Optimal structural design of glass curtain-wall systems

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Glass curtain-wall systems are extensively used in modern construction. They can be manufactured as building facades with high-efficiency properties prescribed by the designer; among these properties, the most important are high strength-to-self-weight ratio, serviceability requirements, recyclability of the constituent parts, as well as transparency and overall aesthetic characteristics. The structural performance of curtain-wall systems has to be meticulously analysed and designed to fulfil structural Eurocodes requirements because facades are, in most cases, subjected to strong environmental actions. In addition, as a second design step, by applying advanced finite-element analysis schemes and taking into account structural design criteria, an optimal structural design of the glass curtain-wall system has to be carried out to achieve cost minimisation once structural integrity and serviceability requirements have been fulfilled. The optimal structural design approach proposed in this paper leads to significant conclusions that can be used for the selection of mullions, transoms, anchoring details and glass panels with reference to the predominant environmental actions of wind and earthquake. The proposed methodology is illustrated by means of a numerical application to a typical building facade case study.

Notation

A_{Ed}	seismic action
b	distance between vertical mullions
c_{pe}	external pressure coefficient
d_t	inter-storey drift
E	modulus of elasticity
f	strength of aluminium alloy
G_k	permanent action
h	storey height
L	characteristic length of structural member
Q_k	variable action
$q_{p(Ze)}$	peak velocity pressure
T_k	thermal action
t	thickness of structural element
u	out-of-plane deflection of structural member
v	reduction factor
v_m	mean wind velocity
w	wind pressure acting on surface of building facade
ρ	unit mass of a material
σ_v	von Mises stress
ψ_{0i}	partial factor of a variable action

1. Introduction

The structural system selection of a building's construction members generally involves the choice of the lightest members composed of the most economical material, allowing the most efficient configuration that is appropriate to the anticipated loads (Ali and Armstrong, 2006). 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 relatively new but efficient design solution. The efficiency of such a design solution is based on the similar properties of the two materials, namely the glass and aluminium, which have similar high strength to self-weight ratio, resistance to corrosion, sustainability, recyclability and transparency.   Q2

The curtain-wall system is a typical secondary structure in buildings, and combines aluminium and glass. This system provides all the required functions of an external wall that usually does not contribute to the load-bearing characteristics of the building structure. From the 1960s, it was realised that a curtain-wall system could enhance a building's interior natural lighting and concurrently contribute to achieving an improved aesthetic exterior design. This means that the principal structural mission of a curtain wall is to isolate the interior of a building from the external environment and, in particular, from the impact of environmental actions. Although various researchers have addressed certain aspects of curtain walls, none has incorporated the concurrent action of wind and seismic actions. The scope of the present paper is the preliminary development of an optimal design approach for the main parts and brackets of curtain-wall systems in an analysis based on the simultaneous action of high winds and earthquake. In addition, a parametric study with respect to the critical curtain-wall design parameters is carried out. The respective results are discussed in detail.

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2. Description of optimal curtain-wall systems and performance criteria

According to Overend (2005), when designing structural glass systems three principal considerations have to be taken into account: performance, appearance and economy. In curtain-wall systems, these requirements are closely connected to the form and the position of the supporting metal structure and anchoring system to the building frame. The curtain-wall system 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). 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 facades. In addition, any other load combination case, such as seismic action, should be meticulously considered to maximise the structural safety and minimise any hazards presented to humans.

The vertical members of a curtain-wall system are usually supported on each storey's diaphragm members. In 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 worth noting that, in addition to 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 constraints acting on the supports. An approach considering both the structural codes' specifications for curtain-wall strength and serviceability requirements and the minimisation of the project cost is here proposed, taking into account the aforementioned needs for the building facade and targeting aluminium profile optimisation at different wind load zones.

Previous studies on wind loading and building aerodynamics have emphasised the significance of the distribution and the application of wind pressures on building facades (Baniotopoulos and Stathopoulos, 2007). Recent research efforts have focused on safety and hazards attributable to seismic action with respect to the non-structural components in buildings, such as the facades systems (Palermo *et al.*, 2010). The structural system's performance analysed below must satisfy the ultimate and serviceability limit states design values provided by structural codes (e.g. EN 1990: Basis of **Q3** structural design) and EN 1999-1-1 (BSI, 2000) (relating to the 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 applied in sequence with a design target of the maintenance of the von Mises stress σ_v under the limit of the ultimate f_u or the proof strength $f_{0\cdot2}$ of the structural aluminium alloy used, where f_u is the ultimate tensile strength of the alloy. When considering the serviceability limit state design, the frequent load combination applies and the aluminium section's deformation must be less than $u = L/250$, where u is the mid-span deflection and L is the total length of the member.

3. Structural analysis modelling

3.1 Finite-element model and related issues

For the purposes of the present study, conducting an analysis of a typical curtain-wall system led to the determination of the most critical parts of the system. Figure 2 shows the finite-element model used to simulate the structural response of a curtain-wall structural module. This model consists of a structural glass panel unit with double glazing that covers two continuous storeys of height $h = 3 \cdot 0$ m. The glass is supported by an aluminium framework, such that the vertical mullions are connected on three successive horizontal diaphragms (floors), to create a two-span vertical static system (Figure 3). Along the horizontal axis, the overall model consists of three aluminium vertical mullions positioned at a distance of $b = 2 \cdot 00$ m from each other, and interconnected by aluminium horizontal beams (transoms) at each 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 ten-storey building with quadrilateral 30×20 m plan, with curtain walls attached to its facades, has been considered using a structural analysis based on EN 13830 (BSI, 2003) for a typical glass–aluminium system.

At specific points along the mullions, bolted brackets formed by double aluminium L-shaped angles have been attached to **Q4**
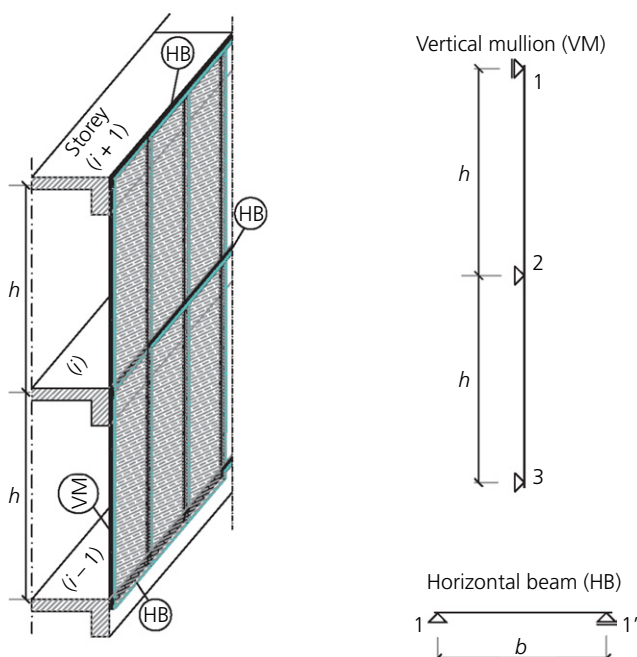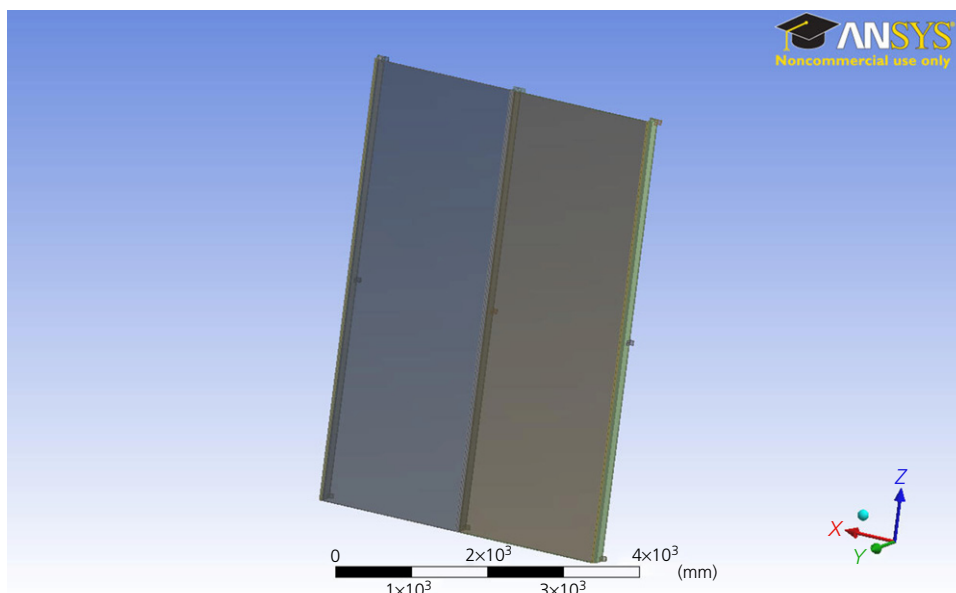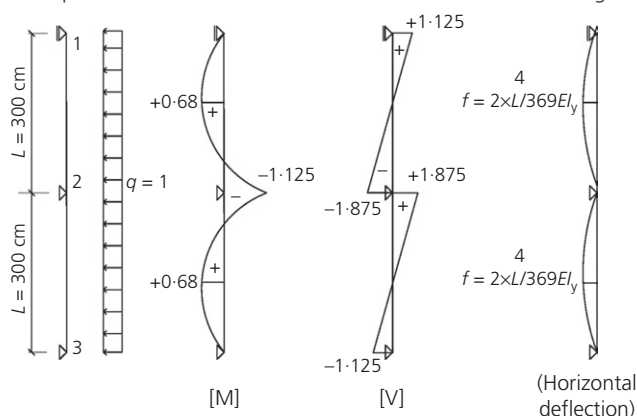

Figure 1. A typical module of the curtain-wall system

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Figure 2. Finite-element model of the module of a curtain-wall
structural system

Two-span vertical mullion with transversal unit distributed loading

Figure 3. Two-span vertical static system of mullion

connect the overall system to the load-bearing building struc-
ture. Wind, seismic, thermal actions and any other design load
imposed on the building according to the limit design states
are defined in accordance with Eurocode standards. A proper
assessment of the design loads and the subsequent analysis
leads to an accurate estimation of the range of von Mises
stress, σ_v, as well as the maximum deformations of the system.

The present analysis of the overall system, as well as the analysis
of the independent parts of the structural system, was carried
out using the Ansys Workbench finite-element method software.
The structural materials employed were aluminium and glass,
whereas some special connection parts (bolts) were made of
galvanised steel. The modulus of elasticity of aluminium is
$E = 70\ 000$ N/mm^2 and its unit mass, $\rho = 2700$ kg/m^3. It is **Q5**
worth emphasising that the stress–strain curve of aluminium
used to describe the material characteristics depends greatly on
the specific alloy and the treatment employed. For the present
application, structural aluminium alloy EN AW-6060 ET,EP,
ER/B T5 ($t \leq 5$ mm, $f_{0.2} = 120$ N/mm^2, $f_u = 150$ N/mm^2, mini-
mum elongation $A = 8\%$, $f_{HAZ} = 50$ N/mm^2, $f_{HAZ} = 80$ N/mm^2)
has been selected. The actual 0.2% proof strength ($f_{0.2}$ proof
strength) corresponds to a value of plastic strain equal to 0.002.
The glass structural behaviour has been considered as brittle
and exclusively linear elastic, where its modulus of elasticity is
approximately $E = 71\ 700$ N/mm^2, almost the same as for alu-
minium, and its unit mass is $\rho = 2530$ kg/m^3, which is slightly
less than for aluminium.

3.2   Verification of actions and dominant design states
In relation to the combination of actions, it should be empha-
sised that several combinations for different limit states of the
permanent actions, G_k (self-weight and so on), variable loads,
Q_k (wind pressure, w, thermal action, T_k, and so on), 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 facade. The
design values of the wind pressure, w, on the surface of the
structural model varied depending on the installation height
(estimation of the peak velocity pressure, $q_{p(Ze)}$) and the corre-
sponding external pressure coefficient, c_{pe}, for the different
discrete areas of the windward side of the building. The peak

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velocity pressure can be calculated based on paragraph 4·2 of EN 1991-1-4 using a mean wind velocity with a value of $v_m = 27$ m/s. The corresponding external pressure coefficient is dependent on the size of the wind-loaded area and can be calculated according to paragraph 7·2 of EN 1991-1-4. In this analysis, the estimation of the most representative wind-loading areas (area 1 to area 4) of the building facade is based on the calculation of the critical wind pressure, $w_{AREA(i)} = q_{p(z)} \cdot c_{pe}$, with respect to the distinct areas A, B or C of the facade and to the reference height above ground level, z_e, of the structural module.

Q6 In the combination of actions for seismic design states, the partial factor, ψ_{02}, is used for quasi-permanent variable actions as the dominating action of wind pressure w might be zero in accordance with the Annex A of EN 1990. For the purposes of the present research, the value of the partial factor $\psi_{01} = 0·2$ has been introduced as a frequent variable action for the wind action during a possible seismic design state on this secondary structure. The limitation of inter-storey drift, d_t, is based on: (*a*) EN 1998-1, section 4·4·3·2, for ductile non-structural elements attached to the building, with a limit of $d_t = 0·0075h/v$; (*b*) the default value of Annex XX of EN 13830 (BSI, 2003) with a limit of $d_t = 0·005h/v$, where h is the typical storey height and v is the reduction factor.

As has been already mentioned, analysis of certain critical independent parts of the system such as aluminium mullions and brackets (angled aluminium connections with galvanised steel bolts) is performed in the following section. It is speculated that, in this way, more accurate results regarding the structural behaviour of the system can be extrapolated, because the high computational demands of full-scale curtain-wall models can potentially cause numerical instabilities. 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 analysis

To discover an optimisation mechanism for 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 the four distinct wind-loading areas (Figure 4). Also included is a comparison of different cross-sectional thickness approaches for a critical angle bracket, bolted both on the mullion and the building, for the system at a given area (Figure 5), or of optimal thickness for distinct loading areas (Figure 6).

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. As shown in Figure 7, the deformation of the glass panel is greater during the load combination of self-weight, wind
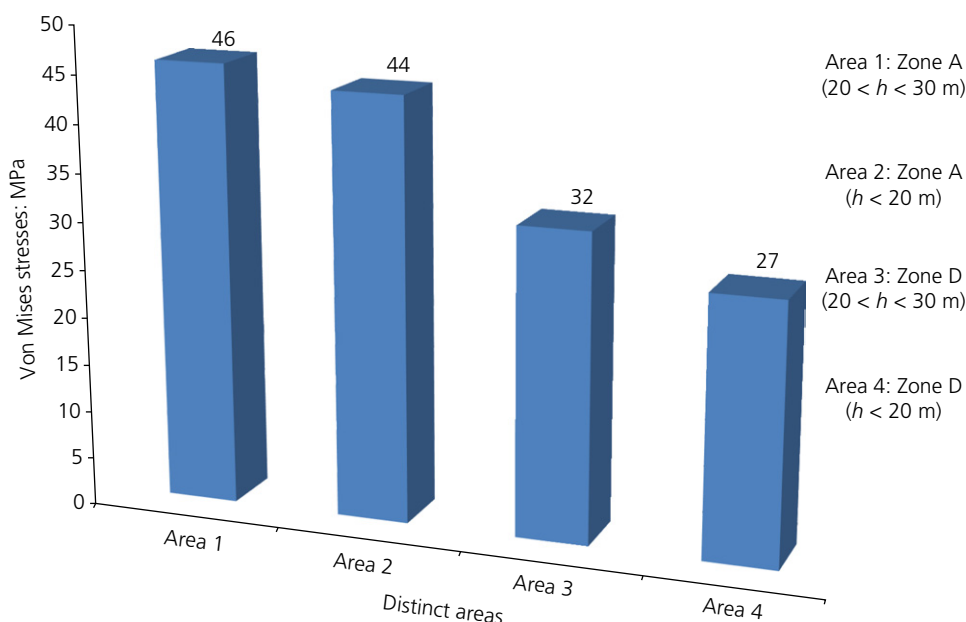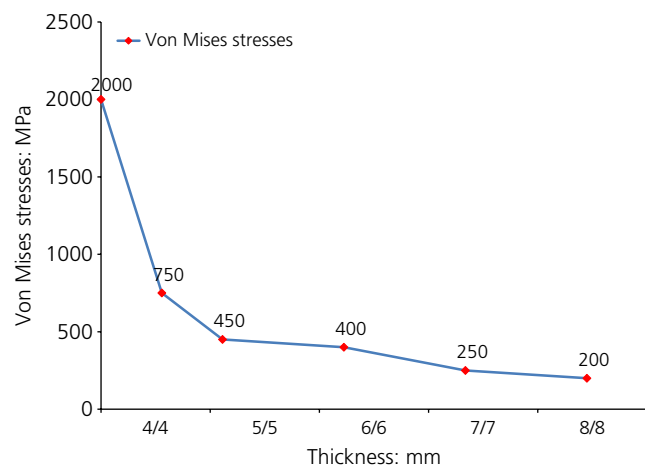

**Figure 4.** Von Mises stress distribution on mullions at distinct facade areas

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Figure 5. Minimisation of the cross-sectional thickness (in mm) for a typical bracket

Figure 6. Comparison of the results for optimal thickness of a bracket within distinct loading areas

and the least possible temperature (−20°C) than the same combination with the maximum possible temperature. This fact seems reasonable because, during low temperatures, glass panels tend to contract, with the result that they bend towards the negative values of the y axis, as shown in Figure 7. The wind loading is imposed along the direction of the aforementioned deflection (negative values of y axis) and, consequently, the wind action is added to the negative temperature action. In contrast, during high temperatures, the glass panel tends to expand, with the result that it bends towards the positive values of the y axis and, therefore, the result of the latter action is subtracted from the wind action.

The most critical design state, in particular for the bracket systems, is the seismic design condition where the critical direction of the seismic action is parallel to the glass surface. This design state includes combinations, with participation of the wind pressure, w, on the external surfaces of the building (as a frequent variable action). This analysis leads to a range of von Mises stresses, σ_v, which exhibits its maximum near the lower support of the mullion owing to the inter-storey drift during the seismic event. As shown in Figure 8, certain L-shaped brackets at the extreme loading areas of the building fail exactly under this specific critical seismic loading, as can be seen by the value of the von Misses stresses that are well above the ultimate strength of the alloy.

The present approach includes a plethora of analyses in structural models with various cross-sectional dimensions of the principal structural members. The results of the comparative analysis shown (Figure 9) reveal the von Mises stress values of the critical double-angle bracket of the system. For the purpose of comparison, the structural model consists of equal cross-sectional thickness on both sides of the angle bracket.
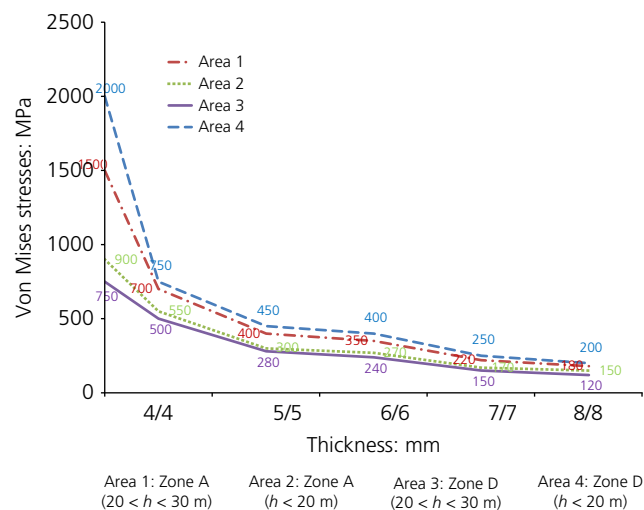
On the other side, an optimal strengthening design for curtain **Q7** walls has been attempted, for example, strengthening by increasing the number of double-angle parts in each bracket (e.g. two or even three double-angle constituents instead of one). The comparative analysis (Figure 10) shows clearly that the stresses of the critical bracket (von Mises stresses) decrease as the number of double-angle (L-shaped) parts increases. Similar examples show that, when reducing the height of the mullion profile from 200 mm to 180, 160, 140 and 120 mm, as depicted in Figure 11, the von Mises stresses increase to exceed the specified limits.

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 thus be used to improve the robustness of a curtain-wall system.

5.   Conclusions

Since the inception of glass–aluminium facades, they have tended to be designed empirically, and only recently have relevant standards been developed, such as EN 13830 (BSI, 2003). The approach proposed in this paper is intended to contribute to these efforts by providing engineers with an effective technique and relevant insight to optimise the design of glass–aluminium facades in terms of their structural performance. To this end, different analysis models have been developed and relevant graphs have been obtained and presented.

The analysis and the respective comparative studies confirm a discrepancy between the results of previous research and those

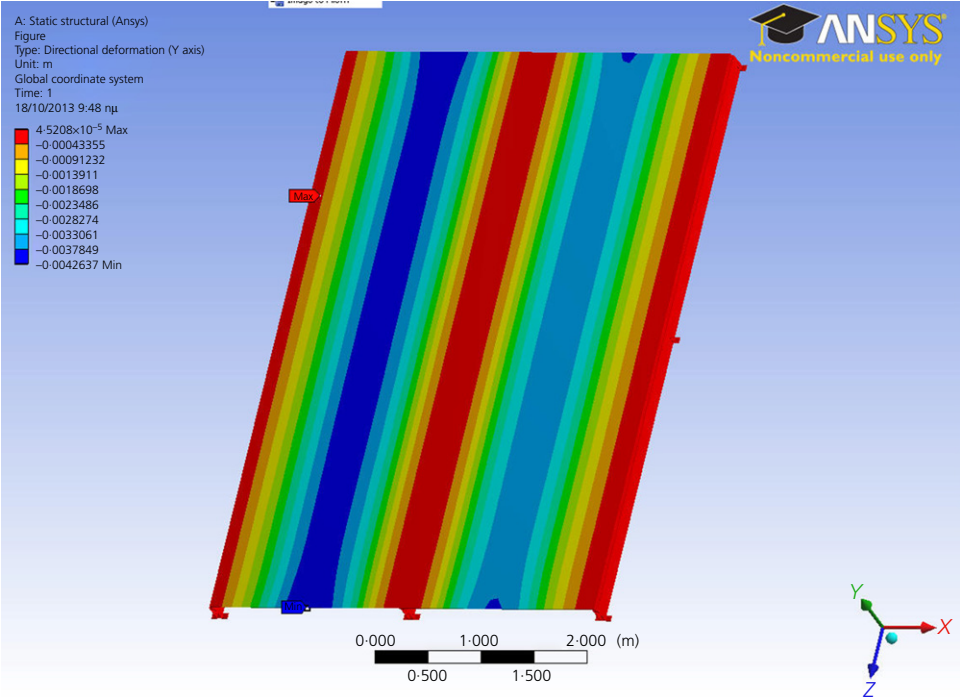**Structures and Buildings**
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Figure 7. Distribution of deflections of curtain-wall module
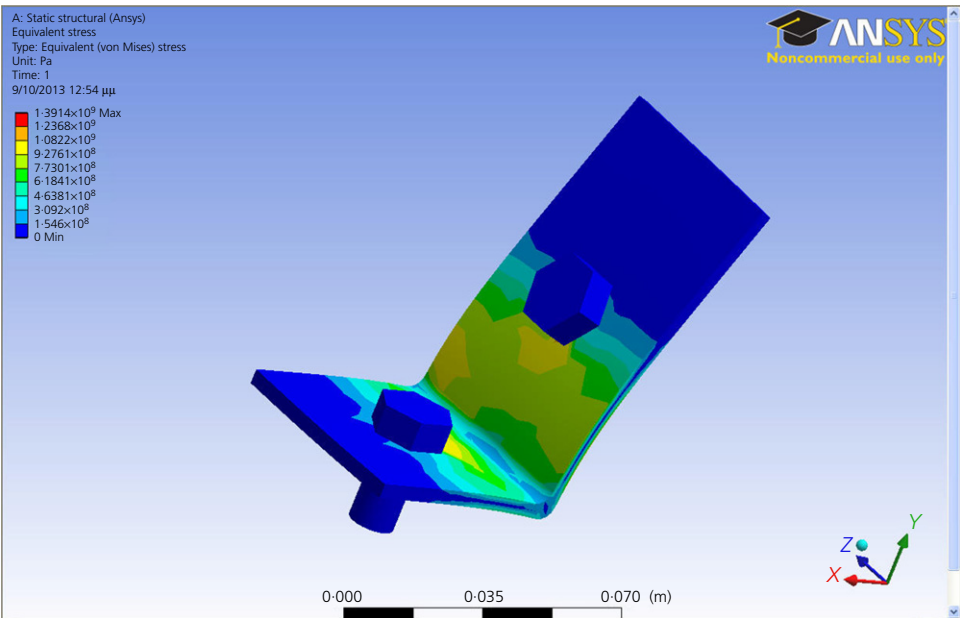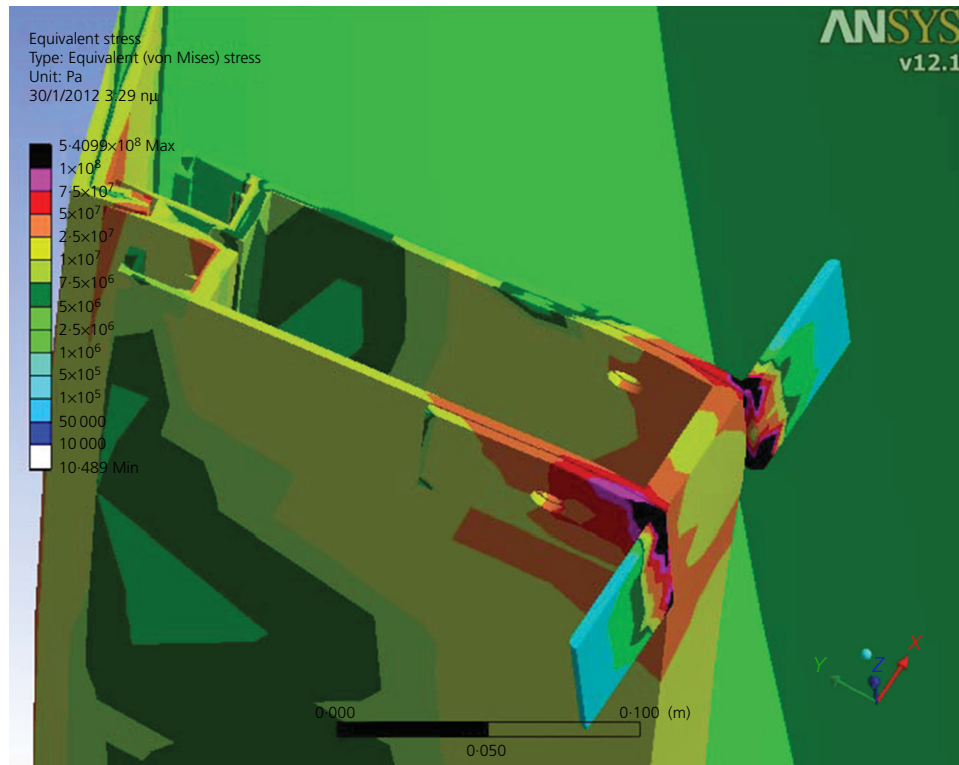corresponding to critical wind loading

**Figure 8.** Critical von Mises stress distribution on a typical angle
bracket

of the present study. 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, in this case wind, and the critical seismic design state which includes the frequent value of the

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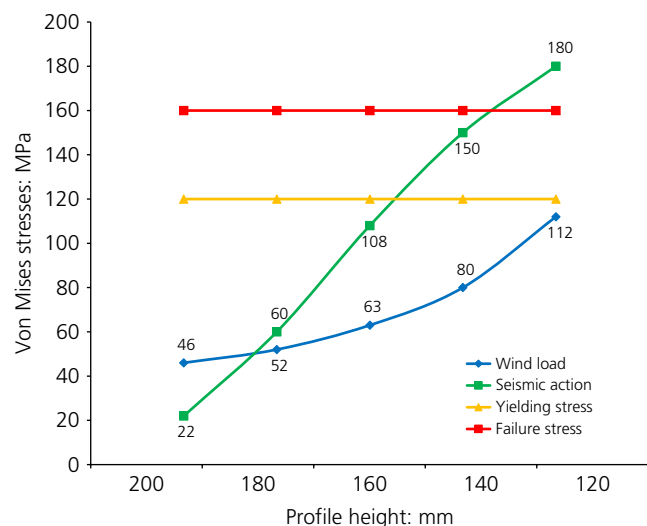Baniotopoulos, Nikolaidis and Moutsanidis

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Figure 9. Complex finite-element model. Stress distribution on
the double-angles of a critical bracket
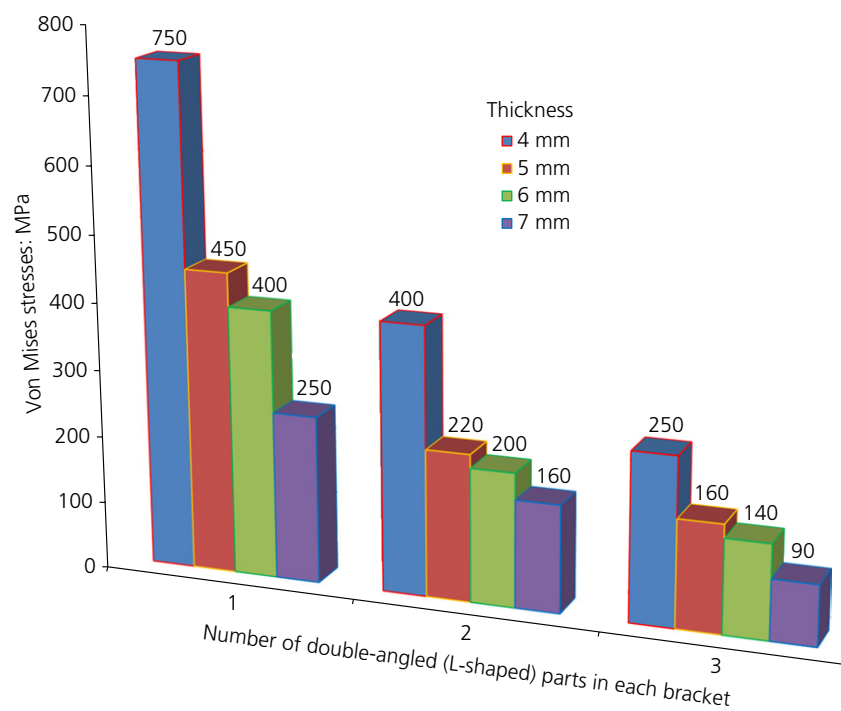
Figure 10. Decrease of von Mises stress due to increase of the
number of angle brackets

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Figure 11. Increase of von Mises stress due to decrease in cross-sectional dimensions

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 EN 1998-1, section 4·4·3·2 limits is more critical than analysis based on Annex XX of EN 13830 (BSI, 2003) default limits, for a typical glass–aluminium system. High-strength glass should be used along with an optimal design of the structure to withstand extreme environmental and accidental actions.

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Q3	Is a specific reference needed for EN 1990?	
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