Role of secondary components in the numerical analysis and in-plane seismic performance assessment of glass curtain walls

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Received 11 June 2023; accepted 29 July 2023; published online 21 September 2023
DOI https://doi.org/10.21595/vp.2023.23453

Check for updates

64th International Conference on Vibroengineering in Trieste, Italy, September 21-22, 2023

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Abstract. Glass façades are complex mechanical systems, in which brittle and vulnerable glass panels interact with metal members and secondary components. Under extreme design actions, such as seismic events, glass failure in tension (cracking) or compression (crushing) is a critical condition for structural performance assessment. Compared to full-scale experiments, in this regard, Finite Element (FE) numerical tools can offer a robust support in design. Besides, many primary and secondary façade components should be properly taken into account, because responsible of possible major approximations in their expected mechanical interactions. In this paper, the in-plane seismic response of glass curtain walls is investigated with geometrically accurate and detailed ("MREF") or simplified and efficient ("MSIMP") numerical models. Comparative results are critically discussed, based on dynamic numerical simulations, with a primary attention which is focused on the mechanical performance of glass panels.

Keywords: glass curtain walls, dynamic analysis, seismic performance, numerical modelling.

1. Introduction

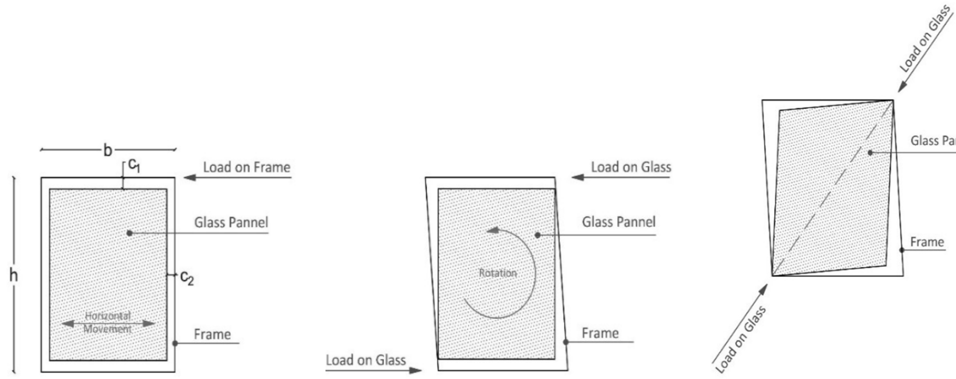
Glass façades, as known, represent a critical component in buildings, and necessitate for specific design / performance assessment tools, especially under extreme design actions [1]. The dynamic performance of façades is in fact governed by multiple interactions of primary and secondary components, where each member can involve critical effects in the mechanical response of adjacent elements. Simplified strategies can be used for seismic assessment, but often with major approximations [2, 3]. The attention should be given especially to glass fragility and real capacity [4], because it could manifest in premature cracks in tension or compressive crushing failure (Fig. 1).

In this paper, the in-plane performance of a glass curtain wall is investigated, based on a refined FE numerical modelling strategy ("MREF") or a more simplified but computationally efficient approach ("MSIMP"). Both model assemblies are subjected to typical boundaries of interest for full-scale experimental setup and protocol, in which quasi-static in-plane cyclic and monotonic loads are imposed to façade prototypes [3].

The discussion of numerical comparative results poses the attention on the intrinsic limits of computationally efficient (but roughly approximate) numerical strategies, compared to more accurate approaches, in terms of global and local performance assessment for similar systems. As shown, these limits are quantified, by taking advantage of the MREF model, especially in terms of glass panel response and expected stress peaks.

2. Reference system

As a reference, the experimental setup and façade prototype presented in [3] was taken into account for present investigation. The façade is 7.8 m high and 5.38 m wide, and is characterized by a constant inter-story height of 3.4 m (Fig. 2(a)). The supporting metal structure for the set of twelve glass panels is composed of five aluminium mullions and six transoms (Fig. 2(b)). The typical transom-to-mullion mechanical connection is realized as a partially rigid U-shaped steel joint, which is connected by means of a few steel bolts.

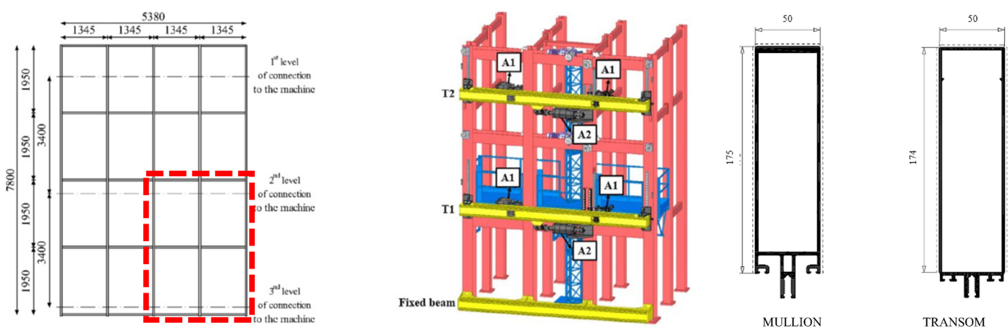


a) b) c)

Fig. 1. Typical response of glass panels in curtain walls under in-plane seismic action: a) rigid horizontal movement of the panel; b) frame deflection by panel horizontal movement; c) combined horizontal and rotational movement. Reproduced from [5] under the terms and conditions of a CC-BY license

Glass panels consist of insulated glass units (IGUs), with 44.2+16+44.2 mm section, where two 2-ply laminated elements (4+4 mm thick annealed glass layers, with 0.76 mm PVB bonding) are spaced by a 16 mm cavity. The clearance between glass panels and frame is about 6 mm.

At the ends of each transom, two setting blocks are used to support IGUs. They consist of an aluminium plate with a layer of plastic material (rubber pads) on top, and have a primary mechanical role, given that they are expected to facilitate the interaction of glass panels with frame members, preventing premature glass failure, and are typically subjected to major reaction forces under external design actions (i.e., Fig. 1). IGU panels are then fixed in position by means of pressure plates, which are screwed to the aluminium frame.



a) b)

Fig. 2. Reference experimental façade [3], with evidence of a) test setup and b) frame sections (dimensions in mm). Figures adapted from [3] with permission, license agreement no. 5603661158697

3. Numerical modelling

3.1. Strategy for refined or simplified models

The numerical investigation was carried out in ABAQUS [7] and SAP2000 [8].

As also discussed in [6], the refined model in ABAQUS/Standard (MREF) consisted of three-dimensional solid brick elements (C3D8R type), which were used to reproduce the nominal geometry of primary and secondary façade components. For the purpose of present study, 1/4th of the experimental sample schematized in Fig. 2(a) was taken into account, with appropriate boundaries. Through the modelling phase, a special attention was given to the description of basic façade components (including the realistic reproduction of IGUs [9, 10], pressure plates, frame detailing, etc.), as well as to their possible mechanical interactions under in-plane seismic loads. To this aim, *surface-to-surface* contacts (with penalty + "hard" normal options) were introduced along all relevant interfaces. An example of model detailing is shown in Fig. 3.

Mesh size was defined to avoid distortion in façade elements, especially its flexible components affected by local deformations under the imposed displacement path. The FE system corresponding to 1/4th of façade consisted of ≈431,000 brick elements and 1.510,000 DOFs. Based on experimental methods described in [3], the typical simulation was defined as a displacement-controlled, Dynamic Implicit step with imposed in-plane deformations (45 mm of maximum displacement, corresponding to ≈1/175 the façade height, in a time interval of 45 seconds).

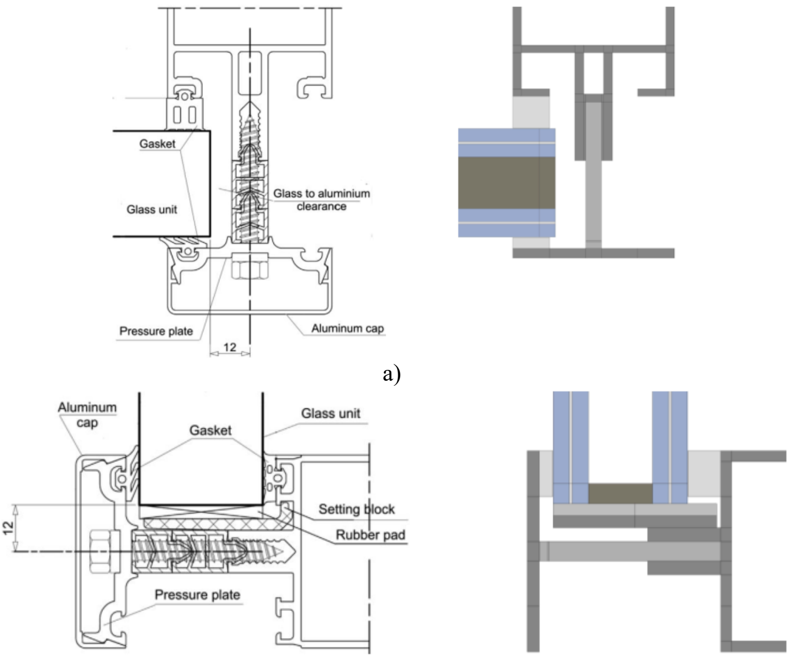


Fig. 3. MREF model (ABAQUS): cross-section of a) glass-to-mullion and b) glass-to-transom interaction. Figures reproduced from [6] with permission

The geometrically simplified model (MSIMP) was described in SAP2000, and inspired by strategic modelling steps discussed in [3] for the same façade prototype. The typical simulation consisted of nonlinear Direct-Integration time-history analysis, with the same strain rate of MREF (1 mm /sec). Differing from MREF, key features in MSIMP can be summarized as follows [6]:

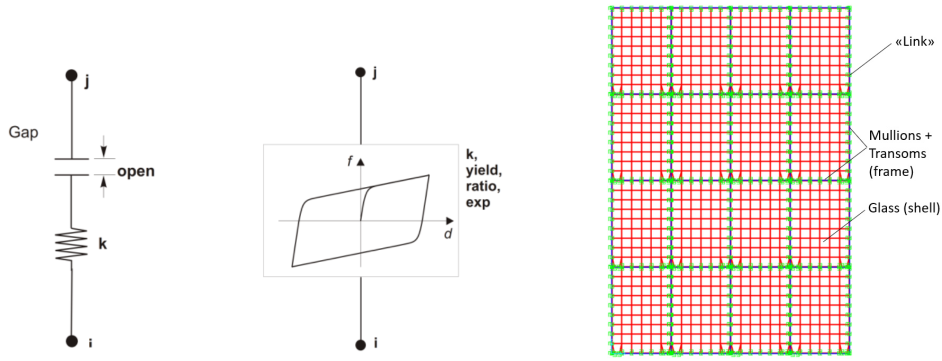
1) Monolithic 2D shell elements to describe IGUs (with total thickness corresponding to the sum of IGU glass layers), thus disregarding 2-ply laminated sections, cavity, edge spacer connections, pressure plates, etc.

2) 1D frame elements for mullions and transoms (with equivalent geometrical and mechanical properties).

3) a set of "Gap" and "Wen" link joints (Fig. 4(a)), which were used to reproduce the mechanical interaction of IGUs with frame members, especially in the region of setting blocks,

and possible contact with frame – along the edges – after clearance closure.

Due to its high computational efficiency, the MSIMP assembly described the whole geometry of the experimental prototype, see Fig. 4(b). The chosen mesh size resulted in ≈450 frame elements, ≈1200 shell elements and ≈1600 joints.



a) b)

Fig. 4. MSIMP model (SAP2000): a) detail of "Gap" and "Wen" links and b) front view. Figures reproduced from [6] with permission

3.2. Material properties

Input material properties for primary and secondary MREF components were calibrated as in Table 1 [6]. To note that a linear elastic constitutive law was taken into account for most of materials, through the parametric study. In this regard, the post-processing stage was carefully focused on the analysis of stress peaks in all façade elements, to ensure the correctness (for the purpose of present study) of linear elastic material characterization. For aluminium, an elastic-plastic material behaviour (with hardening) was used, with f_y = 120 MPa the yielding stress, f_u = 160 MPa the ultimate stress and e_{pl} = 0.08 the corresponding elongation. For MSIMP, glass and aluminium were successively described as linear elastic, with input from Table 1.

Table 1. Input material properties

Material	Density [kg/m^3]	Modulus of elasticity [MPa]	Poisson' coefficient [–]	Constitutive law [–]
Steel	7850	210,000	03	Linear elastic
Aluminium (6060 T5)	2700	70,000	0.3	Elastic-plastic with hardening
Annealed glass	2500	70,000	0.23	Linear elastic
PVB	1200	2	0.4	Linear elastic
EPDM	1000	2	0.4	Linear elastic
Silicone	1400	2 / 2 / 100	0.4	Linear elastic

4. Discussion of numerical results

4.1. Load-displacement response

The post-processing analysis was primarily focused on the elaboration of global and local structural behaviours for the façade under in-plane lateral deformations. For both MREF and MSIMP models, this stage included a first comparison of load-displacement response towards the experiment in [3], but also a more accurate analysis of local phenomena, such as (i) stress distribution in components, as a function of the imposed displacement; (ii) analysis of contact forces and reactions in setting blocks; (iii) sensitivity studies (for MREF) in terms of material

ISSN PRINT 2345-0533, ISSN ONLINE 2538-8479

properties and friction for contacts; (iv) effect of boundaries (for MREF), with respect to the full-size setup in Fig. 1(a). Fig. 5, in this regard, shows the numerical response for the façade subjected to monotonic in-plane displacement (1 mm/sec), as a function of the corresponding reaction force, compared to the experiment in [3]. The numerical results, especially for MREF, have good agreement with the test, for most of the recorded path. The final stiffness / resistance overestimation in MREF derives, at around 40 mm, from local indentation of IGUs in mullions. The MSIMP model, on the other side, tends to underestimate the expected resistance, especially in range of 5-30 mm. Such a global result confirms the key role of an appropriate calibration for model components and for their mechanical interactions, and thus the need of refined computational strategies.

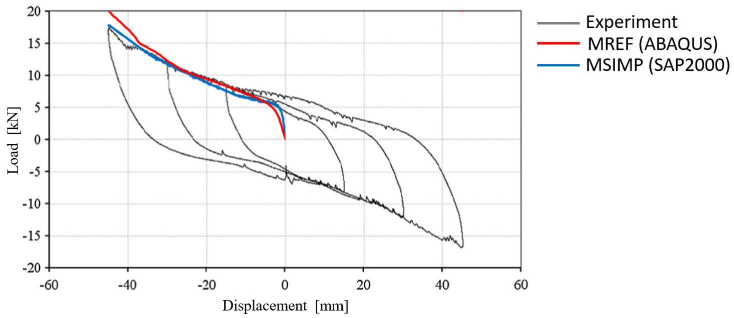


Fig. 5. Load-displacement response of MREF (ABAQUS) and MSIMP (SAP2000) models, compared to the reference experiment. Figure adapted from [6] with permission

In Fig. 5, it can also be seen that MREF and MSIMP curves have local discrepancies in the whole load-displacement path, which suggest further investigations. Their variable scatter is maximized especially for (a) the initial phase (i.e., elastic stiffness) and (b) the progressive / ultimate deformation stage, where the MSIMP assembly seems respectively (a) more rigid and (b) less stiff / resistant than MREF. In both cases, the progressive arrangement of IGU panels within the frame members, when subjected to increasing in-plane lateral deformations, has major effects on the façade performance, and still depends on the interaction of glass panels with secondary components.

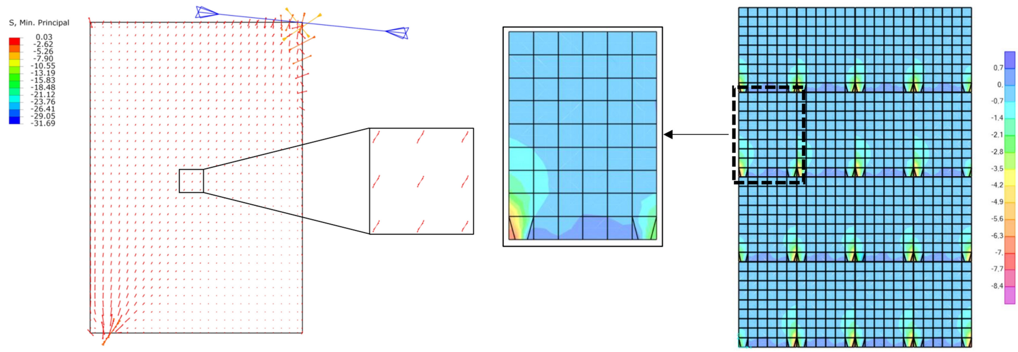
4.2. Local performance assessment

The analysis of local phenomena further highlights possible consequences for structural safety considerations. Among others, stress peaks in IGUs are of primary interest to verify the possible fracture of glass. Fig. 6, in this regard, shows the typical compressive stress distribution in glass elements at the imposed in-plane lateral displacement of 45 mm.

As it can be noted in Fig. 6(a) for MREF, glass elements approach a peak of ≈30-32 MPa in compression, in the region of setting blocks, with a typical diagonal propagation of stresses which can be also observed in the schematic model of Fig. 1 and agrees with the discussion of experiments reported in [3]. The tensile stress peak was indeed measured at the glass edges, and quantified in ≈38 MPa.

For MSIMP, see Fig. 6(b), the local rotation and translation of glass elements was found mostly uniform in the height and width of the examined full-size façade system, and this evidence further confirms the use of equivalent boundaries for the MREF model.

Most importantly, the compressive stress in glass in Fig. 6(b), at the same imposed displacement of 45 mm, is still located in the region of setting blocks, but hardly achieves a maximum of ≈8-9 MPa, as a major consequence that the mechanical interaction of IGUs with frame members is not sufficiently captured by the simplified numerical assumptions. In this regard, it is important to note that such an intrinsic limit of simplified numerical procedures was also emphasized in [3], where the compression peaks for glass elements close to setting blocks were quantified in ≈5 MPa, at the imposed displacement of 45 mm.



a) b)

Fig. 6. Analysis of compressive stress peaks in the region of setting blocks (legend values in MPa), for MREF (ABAQUS) and MSIMP (SAP2000) numerical models, at an imposed in-plane lateral displacement of 45 mm. Figures reproduced from [6] with permission

Certainly, it is important to note that – for present simulations – the above stress peaks were found remarkably low, compared to the reference characteristic strength of glass (which is equal to 45 MPa in tension and ≈10 times higher, that is ≈450 MPa in compression, for annealed glass). Also, lack of glass fracture was experimentally observed at the imposed displacement of 45 mm, for the reference test discussed in [3], and this aspect further justifies – for the present numerical investigation – the use of linear elastic material properties according to Table 1.

In any case, the herein discussed numerical investigations highlight that careful consideration should be taken into account in the use of approximate modelling strategies for the structural performance assessment of similar systems, especially in terms of glass-to-frame mechanical interactions. Overall, the MREF model manifested compressive stress peaks in the order of ≈4-5 times higher than MSIMP, which is obviously computationally efficient but not sufficiently accurate and thus realistic for conservative design considerations. In this sense, further efforts will be spent for the optimization of refined numerical strategies, towards the definition / calibration of enhanced / efficient approaches for the description of secondary components in façades.

5. Conclusions

Due to glass fragility and brittleness, façades are well-known complex and rather vulnerable building components, and require specific design and calculation tools, especially under extreme actions. In this paper, the attention was given to different numerical modelling strategies for the in-plane seismic performance assessment of a literature glass façade prototype. Whilst the global in-plane lateral performance was rather well captured by both the herein developed refined (MREF) and simplified (MSIMP) assemblies, possible safety risks were emphasized in terms of local performance analysis, where relevant scatter in the predicted stress peaks in glass (up to ≈4-5 times in compression) was shown. In this sense, the analysis of present results confirmed the intrinsic major limits of simplified procedures, both in global and local response trends, and confirmed the key role of primary and secondary components in the complex mechanical interactions which govern the structural performance of façades.

Acknowledgements

The authors have not disclosed any funding.

This research contribution derives from the M.Sc. Thesis of first author (defended on July

2023), which was elaborated with the precious and temporary co-supervision of Prof. Claudio Amadio (1954-2023).

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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