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# Seismic Behaviour of Point Fixed Glass Façade Systems: State of the Art Review

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## ARTICLE INFO

### **Keywords:**

*facade systems, point fixed glass systems, structural glass, seismic action*

## ABSTRACT

flat glass has been used for many centuries in wall openings and windows. It allows light in and broadens the visual horizon, while protecting from the environmental elements. It also features a good potential for energy savings during the lifetime of the building. The technological developments it benefited from, in the last decades, transformed common plate glass into a stronger material, with safer and more predictable failure and some degree of post breakage capacity; even pseudo-ductility. For this reason, at present day, glass is a structural material with established credits. This allows for new buildings with dematerialized contours: the glass skin buildings; which are taking over the set in modern cities. There are several types of glass façade buildings, depending on the system used to fix the glass to the main structure. Point Fixed Glass Façade Systems (PFGFS) feature an advantage in terms of architectural expression allowing for greater transparency, since no mullions and frames are required for additional support, only discrete point fixing. The design codes for structural glass are still under development, and one of the aspect that needs further attention is the behaviour of PFGFS when subjected to seismic action. This aspect is of the essence in the sense that forensic analysis to past earthquake events showed that important damage has been observed to GFS due to the in-plane racking actions. This may have severe costs in terms of human losses and in terms of economic costs (repair and downtime). The present paper addresses this theme by presenting an overview of its key aspects, review of past research, both analytical and experiment for PFGFS under seismic loads, design code provisions for different countries as well as recommendations for prediction of racking capacity of Point Fixed Glass Façade Systems. The work presented in this paper is established in the framework of the ongoing research project: GF Seismic (FCT POCI-01-0145-FEDER-032539).

## **Introduction**

Glass is a sustainable material (basically made from 75% molten sand and 25% chalk soda and can be 100% recycled [1], it is transparent and slender, and can create the feeling of real contact with the exterior. It is important to notice that façade systems play an important role in buildings in order to provide entrance of sun light, air protection, most importantly adequate indoor environments by controlling comfort and adequate use of energy (both for heating and cooling).

Different materials can be used for façade systems, the selection will depend on the architectural design of the building, two types of façades can be distinguished [2]: i) Opaque façades, constructed with layers of solid materials such as masonry, stone, precast concrete panels, metal (aluminium, stainless steel). ii) Glazed Facades, such as curtain walls or storefront facades, consisting in translucent glazing material and metal framing as secondary components.

Current tendency for building construction aims to create lighter, bigger and more spacious facilities, therefore frameless glass façade systems have gained popularity over the past thirty years, due to their ability to allow high transparency on the building's façade while using less elements for the support of the glass panels. The current use of bolted structural glass façades started with the plate suspended assemblies of the 1960's and 70's [3], with the introduction of Pilkington's Planar system in 1981 followed by RFR's La Villette ball-joint systems to nowadays point fixing techniques. Modern frameless glass façade systems include bolted spider arms connections, providing a point support on the glass panels usually on the corners of each glass panel, according to its size intermediate points may be required. Structural supports for these systems may vary from truss, cable and steel support systems [4]. In general, in a Glass Façade System (GFS), four basic components may be identified: glazing panels, bolted fixings, glazing support attachments and the main support structure.

### **Damage To Glass Façade Systems In Past Earthquakes**

Non-structural damage has been constantly reported in past earthquakes [5], investment on non-structural components in construction (including contents) for a typical office are 82% and for hospitals up to 92% of total building costs [6], pointing out the great investment there is in non-structural components and contents rather than structural components and framing. After the San Fernando earthquake in 1971 (California), where several buildings were reported with glass damage [7], it became clear that non-structural components can be very vulnerable to strong shaking, damage to non-structural components not only can be very costly but also can pose real threat to life safety, therefore reducing damage to those elements has been an important engineering task for the past decades.

From the 1985 Mexico City strong earthquake some lessons were learned on glass damage, window glass falling was the second most serious non-structural damage well documented [8]. On the latest strong earthquake on 19th September 2017 Puebla, Mexico, damage was reported on medium high buildings (8-12 stories) and mostly due to structural irregularities, important non-structural damage was observed on in-fill walls (masonry facades of buildings were severely damaged) and glass window falling according [9].

An important correlation between the inter-storey drift and the glass damage was reported on several post-earthquake damage assessments [10]. Flexible glass façade systems enclosed by metal curtain walls and mullions presented less damage in past seismic events [11], mainly due to the high deformability of silicon allowing for a better accommodation of drift demand during ground shaking. Further, it is reported that glass damage consistently increases with larger window areas and irregular plan configurations [12]. Therefore, due to the significant increase of glass usage in

buildings, an increasing interest rise about controlling their possible damage. An example of curtain glazing falling out is shown in figure 1.

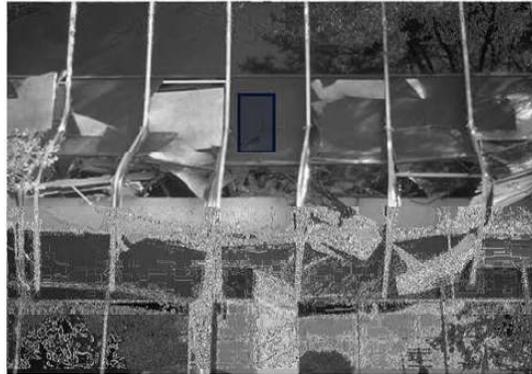


Fig. 1. Kaiser Permanente Building, Granada Hills, California, cladding offset [6].

A damage extent report of the Christchurch earthquake in 2011 (New Zealand,) showed that heavy damage was observed in spider glazing [10], as can be seen in figure 2, this behaviour was originated around the “spider” that holds each glass pane, likely a result of the “spider” creating stress concentrations in these regions due to the restraint of the connection to the structure. In table 1 is presented a resume of percentage of glass damage per seismic event for some of the significant earthquake events of the past 50 years, in figure 3 a chart with the data from table 1 is shown.



Fig. 2. Examples of damage to spider glazing systems on buildings [10].

TABLE I: DESCRIPTION OF PERCENTAGE OF DAMAGED GLASS FAÇADES ON PAST EARTHQUAKES.

SEISMIC EVENT	DATE	REPORTED DAMAGE ON FACADES	DATA
San Fernando (SF), California, USA	9-Feb-1971	30 % of building's façades sustained broken glass	50 high rise buildings in locations away from the epicenter [49; 50].
Guerrero-Michoacan (GM), Mexico	19-Sep-1985	50% of buildings with structural damage presented glass damage. 25% of buildings presented serious damage and glass falling.	263 multi-story office buildings [8; 49].
Northridge (No), California, USA	17-Jan-1994	25% of the storefront windows presented damage  CW systems in general performed well, damage was more frequent for low-rise storefront windows.	Over 14 buildings with limited non-structural damage and no structural damage reported in downtown Bunbank [49]. High rise curtain walls systems.
Kobe (Ko), Japan	17-Jan-95	General glass fracture and deformation on glazing frames, differences were observed in façade orientation, southerly oriented glazing panels were damage above 70% in comparison to northerly façades with less than 15% damage. Tall buildings didn't showed representative structural damage nor major glazing damage.	Several buildings were asses, low (up to 60 m height) to height buildings (above 60m height) [49].
Bam (Ba), Iran	26-Dec-2003	70 % buildings of the area were destroyed and buildings with no significant structural damage presented important non-structural damage (glass fallout).	Field investigation in Bam epicenter town of several medium to height buildings [13].
Christchurch (Ch), New Zeland	22-Feb-2011	The glass damage was recorded for all lightweight cladding that contained glass. Nearly half of all glazed lightweight claddings had glazing damage and 39% presented a falling hazard. Only 60% of infill systems were deemed either operational or immediate occupancy. 17% were	371 façade systems on 271 buildings were surveyed [10].

deemed high hazard, the highest of the facade groups.

Central (Ce), Italy	30-Ago-2016	Overall good performance of glazing systems attributed to the quality of the interface between the glass panels and the supporting frames (silicon).	From 300 inspected buildings with different structural systems (schools, hospitals, public and residential buildings) [52].
Kaikōura Japan (Ka)	13-Nov-2016	Entire temperate glass panels shattering due to stress concentrations, this behavior was attributed to the incapability of traditional systems to accommodate structural deformations (the amount of the deformation the spider glazing system can accommodate is around 1% drift ratio) with no redundancy like framed systems.	Several multi-story buildings of modern construction (built in the 1980s or recently) in Wellington observed in the immediate aftermath of the Kaikōura earthquake [14].
Mexico City (MC), Mexico	19-Sep-2017	40% of the buildings suffered substantial damage on façades and structural components.	25 buildings with different features and full range of damage, from 8 to 12th stores [9].

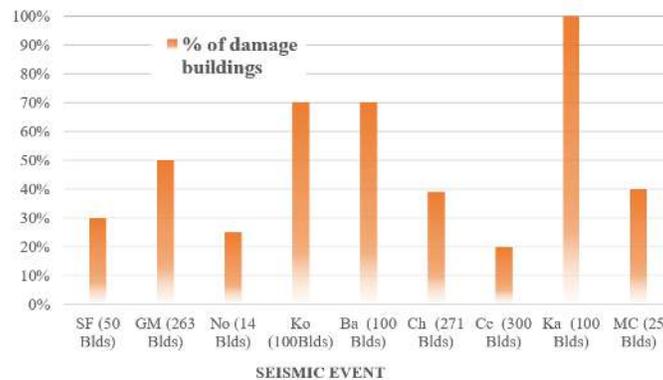


Fig. 3. Percentage of damage per major seismic event listed on table 1.

### Structural Façade Configuration For Point Fixed Glass Façade Systems

Different point fixed glass façade systems (PFGFS) were developed due to architectural requirements, over time, industry evolved according to market necessities, even though glass façade systems are not standardized, four basic components can be identified for bolted glazing systems and are explained below: glazing panels, bolted fixings, glazing support attachments and main support structure.

#### *Glazing Panels*

Usually toughened glass and laminated glass are the most common types of glass panels used for façades. Toughened glass induces a favourable tension field all over the surface of the glass panels due to a process of heating the panels at high temperatures (600°C-650°C) followed by a rapidly cooling process, allowing balanced stress condition across the thickness of the glass panel, one important property of this type of glass panels is the capacity of fragmenting into small particles after fracture.

Laminated glass, on the other hand, is produced by a process of bonding two or more layers of glass with an intermediate interlayer. The most popular interlayer is PVB (polyvinyl butyral), other type of interlayers are: Ethylene Vinyl Acetate EVA or SentryGlass (SG). Commonly known as safety glass, when subjected to sufficient impact to break the glass, fragments typically remain intact, firmly adhered to the PVB interlayer [15]. Depending on factors like shape, size of glass, edge treatment, quality of holes, etc. Resistance of the glass panel will vary, for point fix glass, stresses near the holes and glass thickness will determine the resistance of the panels and final design will take into account panel deflection.

#### *Bolted Fixings*

Bolted fixings provide point support to the glass panels and transfer the glass self-weight and lateral loads to the structural support. The bolted fixings are usually located towards the corners of the glass panels and additionally at intermediate points on long edges. Several types of bolts exist: enhanced countersunk fixings (allow to transfer out of plane and in plane loads directly through to the bolt and glass interface), articulated bolts fixings (allow for accommodate rotation of the fixing to glaze support), different type of spider arms and bolt fittings are shown in figure 4. All hardware is made of high quality mirror polished stainless steel (graded 304, 316, 316LM), ensuring best possible protection against oxidation and corrosion. Principal elements of a spider arms fixing are shown in figure 5.



Fig. 4. Spider arms and bolt fittings for the PFGFS connections [16].



Fig. 5. Glass façade spider arms components [17].

There is no direct contact between glass panels and steel bolts, an intermediate polymer material with smaller elastic modulus is used to help with the uniform distribution of tension around the holes. Bolts can be placed with the head inside or outside the glass panels, also double glazing systems can be used introducing a special bolt fixing allowing this feature (in figure 6 are displayed different types of bolts). A point fixing embedded in the glass panel is also possible as well as silicon fixing of the bolts to the glass panels, although those systems may be of limited use due to its durability in a long term behaviour [17].



Fig. 6. Different type of bolts for interior point fixing (from [18]).

### *Glazing Support Attachments*

Glazing support attachments provide mechanical support and allow the transfer of loads to the main support system. Many types exist on the market, some of them are: Spider supports, angle brackets, pin brackets and clamping devices, in general these attachments are defined by an architectural/aesthetics assessment on the façades.

### *Support Structure*

The main job of the support structure is to transfer loads from the glazing support attachments to the building structure itself, as well as for the glazing support attachments, support structures may be different according to the architectural requirements, but two of the most common systems are steelwork structures (trusses and fins) and cable systems (rod or wires working under tension loads), figure 7 shows examples of those systems.



Fig. 7. Examples of façade support structures from GLASSCON Projects (from web site [18]).  
Analytical and Experimental Studies for PFGFS

Experimental and analytical studies have been performed over the past 30 years for seismic performance of framed glass façade systems, focusing on their behaviour after mayor earthquakes ([12]; [20]; [21]; [22]). One of the most significant experimental work on this topic developed at the Building Envelope Research Laboratory of the University of Missouri-Rolla (UMR), investigating the serviceability and fallout resistance of popular curtain wall systems used on mid-rise buildings under simulated earthquake [23]. Figure 8 shows the test set-up used for the testing program at UMR.

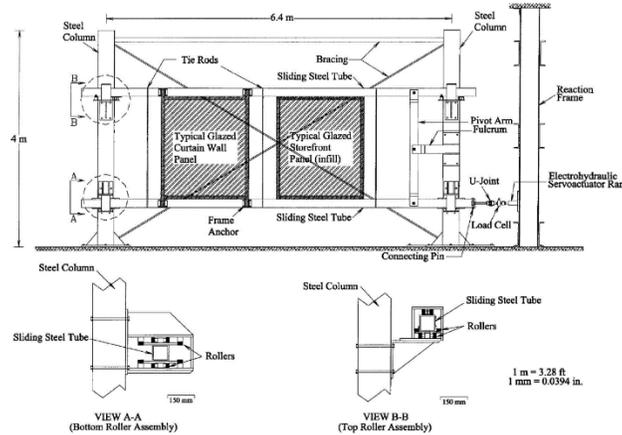
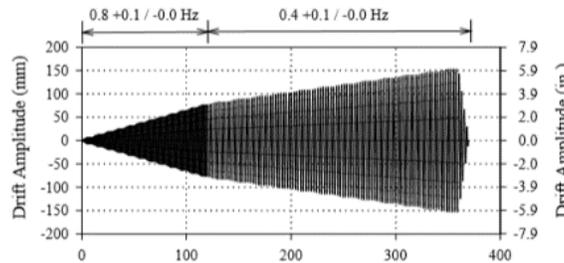


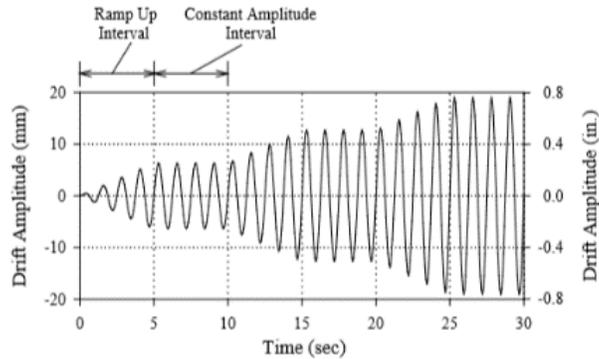
Fig. 8. Dynamic Racking Test facility at the Building Envelope Research Laboratory Department of architectural Engineering, The Pennsylvania State University [23].

The so called “crescendo tests” were performed by means of hydraulic controlled actuators increasing lateral displacement to glazed systems, figure 9 shows the sinusoidal progressively increasing racking amplitudes. Those experimental studies lead to a number of recommended revisions, namely: “NEHRP Recommended Provisions for the Seismic Regulations for New Buildings and Other Structures (FEMA 450)” which were published in the 2000 NEHRP Provisions FEMA 451 [45]. The experimental work layout allowed to develop industry-accepted test protocols published by the American Architectural Manufacturers Association (AAMA) as: “Recommended dynamic test method for determining the seismic drift causing glass fallout from a wall system” published on AAMA 501.6 in 2001 ([24]; [25]; [26]).

Several tests were conducted based on AAMA 501.6 test set-ups for framed glass façades, e.g. the work developed by [27]-[28] on full-scale curtain walls with IGU configurations, in order to determine service and ultimate limit drift behaviour and glass fitted with anchored pet film among others [29].



a) for full time load



b) for the first 30 seconds of time.

Fig. 9. Crescendo load path for dynamic test.

For Point Fixed Glass Facade Systems (PFGFS), a limited number of recent experimental tests and analytical studies have been performed. Experimental work and Finite Element (FE) models were developed to study parameters such as clearance between bolt and holes, variation in hole diameter and distance between hole and glass panel edge. It has been reported that for in-plane loads on glass panels, increasing the clearance between bolt to glass hole and the distance between hole and panel edge, enhanced the stress development on the glass panels [30].

In order to improve the behaviour of PFGFS in areas of high seismicity, the seismic performance of specially design spider arm systems connecting the glass to structural support frames was assessed [31]-[32], including large horizontally slotted holes allowing isolated horizontal translation (figure 10), for that purpose, special low modulus silicon sealant was used to allow rigid body translation during the racking actions. The sizes of the slotted holes need to be calculated according to the glass façade drift demands from the building. During the experimental test [30], the façade frame was subjected to in-plane displacement in incremental magnitudes of three cycles of elastic drift condition (0.4%), one cycle of inelastic drift condition (2.5%) and a third drift capacity of (2.9%). The system behaved very well, accomplishing all code criteria with glass panels remaining intact, only when the frame was racked beyond the design range of the spider slots the glass panels showed noticeable rotation but no glass nor bolt failure were observed.

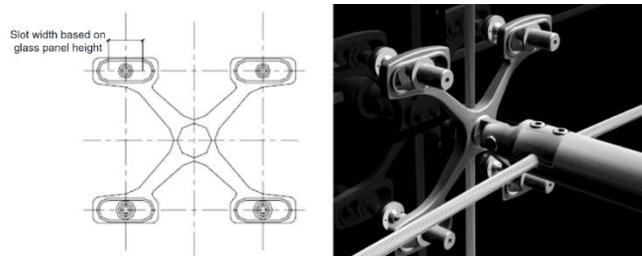


Fig. 10. Spider arms with horizontally slotted holes [31].

A standard testing protocol was developed [33] and use to undertake racking test on typical PFGFS for low moderate seismic regions such as Australia. The test results allowed to calibrate finite element models that were extended to other PFGFS systems and geometric configurations. The aim was to assess the in-plane racking performance of PFGFS in terms of its lateral drift capacity, for this purpose two full-scaled laboratory tests were developed: a) with X type spider arms and

countersunk bolt fittings for laminated glass panels joined with silicon weather sealant, b) K-type spider arms and button head bolt fittings. Both tests were subjected to 100kN in-plane lateral load and more than 150mm in plane displacement, figure 11 shows the test layout.

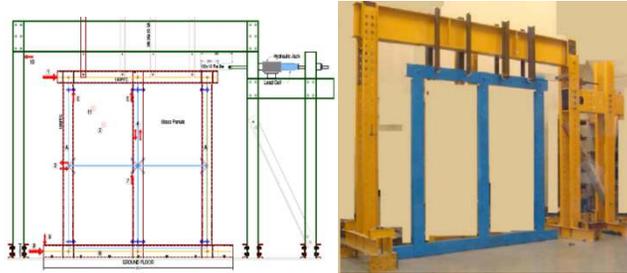


Fig. 11. Structural support frame for reaction frame and location of LVDTs and hydraulic jack [33].

Two tests were completed, PFGFS with pinned X-type (test #1) and fixed K-type spider arms (test #2), results showed that the systems had large in-plane drift capacities due to a rigid body translation [16]-[34], 2.1% of lateral drift ratio for the test #1 and 5.25% for test #2. Larger drift capacity was associated with three main mechanisms: built-in standard gaps between the bolts and holes within the spider arm and structural support frame connections, possibility of the In-plane rigid-body rotation of the spider arms and deformations and yielding of the spider arms allowing the system to move laterally. Failure occurred when out-of-plane movement induced by combined local bending and diagonal tensile stresses around spider arm bolted connections, lead to initiation of cracking in one of the glass panels (figure 12).



Fig. 12. The PFGFS after failure of a glass panel (Test #2)) [30].

A computer algorithm to predict the strength and facilitate the optimization of a variety of glass bolted connections was carried out [35]. Several parameters affecting the behaviour of the system (shape of bolt, hole, closeness of fit, etc.) were studied, along with the results of a Finite Element (FE) analysis.

The effects of seismic loading in point fixed glass panels firstly using a simplified method to determine the seismic forces transmitted to façade panels, based upon the elastic response of the system, was studied [36]. FE model was developed and seismic load was applied with a dynamic time history analysis. Laminated glass panels and a set of different parameters were considered,

variations on thickness of glass panels and interlayer type (PVB and SentryGlass). Results showed that the simplified methods to determine seismic forces transmitted to façade panels were able to capture resonance effects induced by building’s natural frequency that were obtained by numerical simulations using the time history analyses. It was concluded that special attention should be taken into account to avoid loads that will induce natural frequencies on glass panels close to building’s natural period, and that given the case, improvement of seismic behaviour with the use of special devices to allow an increase of damping ratio is necessary.

Furthermore, FE models were undertaken to model PFGFS including structural support frame to which racking load was applied [37], non-linearity was modelled both for the behaviour of the built-in gaps and for the out-of-plane differential movement of glass panels and the deformations of the sealant, spiders on the other side, were modelled as linear elastic elements. The FE models were used to predict the racking performance of the PFGFS with different configurations: multiple grid, sealant types (weather sealant, structural and special purpose sealants), sealant thickness and glass geometry, glass thickness (12, 10 and 15 mm). Finding out that the racking performance of the PFGF systems increased when the stiffness of the silicone sealant was reduced while its thickness increases, when panel height to width ratio was increased as well as glass thickness.

#### Code Provisions for In-Plane Drift Demands

Glazing systems can be designed using a variety of glass configurations for frame, glass types (material, heat-treatment) and method of glass-to-frame attachment, but due to all those different configurations, in-plane load, namely seismic load and displacement (drift) response, will be different, therefore an increasing need to include these structures not only as general non-structural elements, as the current design considerations are in codes, but to define expected behaviour under different conditions. Nowadays, further experimental tests and finite element analysis are required in order to investigate the performance of non-typical configurations of glazing systems under seismic loads, therefore most of the designers follow general rules for lateral displacements tolerances, due to the lack of published studies specially for PFGFS.

Design codes specify design loads for out-of-plane and in-plane serviceability and ultimate limit state criteria for buildings, common practice of design codes specify limitations to inter-story drift in reference to the structural frame to avoid damages to the non-structural components, this includes glass facades. In table 2 a report on codes that refer to glazed facades are enlisted [39].

TABLE II: Specification of Codes Regarding Design and Verification of Glazed Curtain Walls [39]

Region	Code	Seismic capacity?	Seismic demand?
USA	AAMA 501.6 (2001)	Yes: definition of a testing procedure	No
USA	FEMA 450 (2003)	No	Yes, in terms of drift
USA	ASCE 7-10 (2013)	No	Yes, in terms of drift
Japan	JASS 14 (1996)	No	Yes, in terms of drift
Europe	UNI EN 13830 (2015)	Yes: definition of a testing procedure	No

Almost all the current design code provisions include specification for Inter-story drift ratios limitation under lateral load (IDRs), in general those limits are specified according to the building’s main structural seismic resistant system. In table 3 are enlisted different codified IDRs for buildings ([33]; [39]). No straight specifications exist for glass façades, current practice specifies to develop experimental set-ups for non-typical configurations, and different treatment is given to the non-structural elements on each design code.

TABLE III: Specification of Codes For Inter-Storey Drift Ratios.

Code	Aimed for	Type of structure	Drift limit
AS/NZS 1170.0 (2002) [40]	General Structural Design Actions	Brittle masonry wall Inter-storey drift at ultimate limit state For unbraced frames and multi-storey buildings subjected to lateral loading	0.00167H <sub>w</sub> <sup>(1)</sup> 0.015H <sub>s</sub> <sup>(2)</sup>
AS 3600 (2009) [41]	Concrete structures	Inter-storey drift for ultimate limit state of 500 year RP. Event	0.002H <sub>s</sub> 0.0225 H <sub>s</sub> (2.25%)
NZS 1170.5 (2004) [42]	New Zealand standard for "earthquake actions"	2500 year RP near fault event	0.037H <sub>s</sub> (3.75%)
California Building Code (CBC, 2002) [43]	Provisions for design building	Serviceability Seismic provisions for facade systems of buildings for Seismic Zone 4	max (span/250; 2xglass clearance) 0.02-0.025H <sub>s</sub> (2%-2.5%)
Australian standard "AS 1288 (2006) [44]	Glass in buildings- selection and Installation"	Serviceability conditions	0.002H

FEMA 450-1 (2003) [45]	Structural design criteria	Structures that not include masonry seismic resistant systems (Seismic group I)	0.02Hs
EC-8 (BS EN 1997-1:2004) [46]	Buildings with non-structural components with no ductility	Damage limitation	0.0075Hs
ASCE/SEI 7-10 (2010) [47]	For experimental layout carried out with AAMA specifications Guideline for Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings	Ultimate limit state for steel framed buildings	0.0225Hs
CSA-S832 (2006) [48]		Ultimate state	$\Delta_{fallout} > 1.25 ID_p^{(3)}$ or 13mm
		Ultimate limit state	0.02Hs

(1) Hw masonry wall height.

(2) Hs story height.

(3) I: importance factor; Dp: relative seismic displacement.

### Conclusion

An overview of current research regarding Structural Glass Façades has been presented, focusing on Point Fixed Glass Façades Systems (PFGFS). It is important to recognize that the in-plane racking performance of typical PFGFS it's an ongoing research topic, aiming to develop clear guidelines for testing protocols and analytical techniques. Simplified approaches for designer

engineers are required to be developed as well as clear code specifications as it has been developed for Curtain Wall Façades Systems.

#### Acknowledgment

Financial support from the Portuguese Foundation for Sciences and Technology (*Fundação da Ciência e Tecnologia*) under contract grant POCI-01-0145-FEDER-032539 (GF-Seismic | Structural Glass Facades Subjected to Seismic Load) is gratefully acknowledged.

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