Building information modelling design and analysis of glass structures

C Popa*

1 Technical University of Civil Engineering Bucharest, Romania

* E-mail: ciprian.popa@allbim.net

Abstract. The present article describes the importance of analysing, designing and maintenance of glass structures. Building Information Modelling is a work method that covers the entire lifecycle of a building by centralizing all the information inside a unique 3D model. Glass structures are a special case where precision and proper maintenance are vital for ensuring safe and economic exploitation. The article also illustrates a practical example of designing and maintaining a glass structure using different software solutions available on the market.

1. Introduction
Glass structures are special, and to most of the public they can generate fear and doubt regarding the safety they offer. There are many impressive glass structures in the world, having different sizes and functionalities. Most of them are designed in non-seismic areas, but in some areas such as Romania, an earthquake can be an additional source of fear when being inside a glass structure (figure 1), crossing a glass bridge (figure 2), or just swimming to an apartment situated across the street (figure 3). This article describes three different approaches when designing Glass Structures in Seismic Areas and also discusses a practical case study.

The case study presents the reactions and deflections a glass cube structure gets from horizontal forces, generated by wind loads in comparison to those that are generated by a typical Romanian Earthquake in Bucharest. The structure is the entrance to Apple Store, located in NY, USA, but the actions are evaluated as if this structure were located in Bucharest Centre. In figure 4 we can see a...
simulation in Google Earth of the Location of a Glass Cube Structure in Bucharest.

2. Seismic design approaches for glass structures
In seismic areas, seismic actions have to be taken into account, as experience shows that the collapse of a glass element, whether it is a primary or secondary structural component, may result in a high number of deaths and injuries. Eurocode 1998-1 offers the combination rules for combining seismic loads with other permanent and live loads. ULS verification will include the effects of gravitational and climatic loads from combinations according to equation 6.10 and equation 6.12. [4].

When designing structural glass elements, three distinct situations can be identified:
- earthquake resisting elements made entirely of glass;
- structural elements made with glass and other materials which possess certain ductility;
- glass elements that are not part of the earthquake resisting structure, they are not loaded with horizontal force, but they are relevant for the inhabitants’ safety (ex. Interior wall panels, edge curtain walls).

2.1. Earthquake resistant glass elements
The first category of elements will be designed according to 5.5.2.1 of EN 1990, to withstand the design seismic force without any damage (ex: cracking), for the EN Seismic Combination 6.4.3.4 of EN 1990). The seismic force will be evaluated according to EN 1998, assuming a behaviour factor of q=1. By using this elastic design approach, structural integrity is assured even after the seismic event.

According to Eurocode 8, the design seismic action for the no-collapse requirement is calibrated for a reference probability of more than 2% within the reference return period.

The structures for which earthquake resisting structure include glass elements and other materials will be designed so that the evaluated stresses will not cause cracking for the reference seismic action, in design combination with the other actions according to 6.4.3.4 of EN 1990.

The ULS check for the primary seismic-bearing elements must consider the contribution given by the glass structure to the seismic action resisting system considering a non-ductile behaviour. The glass structure may be part of the lateral and vertical force, but it cannot be part of the energy-dissipation systems.

The ULS checks will be based on linear analysis with energy behaviour factor q=1 (no energy
dissipation and no ductility). A primary seismic member and its connections must be designed and detailed to support loads for the whole structure and from other elements (of superior order), in addition to its self-weight and out-of-plan load, when subjected to displacements caused by the most unfavourable seismic design scenario.

Also, glass structural members that do not pertain to an earthquake resisting structure, but are relevant for the inhabitants’ safety, shall withstand without collapse the calculated stresses generated by the reference seismic action.

2.2 Structural elements made with glass and ductile materials
If the resisting structure for earthquakes includes a dissipative system (e.g. a hybrid seismic structure composed of the glass system and another material, like RC (reinforced concrete) or a steel frame), the design should follow the principles of Capacity Design (Hierarchy of Resistance). Failure of the glass system is only accepted for displacements greater than the ones produced by the seismic action correspondent to the no-collapse requirement. The hierarchy of resistance aims at ensuring an overall dissipative and ductile behaviour, as it is specific for structures made from different materials than glass. Additionally, the hierarchy of resistance aims at avoiding brittle failure and unstable mechanisms formed prematurely. To achieve this, the capacity design procedure will be adopted, which is used to obtain the hierarchy of resistance for the different structural elements and choosing failure modes that guarantee a favourable plastic mechanism and avoiding brittle failure modes.

The connection for the primary seismic loaded members shall be designed and checked with the seismic action associated with the no-collapse requirement. The check has to consider both relative displacements and internal stresses.

According to the French Technical Recommendation “Preposition de fische (CSTB et SNFA)” [5]:
“Seismic action is divided in two types of solicitations: a dynamic solicitation due to ground movement and a static deformation induced by building floor drift. The amplitude of calculated action depends on building importance, type of ground and seismicity region. In France, the application of seismic regulations based on Eurocode 8 led to recommendations on façade conception and dimensioning. The validation criterion has been chosen as no elements fall, with performance conservation for important buildings (hospitals, firehouses…). The experimental tests carried out on glass façades (curtain walls and structural glazing kit) showed a large elastic deformability of the metallic frame under dynamic solicitation (succession of increasing accelerations until 16 m/s² at different frequencies between 1 and 15 Hz applied on a 3 m x 3 m mock-up) inducing few systems degradations. Degradations have been observed during floor drifting (static cyclic increasing displacement until 60 mm at the head of a 3 m x 3 m mock-up) with glass breakage. Recommendations concern calculation of anchoring to the structure, dimensioning of metallic frame, type of glass to use.”

2.3 Glass elements that are not part of the earthquake resisting structure
When modelling an entire building, the strength and stiffness of the secondary elements is neglected, considering that in case of their failure, the ultimate resistance of the main structural system can guarantee the building’s integrity and safety. Special considerations have to be made when dealing with lateral forces generated from seismic actions. In some situations, the in-plane stiffness provided by secondary elements can have a significant contribution to the inter-story lateral stiffness, even if, due to the lack of ductility, no allowance is actually given to including such stiffness in the calculation model [6].

Based on these premises, two requirements can be specified:
• under ULS (Ultimate Limit State), the strength and stiffness of the structural system, relying only on the primary elements, shall be verified and the secondary elements shall be checked for the lateral loads directly applied onto them; also, they will have imposed displacements which originate from the primary system deformations;
• under SLS (Serviceability Limit State), in case the contribution of secondary elements to the
overall system stiffness is relevant, the resultant stresses on the secondary elements will be added to the lateral loads directly applied onto them.

The inter-story drifts require being limited in accordance with the displacement compatibility in regard to glass elements. The secondary seismic member and its connections shall be designed and detailed to avoid cracking during the earthquake event associated with the no-collapse requirement. Moreover, these secondary elements and their connections must withstand their self-weight and also the out-of-plane loads when subjected to the displacements caused by the most unfavourable seismic design condition. Second Order effects \((P-\delta)\) need to be taken into account when designing secondary seismic members.

Glass secondary structural elements in seismic areas should be executed after the hardening of the concrete structure or the assembly of the steel frame and after the displacement has settled. These elements are allowed to be in contact with the structures (ex: without separation joints) as long as they do not have a structural connection with them.

Beyond the safety margin of the compatibility check, appropriate measures should be taken into account for the secondary structural elements in order to avoid cracking, brittle failure or collapse of the glass during an earthquake event due to the drift of the structure. Partial or total out-of-plane collapse is not unlikely, thanks to the high strength-to-mass ratio of the glass elements. This movement is allowed through the usage of a larger than typical clearance between the glass and the steel framing. A simple formula to calculate the required clearance for a flat rectangular panel is given in equation 1, which is taken from the American Standard ASCE 7-10 Minimum design loads for buildings and other structures [7].

\[
\delta = 2c_1(1 + hc_2/bc_1)
\]  

where:
- \(\delta\) is the horizontal seismic drift over the height of the panel being considered,
- \(c_1\) is the average clearance on the vertical sides,
- \(c_2\) is the average clearance on the top and bottom,
- \(h\) is the height of a rectangular panel,
- \(b\) is the width of a rectangular panel.

This concept of movement and flexibility must be extended throughout the structure, especially in the point support areas.

3. Case study: seismic analysis of a glass cube structure in a seismic area

![Figure 5. Real structure / Analytical model for Glass Cube Structure.](image)

The Analysis Model in figure 5 is a perfect cube with the side of 9.75 m, enclosed with laminated glass panels with 2 intermediate laminated glass vertical fins per side. The roof is a laminated glass panel with
horizontal ribs also from laminated glass. The vertical and horizontal fins are connected via a hinged bolt connection. The structure has been described in more detail in a previous article in Bulletin of Transylvania University of Brașov [8].

The cube is the entrance to an Apple Store, and in this example only the superstructure has been modelled with a hinged support from the ground. The loads evaluated for this structure are specific for Bucharest, i.e. a snow load of 1.60 kN/m², a live load of 0.5 kN/m², a Temperature Variation of +25 °C, and wind load with a reference speed of 30 m/s. The Earthquake load has been modelled using the design spectrum method according to P100-1/2013 (figure 6).

![Figure 6. Design Seismic Spectrum according to P100-1/2013.](image)

The results of the modal analysis can be seen in figure 7.

![Figure 7. Modal analysis results.](image)
As can be seen, the structure is very stiff due to the strong ribs, having a dominant vibration period of just 0.05 seconds. The graphic display of the displacement can be seen in figure 8.

![Figure 8. Rib vibration modes and mass participation factors.](image)

The purpose of this analysis is to compare the maximum results in terms of stresses and deflections for a full complete glass structure in order to evaluate which scenario (Gravitational or Seismic) dominates the design. In figure 8 we can observe a comparison from the point of view of maximum 3D deflections. The isolines on the left side show a maximum value of 18.8 mm corresponding to the SLU Envelope of combinations generated according to equation 6.10 from EN 1990. On the right side, we can observe the maximum deflection of 4 mm from the SLU Envelope of combinations generated according to equation 6.12.

In the first model, we can observe that the deflections are higher in the mid span due to the wind load which manifests a higher resultant force in the middle of the vertical panel, while in the second model (Seismic combinations), we see a smaller maximum deflection, situated on top of the structure. Thus, it may seem that the earthquake generates smaller deflections than wind.

Looking at the base shear resultant forces, the results are not consistent with the deflection ones. The maximum horizontal reactions from the envelope of combinations generated with equation 6.10 (Gravitational & Climatic loads) generate a maximum of 176.50 kN, while the maximum shear force generated with seismic combinations is 172.0 kN.

![Figure 9. Maximum deflection from Ec. 6.10 combinations vs. maximum deflections from Ec. 6.12.](image)
4. Conclusion
The case study presented above illustrates that the reactions from the base for a structure with a height/width ration of 1 and a rather tall height (~10 m) are almost identical to the horizontal forces resultant from Wind and Earthquake. Although the base shear forces are almost identical, the displacement distribution is very different. Maximum deflections from wind appear in the mid-section of the vertical panels, while maximum deflection from seismic forces appears on the upper part of the structure. Modal analysis also offers an insight into the way the structure behaves, and by studying the Eigen frequencies, the torsion sensitivity can also be taken into account. The modal analysis also helps determine the fundamental vibration period, which is essential in adopting or not a base isolation method.

In conclusion, it is important to consider seismic forces for any glass structure with primary elements made of glass, along with the other gravitational and climatic loads.

References
[1] www.apple.com
[2] http://www.meteoweb.eu/foto/cina-lo-spettacolare-ponte-vetro-sul-grand-canyon-galleria/id/707307/#13
[3] https://www.dezeen.com
[4] Feldmann, Kasper M 2014 Guidance for European Structural Design of Glass Components JRC Scientific and Policy Reports p. 68-70.
[5] Proposition de fiche (CSTB et SNFA): Disposition applicables aux façades légères en zones seismique
[6] O’Regan C 2015 Structural use of glass in buildings Volume 2, p.79
[7] ASCE/SEI7-10: Minimum design loads for buildings and other structures. Reston, VA: ASCE Press, 2010
[8] Popa C 2016 FEM analysis of glass structures using BIM software Bulletin of the Transilvania University of Brasov 9 (58) Proceeding of the International Scientific Conference CIBV 2016 p.109

Figure 10. Maximum base shear force from Ec. 6.10 vs. maximum shear force from Ec. 6.12.