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DESIGN OF CABLE-NETS FOR GLASS FAÇADES

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Abstract: *The studies of cable-nets supporting glass façades are presented. Numerical modelling of the net, point-fixed bolted (spider) attachment and glass panes is described in some details using ANSYS software. Basic entry data concerning geometry, glass and cable properties are introduced based on current European Standards. Commonly recommended cable prestressing and the transverse wind loading in accordance with Eurocode 1 are employed. Partial results of large parametric studies are presented, covering various cable-net geometry, set of glass thicknesses and cable diameters. Finally, the study of a failure of some cables and robustness of the cable-net is demonstrated.*

Keywords: Cable-net, prestressing, glass façade, nonlinear analysis, anchorage failure, robustness.

1. Introduction and analysis

Large-scale glass façades are frequently supported by prestressed cable-net systems using point-fixed fittings to attach glass panes, see Fig. 1. The systems and basic elements (laminated or insulated glass units, point-fixed bolted (spider) or clamped fittings, prestressed stainless steel cables incl. anchors) are described in some details by Komlev and Machacek, 2022, 2023.

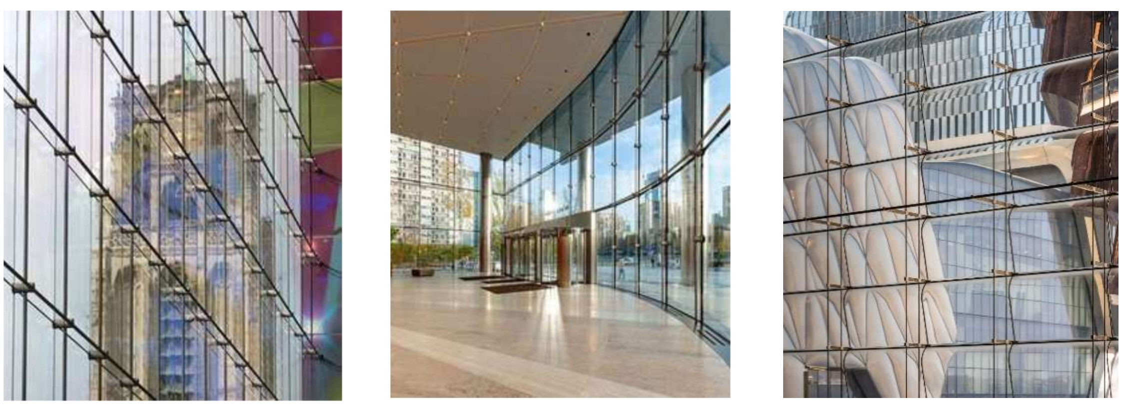

Fig. 1: Market Hall Rotterdam (2014), Mennica Tower Warsaw (2019), Hudson Yard 20 N. Y. (2018).

The typical cable-nets with laminated glass panes attached by spider fittings were analysed by the authors using software ANSYS 2021/R2 and facilitating by use of the Python code. FE modelling employed elements SOLID 186 (glass), SOLID 187 (spiders) and BEAM 188 (cables). Frictional contact surfaces were introduced in the all mentioned elements. The prestressing was applied on each cable at its one end in the direction of the cable axis. The transverse loading represents wind loads in accordance with EN 1991-1-4 (region III, terrain III, force coefficients for suction -1.2) as a characteristic pressure of F_{wk} =1 kPa (in case of the serviceability limit states, i.e. for deflections) and design pressure of F_{wd} =1.5 kPa (in case

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of ultimate limit states, i.e. for stresses and cable loads). These loadings were applied as the uniform area loadings following the cable prestress in the next, final loading step.

After the successful validating of the modelling using experiments by Yussof (2015) and verification using data by Shang (2014) (for details see Komlev and Machacek (2023)) this paper presents results of parametric studies concerning the realistic configurations of cable nets, laminated glazing and robustness of the façades after failures of some cables.

2. Basic data

The studies cover an arbitrary chosen façades with cable-nets according to Fig. 2. The glass panes are attached by spider point-fixed bolted fixing, while the 5 mm gap among the panes for silicon sealing is considered.

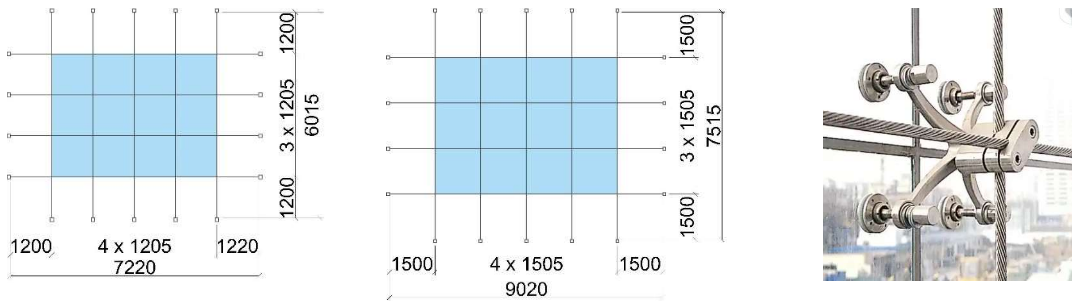

Fig. 2: Cable-nets analysed in the study and "spider" fixing of the glass panes.

The laminated glass was considered from two glass panes of various thickness with PVB (polyvinylbutyral) 0.76 mm interlayer. In accordance with standards EN 16612 (Glass in buildings - Determination of the lateral load resistance of glass panes by calculation, CEN, 2019) and CEN/TS 19100-2 (Design of glass structures - Part 2: Design of out-of-plane loaded glass components, EN-CENELEC, 2021) the equivalent thicknesses for numerical analysis were established (see Tab. 1), while shear factor taking PVB into account was considered as $\omega = 0.3$.

Laminated glass	Equivalent thickness for deflections [mm]	Equivalent thickness for stresses [mm]
4+0.76+4	6.63	7.32
6+0.76+6	9.75	10.74
8+0.76+8	12.86	14.15
10+0.76+10	15.98	17.57
12+0.76+12	19.10	20.98

Tab. 1: Laminated glass used in the study.

Glass properties according to EN 16612: modulus of elasticity 70 GPa, density 2 500 kg/m^3, compression strength 1 000 MPa, Poisson's ratio 0.23 and the design bending strength for the thermally toughened safety glass follows from the standard formulas based on class CC3 consequences (see EN 19100-1) for $\gamma_{MA} = 2.0$ and $\gamma_{MV} = 1.3$. Resulting design bending strength gives $f_{gd} = 75.7$ MPa.

Stainless steel Macalloy cables 1 x 19 with modulus of elasticity 107 GPa, diameters, breaking and design loads according to Tab. 2 were considered in the study. The prestressings were assumed to be 30 % of the design loads in accordance with the published recommendations.

The deflections in the serviceability limit states (for the characteristic loadings) are limited in accord with EN 16612 either to $L/65$ or 50 mm, with L as the shorter span. The absolute value seems to be rather strange in respect to the net dimensions and so only limit $L/65$ was taken into account. The respective value for the 1 200 x 1 200 [mm] net gives 92.5 mm and for the 1 500 x 1 500 [mm] net results in 115.6 mm.

Diameter [mm]	Breaking load [kN]	Design load [kN]	Prestressing load [kN]
14	139	92.7	27.8
16	182	121.3	36.4
19	212	141.3	42.4
22	285	190.0	57.0
26	398	265.3	79.6

Tab. 2: Stainless steel strands Macalloy 1 x 19 used in the study.

3. Results of studies

3.1. Strengths and deflections

Results of parametric studies with the net of 1 200 x 1 200 [mm] is presented in Tab. 3, of the net 1 500 x 1 500 [mm] in Tab. 4. The nets not satisfying either glass design bending stress (< 75.7 MPa) or limit deflections (for the net 1 200 x 1 200 < 92.5 [mm] and for the net 1 500 x 1 500 < 115.6 [mm]) are shown in italics (Note: not satisfying nets with even lower dimensions were in these tables excluded).

Laminated glass [mm]	Cable diameter [mm]	Cable prestress [kN]	Maximal cable force [kN]	Maximal glass stress [kN]	Maximal deflection [kN]
10+0.76+10	*14*	*27.8*	*36.1*	*55.3*	*102.5*
4+0.76+4	16	36.4	42.2	75.7	91.5
6+0.76+6		36.4	42.5	58.6	87.0
10+0.76+10		36.4	43.9	51.8	83.6
4+0.76+4	19	42.4	48.9	68.9	79.3
6+0.76+6		42.4	48.0	40.3	74.9
10+0.76+10		42.4	49.8	37.7	72.4

Tab. 3: Results for net 1 200 x 1 200 [mm].

Laminated glass [mm]	Cable diameter [mm]	Cable prestress [kN]	Maximal cable force [kN]	Maximal glass stress [kN]	Maximal deflection [kN]
12+0.76+12	*19*	*42.4*	*57.6*	*62.0*	*120.7*
8+0.76+8	22	57.0	69.3	64.3	102.0
10+0.76+10		57.0	69.6	61.4	99.1
12+0.76+12		57.0	70.2	58.8	97.5
8+0.76+8	26	79.6	89.9	59.6	80.4
10+0.76+10		79.6	90.4	57.4	78.1
12+0.76+12		79.6	90.9	56.2	76.8

Tab. 4: Results for net 1 500 x 1 500 [mm].

The maximal cable forces seem to be rather low in comparison with the design cable load given in Tab. 2. Therefore, in spite of generally recommended prestressing value of 30 % much higher prestressing seems to be appropriate.

3.2. Failure of anchors and net robustness

A failure of the anchorage of various cables in the 1 500 x 1 500 [mm] façade cable-net was studied and the decisive case is presented in Fig. 3.

The cable-net with cables of Ø 22 mm and laminated glass panes 10+0.76+10 [mm] under the above specified wind loading and full prestressing according to Tab. 4 demonstrated the worst total behaviour with failure of the mid vertical cable (V3), resulting in increasing the deflection of 11 % (109.9/99.1), glass stressing of 19 % (73.2/61.4) and the neighbouring cable forces increase of 12 % (69.4/61.8).

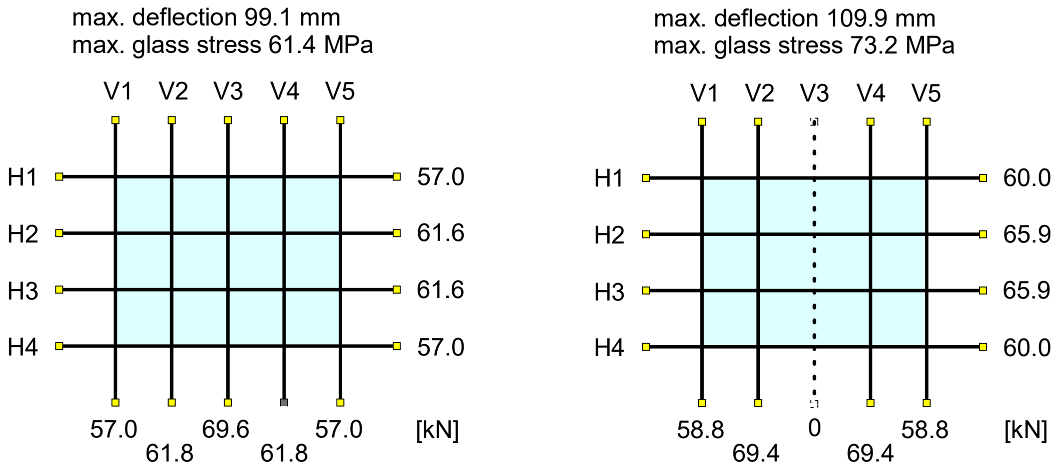

Fig. 3: Cable-net 1 500 x 1 500 [mm]: Full prestressing (left) and failure of cable anchorage V3 (right).

Potential failures of other cables in the above cable-net under the wind loading show the substantial increase of the most loaded vertical cable V3: a failure of the V2 cable gives the increase of 9 %, a failure of the V1 cable gives 3 %, a failure of the H2 cable gives 13 % and a failure of H1 cable gives the increase of 11 %.

Partial loss of the 1/3 or 2/3 of the original prestressing was also studied, including the decrease of prestressing of all cables or each of the individual cables. The results of these studies will be published elsewhere.

4. Conclusions

The paper follows up the previous papers of authors (Komlev and Machacek, 2022, 2023) with presenting results of parametric studies concerning strength and deflections of realistic façade prestressed cable-nets covered by laminated glass panes attached by fixed-point bolted fittings under wind loading.

The study also presents some results of individual cable failures. It is obvious, that the impact of failure of mid cables is decisive, while failures of the edge cables are less dangerous. The full study covers both partial and full loss of the prestressing and will be presented elsewhere.

The following studies of the authors (under way) investigate the optimal prestressing values, thermal effects influencing the façade cable-nets and dynamic behaviour of the cable-nets.

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