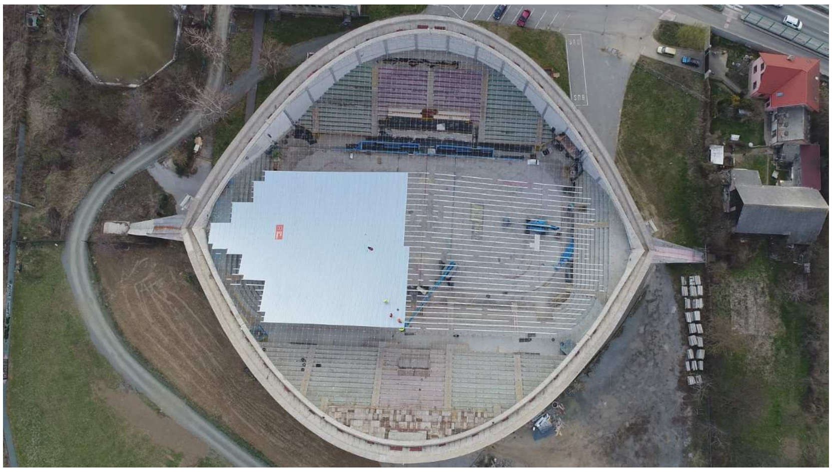

Figure 2. Top view of the roof under construction in 2020.

2.1. Cable net structural design

As the cable net exhibits a nonlinear response and cable forces are strongly affected by the cable net geometry, a form-finding computational procedure was applied to find the cable net geometry and initial cable forces. Taking into consideration, that the force in any of the cables should not drop below zero during its entire life cycle, a pre-stressing force of 30 kN in each stabilising cable was computed, while in carrying cables the largest force reached 236.8 kN.

3. MODAL ANALYSIS OF THE CABLE ROOF

For verification the preliminary assumptions and the structural response estimated during the structural design stage, a dynamic characteristics estimation of the real structural system plays an important role. Identified modal parameters from a field dynamic test with those computed using FEM are presented.

3.1. FEM modal analysis

Eigenfrequencies and eigenmodes of the numerical model were calculated using FEM modal analysis. Prior to modal analysis the form-finding procedure was applied to obtain a stress-displacement equilibrium of the structure, therefore a prestress and geometry of the cables and the supporting structure were included. Obtained eigenmode is shown in Fig. 3 (left).

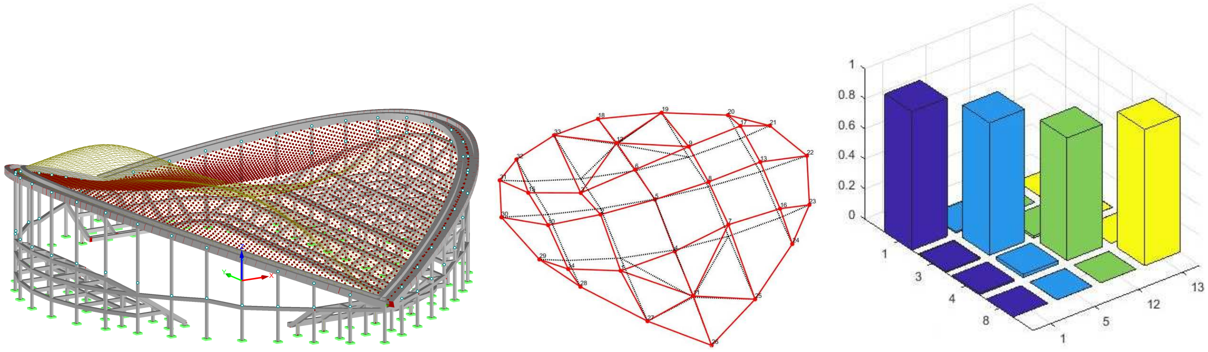

Figure 3. 1st eigenmode from FEM modal analysis (left); 1st eigenmode from field test (middle); MAC (right).

3.2. Dynamic test

Free decay vibration excited by mass releasing is analysed. For this purpose, a permanent monitoring system was used to collect data from 17 accelerometers with a resolution frequency of 20 Hz. The frequency domain decomposition (FDD) method was applied to identify modal parameters of the system from collected data, such as eigenmodes (1st eigenmode is shown in Fig. 3, middle) and eigenfrequencies (Table 1).

3.3. Identified modal properties verification

The obtained modes were verified using MAC defined as (Brincker and Ventura, 2015)

$$MAC(\mathbf{a},\mathbf{b}) = \frac{\left|\mathbf{a}'\mathbf{b}\right|^2}{(\mathbf{a}'\mathbf{a})(\mathbf{b}'\mathbf{b})} \tag{1}$$

where *a* is a vector of the mode from the FEM model and *b* is a vector of the mode identified from full-scale measurement. The MAC criterion for the modes was 0.85, which was satisfied for four eigenmodes, as is shown in Fig. 3 (right).

Table 1. Identified eigenfrequencies from a field test and FEM modal analysis, was validated by MAC.

Identified eigenfrequency	1st	2nd	3rd	4th
Field test	$f_{0,1}$ = 0.699 Hz	$f_{0,3}$ = 1.004 Hz	$f_{0,4}$ = 1.135 Hz	$f_{0,8}$ = 1.921 Hz
FEM modal analysis	$f_{0,1}$ = 0.578 Hz	$f_{0,5}$ = 0.699 Hz	$f_{0,12}$ = 1.084 Hz	$f_{0,13}$ = 1.153 Hz

4. AERODYNAMIC ANALYSIS

Aerodynamic CFD analysis of the stadium has been performed during the structural design stage to obtain a wind loading of the roof (Fig. 5).

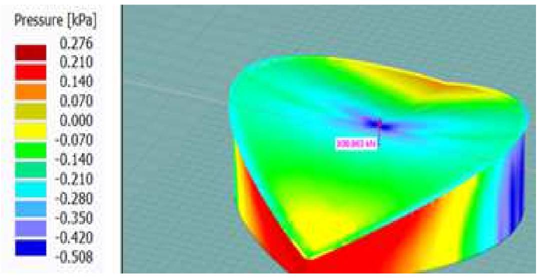

Figure 5. Aerodynamic pressures from CFD simulation.

3. CONCLUSIONS

The dynamic test demonstrated an appropriate procedure for modal characteristics identification and consequently for the verification with those obtained using FEM. Wind loading of the roof using CFD model was computed as well. Obtained modal characteristics and wind pressures will further be applied for aeroelastic response analysis.

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