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Numerical assessment of vibration control systems for multi-hazard design and mitigation of glass curtain walls

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ABSTRACT

Glass systems and facades are widely used in building structures, due to a multitude of aspects. Beside these motivations, from a pure structural point of view, glazing envelopes represent one of the most critical components for multi-storey buildings under the action of exceptional loads as impacts, explosions, seismic events or hazards in general. Such systems represent in fact the first line of defense from outside. Given the current lack of specific design regulations for the mitigation and enhancement of glass curtains under extreme loads, as well as the typically brittle behaviour and limited tensile resistance of glass as material for constructions, the same facades require specific, *fail-safe* design concepts.

In this paper, the feasibility and potential of special mechanical connectors interposed at the interface between a multi-storey primary building structure and the enclosing glazing facade are investigated via accurate Finite-Element (FE) numerical models, under various impact scenarios. At the current stage of research, careful consideration is given both to the observed global performances as well as to local mechanisms, based on computationally efficient FE models inclusive of damage models to account for failure mechanisms in each system component. Compared to earlier research efforts, the attention is focused on the multi-hazard performance of a given case study building, subjected to extreme loadings such as seismic loads or blast events. As shown, even the typically different features of the examined loading conditions, when the proposed vibration control devices are properly designed and the curtain wall is considered as part of a full 3D building, the final result is an overall assembled structural system in which the glazing facade can work as a passive control system for the building system, in the form of a distributed Tuned-Mass Damper (TMD), with marked benefits in terms of protection level as well as design optimization.

1. Introduction

Glazing facades are widely used in building structures, due to a series of aesthetic, thermal, lightening aspects. In most of the cases, wide transparent surfaces are created in commercial, residential as well as strategic buildings, including airports, museums, offices, etc.

From a structural point of view, however, under the action of exceptional loads as impacts or hazards in general, glazing envelopes represent a critical component for multi-storey buildings, due to the typically brittle behaviour and limited tensile resistance of glass panes, as well as to connection detailing etc., hence requiring specific, fail-safe design concepts [1,2]. In this regard, the appropriate estimation of the vulnerability of glazing systems under extreme loads, as well as the prediction of their actual dynamic behaviour under exceptional loads (including the interaction between a given envelope and the substructure/primary building), or the implementation and development of advanced retrofitting and enhancing techniques, consequently, are currently open topics still attracting the attention of several studies. Analytical, experimental and/or Finite Element (FE) numerical investigations can be found in the literature for glazing envelopes under seismic events (i.e. [3,4]), blast, explosions and accidental impacts (i.e. [5–10]), fire (i.e. [11,12]), hurricanes and climatic loads (i.e. [13–16]). Beside these efforts, the same issues still require further extended studies.

In this paper, taking advantage of major outcomes of an ongoing research investigation, careful consideration is paid for the multi-hazard performance of glass curtain walls, as well as to maximum effects mitigation due to seismic loads and blast events, being representative of emergency situations for protection of people. In doing so, the effects of special mechanical connectors interposed at the interface between a given multi-storey primary building structure and the enclosing glazing curtain wall are preliminary investigated via efficient FE numerical models, under various extreme loads scenarios. Such a special connectors are intended to act at the curtain-to-building interface, given a

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reference curtain wall and building. The major outcomes of the current paper, in addition, are representative of preliminary studies aimed to assess the feasibility and potential of the explored design concept. In this sense, extended experimental studies (both at the small-scale/connector level as well as at the full-scale/prototype level) would later on represent a key aspect for the validation and full optimization process.

Differing from existing studies related to retrofit and enhancement of glazing facades under extreme loads, being mainly related to single-hazard analyses only, as well as to single facades components only (i.e. [3,17]), as a main goal of the current project, the benefits or critical issues of such devices are hence preliminary assessed as potential tools for multi-hazard mitigation of traditional curtain walls, by taking into account both local and global structural aspects. As shown, when properly designed, the proposed connectors can in fact markedly improve the overall dynamic performance of a given glazing system. At the same time, part of these benefits are implicitly transferred also to the main building the facade belongs, both in terms of global building dynamic response and local performance of the curtain wall components. The final result, consequently, consists in a fully assembled structural system in which the glazing facade can work as a passive control system for the primary structure, in the form of distributed Tuned-Mass Dampers (TMDs).

2. Glass facades under exceptional loads: summary of current design philosophy and regulations

Design and mitigation of buildings under multi-hazards, including natural events (i.e. earthquakes, windstorms and hurricanes, floods) as well as accidental or human-induced exceptional events which may occur during their lifespan, represents the optimal goal of design, as well as the result of multidisciplinary issues and competences [1]. Such a design must in fact accommodate pure structural requirements aimed to enhance the response of a given building under an assigned loading configuration, but also thermal, economic, social, technological decisions. In doing so, it is clear that new techniques and methodologies aimed to assess the vulnerability of structures, control their dynamic performance or reduce their demand - together with reliability evaluations and risk analysis/management - have a crucial role, see [18].

In the specific case of structural glass facades subjected to exceptional loads, being representative of a part of often complex mechanical systems and buildings, but also of the first line of defense from outside, their optimal structural design is strictly dependent on the actual performance (i.e. stiffness, resistance, redundancy, etc.) of single structural materials and components, as well as their reciprocal interaction under the assigned combination of loads. As such, careful consideration should be paid not only for the glass panels composing the enclosure, but also for anchoring systems, supports, framing members, etc (see for example [19,20]).

In the case of unitized glass curtain walls (UGCW, in the following), pre-assembled modular units, typically consisting of insulating glass elements, are sealed to aluminum or steel framing members and fixed to the main building via rigid brackets, see Fig. 1. In terms of structural performance, these systems are traditionally designed to resist ordinary loads only, i.e. vertical loads due to self-weight and standard wind pressures acting in the direction orthogonal to glass panes surface, while enhanced-resistant UGCWs are properly designed, when required, for special buildings only. In both the cases, such a structural requirements must accomplish with other design issues, most of them related to the thermal performance of curtains, including also air infiltration, water penetration, condensation, glass surface distortion, etc (i.e. [21–23]). Thermal and structural aspects, in most of the cases, are strictly related (i.e. [24–26]) and should be jointly optimized at the preliminary design stage.

Generally speaking, the structural design of glass panels and framing components is then conventionally carried out by taking into account single facade components only, i.e. by assuming ideal restraints at the glazing module restraints as well as equivalent simplified formulations for the description of design loads and for local verifications, rather than exploring and optimizing the structural performance of curtain walls and related buildings in the form of 3D full assemblies.

In general terms, due to the relatively weaker tensile strength and brittle behaviour of glass as material for constructions [1,2], as compared to concrete, steel or timber elements of traditional use, glass windows and facades are typically fragile, and therefore highly vulnerable to extreme loads, shocks and impacts in general. Glass fragments represent in fact a critical issue for people, hence cracking of panes should be generally prevented (i.e. Fig. 2). As a result, specific *fail safe* design rules (still required for glass systems in general under ordinary loads, see [2] are needed especially when exceptional loading configurations are expected to occur. Appropriate design methods as well as mitigation tools should be in fact considered, aiming to enhance the security level, hence minimizing possible injures and optimizing the structural performance/cost of the system itself. In the specific case of structural systems composed of glass, major uncertainties are also represented by high scatter in the material tensile resistance, being this value highly susceptible to geometrical features, thermal and edge treatments, loading conditions, presence and position of holes, etc. (i.e. [27–31]). From a practical point of view, these aspects are conventionally accomplished by assuming a linear elastic behaviour for glass, and properly limiting maximums stresses and deflections under the assigned combination of loads [1,2].

As also in accordance with available design standards and regulations for buildings under exceptional loads such as seismic loads or blast events, a key role in design assumptions and performance limitations is given by the role assigned to glazing systems acting as a part of a whole building. As far as the given glass system to verify can be considered as a *secondary* component, compared to the primary structure, partial damage is in fact generally accepted by currently available design regulations. This is not the case of structural glass assemblies of *primary* importance within a given structural system, where the glass elements or facade components should in fact able to properly resist to the incoming impulse, as well as to accommodate the overall deformations of the building as a full three-dimensional assembly, including both out-of-plane and in-plane displacements. In the latter case, it is hence clear that special joints, mechanical connectors and fasteners are mandatory, together with connections detailing, in order to satisfy design standard limitations and avoid severe damage. In doing so, however, no specific rules are available for glass curtain walls designers.

Regarding the seismic design and verification, for example, general European standards for buildings can be applied also to glass curtain walls, without specifications (see for example [32]). In that document, secondary components only are in fact considered, and no specific regulations are available to account for the importance or typology the curtain wall belongs, as well as for detailing, anchoring systems, materials, etc. As a general rule, the building as a whole is only required to do not exceed specific inter-storey drift values. The mentioned EU regulations are in line with other standards for seismic design of buildings, see for example the New Zealand NZS 1170.5 [33] document. More detailed provisions are included in US FEMA 450 [34], even for so called "*secondary non-structural cladding systems*" only. Compared to the European or Australian scenarios, specific drift limit values are required for glazed curtain walls, storefronts and partitions, and hence should be satisfied to avoid glass fallout. Drift limitations are also given, as a reference design criteria, by the Japan Standards [35].

Actually, given a traditionally framed glass unit like Fig. 1, for example, no specific considerations are given by most of existing standards to its real performance under seismic loads. Research efforts and case studies observations highlighted, over the last decades, that sealant joints proving glass-to-frame bonding could have a key role in preventing glass failure. It was also observed, however, that most of the gaskets in use for such facades are not able to accommodate the