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ANALYSIS OF POINT SUPPORTED-GLASS WALL SYSTEM UNDER WIND LOAD

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Abstract: Pre-tensioned point supported glass walls are widely used in modern architecture today. This paper deals with the stability of glass support structure to predict the collapse behavior of the same. All windows in their corners are connected to spider arm thus transferring the wind force on the bowstring structure. The results of the analysis provide load-displacement relationship and influence of the pretension forces as well as temperature effect on the stability of support structure.

Keywords: FEM analysis; point supported glass walls; stability; pre-tension system, temperature effects

INTRODUCTION

Figure 1 represents the structure used for the stability analysis in this paper. The main components of the support structure are: TR-F (B) – Tension Rod-Front (Back), SP – Strut pipe, VR – Vertical Rod and HR – Horizontal Rod.

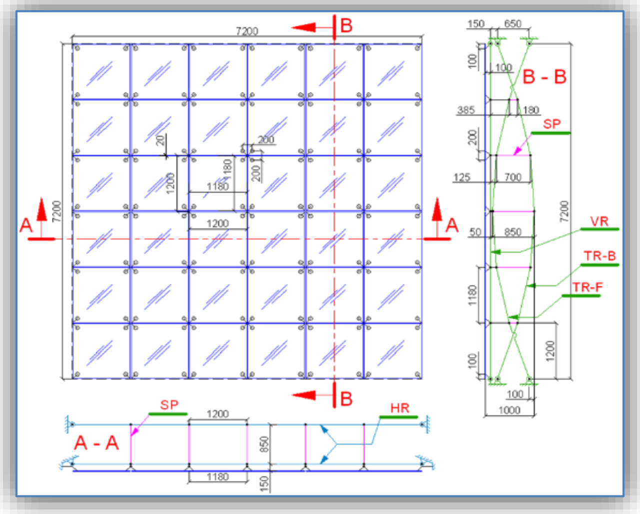

Figure 1. System used for the analysis

TR-F and TR-B form "front" and "back" arch of the so called "bow and arrow" system. The crossed bows are hold strained with the elements marked as SP on Figure1. They play the role of "arrow" in the system. TR-F and TR-B can only take tension forces, while SP can be exposed to compression forces.

Two arches crossed set take the pressure difference which exists between outside and inside of the window panels. The force from the windows is transferred through the "arrows" to one of the arches, front or back one.

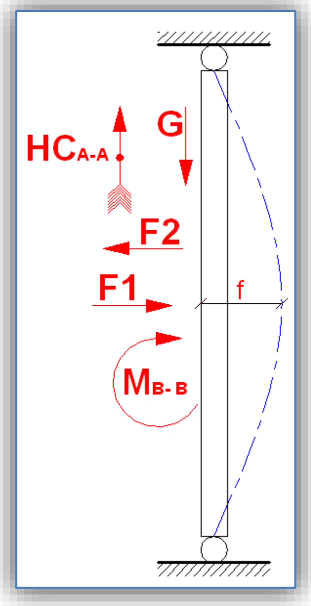

Figure 2. Functions of structure

VR or DLR – Dead Load Rod (element for receving dead load) is set vertically and close to the window panels. The reason why VR is set near the window panels is to eliminate the bending moment caused by dead load and the distance from the panels to the support points.

The elements on Figure 1 designated as HR are used to give stability of support structure in A-A plane. They do the role of "stabilizers" of the support structure in the horizontal plane.

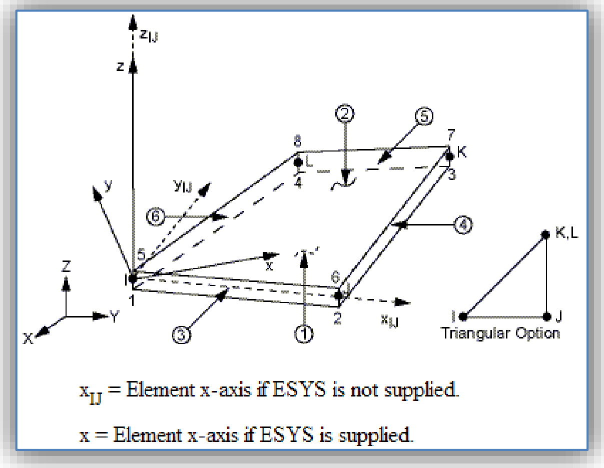

Figure 3. SHELL63

On Figure 2 are shown functions [1, 2, 3, 4] that support structure should perform. The structure needs to resist to transversal forces F1 or F2, axial forces marked as G, resists with bending stiffness $M_{B\text{-}B}$, resists with torsion stiffness $HC_{A\text{-}A}$.

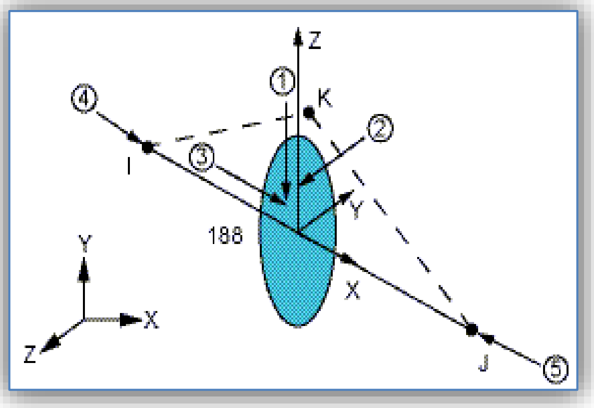

Figure 4. BEAM188

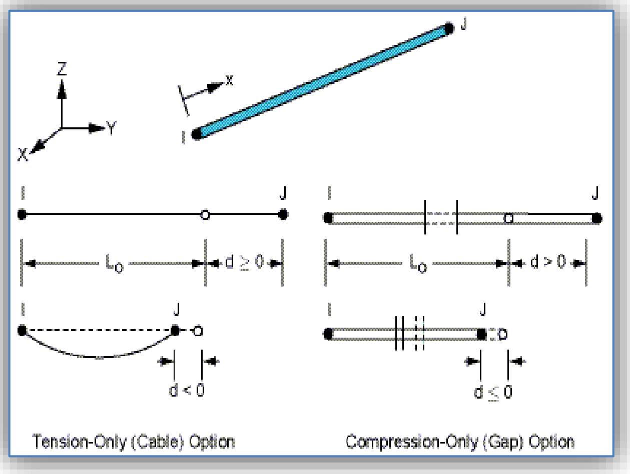

Figure 5. LINK10

Generally speaking, glass support system should perform the same way as simple beam with two point support providing transversal, axial, bending and torsion stiffness.

MODELING THE SYSTEM

In order to perform the FEM analysis it's necessary to select the material properties of the elements constituting the support structure. They are given in Table 1.

Next important step is defining the type of finite elements that will be used for building the model. It is very important because it will affect structure behavior. The elements which are selected are:

≡ SHELL63 – this element simulates glass panel behavior (Figure 3). Acts as membrane which can take bending. This element has six degrees of freedom at each node;

≡ BEAM188 – this element is suitable for analysis of slender to thin beam structures. It's linear element with two nodes (Figure 4) and it has six degrees of freedom at each node. It is used for modeling the spider and the arrow of the support structure;

≡ LINK10 – this element can perform only tension or compression (Figure 5). It is used for modeling the arches, front and back, as well as the horizontal stabilizers.

After material and physical properties are defined and finite elements are selected, support structure of the glass curtain wall is ready to be analysed. The whole support structure is modeled in Ansys (Figure 6a).

Table 1: Selected material and physical properties

Window Panel	E_{glass}=72 000 N/mm^2; μ=0,3; α_T=0.6 x 10^{-5}/°C; δ=12 mm; ρ=2,52 x 10^{-6} kg/mm^3; m=50 kg/panel; $R_{p0,2}$=R_m=80 N/mm^2;
Strut Pipe	E_{steel}=200 000 N/mm^2; μ=0,3; α_T=1.8 x 10^{-5}/°C; Ø=20 mm→A=314 mm^2; I_{zz}=7853,98 mm^4; ρ=7,83 x 10^{-6} kg/mm^3; m=0,0025 kg/mm; $R_{p0,2}\approx$300 N/mm^2;
Tension Rod	E_{steel}=200 000 N/mm^2; μ=0,3; α_T=1.8 x 10^{-5}/°C; Ø=13 mm→A=133 mm^2; ρ=7,83 x 10^{-6} kg/mm^3; m=0,001 kg/mm; $R_{p0,2}\approx$300 N/mm^2; $\sigma_{pre\text{-}stress}$=10 N/mm^2; ε=0,00005;
Vertical Rod	E_{steel}=200 000 N/mm^2; μ=0,3; α_T=1.8 x 10^{-5}/°C; Ø=10 mm→A=78,5 mm^2; ρ=7,83 x 10^{-6} kg/mm^3; m=0,0006 kg/mm; $R_{p0,2}\approx$300N/mm^2; $\sigma_{pre\text{-}stress}$=10 N/mm^2; ε=0,00005;
Horizontal Rod	E_{steel}=200 000 N/mm^2; μ=0,3; α_T=1.8 x 10^{-5}/°C; Ø=6 mm→A=28 mm^2; ρ=7,83 x 10^{-6} kg/mm^3; m=0,00022 kg/mm; $R_{p0,2}\approx$300N/mm^2; $\sigma_{pre\text{-}stress}$=10 N/mm^2; ε=0,00005;

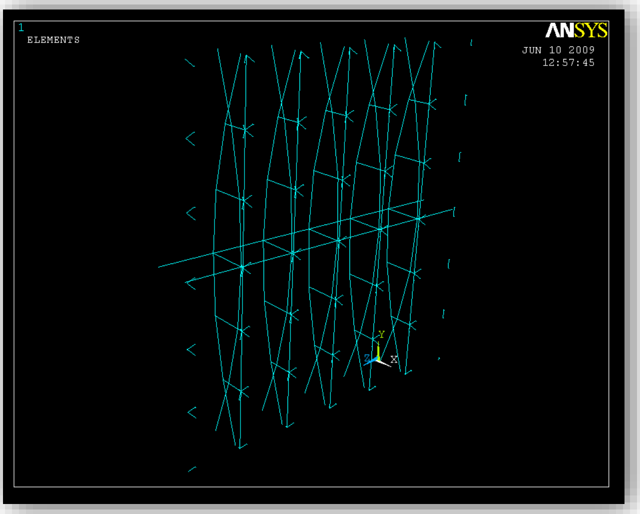

Figure 6a. Completed FEM model

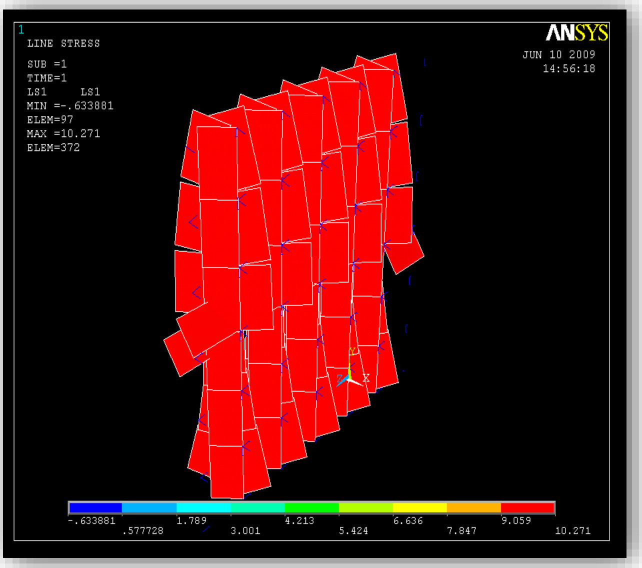

Figure 6b. Pre-tensioned struc. with 10MPa

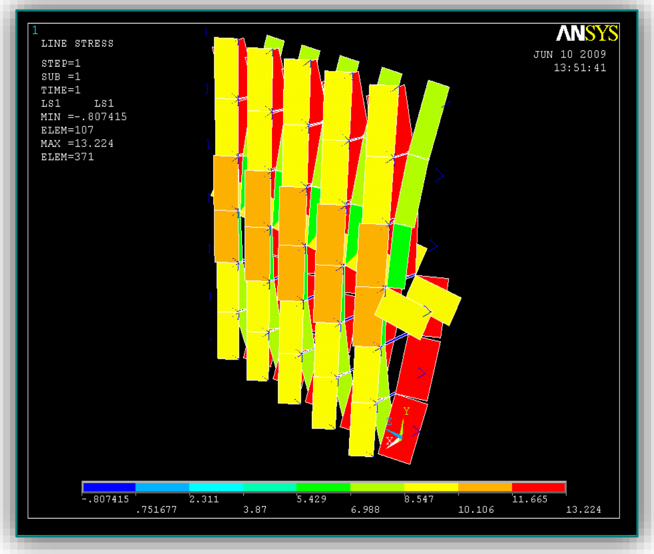

Figure 7. System with 100N at each arrow

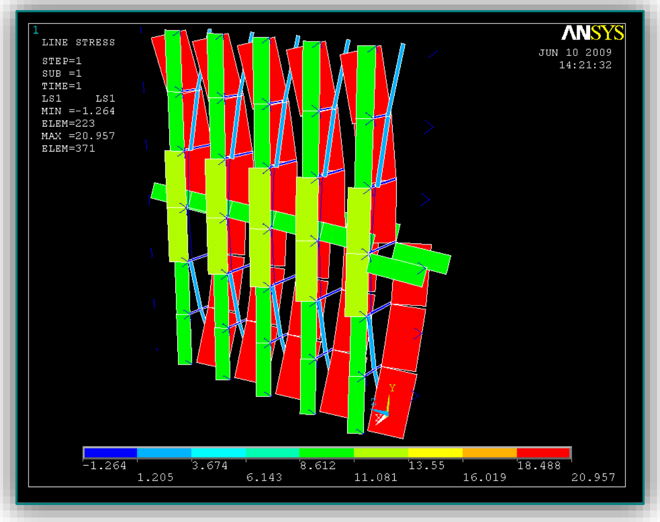

Figure 8. System with 330N at each arrow

ANALYSIS OF THE SYSTEM UNDER EXTERNAL FORCE

The goal of the analysis is determination of the capacity of the support structure with pre-tension of 10MPa (Figure 6b) to receive lateral load or maximal load that each "arrow" can take without causing loss of stability of the system. At the beginning each arrow is loaded with force of 100N. The force is increased step by step considering the condition $\sigma < R_{p0,2}$ until the system becomes unstable.

Figure 6b, 7 and 8 show that increasing the load from 100N till 330N causes TR-B to become additionally stressed, while TR-F is relaxing. When the force at each arrow reaches 350 or 360N the system losses stability and causes rigid body motion. The undefined motion of the support structure is explained on Figure 9.

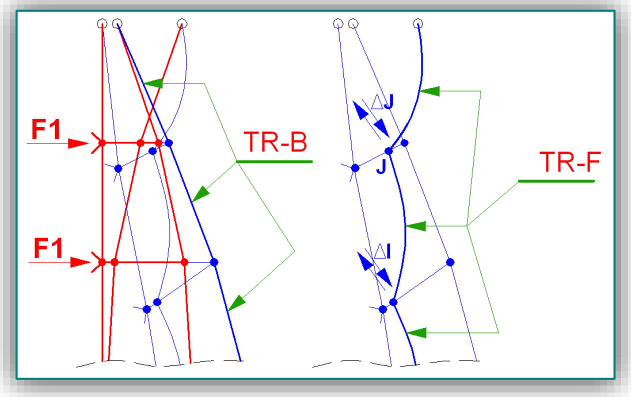

Figure 9. Support structure losing stability

Glass support structure (Figure 9) is losing stability when the nodes I and J become free to move. In this case, TR-F is completely relaxed from tension and practically doesn't participate in the support of the glass wall.

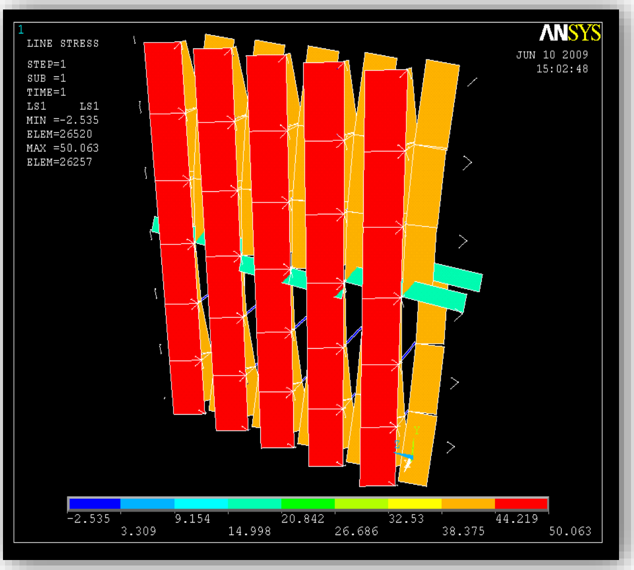

Figure 10. TR=40, VR=50, HR=20 MPa

ANALYSIS OF THE SYSTEM WITH MODIFICATIONS

The system on Figure 6 is modified in order to receive provisional wind load of 100 kg/m² [5]. The area of window panel is 1.2 m². The force that one arrow will take is approx. equal to 100 kg/m² x 1.2m² = 144 kg or 1440 N.

Considering that the analysis is linear, we can calculate the necessary pre-tension of the arches TR-F and TR-B, knowing that 350N is the boundary force which can be applied before system losses stability. Therefore, 1440/350 ≈ 4 meaning 4 times larger pre-tension than the one for the primary system with 10MPa. The first adopted modification is pre-tension of the arches equal to 40 MPa.

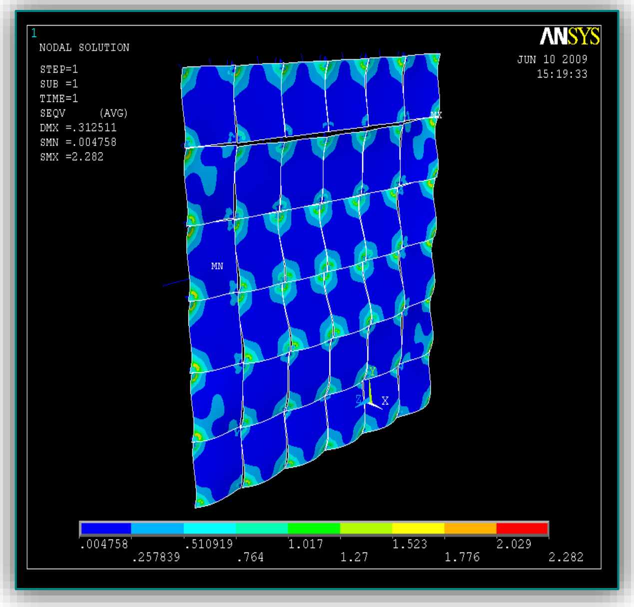

Figure 11. Stresses from dead load

Each VR takes the dead load of five panels (1panel=50kg). Total force that each VR receives from dead load is 5 x 50 kg x 10 m/s² = 2500N. According to Tab. 1 for VR cross section is equal to 78.5 mm². The force of 2500N reduced to cross section of VR is normal stress of the element equal to 40MPa. For safety reasons (earthquake and anti-lock) this value is increased for 10MPa. Second adopted modification is 50 MPa pre-tension of VR elements.

Horizontal stabilizers-HR is assumed to be pre-tensioned with the force that can eventually show up in the plane of the façade. According to Tab. 1 the cross section of HR is 28 mm². It is supposed that the force in A-A plane cannot be larger than 50 kg. In order to prevent front HR to stay stressed, it is adopted 20 MPa pre-tension of HR.

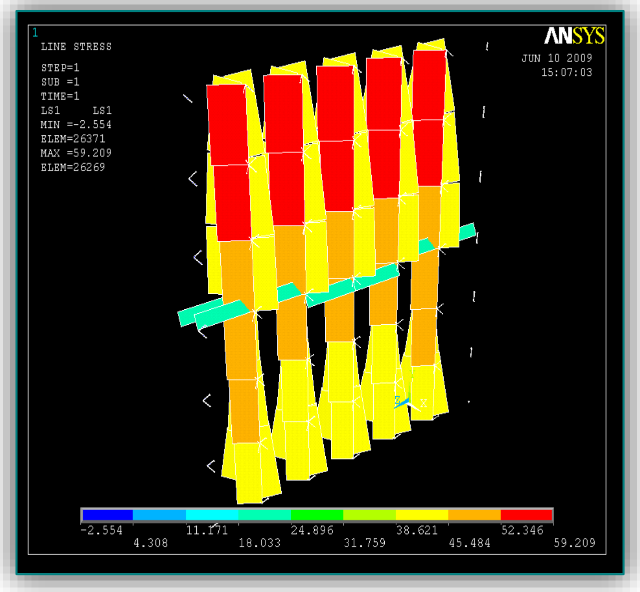

Figure 12. Stresses from dead load

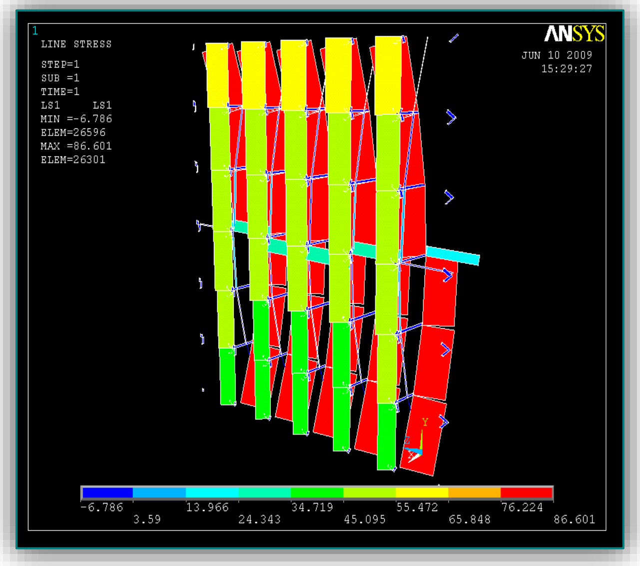

Figure 13. Stress in support structure

The changes of the initial system are shown on Figure 10 and 11. Figure 10 shows only the support system without the panels attached. Figure 11 and 12 shows the general system under dead load with and without panels shown.

It can be noticed from Figure 12 that the most loaded VR elements are the one on the top of the structure – 59 MPa. The lowest are less stressed. They should always carry minimum tension in order to maintain the stability of the system.

When the glass supported structure is subject to wind load of 100 kg/m² and dead load of all elements we get the results shown on Figure 13. Support system is on edge to become instable. The tension stress in the front arches TR-F maintains value from 3 to 13,5MPa.

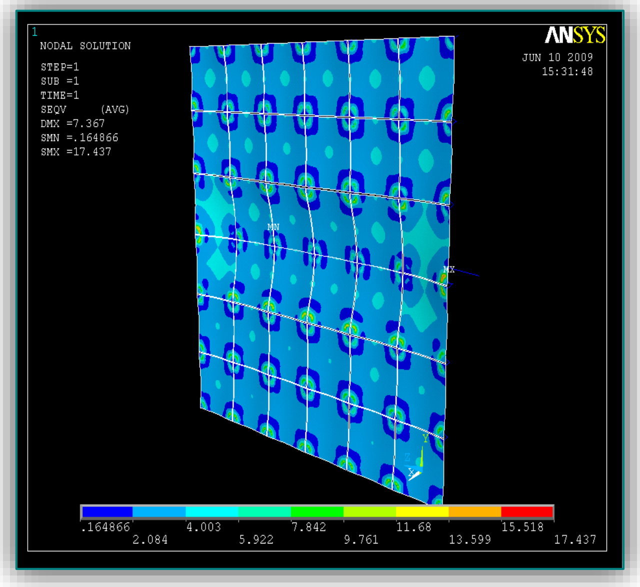

Figure 14. Stress distribution in panels

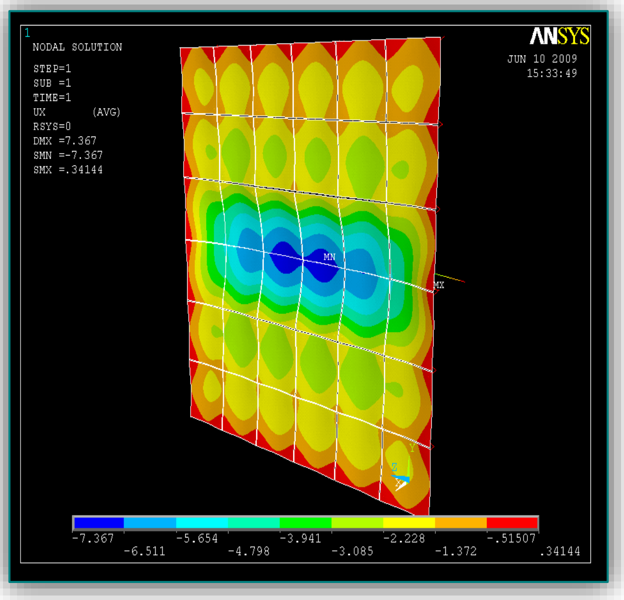

Figure 15. Total displace. in wind direction

The stress distribution of the wind panels is shown on Figure 14. Maximal value of the stress appears around the connection point with the spider arm with value of 17.4 MPa, while the average value is between 6 to 10 MPa. The thickness of the window panel is acceptable, it can be subject for further optimization, but it is used as it is in following analysis.

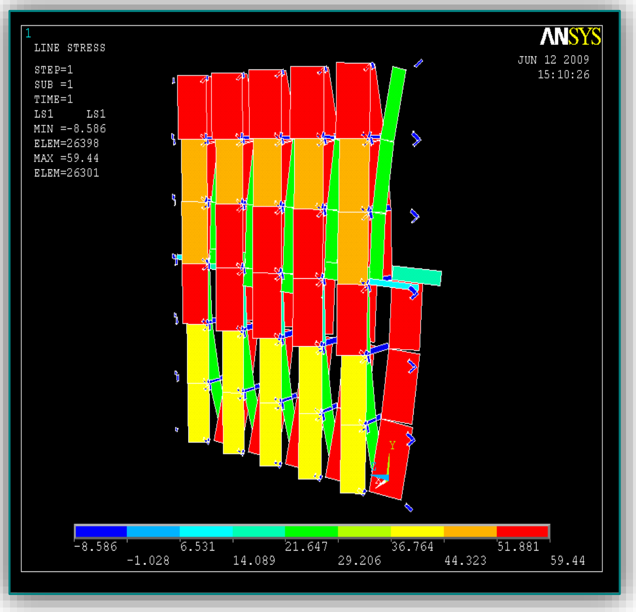

Figure 16. Modified support structure

On Figure 15 is shown total displacement of the glass curtain system. Maximal displacement is on the middle of the system and is equal to 7mm. The deflection of each panel is different and is in the range of 3-4 mm (we can calculate deflection as difference between absolute displacements). It should be noticed that above analyzed structure is usable only for pre-defined referent temperature. The referent temperature at which properties (Tab.1) are defined is approximately 23 до 25°C and the system can be considered stable for this temperature.

The structure is enhanced by changing the sections of the arches from Ø= 13 mm to Ø=20mm (A=314mm²). The results for wind load of 100 kg/m² are shown on Figure 16. The normal stress in TR-B is decreased from 86.6 to 59.4MPa and the stress in TR-F is increased to value of 21.6 to 60 MPa. The support structure now is stiffer and displacements are smaller. The last modification shows that small change in dimensions significantly contributes the stability of the system.

ANALYSIS OF THE SYSTEM INCLUDING TEMPERATURE EFFECT

Physical and mechanical properties of elements are given at nominal temperature. Above and below this temperature properties have different values.

In summer, temperature is higher than the nominal and steel elements extent causing pre-tension stress to decrease. Opposite to this case, in winter the elements are shrinking and add additional tension to the original pre-tension stress.

Support structure of the glass curtain wall is inside the building. It is exposed to sun radiation because windows are transparent and this radiation transforms in to heat [6, 7]. The infrared spectrum from the sun radiation completely transforms in to heat and it is up to the panels to filter this part of the light.

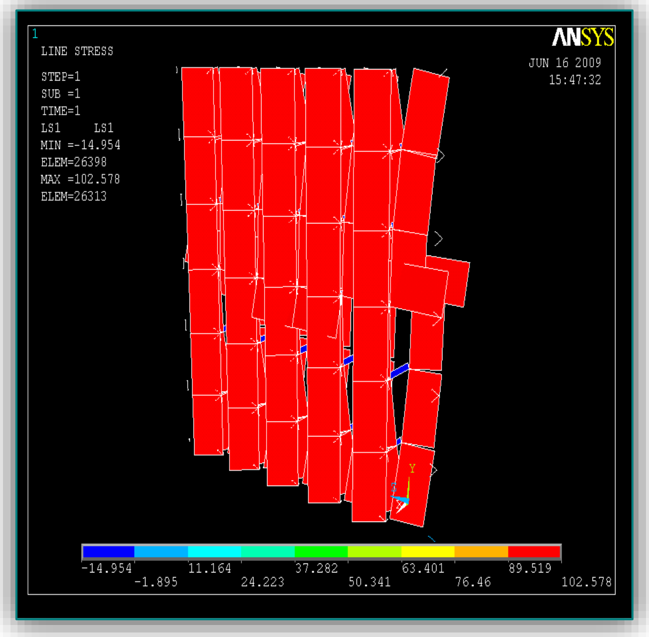

Figure 17. Pre-tension 100MPa*(nom.temp)

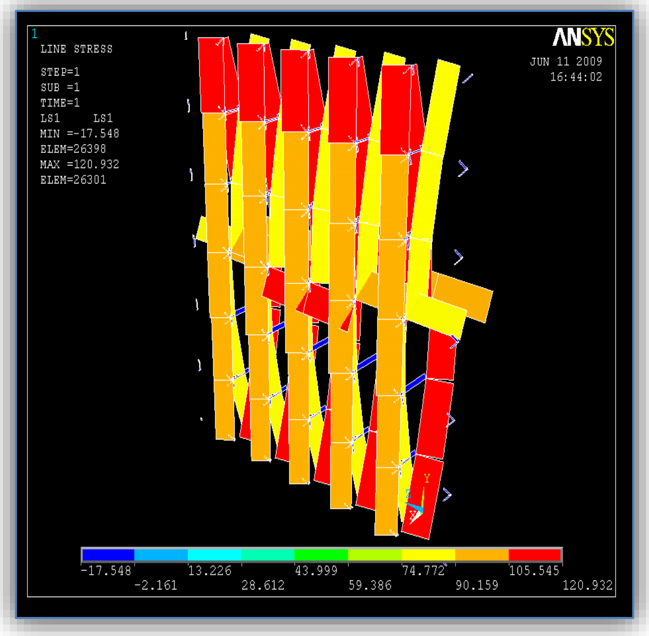

Figure 18. DL and wind load*(nom. temp)

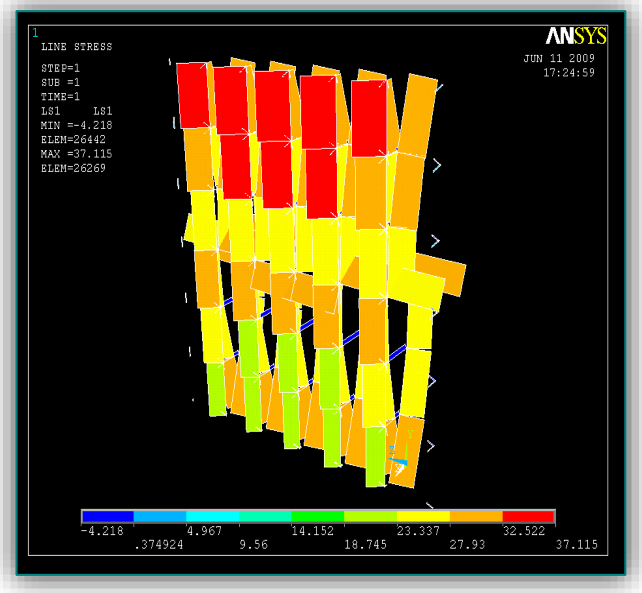

Figure 19. Dead load *(hig. temp)

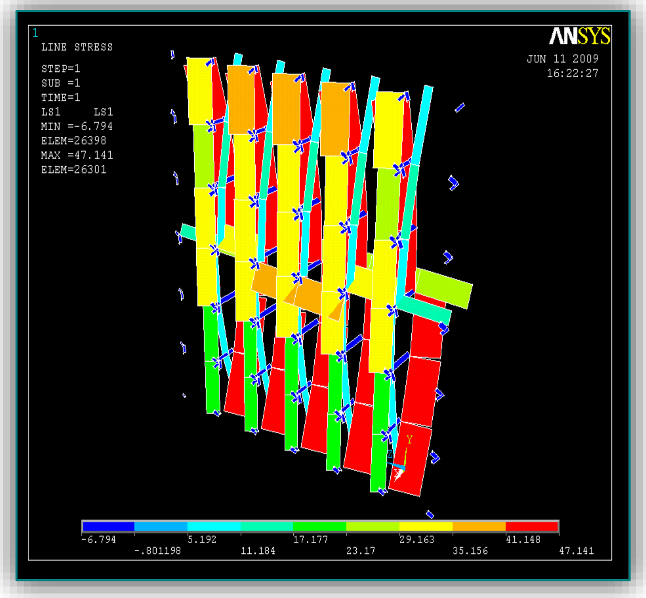

Figure 20. DL and wind load *(hig. temp)

In winter, panels should work as good isolators keeping the heat inside the building and keeping the structure at nominal temperature. Generally it is very important to know exact working conditions of the structure in order to design support structure [8,9].

The model given on Figure 16 will be exposed to equal heating in summer for +20°C, and cooling in winter for -20°C from the nominal temperature of 23 to 25°C. The model will expand and shrink with stress change $\sigma = E \times \alpha_T \times \Delta T$ [10].

Finally, the design condition for the support structure is that allowed stress should be smaller than 1/1.5 from $R_{P0,2}$ [10]. It is above economy savings of material.

SUMMER MODEL ANALYSIS

The model for simulation at high and low temperature is shown on Figure 17 and 18. Compared to the referent model (Figure 16), the difference consists in pre-tension value of the TR, VR and HR elements at nominal temperature. It is increased to 100 MPa.

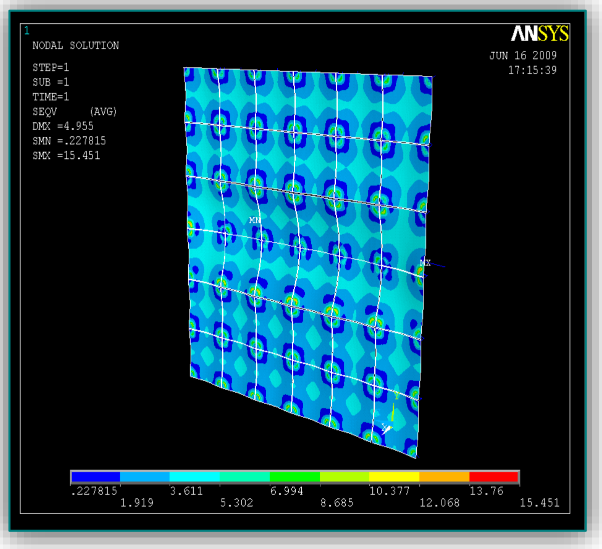

Figure 21. Stress distri. in panels*(hig. temp)

Figure 22. Total disp. in wind dir.*(hig. temp)

At higher temperatures (Figure 20), the support elements are relaxed compared to nominal temperature (Figure 18). The value of the stress in TR-F is equal to 11 MPa, while in the back 47 MPa. The analysis of the summer model shows that at higher temperatures TR-F elements have relaxed from 90 to 11MPa tension, while TR-B stress decreased from 120 to 47 Mpa (Figure 18, 20).

This is acceptable from stress point of view, but affects the stability of the structure. The higher temperatures lower the capacity of the glass support structure to stay stable.

If Figure 14 is compared with Figure 21 we can see that stresses in the window panels are lower in the last case. This is because the last model is generally stiffer than the one on Figure 14 and has smaller displacements (Figure 22). The additional stiffness comes from the increased pre-tension.

WINTER MODEL ANALYSIS

Lower temperature increases pre-tension stress which is shown on Figure 23 from value of 100MPa to value of 160-180 MPa. Decreased temperature makes support structure stiffer.

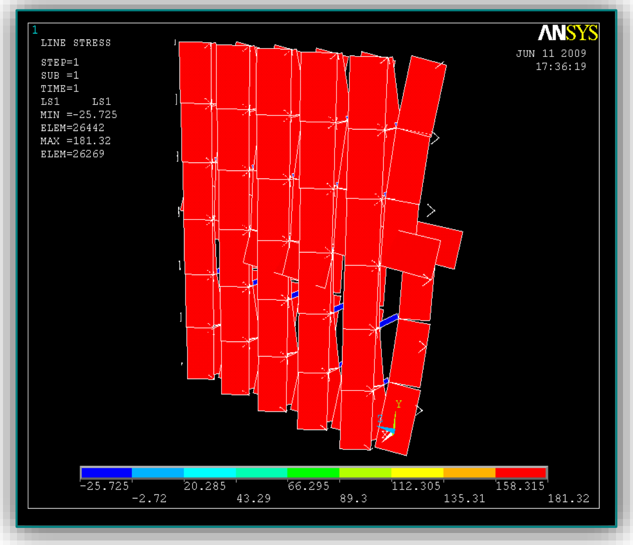

Figure 23. Dead load *(low. temp)

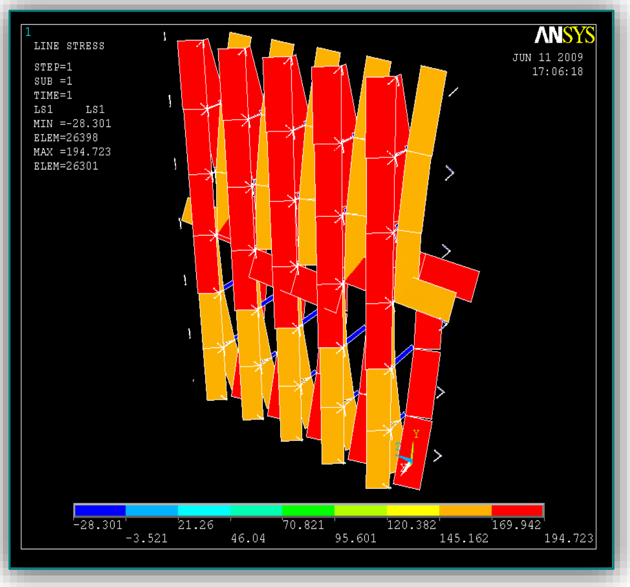

Figure 24. DL and wind load *(low. temp)

Analysis at nominal temperature (Figure 18) show that normal stress in TR-F is equal to 90 MPa and at TR-B is 120 MPa when the system is under dead and wind load. Analysis at lower temperature (Figure 24) shows that this values increases. The stress in TR-F is increases to 150 MPa and at TR-B is 195MPa. The stress distribution (Von Misses) of the window panels (Figure 25) is similar to the one at higher temperature. The maximal value is equal to 15.5 MPa.

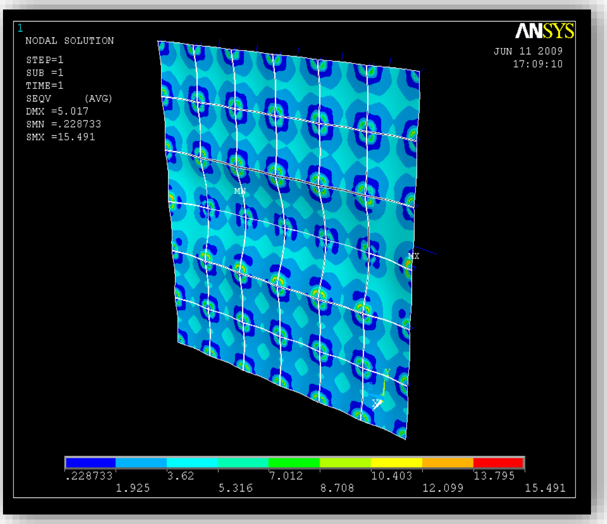

Figure 25. Stress distri. in panels*(low. temp)

Figure 26 shows maximal displacement (5mm) of the structure. Maximal displacement of panels is 3mm. The displacement at higher temperature is 4.8 mm and at lower temperature is 5mm. It looks contradictory, but there is logical explanation.

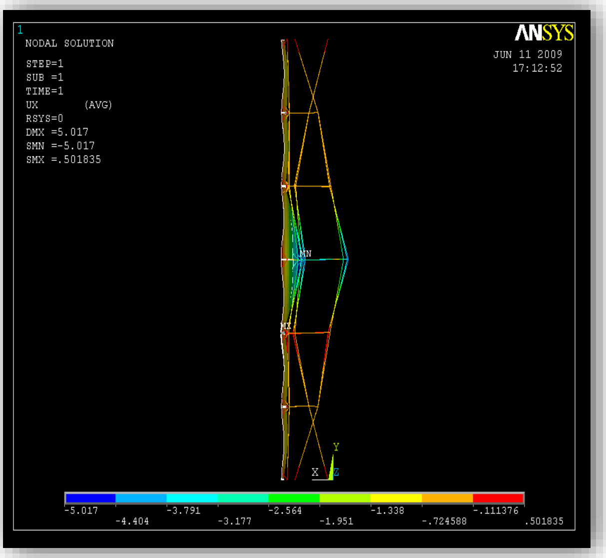

Figure 26. Total disp. in wind dir.*(low. temp)

Lower temperature causes shrinking of elements. Therefore, is affecting the arrows with higher compression force. This force is initiating deformation of the arrows and shifting the façade wall towards inside. This initial displacement is added on the total displacement with the wind load. At higher temperatures, initial displacement is in opposite direction, from the support structure towards the panels. In summer, total displacement is equal to absolute displacement from the wind minus initial displacement from the temperature.

CONCLUSION

Conclusion can be summarized as:

- TR-F and TR-B form arches that receive the wind force or force that comes from pressure difference between outside and inside of the building;
- HR elements work as horizontal stabilizers of the support structure and they take the lateral load which is in plane with the glass curtain wall;
- VR or DLR take dead load from the window panels and they should be set near the window in order to avoid the effect of bending.

All stresses in the support structure should be lower than the value 1/1.5 from the yield stress $R_{p0,2}$ in order to be on the save side; There should be minimum pre-tension at higher temperatures in the relaxed elements (i.e. arches) in order to prevent losing stability; The level of minimum pre-tension at full load should be subject for optimization.

Note: This paper is based on the paper presented at The 12th International Conference on Accomplishments in Electrical and Mechanical Engineering and Information Technology – DEMI 2015, organized by the University of Banja Luka, Faculty of Mechanical Engineering and Faculty of Electrical Engineering, in Banja Luka, BOSNIA & HERZEGOVINA (29th – 30th of May, 2015), referred here as [11].

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