SEISMIC HAZARD MITIGATION OF MULTI-STOREY BUILDINGS VIA VIBRATION CONTROL SYSTEMS AND ENHANCED GLASS CURTAINS

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Introduction. Glass facades are widely used in building structures, due to a series of aesthetic, thermal, lightening aspects. Wide transparent surfaces are realized in commercial, residential but also strategic buildings (airports, museums, offices, etc.). From a structural point of view, however, these envelopes represent a critical component for buildings, due to the brittle behaviour and limited tensile resistance of glass, as well as to possible criticalities deriving from connections, detailing, etc., hence requiring specific fail-safe design concepts (Haldimann et al., 2008; Feldmann et al., 2014). The estimation of the vulnerability and actual dynamic behaviour of glazing systems under exceptional loads (seismic events, explosions, fire, natural hazards, see Figs. 1a to 1c - including their interaction with the building they belong - is currently an open topic, attracting the attention of several studies (Behr et al., 1995; Zhang et al., 2013; Mackalicka et al., 2016; Behr, 2009; Masters et al., 2010; Bedon and Amadio, 2017a; Larcher et al., 2016). However, further efforts are still required. In this paper, the seismic performance of glass curtain walls is investigated. The feasibility and potential of special mechanical connectors interposed at the interface between a given multi-storey building and the enclosing curtain are numerically investigated in ABAQUS (2017). The final result, as shown, consists in a full 3D assembly in which the facade works as a passive control system for the building, in the form of a distributed Tuned-Mass Damper (TMD), with enhanced global and local structural benefits (Bedon and Amadio, 2017).

![Fig. 1](image1)

Fig. 1 - (a)-(b)-(c): damage in glass facades under seismic events or explosions, with (d) example of UGCW installation process, (e) detail of the typical glass-to-frame connection and (f) traditional rigid bracket.
**Design philosophy and regulations.** Glass facades are usually designed as constructional components aimed to resist ordinary loads only (self-weight, wind), while enhanced curtains are properly calculated and generally over-dimensioned for special structures only. There, appropriate safety levels are mandatory, especially if exceptional loads are expected. Glass fragments represent in fact a critical issue for people, hence cracking of facade panes should be prevented. For the seismic design of glass curtains, general EU standards for buildings can be taken into account (i.e. EC8 (2004)). There, however, secondary components only are considered and no regulations account for the curtain wall typology, or for anchoring systems, materials, etc. The building as a whole is only required satisfy specific inter-storey drift values.

**Distributed TMD concept.** In this paper, unitized glass curtain walls (UCGWs) consisting of pre-assembled modular units, with insulating glass panels sealed to metal frames and fixed to the main building via rigid metal brackets (Figs.1d to 1f), are investigated under seismic events, with careful consideration for their role in the dynamic response of the buildings they belong. A novel design concept, consisting in a distributed TMD, is then numerically assessed. Based on such a design concept, glass curtains are actively involved in the dynamic performance of the enclosed building, with expected marked global and local benefits. The proposal takes advantage from the consolidated use of passive control systems in civil engineering applications, and specifically from the wide use in buildings of TMDs to wind and seismic loads effects (Lee et al., 2006; Hoang et al., 2006; Moon, 2016; Mohebbi and Joghataie, 2012), see Fig. 2a.

**Preliminary design.** Assuming that the single UGCW modular unit is connected to the primary structural system by means of four corner brackets, special mechanical connectors are proposed to replace traditional restraints, so that the feasibility and potential of the distributed TMD concept could be properly assessed. The typical control system can take the form of a viscoelastic (VE) solid damper, consisting of two metal plates and a rubber layer (thickness \( h_d \) and surface area \( A_d \)), see Fig. 2b and Bedon and Amadio (2017a, 2017b). The base plate is bolted to the inter-storey floor of the primary structure, while the UGCW frame is rigidly connected to a sliding plate, so to enable possible crushing and rotations of the VE layer when the UGCW panels are subjected to external pressures. A preliminary estimation of the mechanical properties of such a device (stiffness \( K_d \) and damping term \( c_d \)) can be carried out based on classical theories (Chopra, 2011), hence:

\[
K_d = \frac{M_{\text{glass}} \pi^2}{T_{1,\text{glass}}^2} \quad \text{and} \quad c_d = \xi \cdot c_{\text{cr}} / 4 = \xi \cdot 2M_{\text{glass}} \omega_{1,\text{glass}} / 4
\]

(1) (2)

with \( M_{\text{glass}} \) the mass of a single glass panel, \( \omega_{1,\text{glass}} \) the operating frequency of the UGCW module, \( \xi \) the damping coefficient of rubber and \( c_{\text{cr}} \) its critical value. For design purposes, a high damping rubber was taken into account. The fundamental period \( T_{1,\text{glass}} \) of the UGCW module, in addition, was set equal to the building period \( T_1 \). Possible tearing of the VE layer was then prevented, through the parametric numerical investigation, by limiting its shear deformations:

\[
s_d \leq s_{d,\text{max}} = \min(2h_d, 30) \quad \text{in} \, [\text{mm}]
\]

(3)

**Case study building.** An UGCW spanning from floor-to-floor was taken into account for the FE study (2.90 m×1.6 m the size of each module). The UGCW was assumed belonging to a 4-storey, steel frame building with residential destination (category of use ‘A’, based on EC1 2004), located in an earthquake-prone region of Italy, see Figs. 2c and 2d. Overall base dimensions of 10 m×20 m were taken into account, with 12 m the total height, 3×2 bays in the longitudinal and transversal directions. Inter-storey floors consisting of in-plane rigid, steel-concrete composite slabs were then considered. All the steel members, S275 grade (\( f_y = 275 \, \text{MPa and} \, f_u = 360 \, \text{MPa the yielding and collapse stresses}), were supposed designed in accordance with EC3 (2004) provisions, based on permanent and accidental loads at the Ultimate (ULS) and Service (SLS) Limit States.

**Global dynamic effect of dissipative UGCWs.** The overall dynamic effects due to UGCWs with VE fasteners was first considered. To this aim, eigenvalue FE numerical investigation were
carried out in ABAQUS, on the full 3D steel frame inclusive of the glazing envelope (Fig. 2c). The numerical modelling of the examined structural system was carried out in accordance with past numerical efforts, as for example reported in (Bedon and Amadio, 2017a, 2017b), and generally consisted of computationally efficient but accurate FE models composed of beam and shell elements, as well as properly calibrated mechanical constraints able to reproduce the actual performance of a single constructional member, as well as its interaction with the other components.

For each VE device, $K_d$ was then estimated with Eq. (1) as a function of $T_1=0.326$ s, as numerically calculated for the 3D frame with a rigidly restrained UGCW. A non-dimensional magnifying coefficient $R_K$ was also defined, through a FE parametric study (with $1 \leq R_K \leq 50$), to assess the input mechanical features effects:

$$K_d = \left( M_{\text{glass}} \pi^2 / T_1^2 \right) R_K$$

(4)

By changing the $R_K$ reference value, no tangible variations were found for the fundamental vibration shapes of the building (Fig. 3a). Interesting variations were observed in terms of vibration periods, for the examined configurations (Fig. 3b). A value $R_K \geq 50$, in particular, proved to coincide with almost fully rigid brackets, hence with null benefits. $R_K$ values $\leq 2$, conversely, gave evidence of local vibration modes of the UGCW, compared to the steel frame, hence suggesting to consider $R_K$ values in the range $\approx 2$-$30$.

Seismic analyses. The dynamic performance of the case study building was then properly investigated. A set of 7 seismic records (two-component acceleration data, consistent with EC8 provisions for type ‘A’ soil, T1 topographic category, 0.35g PGA and 50 years of nominal life (ULS)) was imposed at the building base, through dynamic nonlinear analyses (see Fig. 3c).

In Fig. 3d, the top drift and the VE sliding (absolute maximum envelopes from the set of seismic records) are proposed, as a function of $R_K$. Worth of interest is the effect of dissipative
UGCWs, both in global and local terms. As far as $K_d$ increases, $c_d$ further increases, see Eqs. (1) and (2). However, limited sliding only can occur in VE devices, with minimum damping contribution and hence benefits for the structural components. Based on Fig. 3d, an optimal balance of local and global performances for the examined case study was found to lie in the range of $R_K \approx 3-4$ values.

In global terms (see Fig. 3e), markedly reduced top displacements of the 3D frame were noticed, in presence of VE connectors. At the local level - for properly designed VE devices - maximum stresses in the UGCW components can be also highly minimized. Even the imposed seismic records were found to do not lead glass panes to failure, the $R_K=4$ configuration lead up to $\approx-50\%$ the stresses of the traditionally restrained UGCW. In addition, the flexibility of UGCW supports proved to beneficially affect the distribution of stresses in glass panels. Local peaks of stresses close to the glass supports and edges were in fact generally avoided, due to VE fasteners, see Fig. 3f, with obvious benefits for the overall dynamic performance of the full structural system. These global and local findings derive from the combined flexibility
and damping properties of VE devices, since part of the incoming seismic input energy can be preliminary dissipated. As a result, the UGCW and the steel frame are potentially subjected to a reduced seismic impulse, compared to the same building with fully rigid brackets.

**Conclusions.** In this paper, the feasibility and potential of special mechanical joints interposed at the interface between a given multi-storey primary building and a traditional unitized glazing curtain wall (UGCW) have been investigated via accurate Finite-Element (FE) numerical models, under seismic events.

Based on properly designed fasteners able to introduce additional flexibility and damping capacities in the traditional building, the maximum effects and benefits of such connectors have been shortly emphasized via a case study of technical interest, both in terms of global performances as well as local and component behaviour for the building object of investigation, giving evidence of the potential of UGCWs acting as distributed TMDs for multi-storey buildings under hazards. It is hence expected, based on current research outcomes partly emphasized in the paper, that the same design concept could be further calibrated and optimized, as well as that related design criteria could be fully implemented towards the definition of practical tools for designers.

**References**


ABAQUS(2017). Dassault Systèmes. ABAQUS v. 6.14, Providence, RI


