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OPTIMAL DESIGN OF CURTAIN-WALL SYSTEMS

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ABSTRACT

Glass curtain-wall systems are nowadays extensively used in modern construction due to the fact that they can be manufactured as building façades to possess all those high efficiency properties prescribed by the designer; among these properties predominant role play the high strength-to-self-weight ratio, the serviceability requirements, the recyclability of the constituting parts, as well as transparency and the overall aesthetics characteristics. From a structural engineering standpoint, although usually curtain-wall systems are considered as secondary structural systems, their structural performance has to be meticulously analyzed and designed to fulfill modern Structural Codes requirements because they are in most cases subjected to strong environmental actions. The structural response of standard curtain-wall systems subjected to normative load combinations is numerically investigated within the Eurocodes framework. In addition, an optimal structural design of the glass curtain-wall system is carried out by applying advanced finite element analysis schemes and taking into account structural design principal criteria. The proposed optimal structural design approach leads to useful conclusive remarks for the selection of the basic structural members as well as the anchor details and the glass panels with reference to the dominating actions being the wind and the earthquake action. The proposed methodology is illustrated by means of a numerical application on a typical building façade case study.

1 INTRODUCTION

The structural system selection of building's construction members generally involves the choice of the lightest members of the most economical material, allowing the most efficient configuration that is appropriate to the anticipated loads [1]. The use of aluminium as the material of the main supporting system, the anchors or the brackets of the glass panels in curtain walls is a relative new, but efficient design solution. The efficiency of such a design solution is based on the similarity of the properties of the two materials, i.e. glass and aluminium, being the high strength to self-weight ratio, the resistance to corrosion, sustainability, recyclability, and transparency. As is well-known, a typical secondary structure in buildings that combines both aluminium and glass is the curtain wall system that provides all the required functions of an external wall that, however, usually does not contribute to the load bearing characteristics of the building structure. From the very beginning in 1960's, it was realized that a curtain wall system could enhance building's interior natural lighting and concurrently contribute to achieving an improved aesthetic exterior design. This means that curtain-wall principal structural mission is to isolate the interior of a building from the external environment and in particular, from the impact of the environmental actions. Having as scope the preliminary development of an optimal design approach to the main parts and brackets of curtain-wall systems, in the present paper a parametric study with respect to the critical curtain-wall design parameters is scheduled and carried out, whereas the respective results are discussed in details.

2 PERFORMANCE CRITERIA OF AN OPTIMAL CURTAIN WALL SYSTEM

2.1 Description of a typical curtain wall system

Designing structural glass systems three principal considerations have to be taken into account: performance, appearance and economy [9]. In curtain-wall systems, these requirements are tightly connected to the form and the position of the supporting metal structure and anchoring system to the building frame [4]. The curtain-wall system at hand is usually designed in a modular way consisting of a series of prefabricated aluminium profile components and connection brackets that support the glass panels (Figure 1).

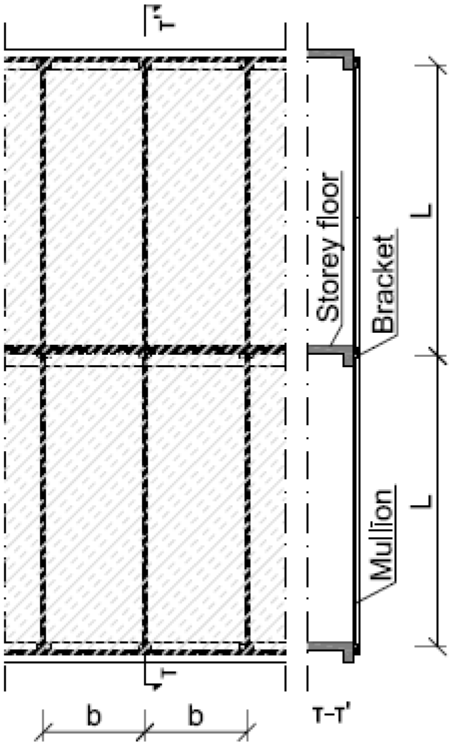

Figure 1. A typical structural form of a curtain wall system

The main vertical mullions often run along two subsequent storeys of the building exhibiting a static system of a member with two spans. Although these systems are secondary structures of the building, they have to be effectively designed to safely resist the variable actions of wind and thermal loads acting on the building façades. In addition, any other load combination case, as is e.g. seismic action, has to be also meticulously considered maximizing in this sense the structural safety and minimizing hazards for the human life.

The vertical members of a curtain-wall system are usually supported on each storey diaphragm members. This way, wind loads are smoothly transferred from the glass surface to the columns and from the columns to the diaphragm members through anchors/brackets. It is noteworthy that besides the wind load, the aluminium framework resists possible seismic actions. The seismic action is transferred to the system from the main building frame as a group of constrains acting on the supports. Taking the aforementioned needs for the building façade into account and targeting to the aluminium profiles optimization at different wind load zones, an approach considering as criteria both the Structural Codes curtain-wall strength and serviceability requirements and the minimization of the project cost is here proposed.

2.2 Performance criteria of curtain wall systems

Previous studies on the wind loading and building aerodynamics emphasized the significance of the distribution and the application of wind pressures on building façades [2], [5], [11]. Recent research efforts were focused on the safety and hazards due to seismic action on the nonstructural components in buildings, as are e.g. the façades systems [10]. The structural system performance analysed below have to satisfy the Ultimate and Serviceability Limit States design values provided by Structural Codes (cf. e.g. EN 1990 Basis of Structural Design) and EN 1999-1-1 (Design of aluminium structures)). With regard to the combination of the actions in an Ultimate Limit States design, the principal and the seismic load combination are both in sequence applied having as design target the maintenance of the von Mises stress σ_v under the limit of the ultimate f_u or the proof strength $f_{0,2}$ of the structural aluminium alloy used. As far as the Serviceability Limit state design concerns, the frequent load combination applies and the aluminium sections deformation has to be less than $u=L/250$.

3 FINETE ELEMENT ANALYSIS MODELLING

3.1 General Description of the Historic Bridge

For the purposes of the present study the analysis of a typical curtain-wall system performed led to the determination of the most critical parts of the system.

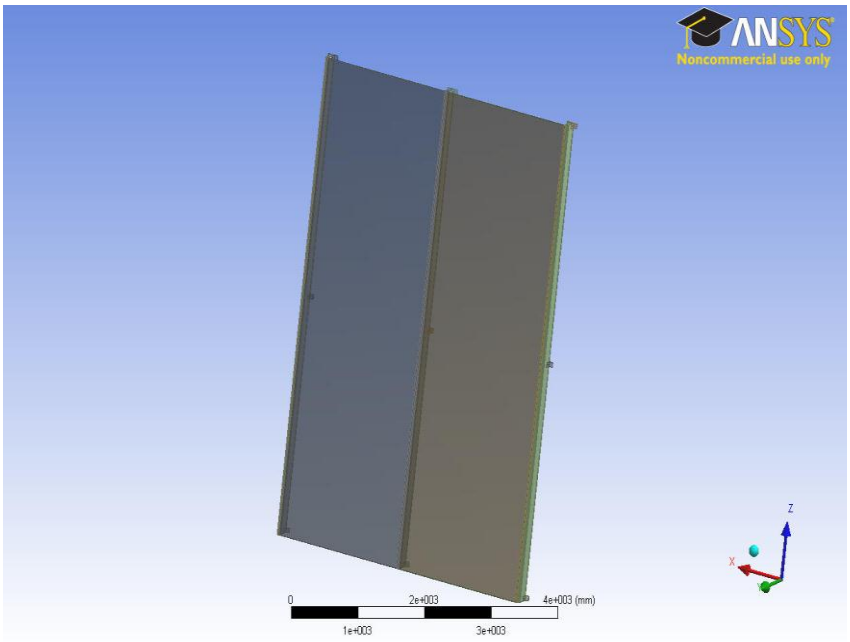

Figure 2. 3-D Finite Element Model of a curtain wall system

Figure 2 shows the FEM model used to simulate the structural response of a curtain-wall structural module. This model constitutes of a structural glass panel unit with double glazing that covers two continuous storeys of height h=3.0m. The glass is supported by an aluminium framework in a way that the vertical mullions are connected on three successive horizontal diaphragms (floors), so as to create a two span vertical static system. Along the horizontal axis, the overall model constitutes of three aluminium vertical mullions in a distance of b=2.00m between each two of them interconnected by aluminium horizontal beams (transoms) at every storey's diaphragm level. Each glass panel is attached to the vertical and horizontal elements of the previously described system. For the purpose of the present research effort, a 10-storey building with quadrilateral 30x20 m plan with curtain-walls attached to its façades has been considered.

On specific points along the mullions, brackets by bolts formed by double aluminium angles L have been attached to connect the overall system to the load-bearing building structure. Wind, seismic, thermal action and any other design load imposed on the building according to the limit design states are defined in accordance toEurocode standards. A proper assessment of the design loads and the subsequent analysis leads to an accurate estimation of the von Mises stress σ_v range, as well as the maximum deformations of the system.

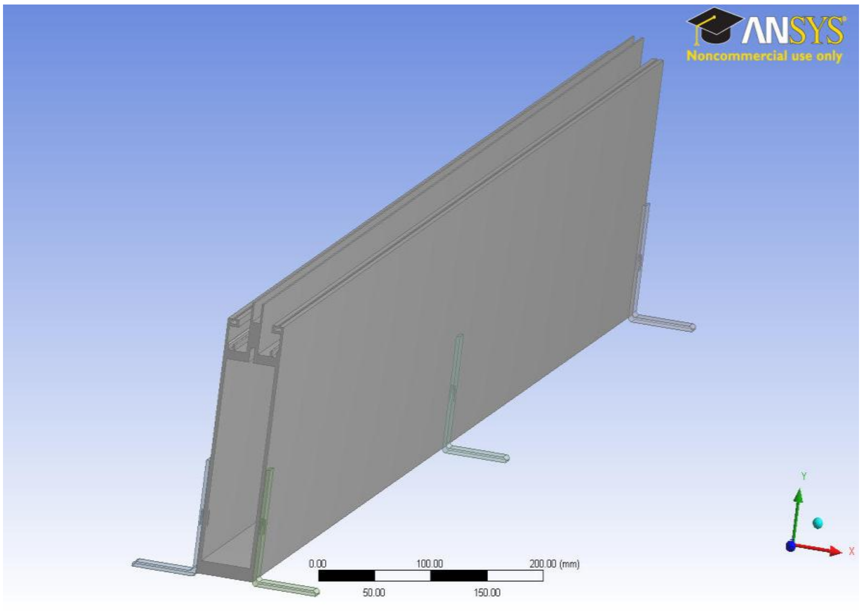

Figure 2. 3-D Finite Element Model for a single vertical mullion

The present analysis of the overall system, as well as this one of the independent parts of the structural details has been carried out by the ANSYS Workbench FEM software (Figure 3). The structural materials employed were aluminium and glass, whereas some special connection parts (bolts) were galvanized steel. The modulus of elasticity of aluminium is E=70000Mpa and its unit mass ρ=2700kgr/m^3. It is worthy to underline that the stress-strain curve of aluminium used in order to describe the material characteristics highly depends on the alloy and the treatment employed. For the present application at hand, structural aluminium alloy EN AW 6060 has been herein selected. The actual 0.2% proof stress ($f_{0.2}$ proof strength) corresponds to a value of plastic strain equal to 0.002. Obviously, the glass structural behavior has been considered as brittle and exclusively linear elastic, with its modulus of elasticity equal to E=70000Mpa and with density ρ=2700kgr/m^3.

3.2 Action analysis and verification of dominating limit cases

As far as combination of actions concerns, it should be underlined that several combinations for different limit states of the permanent actions G_k (self-weight etc.), variable loads Q_k (wind pressure w, thermal action T_k, etc.) and seismic action A_{Ed} have been applied. The leading variable action for these design situations is always the wind pressure w acting on the glass surface of the building façade. The design values of the wind pressure w on the structural model varied depending on the installation height (estimation of the peak velocity pressure $q_{p(Ze)}$) and the corresponding external pressure coefficient c_{pe} for the different discrete areas of the windward side of the building..

In the combination of actions for seismic design states, the partial factor ψ_2 for quasi-permanent variable actions as is the dominating action of wind pressure w might be zero in accordance to the Annex A of EN 1990. For the present research purpose, the value of the partial factor $\psi 1=0.2$ for the leading variable action (wind) during a possible seismic design state at this secondary structure has been introduced. Moreover, as has been already mentioned, analysis of certain critical independent parts of the system (cf. e.g.aluminium mullions, brackets (angle connections with galvanized steel bolts)), are in the sequel performed so that more accurate results on the behavior of the curtain-wall system to be obtained. The software used automatically formulates the self-weight of the structural components by using the density of aluminium and glass, whereas the variable surface loads are applied as pressure distribution on the glass panels of the curtain-wall model.

4 PARAMETRIC CASE STUDY

4.1 Building case study

In order to find an optimisation mechanism to the design procedure, a parametric study has been applied for the main components of the curtain-wall system by using comparison tables and evaluation diagrams. This procedure includes an estimation of cross-section requirements for the critical members of the structural system at distinct loading areas of the building façade (Figure 3), as well as a comparison of different cross-section thickness approaches for a critical member at a given area (Figure 4) or of optimal thickness for distinct loading areas (Figure 5).

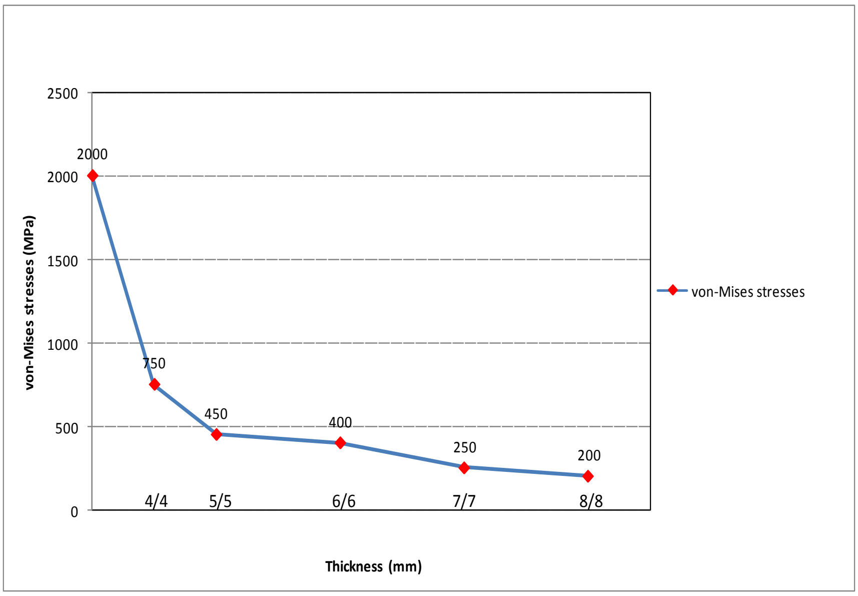

Figure 3. On the minimization of the cross-section thickness for a typical connection bracket

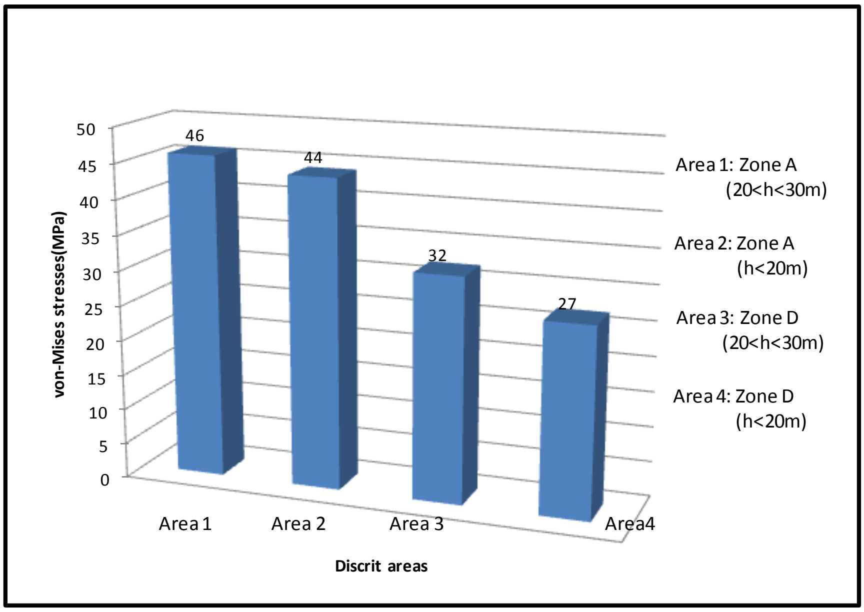

Figure 4. Connection bracket's Von Mises Stress distribution for different loaded areas of the building

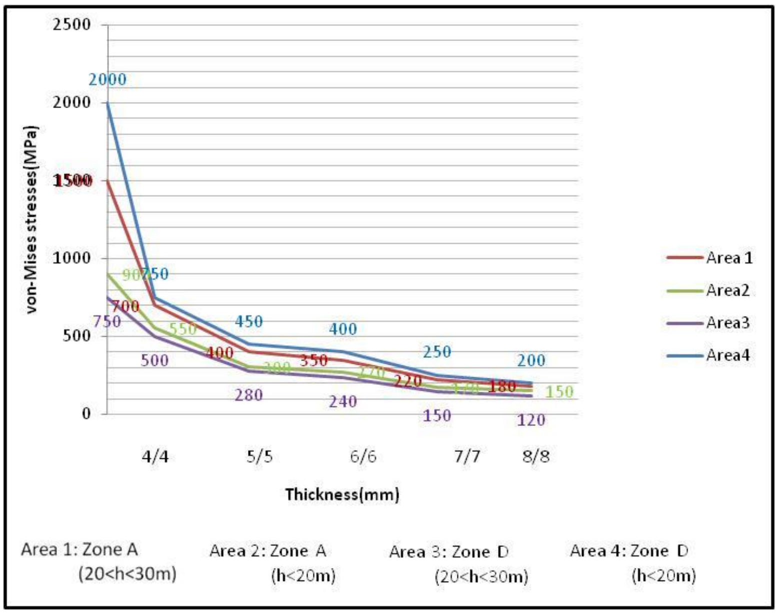

Figure 5. Comparison of the optimal thickness results for distinct loading areas

4.2 Evaluation of results

The evaluation of structural analysis results where the dominating variable action of a loading state is a variation of the temperature T_k or the critical value of the wind load w, leads to an optimal bearing capacity of the system. This evaluation includes the main components of the structural system (mullions and transoms), as well as the bracket systems.

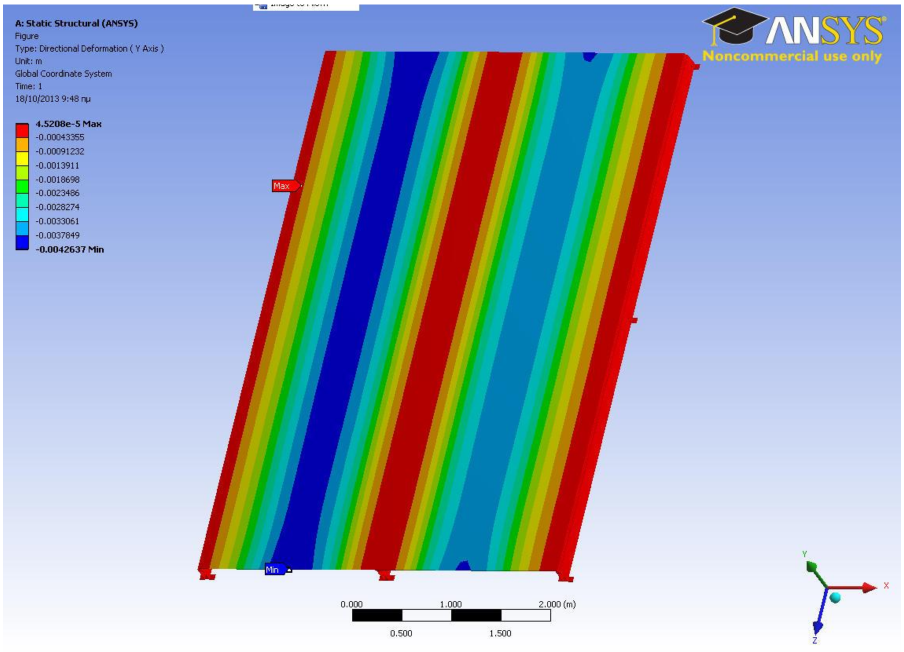

Figure 6 Distribution of deflections of the curtain-wall model for critical wind loading

As is shown in Figure 6, the deformation of the glass panel is greater during certain load combination (cf. e.g. self-weight, wind and the least possible temperature (-20°C)), a fact that is reasonable because during low temperatures glass panels tend to contract having as result to bend towards the negative values of y axis. The wind loading is imposed along the same direction and consequently, the two aforementioned actions are added. In contrast, during high temperatures, the glass panel tends to expand having as result bending towards the positive values of y axis and therefore, the result of the latter action is subtracted from the rest ones.

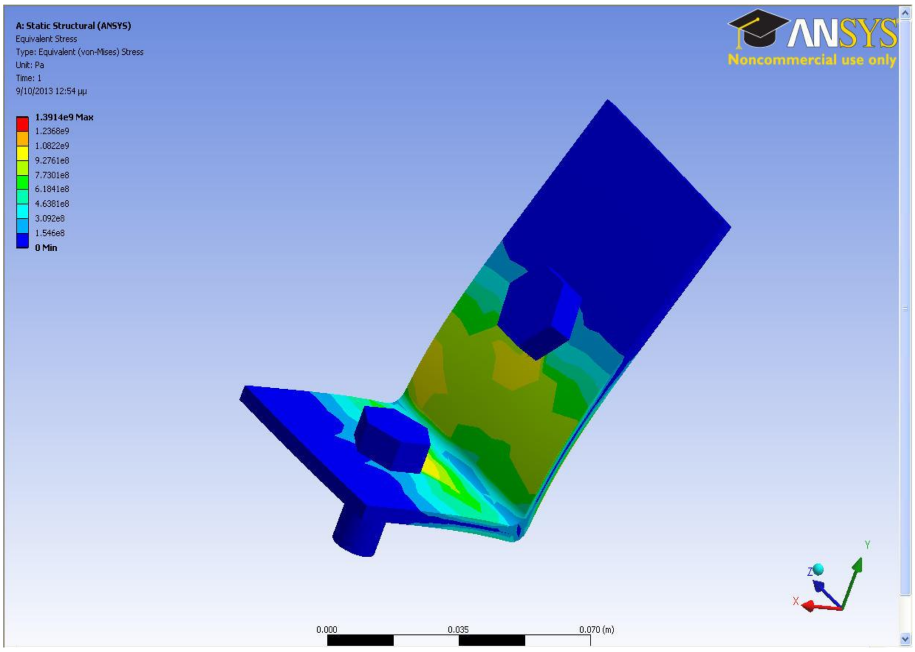

Figure 7. Connection bracket's Von Mises Stress distribution

The most critical design state, in particular for the bracket systems, is the seismic design one with the direction of the seismic action parallel to the glass surface. This state includes a participation of the wind pressure w multiplied by the frequent value coefficient and leads to a von Mises stresses σ_v range exhibiting its maximum on the basis of the mullion due to the local support conditions.

As shown in Figure 7, certain L-shape brackets at the extreme loading areas of the building fail exactly under this specific critical seismic loading. The present approach includes a plethora of tests in structural models with various cross-section dimensions of the principal structural members. The results of the comparative analysis shown in Figure 8 shows that the von Mises stress values decrease as the thickness of an angle bracket increases appropriately. For comparison reasons, the structural model consists of equal cross-sectional thickness on both sides of the angle bracket.

On the other side, an optimal strengthening design for curtain-walls has been attempted, e.g. the strengthening by increasing the number of double-angle parts in each bracket (e.g. two or even three double-angle constituents instead of one). A comparative analysis shows clearly that the von Mises stresses decrease as the number of double-angle (L) parts increase. Similar examples show that reducing the height of the mullion profile from 200mm to 180,160,140 and 120mm respectively as depicted (Figure 9) the von Mises stresses increase beneath the specified limits.

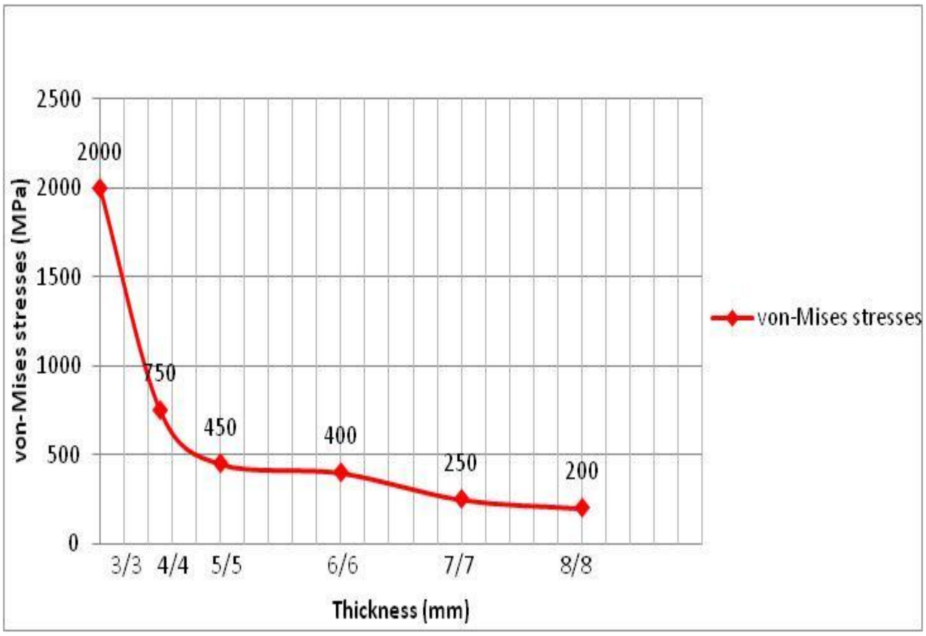

Figure 8. Decrease of the von Mises stress due to the increase of thickness in an angle bracket

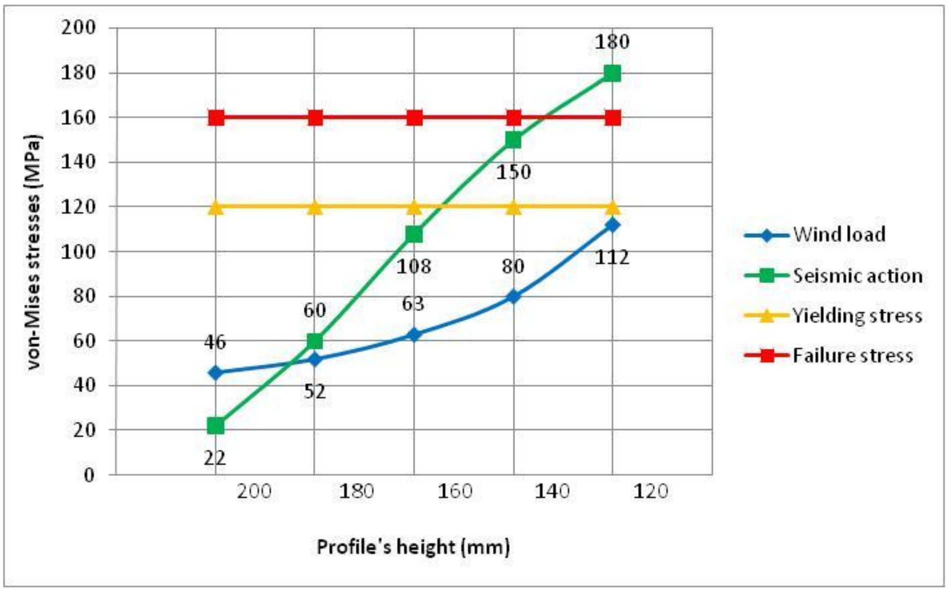

Figure 9. Increase of von Mises stress due to the decrease in cross-section dimensions

5 CONCLUSIONS

Since their appearance glass-aluminium façades used to be designed empirically, whereas only recently relevant standards were developed e.g. EN 13830 (Curtain walling – Product standard, 2003). The proposed approach intends to contribute to these efforts by providing the engineers with an effective technique and the respective insight to optimise the design of glass-aluminium façades regarding their structural performance. To this end, different analysis models have been developed and relevant graphs have been obtained in order to achieve the previously mentioned objective [3], [8].

The analysis and the respective comparative studies confirm a discrepancy between the results of previous research and the present one. From the latter, it is obvious that in highly seismic regions, the structural analysis of curtain-wall systems should always take into consideration the seismic action. A comparison between the ultimate design state with dominating variable action this one of wind and the critical seismic design state that includes the frequent value of the wind pressure shows that seismic action might cause undesirable damage in the anchoring system of the curtain-wall. In this sense, structural analysis based on the EN 1998-1 §4.4.3.2 is more critical than the analysis based on EN13830 for a typical glass-aluminium system.

High strength glass should be used along with an optimal design of the structural elements and details to sustain extreme environmental actions. Moreover, rubber materials should be used at the interface between the glass surface and the aluminium mullion to absorb a part of the energy transfer and reduce dynamic effects. The latter details together with the optimal curtain-wall design could be thus used to improve the robustness of the curtain-wall system.

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