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Drift Performance of Façade Systems

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Abstract

Façade systems in Australia have evolved to suit marketplace demands from an aesthetic, economic and sustainable perspective. The structural design of façade involves the analysis and design of the panels and connections to resist the out-of plane wind pressures and to accommodate in-plane deflections resulting from wind induced building drift, long term floor deflections and thermal movement. In addition, the façade systems need to be able to resist earthquake loading without collapse and an important performance parameter is the ultimate drift capacity of the façade, particularly for glazed curtain wall systems. A literature review has been conducted investigating glazed curtain walls including current trends, damage reported in past earthquakes and research into the seismic performance and drift capacity. This paper also describes the finite element modelling techniques used to investigate the in-plane performance of glazed façades along with a comparison with previous experimental results.

Key words: curtain walls; architectural glass; seismic performance.

1. Introduction

Façades play an important role in building constructions; they provide the interface between the environment outside and the user inside and are used to supply sufficient light and air quality to improve the indoor environment. Façades have had a number of major transitional phases throughout history. Prior to 1890, façades were typically constructed as mass masonry load-bearing walls. Early in the 20th century new construction materials became available and consequently the use of curtain wall systems is increased. Presently we are seeing a drive towards performance based requirement with strong emphasis on sustainable development. This has advanced a number of novel technologies, such as double façade systems and the use of solar technology to enable buildings to produce electrical power. In the future we will see façades continually advancing, through the growth of this technology enabling them to become more interactive with their surrounding environment. Key factors regarding aesthetics, cost, performance, durability, maintainability and sustainability will continue to influence the design.

Ledbetter (2002) stated that the principal factors behind the increased complexity of façades are the number of products placed on the market and the extensive technical aspects of these products from the hundreds of glass-coating-gas combinations that can be used in a glazing unit to the thermal performance, acoustic performance and so on that are implied by the framing system chosen.

Emporis (2007) has classified the façade system into;

- *Exposed structure façades;* having their framework uncovered, which may be directly exposed to the outdoor environment or painted,
- *Applied masonry façades;* differ from curtain wall façades as they are assembled from numerous small elements and they differ from exposed structural façades as they do not support any load, and the structural frame of the building is hidden,

- *Curtain wall façades,* Vigener and Brown (2007) define the curtain wall as being any wall that doesn't resist any loads except for wind load, seismic load and its own self weight, with these loads being transferred to the building via floor and column connection. Curtain walls infills are mainly glass, metal panels and precast panels.

The popularity of glazed curtain wall system is increasing due to a number of facts including aesthetics, increased natural light and sustainability considerations. Structural design of glazed curtain wall involves the analysis and design of the panels and connections to resist the out-of-plane wind pressures and to accommodate in-plane deflections resulting from wind induced building drift, long term floor deflections and thermal movement. In addition, the glazed curtain wall systems need to be able to resist earthquake loading without collapse. An important performance parameter is the ultimate drift capacity of the façade, particularly for glazed curtain wall systems. Severe earthquakes and wind cause damage to the main structural components of buildings as well as to the non-structural elements such as window glass panels and curtain walls. There are two major concerns related to architectural glazing performance during and immediately following seismic event.

- Hazards to people from falling glass.
- Building down time and cost to repair.

Sections 2 to 5 of this paper summarise a literature review on current trends, damage observed in past earthquakes and research into the seismic performance and drift capacity. Section 6 describes finite element modelling techniques used to investigate the in-plane performance of glazed façades and a comparison with previous experimental results.

2. Glazed Curtain wall

A curtain wall is designed to resist air and water infiltration, wind forces acting on the building, seismic forces, and self weight. The glazed curtain wall can be classified into two main types, namely; frame glazed curtain wall and frameless curtain wall.

Frame glazed curtain wall

Framed glazed curtain walls are typically designed with extruded aluminium members, although the early curtain walls were made of steel. The aluminium frame is typically in-filled with glass, which provides an architecturally pleasing envelope, as well as benefits such as natural day lighting. These curtain walls are designed to span multiple floors, and take into consideration design requirements such as, thermal expansion and contraction, building sway and movement, water diversion, and thermal efficiency for cost-effective heating, cooling, and lighting in the building. There are three common types of aluminium curtain wall systems available, namely; stick system, semi-unitized system and unitized system.

Stick wall system is installed piece by piece. Usually, the mullion members (vertical members) are installed first, followed by the transom members (horizontal rail members), and finally the glazing or window units. The stick wall system was used extensively in the early years of metal curtain wall technology, and is still used in modified versions. The advantages of this system are low shipping and handling costs (because of low bulk) and allowance for dimensional adjustment according to the site conditions. On the other hand, the major assembling process is conducted at the site and a large amount of labour support is needed while increases the cost. Following the stick wall system, a *semi-unitized curtain wall design method* was introduced into curtain wall technology. In this system, the mullion members are separately installed and then pre-assembled framing units are placed between them. These units can be up to full story height, or they can be divided into a spandrel unit and vision glass unit. This system needs large amounts of labour for field assembling work and the erection time is also considerably long.

Unitized curtain wall system is the most contemporary method. Sheets of glass and aluminium curtain walls fabricated in factory and installed as a unit are referred to as a unitized curtain wall system. Unitized curtain wall will comprise glass vision panel and spandrel panel mounted in a prefabricated aluminium frame. The production of the whole panel is done at the factory, where the process can be carefully inspected, and tested. According to the façade engineers, a unitized curtain wall is the most airtight and weather resistant cladding and exterior wall system available. The structural section around the panel is fabricated as half sections (female and male) for ease of erection and to facilitate relative movement through articulation. The panels are installed in shingle fashion, starting either from the bottom or top of the building and going around each floor until the whole building façade is complete. The manufacturer must rely on qualified installers to ensure that the air seals are properly installed between the split mullions, in this unitized system.

Frameless glazed curtain wall

A growing number of architects are substituting the design of frame glazed curtain walls with frameless glass walls. With good design these unconventional glass walls can provide energy savings by allowing natural light to enter the buildings. This has a particular potential in architectural expression in terms of transparency, by removing the mullions and aluminium profiles from the pure planar nature of the glass surface, gives it a relief standing out from the transparent planes. Double glazing also can be fixed in this method as more energy efficient concept instead of a single sheet of glass. The two sheets are installed into a sash or frame with an air insulation gap between them creating a sealed unit. Many frameless glazed systems are now available for the use of glass in façades, all aimed at achieving maximum transparency by reducing the support structure such as,

- Point fixed glass on base supported steelwork. These are simple posts, trusses and fins. Trussed posts of various forms may be used to support glazing where the height of glazed walls exceeds 4.0 m
- Point fixed glass on cable systems. Support structures can be constructed almost entirely from tension elements, such as rods or wires, and are therefore very light both physically and visually. Loads have to be transferred, at both ends of the cables, to boundary support structures. The weight of the vertical glazing is either supported by a tie rod hanger system or by each panel being suspended from the above panel.
- Fin walls comprising one-way spanning glazing supported on glass beams or fins. The glazing is either attached continuously to the fins using a soft silicone sealant or is connected intermittently using bolted connections. The structural model is that of a glass plate supported on its edges by glass beams.

Modern frameless glazing systems often bolt on steel support structures, which are important architectural elements and combine structure stability with aesthetic expression. The bolts provide point support to the glazing panels. Applications of bolted glazing systems range from simple structures, as shop windows and settlers, to more complex multi-storey buildings and large atria. Bolted fixings are commonly located towards the corners of the glazing panels, and additionally at intermediate points on long edges. They connect glazing panels to glazing support attachments, which in turn are connected to support structures.

Movement of the glazing panels and of the support structure as a result of thermal effects and under applied loads should be accommodated. If movement is resisted, stresses can be developed in the system. Provision is therefore usually made for bolted fixings, glazing attachments, or elsewhere to allow rotation and movement. Loads that arise as a result of the self-weight of the glazing system, including applied loads and load transfer effects that may occur when glazing panels are broken or removed.

The use of glass connections falls into two categories; such as a bolt through the glass that bears on the glass; or friction plates that are clamped on to the glass by bolts. Friction plates may be used to connect metal brackets to a piece of glass. They are also used to connect glass sheets by using patch plates that cover both pieces of glass. Metal plates are placed on both sides of the glass and clamped together to generate a normal force and a corresponding frictional load capacity in the plane of the glass. A suitable interface is required between the glass and the plates. A soft metal (pure aluminium) or fibre-reinforced plastics are normally used to provide the required coefficient of friction and accommodate any lack of flatness between the glass and the metal plate.

3. Glass damage in past earthquake

Glass damage from earthquakes has historically been reported along with general non-structural damage. However, due to the significant usage of glass in buildings in recent decades, increasing emphasis has been placed on glass damage observations in earthquakes damage reports (Sucuoglu and Vallaban 1997). Sakamoto (1978) points out that, many broken window glass panels were observed in the 1964 Niigata and 1968 Tokochi-oki earthquakes in Japan, especially in flexible structures where nine of the 72 buildings investigated suffered glass damage including one building with 120 broken glass panels, but no other damages.

In the 1971 San Fernando earthquake, several buildings were reported with glass damage, with the amount of damage correlated to the degree of resilience of the glazing sealants (Ayres and Sun 1973). The off-Miyagi earthquake in February 1978 and the 1983 Mid-Japan Sea earthquake caused considerable glass breakage (Sakamoto et al. 1984). The extent of non-structural, mainly glass damage reported in these two earthquakes was greater compared to the Niigata and Tokochi-oki earthquakes. The 1985 Mexico City earthquake was well investigated from the point of view of glass damage. Seven of 263 investigated multistorey office buildings sustained minor to moderate structural damage, while over 50% of investigated buildings received some sort of glass damage and 25% were classified as having serious glass damage. In this earthquake broken glass is reported as the second most serious non-structural damage, following the damage to infill walls.

As expected strong correlation is observed between the inter-storey drift and glass damage, indicating that in-plane deformation response is the dominant cause of damage for window glass (Evans and Kenett 1988). Flexible glazing systems (metal curtain walls and mullions) aggravated glass damage due to drift whereas glass panels enclosed by more rigid glazing systems (precast curtain walls, or glass panels set in the structure) experienced less damage. Further, it is reported that glass damage consistently increases with larger window areas and irregular plan configurations. Glass panels used in the shopfront windows of single storey or low rise commercial buildings were observed to be extremely vulnerable to seismic excitations in all recent US earthquakes (Behr et al. 1995).

Reitherman and Sabol (1995) discuss that, in the 1994 Northridge earthquake, glazing damage was extensive and the principal cause of glass door and window failures was the inadequate edge clearances around the glass to allow the building to deform laterally without bearing on the glass. In some cases glazing damage was so severe that the supporting metal frames buckled. Low-rise buildings that incorporated annealed glass (rather than tempered, wired, or laminated glass required for taller buildings) produced sharp-edged pieces that could have caused serious injuries. Film-coated windows, on the other hand, performed well. An industry survey after the earthquake revealed that glazing incorporating silicon sealant performed better than glazing with vinyl gaskets (Harter 1994; Vallabhan 1994). Systems equipped with Mylar film to provide seismic protection from sharp glass debris performed very well in the case of small window panes, but proved less effective for larger window panes, where the entire pane was dislodged and fell as one big piece (Gates and McGavin 1998). A typical damage of frame glazed curtain wall is shown in Figure 1.

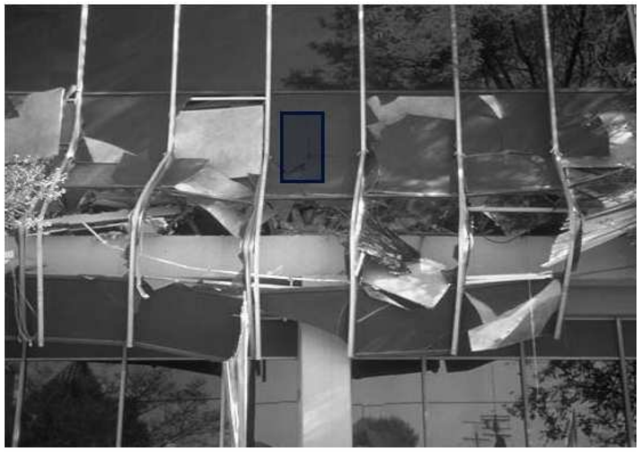

Figure 1 Kaiser Permanetate Building, Granada Hills, California, cladding offset NISEE Steinbruggecollection, photo by Mark Aschheim), (Shahram and Miranda 2003)

More recently the City of Bam, Iran was hit by an earthquake in 2003 destroying 70% of the buildings in the stricken area, and causing extensive non-structural damage to the buildings that remained structurally intact. The observed cases of non-structural damage were mainly architectural façades and damage to false ceilings, glass finishing and windows and door glass, parapets, and other attachments was also observed (Hosseinia 2005).

4. Previous Research and Experimental Investigations on Glazing Systems

A substantial number of laboratory and analytical studies related to the simulated seismic performance of architectural glazing within curtain wall framing systems have been performed over the past few decades. The following includes a summary of previous research findings. Most researchers adopted horizontal, in-plane dynamic racking tests to assess the behaviour and performance of architectural glazing systems on buildings during earthquakes (Sakamoto 1978; Sakamoto et al. 1984; Behr 1995b).

Thurston and King (1992) focused on assessing the behaviour of curtain wall glazing system when subjected to simulated inter-storey drift as may be expected to occur during the response of multi-storey buildings to earthquake attack. Both one-dimensional (planar) and two-dimensional (corner) specimens were tested. Glazing system investigated were, neoprene gasket dry-glazed systems, unitized 4-sided structural silicone glazed systems, a two-sided silicone glazed system and mechanically fixed patch plate systems (with toughened glass). Failure was considered to occur when more than 5% of the mass of glass supported in any frame fell from that frame. The test procedure involved cyclically displacing the floor beam (sliding steel beams) to a designed displacement (steadily increasing towards peak displacement).

Sucuoglu and Vallabhan (1997) focused on the behaviour of window glass panels during earthquakes and developed analytical techniques to determine the dynamic response of window glass and structural glazing systems by using simple mechanical models. Based on the derived expressions, a simple practical procedure was developed for the design of glass panels that would sustain the effects of earthquakes. The dynamic behaviour of window glass panels subjected to earthquake excitation was investigated by assuming two mechanisms consisting of rigid body movement and elastic deformation. The rigid body movement depends on the clearance between glass panel and the window frame, and resiliency of the sealant material whilst the elastic deformation includes diagonal shortening of the glass plate.

Behr (1998) conducted a four year research programme at the Building Envelope Research Laboratory at the University of Missouri-Rolla (UMR) to investigate the serviceability and fallout resistance of various types of architectural glass and related glazing systems under simulated earthquake conditions. In 1996 he performed “crescendo tests” on various types of architectural glass commonly employed in a popular curtain wall system for mid-rise buildings. The first crescendo tests performed at UMR on storefront glass included a lower ultimate limit state, corresponding to the drift required to form a major crack pattern in the glass, and an upper ultimate limit state, corresponding to the drift required to cause glass fallout. While performing the subsequent mid-rise glass tests, he modified the definitions of seismic drift limits for architectural glass to be as follows:

- A "serviceability drift limit" corresponding to the drift required to cause observable glass cracking (a condition that would necessitate glass replacement, but would not pose an immediate life safety hazard); and
- An "ultimate drift limit" corresponding to the drift required to cause glass fallout (a condition that would pose a life safety hazard to building occupants and pedestrians).

Crescendo tests revealed distinct and repeatable dynamic drift limits related to glass cracking and glass fallout for various types of architectural glass tested in a representative storefront wall system and a representative mid-rise curtain wall system. Demonstrable differences in seismic resistance exist between various types of architectural glass commonly employed in building design. Wall system stiffness, glass-to-frame glazing details and glass-to-aluminium edge clearances are also significant parameters in relation to the seismic performance of architectural glass. Behr (2001) found notable differences in seismic resistance exist between architectural glass types commonly used in contemporary building design, with annealed and heat strengthened laminated glass units showing the highest levels of resistance to glass fallout.

Memari et al. (2003) carried out in-plane dynamic racking crescendo tests on full-scale curtain walls dry glazed with six different insulating glass unit (IGU) configurations and one laminated glass unit configuration. All IGU configurations tested were manufactured with an annealed monolithic pane and a laminated pane with an argon fill and an anodized aluminium spacer between the panes. Several parameters were varied in the laminated pane of each configuration including glass pane thickness and glass type in the laminated pane (annealed, heat strengthened, and fully tempered), and PVB interlayer thickness for the laminated pane. Properties of the annealed inside pane were not varied. The test result showed that IGUs performed well.

Memari et al. (2004) conducted a pilot study at Pennsylvania State University to investigate the response of curtain wall mock-ups glazed with 6 mm annealed monolithic architectural glass panels fitted with anchored applied film under simulated earthquake conditions. Three common film-to-frame anchoring methods were evaluated. These preliminary tests indicated that anchorage type can demonstrably influence both the serviceability and ultimate limit states of filmed glass panels.

Behr et al. (2003) devised and developed the concept of using architectural glass panels with modified corner geometries to improve resistance to damage during earthquakes. The primary aspects of the innovations are the removal of material at glass panel corners (e.g., by rounding the glass corners) and subsequent finishing of the glass edges in the modified corner regions to minimize protrusions and edge surface roughness. The rounded corner glass panels with polished edges showed much higher resistances to glass cracking and glass fallout as compared to counterparts with seamed edges.

Saflex Solutia Architectural Glazing (2007) commissioned studies and participated in cooperative efforts with universities and the U.S. National Science Foundation to investigate glazing system performance in seismic events. By using the dynamic crescendo tests they concluded that, laminated glass tends to remain in openings when broken for any reason – wind, hail, wind-borne debris, bomb blast, accidental impact, intentional impact and during seismic activity. Test results revealed, however, that fully tempered laminated glass is not as advantageous in seismic applications when dry glazed, it tends to fold and fall like a heavy blanket if both plies are broken during racking motions. The impressive performance of annealed and heat strengthened laminated glass units in the BERL (Building Engineering Research Laboratory) tests represents a promising step toward the development of seismic-resistant glazing systems.

5. Recent Developments in Seismic Design of Architectural Glazing

Behr (2006) developed a set of seismic design provisions for architectural glazing. These proposed design provisions were modified through several standards and finally adopted by (in a slightly modified format) ASCE 7-02 (ASCE 2002). The seismic test details for glazed frames are provided in ASCE 7-02 whilst the dynamic loading test setup and the loading sequence are shown in Figure 2 and 3.

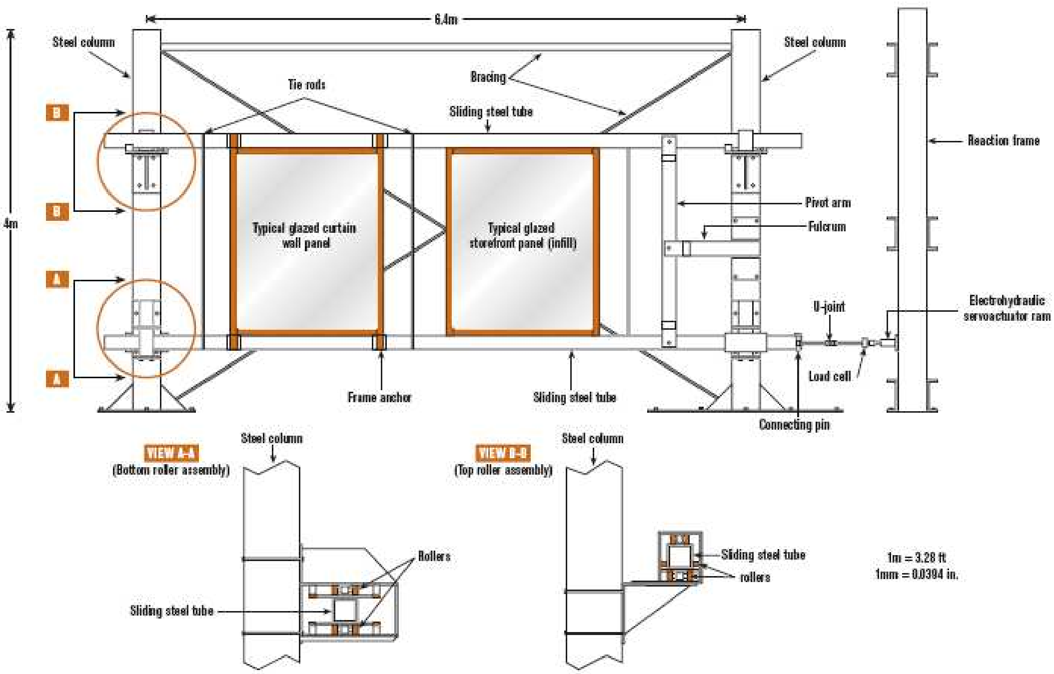

Figure 2 Dynamic racking test (Saflex Solutia Architectural Glazing 2007)

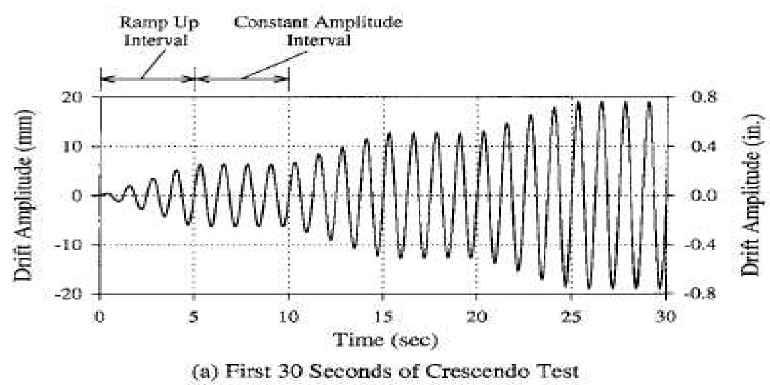

Figure 3 Drift time history for AAMA 501.6 dynamic racking crescendo test (Behr 2006)

In Australia, façades are designed to comply with AS 4420.0 (1996), AS 2047 (1999) and AS1288 (2006). Earthquake design requirements for façades are recommended by AS1170.4 (2007). The code suggests that designers to check the capability of façades to accommodate the required drift for the calculated inter-storey drift. In addition, the inter-storey drift at the ultimate limit state shall not exceed 1.5% of the storey height for each level and the attachment of cladding and façade panels to seismic-force-resisting system shall have sufficient deformation and rotational capacity to accommodate the design storey drift.

6. Finite element modelling

The development of code provisions and test standards addressing a perceived problem leads to increased attention toward the development of analytical procedures. However, only limited published literature exists investigating the seismic performance of glazing systems (for example Memari et al. 2007) related to finite element analysis. Memari et al. (2007) made a comparison between the predicted and measured strain at different locations. The glass curtain wall as shown in Figure 4 considered in the analysis with strain gauges mounted at selected locations on the glass and the aluminium framing was subjected to static racking loading as shown in Figure 6.

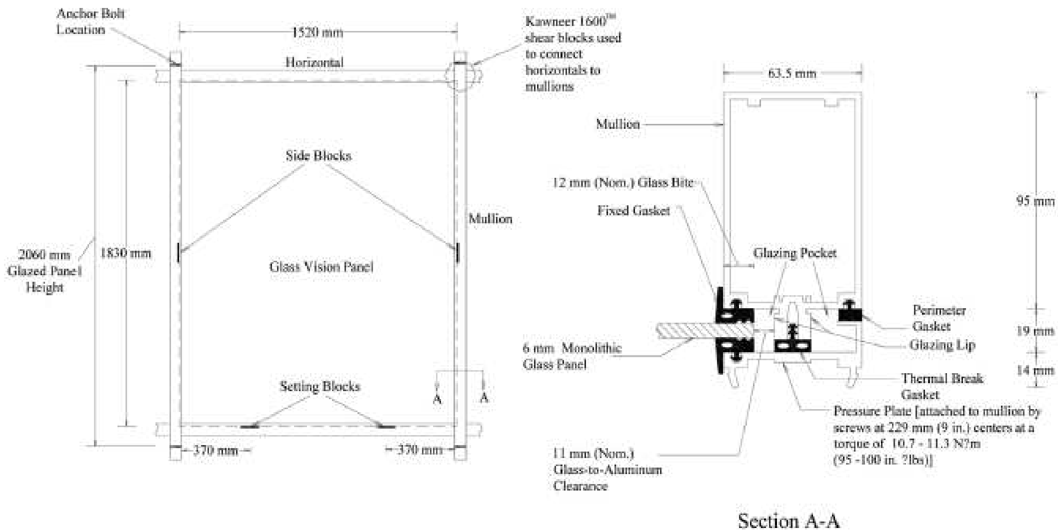

Figure 5 ***General glazing details for curtain wall mock-up test (Memari et al. 2007)***

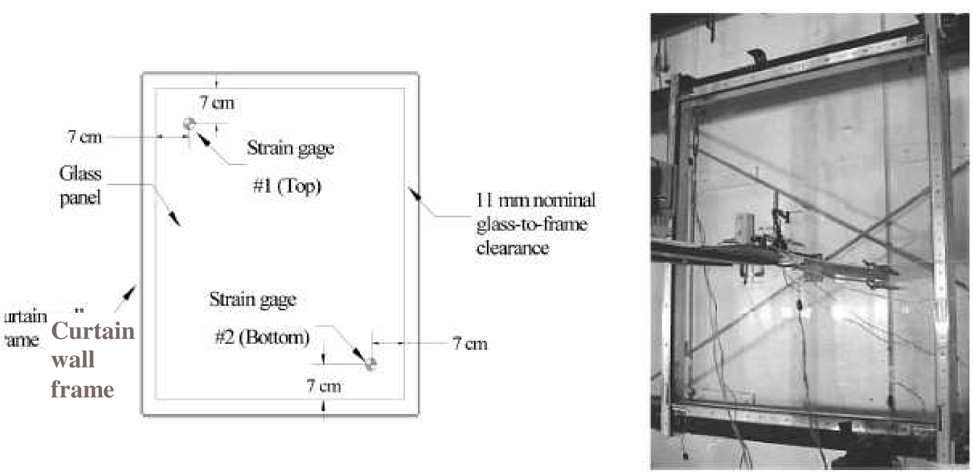

Figure 6 Strain gage locations on architectural glass curtain wall mock-up (Memari et al. 2007)

The load-displacement curve obtained from the test is shown in Figure 7. In the finite element analysis, both the rigid body movement of the glass and the deformation of the glass and frame (after glass to frame contact) are considered in the finite element modelling. Furthermore, the model should consider the effect of gasket friction, frame deformation, as well as the frame connections. They assumed the load application for the experiment was limited to a monotonic loading. The rigid body movement of the glass panel within the aluminium frame before glass to frame contact at the corners is generally resisted by the perimeter gasket friction determined using experimental data during mock-up testing. Therefore, rigid body movement was not directly considered in the finite element model. Instead, only glass and frame behaviour after glass to frame contact at both corners of one diagonal have been considered in the analysis. Consequently, it was necessary to subtract the gasket friction force from the total applied load as direct input into the finite element model analysis.

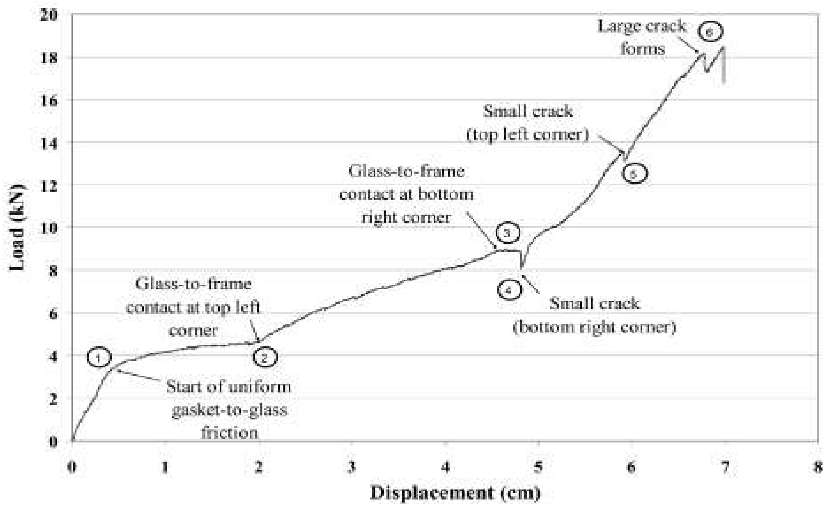

Figure 7 Load-displacement relationship during static (0.01 cm/sec) racking test (Memari et al. 2007)

In this study, the ANSYS finite element analysis program was used to develop the model using several element types. Four-node shell elements (SHELL 63) with six degrees of freedom per node were used to model the glass panel. Aluminium frame members were modelled using two-node beam elements (BEAM 3) with two planar translation degrees of freedom and one planar rotational degree of freedom per node. Finally, two-node link elements (LINK 10) with three planar degrees of freedom per node were used to model the glass-to-frame interface. Table 1 shows the results comparison made by (Memari et al. 2007) and the results show a certain degree of the discrepancy, however the authors of the research did not provide reasons.

Table 1 Comparison between analytical and experimental principal micro strains and crack orientations at the initiation of glass cracking (Memari et al. 2007)

Results	Test top	FEA top	Test bottom	FEA bottom
Maximum principal strain (10^{-6})	+125.8	-39	+30.2	-37.5
Minimum principal strain (10^{-6})	-345.7	-217	-202.7	-224
Angle between maximum principal strain and rosette reference (degree)	25.4	40.1	21.1	38.5

Note: refer to Figure 5 for locations of strain gauges

7. Conclusion and Summary

This paper has presented a literature review on types of glass facades and their behaviour under earthquake loading. From structural point of view, façade glazing systems can be generally classified into two main types, namely framed and frameless (especially point fixed) glazing systems. The conventional method of glazing is framed glazing, however current international trends is towards the installation of frameless glass façade systems for buildings to increase transparency.

From the literature review it has been observed that damage to glass façades resulting from earthquakes is increasingly common and yet there has been limited number of laboratory tests and detailed analyses undertaken. The research conducted to date seems to focus on traditional framed facades with annealed glass. However, the literature review revealed that annealed glass has not performed particularly well in past earthquakes. Some researchers have suggested improvements such as addition of smooth corners around each glass panel and adoption of more robust glass types such as heat strengthened, toughened and laminated glass.

Despite its growing popularity, there is very limited published research on the behaviour of frameless glass façade systems under the in-plane earthquake loading. Seismic performance of point fixed (frameless) glazing is likely to be quite different from conventional framed systems. A reliable and rational testing and analytical work is required to assess the drift performance of such systems. This is part of the on-going research undertaken by the research team to evaluate the vulnerability of glazed facades under in-plane seismic load.

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