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Enhancement of the seismic performance of multi-storey buildings by means of dissipative glazing curtain walls

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ABSTRACT

Glazing facades are widely used in building structures, due to a series of aesthetic, thermal, lightening aspects. From a structural point of view, under the action of exceptional loads as impacts, explosions or seismic events, the glazing envelopes often represent the critical component for multi-storey buildings, due to the typically brittle behavior and limited tensile resistance of the glass panes, hence requiring specific design concepts. In this paper, the feasibility and potential of special mechanical connectors interposed at the interface between a given multi-storey primary building structure and the glazing facade are extensively investigated via accurate Finite-Element models, under the action of a set of seven natural seismic records. As shown, the proposed vibration control devices can markedly improve the dynamic performance of the traditional structure, both in terms of global (i.e. building seismic response) and local performances (i.e. at the component level). The final result, once the input parameters of the vibration control devices are properly designed, is an assembled structural system in which the glazing façade works as passive control system for the primary structure.

1. Introduction and state-of-the-art

In current practice, glazing curtain walls are extensively used in buildings, in the form of cladding envelopes able to provide specific thermal, insulation, weather resistance properties. From a structural point of view, these facades are typically designed in order to provide an appropriate resistance against lateral loads (i.e. wind), as well as to accommodate the deformations of the main structure. Due to the typically tensile brittle and limited resistance of glass, however, the cladding elements often represent a critical component for the entire building and its occupants, especially under the action of exceptional and high-rise design loads such as seismic events, explosions or impacts in general.

Despite a non-effective and expensive over-dimensioning of the glazing components, a valid technological solution for enhancing the structural performance of a given system – compared to traditional design methods – can be represented by special connectors able to reduce the effects of the incoming design loads.

In this respect, special devices have been for example proposed in [1–5], both for cable-supported facades or curtain walls under explosive events, in the form of passive control systems able to avoid the glass panes failure, as well as to preserve the integrity and optimize the primary structure and hence guarantee an appropriate safety level for its occupants.

Passive control and vibration monitoring of structural systems under exceptional or high-rise design loads actually represents, both for buildings and infrastructures, a key topic for researchers and designers (i.e. [6–10]). Within the possible passive technological solutions currently available or under investigation for the mitigation of multi-storey buildings, tuned-mass-dampers (TMD) are widely used in structural engineering to reduce translational displacements and accelerations due to wind and seismic loads in bridges [11–14] and buildings or assemblies [15–19]. Den Hartog [20] first derived analytical expressions to determine the optimal values of mass, frequency and damping ratios of the TMD as a function of the dynamic properties of the structure. Several studies focused on the optimal design of such devices can be found in literature [21–24].

Regarding the dynamic performance of buildings cladded by glazing envelopes, the original TMD concept has been first extended to structural buildings with double skin façades by Moon [25–27], and also recently recalled by Palmeri et al. [28]. In these past works, it was shown through analytical studies that when special connectors are used, double skin facades can efficiently act as passive absorbers for multi-storey buildings under wind or seismic loads, with important structural benefits in terms of stress and dis-

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placement reductions (up to ≈35%, compared to the traditional building).

In this paper, the feasibility and potential of distributed, dissipative devices able to control and mitigate the maximum vibrations and stresses due to seismic events on traditional multi-storey buildings with glazing envelopes is investigated via Finite-Element (FE) numerical simulations, by taking into account a reference case study. Compared to [25–28], the current study is carried out by considering the typology of glazing curtain walls, namely composed of modular units (i.e. the insulated glass panels (IGUs) and a metal supporting frame) directly connected to the steel structure via fully rigid connectors.

The FE investigation is first carried out in ABAQUS [29], by means of accurate 3D models able to describe a full building assembly representative of a seismic resistant, 4-storey residential steel-framed building (with or without vibration control systems). Additional FE studies are also performed at the component level, in order to properly assess the effects of a given seismic load on a single IGU unit, as a part of the full building. In it, the critical aspect is in fact often represented by the maximum out-of-plane displacements achieved during the assigned seismic event, as well as by the corresponding maximum stresses.

The FE parametric study is developed by taking into account several mechanical configurations (i.e. stiffness and damping properties) for the proposed vibration control devices, so that both their effectiveness and criticalities could be properly emphasized. The exceedance of the tensile resistance of glass as well as the avoidance of excessive deformations at the devices level should be in fact avoided, for optimal design purposes. As shown, when properly designed in terms of stiffness and damping features, the investigated control devices can strongly enhance the dynamic performance of the given steel-framed system, both in terms of global dynamic performance as well as in terms of maximum deformations and stresses in the IGUs. Due to the implemented dissipative devices, the mass belonging to the glazing curtain wall is in fact efficiently involved in a kind of distributed, passive control system derived from the TMD concept. It is thus expected, based on the discussed FE study, that the current research investigation could provide useful background towards the fully development of this innovative design approach.

2. Design concept and theoretical background

The design concept of building structures equipped by vibration control devices and dissipative glazing curtain walls takes inspiration from the tuned-mass-damper (TMD) concept and from the implementation in traditional glazing facades of special connectors able to act as passive impact absorbers.

Recent applications of special connectors have been proposed in the last years for glazing cable supported facades under explosive events [1–4], in the form of viscous spider connectors for glass panes, as well as friction dampers or elasto-plastic restraining systems for the bracing cables, while special viscoelastic or ADAS brackets acting as passive control devices for curtain wall modular units have been proposed and extensively numerically investigated in [5]. In these past research projects, the potential of such devices for improving the dynamic performance of the cladding system was emphasized, but the overall performance of the full structural assembly consisting of the glazing façade and the cladded building was not properly explored.

The use of passive vibration control systems for the enhancement of the dynamic performance of tall buildings under wind pressures and seismic events was first explored in [25–27], where a theoretical study was carried out on building structures with double skin facades, in order to find an optimal correlation between the primary structure, the (double skin) glazing façade and the devices' mechanical properties. The same concept has been recently analytically investigated also in [28], where it was further highlighted that double skin facades with appropriate vibration control connectors can provide marked contribution in the reduction of the effect due to seismic events on tall buildings, with a reduction of the expected maximum displacements up to 35% the deformations of the traditional building structures.

In this research project, the design concept of glazing curtain walls acting as passive absorbers for building structures under seismic events is further extensively investigated via computationally efficient but accurate FE models, both in terms of global dynamic performance and structural effects of a given design seismic load, as well as at a component level (i.e. maximum stresses and deformations in the glazing modular units).

In accordance with [25–28], the dynamic performance of a building structure with glazing facades and vibration control devices can be rationally described as schematized in Fig. 1.

The primary structure, having total mass M_{struct}, with specific stiffness (K_{struct}) and damping (c_{struct}) properties, interacts with the cladding glazing façade – namely representative of an additional mass ($M_{glass,tot}$) on the primary structure – via special mechanical connectors replacing the typically fully rigid supports.

From a theoretical point of view, see Fig. 2, the dynamic response of the system of Fig. 1 can be in fact rationally associated to a single-degree-of-freedom (SDOF) system interacting with the additional mass representative of the full glazing envelope, via a series of distributed vibration control devices, whose mechanical performance can be described in terms of elastic stiffness $K_{d,tot}$ and damping coefficient $c_{d,tot}$.

Under a given design load, see Fig. 2, the governing differential equations representative of the dynamic performance of the SDOF-TMD system are [26]:

$$M_{struct}\ddot{u}(t) + C_{struct}\dot{u}(t) + K_{struct}u(t) = P(t) + C_{d,tot}\dot{u}_d(t) + K_{d,tot}u_d(t) \quad (1)$$

$$M_{glass,tot}\ddot{u}_d(t) + C_{d,tot}(\dot{u}_d(t) - \dot{u}(t)) + K_{d,tot}(u_d(t) - u(t)) = p(t) \quad (2)$$

where $u(t)$ is the deflection in time of the primary structure, while $u_d(t)$ denotes the relative displacement of the glazing curtain wall – depending on the stiffness $K_{d,tot}$ and damping ratio $c_{d,tot}$ of the devices.$P(t)$ and $p(t)$, being representative of the force acting on the main mass or on the TMD mass respectively, for the case of seismic loading condition are given by:

$$P(t) = -M_{struct}\ddot{u}_g(t) \quad (3a)$$

$$p(t) = \frac{M_{glass,tot}}{M_{struct}}P(t) \quad (3b)$$

with $\ddot{u}_g(t)$ the exciting base acceleration.

In this study, assuming that the single glazing component is connected to the adjacent steel frame with four special dissipative devices (i.e. one device at each panel corner), the preliminary estimation of the devices' stiffness and damping properties can be carried out based on Fig. 3.

In accordance with Fig. 3, M_{glass} represents in fact the total mass of a single façade panel (plus the supporting aluminum frame), while K_d and c_d denote respectively the stiffness/damping ratio of a single device, with $K_{d,glass} = 4K_d$ and $c_{d,glass} = 4c_d$ denote the resulting values at the level of glazing modular unit.

From a practical point of view, the typical device can be supposed a viscoelastic (VE) solid damper composed of three metallic plates and a middle layer, namely a natural rubber. The VE layer is has nominal thickness h_d and a square base surface $A_d = l_d^2$ (see Fig. 3b and c). Two steel plates are directly attached to the struc-