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Experimental and numerical investigation of cyclic response of a glass curtain wall for seismic performance assessment

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HIGHLIGHTS

- One among the few glass facade experimental campaigns worldwide realized till now.
- An innovative machine adopted for the first time in occasion of performed tests.
- Interesting results are discussed in terms of experimental and numerical outcomes.

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ABSTRACT

In contemporary architecture, the use of the glass curtain walls is increasingly growing. However, after experiencing earthquake motions, they have sometime shown damage, which might cause considerable life-safety hazards for pedestrian and occupants of buildings, as well as significant economic losses to owners, due to downtime and cost for repairing. This work aims to investigate the behaviour of such systems under seismic loads, so to contribute to the enhancement of the capability of designers and manufacturers in dealing with seismic vulnerability of glazed systems and reducing earthquake induced losses. This study shows cyclic experimental tests performed at the Construction Technologies Institute (ITC) of the Italian National Research Council (CNR) for seismic performance assessment of a full-scale aluminium-glass façade, designed and manufactured according to a standard technology for the European market. A non-linear finite element model has been calibrated according to experimental results. The aim is understanding further aspects of the lateral behaviour of these non-structural elements and also giving useful information for numerical simulations of similar façades, that in the next future should be performed even in the absence of experimental data.

1. Introduction

Recent architectural trends, focused on the research of even greater transparency in building envelopes, have favoured the diffusion of modern and innovative glazing systems.

However, recent seismic events have shown the vulnerability of such non-structural elements, highlighting how earthquakes pose a real threat about their performance and safety, since failure may provoke significant economic losses and injuries to pedestrians and occupants. Unfortunately, scientific research based on experimental tests on this issue is not sufficiently developed and therefore there is also a lack of standards that specify how to obtain satisfactory seismic performance. For this reason, there is a strong sense of experiencing glass façades, possibly on a real scale.

Curtain walls are thin, usually aluminium-framed wall, containing in-fills of glass, metal panels, or thin stone. The framing is anchored to the building supporting structure by means of connections at the floor/beam level, by allowing necessary tolerances of installation and building natural movements. Such façades do not contribute significantly to the load bearing or the stability of the

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building structure, so they are usually intended as "non-structural" elements.

During an earthquake, potential failure of one of the infill panels can be an extremely dangerous threat to the exposed public inside or outside the building (Fig. 1). If the façade is not properly designed and installed, the drift between adjacent storeys induced by the earthquake accelerations could provoke glass (or any other cladding material) breakage and potential fallout [1].

In order to assess the performance of architectural glazing systems on buildings during earthquakes, different experimental and numerical studies have been performed over the past few decades. First studies were focused on the behaviour and the failure mode of window glazing panels under horizontal, in-plane dynamic racking tests (unidirectional and/or cyclic tests), investigating the influence of various parameters, such as sash, glass and sealant type, location of fixings, loading type, edge strength [4–6]. McCue et al. [7] analysed the seismic performance of a mock-up unit of a curtain wall under out-of-plane racking tests. Other studies were focused on the seismic behaviour of different non-structural elements (walls, partitions, openings) [8,9]. These studies firstly evidenced that the performance of a glazing system is strongly dependent on the response of a building to an earthquake, which is affected not only by the stiffness and the mass distribution of the load carrying structure, but also by the stiffness and masses of non-structural elements which are not adequately separated from the load carrying elements.

Following these first studies, a number of experimental racking tests has been carried out on full size glazing systems, by evidencing how the displacement rate is the main parameter affecting the behaviour of the tested systems [10–13].

Shaking table tests were also performed by some researchers [14–16] to evaluate the behaviour of glazing system under a base excitement in different directions.

The influence of the glazing unit and of the glass type have been also investigated and compared in various works [17–19]. Laboratory tests have also been performed on various combinations of architectural glass and framing members. Wooden frames have recently acquired great interest among researchers [14,20–23] for their high dissipation capacities.

Different load protocols have been developed and used to make some experimental tests [13,24–26], among which the *crescendo test* [27,28] is surely the most commonly adopted. It is characterised by a concatenated series of sinusoidal cycles at increasing amplitude and it has been included in the AAMA 501.6 recommendations [29] to assess the horizontal racking displacement amplitude of glazing system frame, which might provoke fallout of glass panels.

Starting from the observation of experimental results, various authors developed analytical models to predict the critical drift that causes glass damage. Sucuoglu and Vallabhan [30] developed analytical techniques to determine the dynamic response of window glass and structural glazing systems by using simple mechanical models. Memari et al. [31] developed predictive models to estimate the ultimate drift capacity of full-size curtain walls based on low cost testing of small-size glass plate and aluminium frame segments. Memari and Shirazi [32] proposed a seismic rating system to evaluate architectural glass by assigning a score to curtain walls based on geometric, mechanical properties and seismic drift demand. Such a score is intended as an indicator of the seismic vulnerability of the wall so that a retrofit action can be undertaken by building owners. O'Brien et al. [33] formulated a closed-form equation to predict the drift corresponding to glass cracking failure for several curtain wall and storefront systems. Khoraskani [34] derived the maximum allowable lateral force that may be exerted on the panel using the theory of plates and Huveners et al. [35] proposed a mechanical model to predict the in-plane stiffness of the system, the largest maximum principal stress and the maximum normal and shear stresses in an adhesive bonded joint.

Some finite element models have been developed by several authors [36,37–41] in order to predict the general behaviour of glazed curtain wall systems and the drift at glass cracking and fall-out during seismic actions.

Caterino et al. [41] have been developed and calibrated two finite element models with reference to two different stick curtain walls (said types "A" and "B", respectively), on the basis of experimental data gathered at the ITC-CNR laboratory. Mullions and transoms of the aluminium frame were modelled using "beam" elements, where cross-sections were modelled in detail using the "Section Designer" tool available in SAP2000 [42]. Glass panels were modelled as elastic "shell" elements and their thickness was assumed to be the sum of the single layers composing the panel.

The role of the moving beams has been modelled adding a "rod" (i.e., equal horizontal displacement) type constraint among the joints of the aluminium frame fixed to such beams. The main components of the proposed model are the rotational stiffness of the transom-to-mullion connections, the clearance between glass panels and aluminium frame, the frame local stiffness in the interaction between glass and aluminium when the contact happens and the mechanical behaviour of gaskets.

The mechanical interaction between glass panels and aluminium frame is due to the silicon gasket installed along the four edges of the panel. This is true up to the moment in which lateral deformation of the frame causes the closure of the clearance

(a) (b) (c)

Fig. 1. Glazing damage observed in past earthquakes: (a) 1994 Northridge Earthquake, (b) 2010 Chile Earthquake, (c) 2011 Christchurch Earthquake [2,3].