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CABLE-NET SYSTEMS SUPPORTING GLASS FACADES

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Abstract: *Prestressed cable-nets supporting large glass facades are increasingly used for unique structures and studied both experimentally and numerically. Presented paper deals with numerical geometrically nonlinear analysis of planar and double curved cable-nets without and with glass panes attached to the net with clamped fittings. The numerical model established in ANSYS is described and fully validated by published tests (Yussof, 2015). The results confirm the need for taking the glass stiffness into account. It is proved a greater stiffness of curved cable-nets in comparison with the planar ones and a need for careful arrangement of prestressing for curved cable-nets in sagging/hogging cables. Another study will follow with detailed research concerning optimal and safe design of the systems.*

Keywords: Cable-net, Prestressing, Glass facade, Nonlinear analysis.

1. Introduction

Glass facades due to its transparency and aesthetics has become predominant in the modern exposed building, airport and exhibition halls. With enlarging the façade area the new technologies of the glass supported systems emerged, namely with use of tension elements, either in truss form or cable nets. Single-layer cable-net systems proved to be an excellent choice in case of extremely large glass facades areas since the first applications for the Hilton (Kempinski) Hotel in Munich airport (SBP, Schleich Bergemann Partner Stutgart, 1993) and others, e.g., the Beijing New Poly Plaza (Skidmore et al., LLP San Francisco, 2013; Sarkisian et al. 2007) and the Sea-Tac International Airport Seattle (Fentress Architects, 2005), Fig. 1.

Hilton Hotel has 25x40 m planar cable-net with prestressed stainless steel cables Ø 22 mm and mesh 1.5x1.5 m, giving deflection due to wind max. 0.9 m. The Beijing New Poly Plaza has 90x60 m planar cable-net supported by V-shaped huge cables. The laminated glass panes have thickness 2x6 mm and size 1.3x1.3 m. The vertical and horizontal cables have Ø 26 and 34 mm, respectively. Sea-Tac Seattle Airport has 5 segments 17x21 m, double curved cable-net with stainless steel cables Ø 19 mm and mesh 1.2x2.4 m.

Fig. 1: Hilton Hotel Munich (1993), Beijing New Poly Plaza (2007), Sea-Tac Int. Airport Seattle (2005)

Recent references on cable-net façade systems cover also influence of possible damages (cable anchorage failure, failure of glass pane connectors), e.g., (Yang et al. 2015; Marzuki et al. 2020), blast responses, e.g., (Piyasena et al. 2019), attachment systems (Shang 2014; Zdražilová 2021), adjusted cable ends, etc.

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2. Tests used for validation of numerical analysis

The sophisticated testing model was designed by Yussof (2015) for a detailed analysis of the planar and double-curved cable nets, Fig. 2. The testing rig embodies the net of 7x7 cables with spacing of 305 mm, each of Ø 4 mm 7x7 wire strand core with galvanized steel wires of grade 1770 MPa, minimum cable braking load 10.2 kN, modulus elasticity 82.85 GPa and Poisson ratio 0.3. The load bearing cables were positioned 7 mm lower than supporting cables due to the connecting block in the crossing. The cables were fixed after prestressing and the glass panes (300x300x4 mm with modulus of elasticity 72 GPa) were clamped to the net through steel plates 75x75x3 mm. The double curvature was reached by placing the anchors of cables under/above the datum line according to Fig. 2. The tests were performed for three different values of each cable prestress: 1 kN, 1.5 kN, 2.0 kN. Loading was applied in the four net points up to the maximum value of F = 207.5 N (in total 830 N). Results are used for the analysis validation.

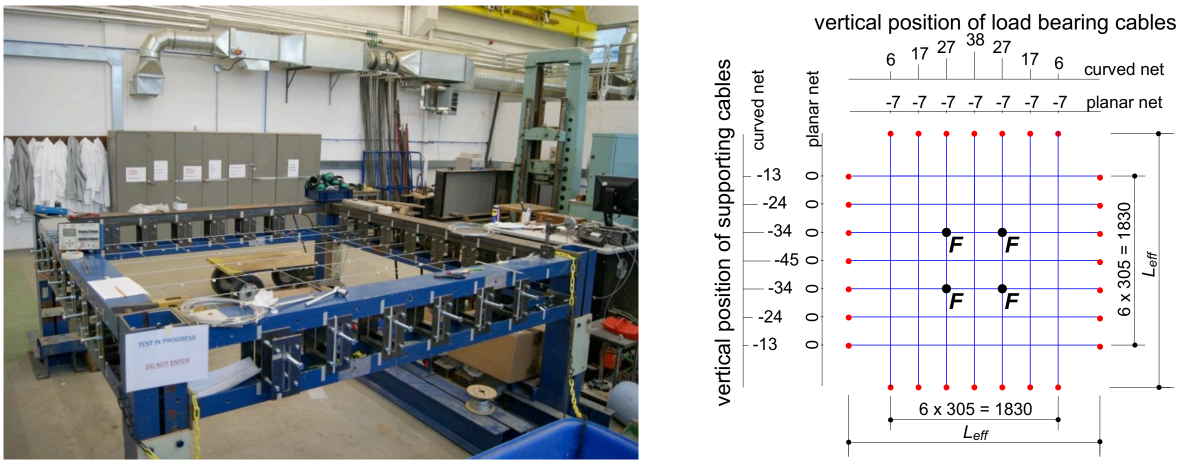
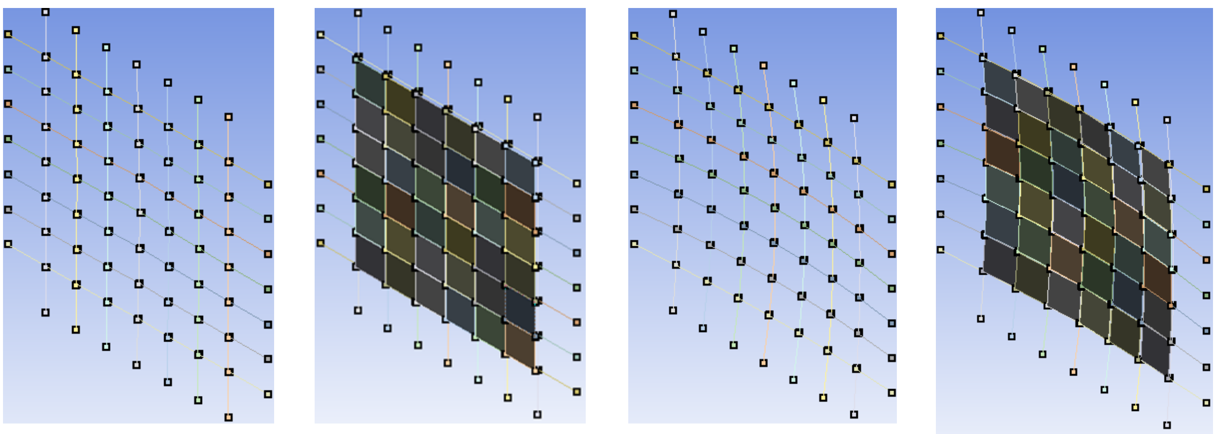


Fig. 2: Test model. Basic cable-net geometrical data and vertical positions of cables at anchors for planar and double curved net with respect to the dating line (Yussof, 2015).

3. Numerical analysis

The ANSYS 2021 R2 software was used for the numerical analyses. The finite element analyses were conducted for 2 numerical models without and with the glass panes (Fig. 3), with the prestress values per cable mentioned above. The finite element models of the cable-net glass facades were created and the elements were assigned with an element type, geometric and material properties in the SpaceClaim application. In general, the cables, glass panels and joints were modelled by using "solid" elements, then they were converted into "shell" elements. After importing the models (see Fig. 2, while according to tests $L_{eff} \approx$ 2800 mm) into the ANSYS Mechanical application, the elements were assigned with an appropriate mesh, boundary conditions and loadings. The prestressing of the cables was set by a pair of forces per cable.



planar cable-net *curved cable-net*

Fig. 3: The planar and curved cable-net models without and with glass panes.

There are three main elements in the cable-net glass facade system, namely the cable-net structure, the glass panes and the glass support attachment. The cables and the glass attachments are using "BEAM188" element type, the glass panes are of "SHELL181" element type.

The geometrical properties of the cables were set to be nonlinear in the analysis steps. The boundary conditions at the ends of the cables were created by the restrictions of displacements along the Y, Z axes and rotation around X-axis for the "X" cables, along the X, Z axes and rotation around Y-axis for the "Y" cables (the direction of the axes is shown in the Fig. 4). "Bonded" connections were established between the glass panes and the glass support attachments, "frictionless" connections between the cables and the glass support attachments respectively. "Bonded" connection doesn't allow sliding or separation between faces or edges. "Frictionless" connection models standard unilateral contact, i.e., normal pressure equals zero if separation occurs. Thus, gaps can form in the model between bodies depending on the loading. The self-weight of the loading system was approximately 3 kg, which contributed 7.5 N in each of the loading point and was considered in the numerical model.

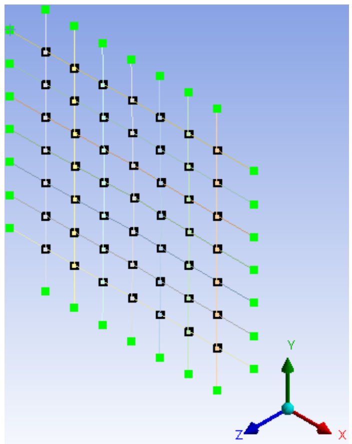


Fig.4 The direction of the axes.

4. Validation of numerical analysis and results

The detailed test and numerical results are demonstrated for maximal vertical deflections being in location of the loading according to Fig. 2. The values are given for both planar and curved cable-nets and all the three prestressings introduced during the tests.

In the case of ***planar cable-net without glass panes*** the nonlinear behavior is obvious for low prestressing (1 kN per cable), while being fairly linear for higher prestressings. ***Planar cable-net with glass panes*** are much stiffer (having smaller deflections) and due to the prestressing the nonlinearity is limited, Fig. 5.

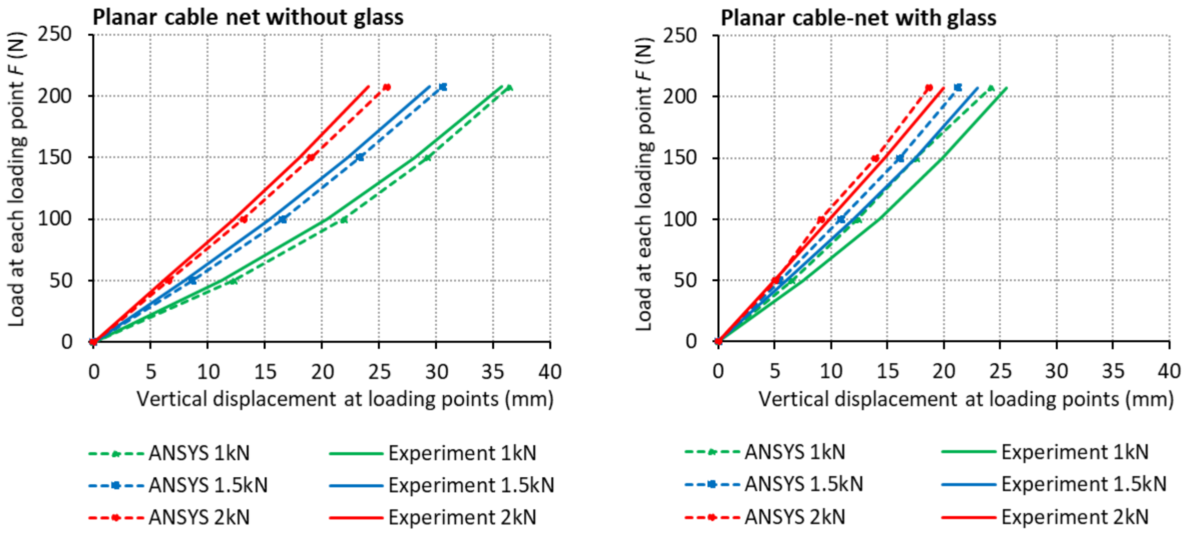


Fig. 5: Maximal deflection of the planar cable-net models with and without glass panes subjected to the three prestressing levels.

In the case of ***curved cable-net without glass panes*** the stiffness in comparison with planar one is higher, deflections reasonably smaller. Again, the nonlinearity is more pronounced for small prestressing (1 kN), however, the stiffness of the curved net contributes to higher linearity of the behavior. The ***curved cable-net with glass panes*** demonstrate nearly linear behavior for all prestressing levels. The influence of the prestressing values seems to be rather less eminent in comparison with the net without glass panes, Fig. 6.

The results of numerical analysis are in reasonable agreement with experimental values. The differences of maximal deflections between the obtained results for planar and curved nets are under 6 % and 7 % respectively. Consequently, the designed numerical models in ANSYS software are acceptable for envisaged parametric studies.

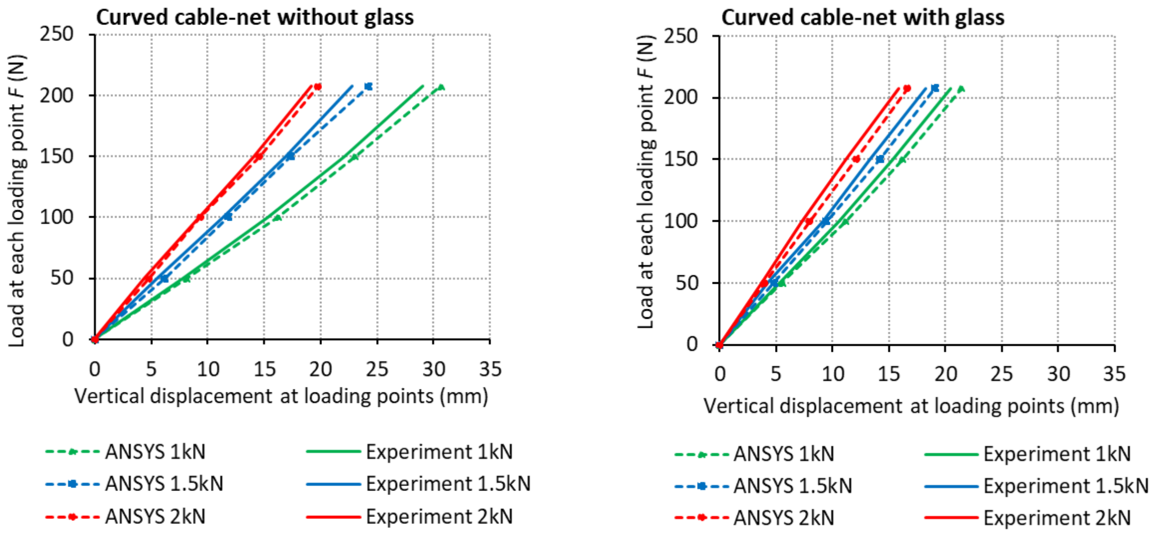


Fig. 6: Maximal deflection of the curved cable-net models without and with glass panes subjected to the three prestressing levels.

5. Conclusions

The paper describes highly demanding experiment concerning cable-nets used for large glass facades by Yussof (2015). The results of tests were used for validation of numerical analysis proposed by using ANSYS software. The numerical model is described for both cable-net without and with glass panes, three levels of prestressings of cables and transverse loading at four point loads.

The results demonstrate favorable contribution due to inclusion of glass panes into analysis which increases the total stiffness of the cable-net. The proper modelling of the glass surface is therefore substantial.

The curvature of the cable-net is another important aspect which also increases the stiffness of the cable-net and contribute to better net behavior enabling lower prestressing of cables. The detailed study of these aspects is under way in the institution of authors.

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