In-plane drift capacity of point fixed glass façade systems

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Abstract

The point fixed glass façade system (PFGFS), also known as a spider glass system, is popular as it is the most elegant option among architects particularly compared to framed glass façade systems. The system is fixed onto the support structure at minimal points using bolts and metal clamps. Generally the racking performance of these systems is not considered at the design stage. If the system does not have enough in-plane drift capacity it will be vulnerable in racking actions mainly during earthquakes and wind actions. A unique real scale in-plane racking laboratory test on a typical point fixed glass façade system was conducted. The major aim of the project is to assess the in-plane racking performance of PFGFS.

In this paper, the laboratory test setup and the experimental results are discussed. A maximum drift of 2.1% was measured which was much larger than initially anticipated due to the rigid body articulation of the system. Analytical studies were carried out to interpret the racking behaviour of the PFGFS using the experimental results and presented and future research prospects are also discussed.

Keywords: Point fixed glass, in-plane drift capacity, façade systems

1 INTRODUCTION

1.1 Background

PFGFS is a relatively new contemporary curtain wall system which provides more transparency and improved aesthetics compare to the conventional framed glass façade systems. In the structural design of glass façades both out-of-plane and in-plane actions are considered by the façade engineer. Self weight, thermal expansion, spandrel beam deflection and in-plane building movements due to wind and seismic loadings are considered for in-plane design whilst wind load on glass panel is the main design action for out-of-plane performance. A typical point fixed glass façade system is shown in Figure 1.

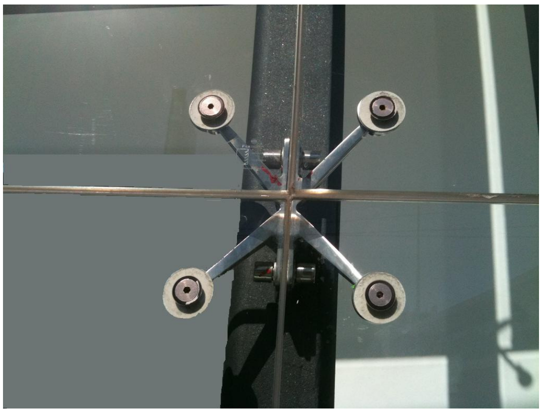


Figure 1 Typical point fixed glass façade system

From the seismic design perspective, glass façades are considered to be drift sensitive non-structural elements and the performance is dependent on the in-plane drift capacity of the glass façade system which should be greater than the in-plane drift demand. Severe earthquakes and winds cause damage to the main structural components of buildings as well as to the non-structural elements such as glass façade systems. There are two major concerns related to glass façade systems performance during and immediately following a major event.

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

A substantial number of laboratory and analytical studies related to the simulated seismic performance of framed glass façade systems have been performed over the past few decades. The most extensive testing programs were performed on framed glass façades at the University of Missouri-Rolla (UMR) and University of Pennsylvania (Behr, 1998, Behr and Belarbi, 1996, Behr et al., 1995, Memari et al., 2003, Memari et al., 2004). Based on these tests, ASCE 7-02 (2002) provides a general expression for assessing architectural framed glass façade systems under in-plane loading as expressed by Equation 1. The drift capacity ($\Delta_{fallout}$) should exceed the drift demand which is a function of relative seismic displacement (D_{p}) and the occupancy importance factor (I)

$$\Delta_{fallout} \geq 1.25 I D_p \text{ or } 13\text{mm whichever is greater} \quad (1)$$

However, seismic performance of PFGFS is different from conventional framed glass façade systems and there are no standards or design guidelines available to evaluate the in-plane drift capacity of such systems. Spider arms are used in PFGFS to connect the glass to the support structure, as shown in Figure 1&2 and the glass to the spider arms are connected using special bolt fittings (Figure 3). Despite its growing popularity, there is very limited published research on the behaviour of PFGFS under the in-plane action. Recently PFGFS with slotted holes in arms were adopted for construction in California (Gowda and Heydari, 2009). The performance of these systems was verified by mock-up tests.

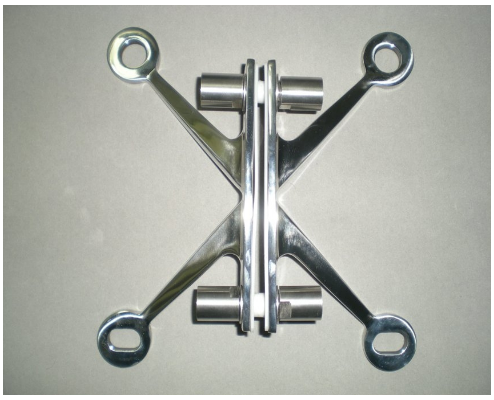


Figure 2 Typical four arms spider with slotted holes and circular holes

1.2 Scope and objective

A research project is being undertaken by Swinburne University of Technology, Australia to assess the racking performance of PFGFS. This involves laboratory experimental study and analytical modelling of PFGFS with toughened glass panels. This paper provides an overview of the laboratory experimental testing and analysis of the PFGFS. Details of the PFGFS configuration and experimental test set-up, instrumentation and test results are presented in Sections 2, 3 and 4 respectively. The racking performance of the PFGFS was simulated using ANSYS finite element software which is described in Section 5. Summary and conclusions are presented in Section 6.

2 SPECIMEN DESCRIPTION

The test was conducted on a typical PFGFS as shown in Figure 4, which consisted of four 1200mm x 1200mm toughened 12mm thick glass panels joined with 8mm thick silicon weather sealant. There are four different types of bolt fittings available in the market to connect the glass-to-spider arms namely, countersunk, button head, swivel button head and swivel countersunk as shown in Figure 3. Spider arms are classified into two main types, when considering raking behaviour; (a) pin connected to the support structure which allows in-plane rotation of glass panels at the spider arm-to-support structure connection (Figure 3) and (b) rigidly connected which does not allow the glass panels to rotate at the spider arm-to-support structure connection (Figure 1 & 2). The test described in this paper was conducted using countersunk bolt fittings and pin connected spider arms representing the cheapest and hence the most common practice.

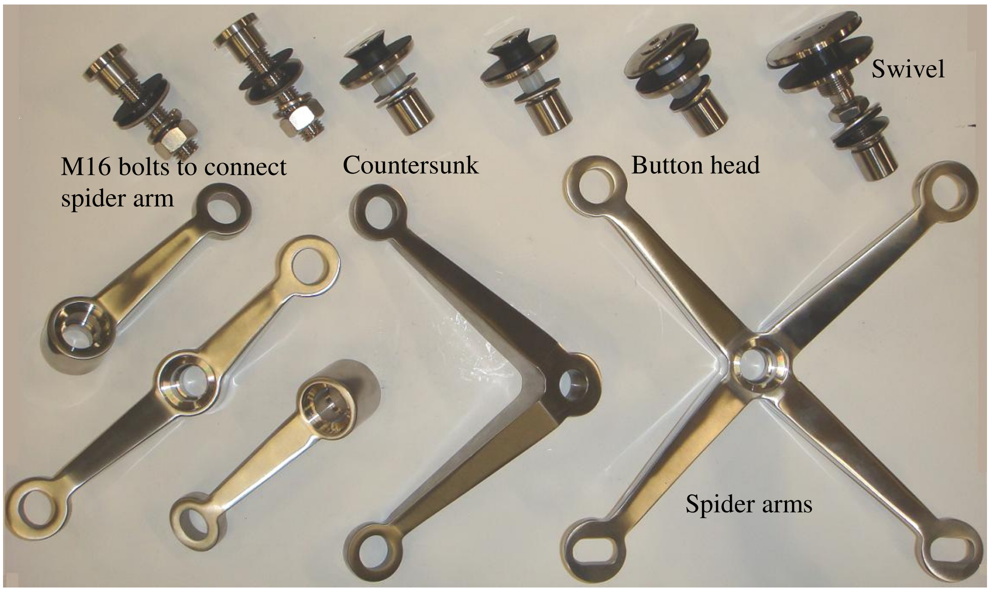


Figure 3 Spider arms for pin connection and bolt fittings

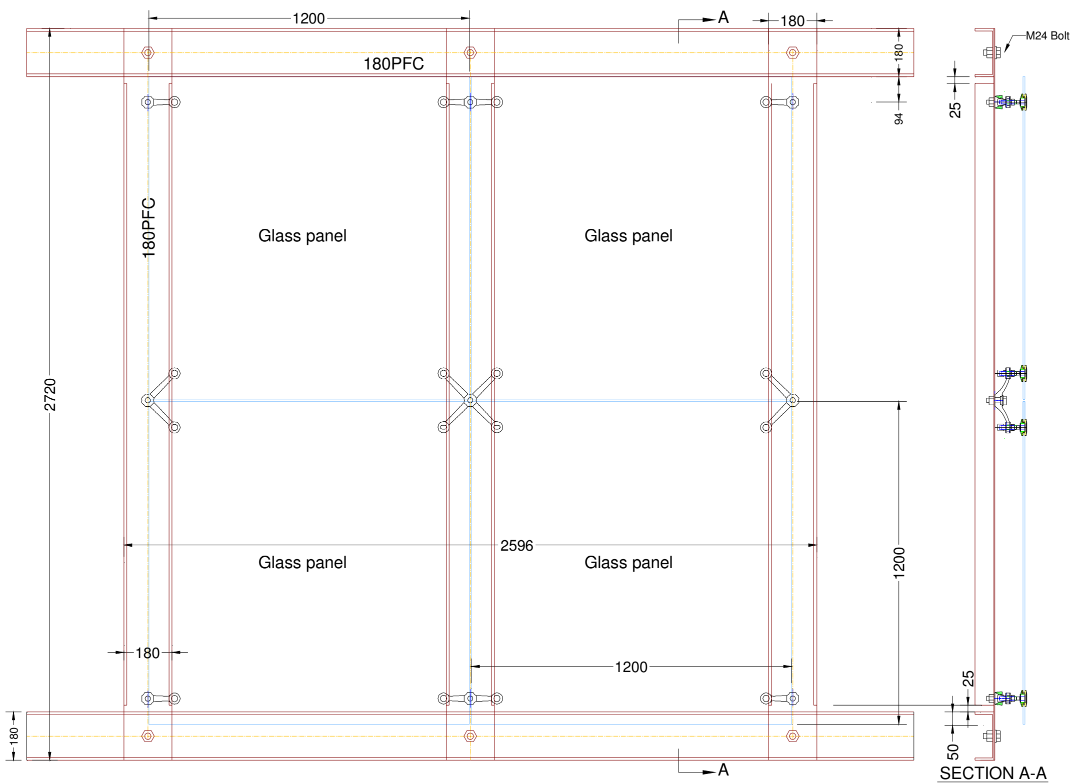


Figure 4 Proposed PFGFS

The glass hole details were prepared according to the location of the glass to spider arms connections and the dimension of the countersunk bolt fittings. A support structure was designed capable to fix four 1200mm x 1200mm glass panels and fabricated using 180PFCs as shown in Figure 4&5. The in-plane racking performance of PFGFS is dependent on three main components, the glass panels, the connection details and the support structure. In this test the support structure was articulated so that the racking performance of the glass panels and the connection details could be assessed.

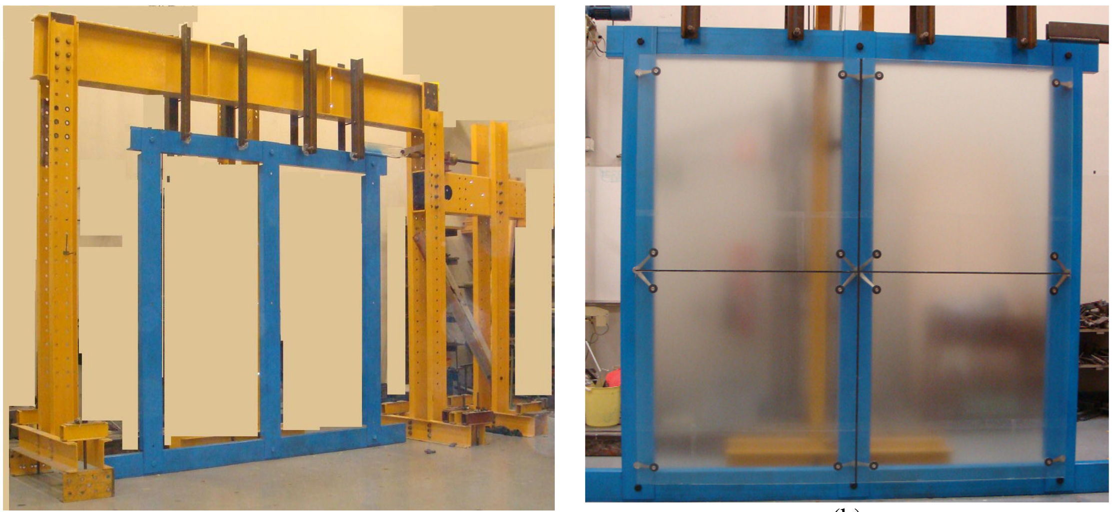
Preliminary analytical studies using ANSYS finite element software indicated that the critical failure modes of the glass panels were due to excessive tensile stress along the tensile diagonal of the glass panels with a predicted load of 24.5kN and a 17kN nominal shear capacity of the 10mm diameter grade 316 stainless steel countersunk bolt fittings.

3 EXPERIMENTAL SETUP

3.1 Detail of the test setup

The support structure (blue frame) was assembled into the test rig (yellow frame) as shown in Figure 5a. Three vertical and two horizontal PFC members were pin connected and snug tightened using M24 bolts to allow the frame to rack as a mechanism. The flanges of the vertical PFCs were cut off at both ends to make a flat outfit at the front side of the support structure (Figure 5). The setup was capable of resisting a 100kN in-plane lateral load and 150 mm in-plane displacement.

The support structure was prevented from moving in the out-of-plane direction by four sets of rollers mounted at the top (Figure 5a). The rollers ensured that the support structure was aligned with the loading direction. Once the support structure was assembled glaziers fixed the spider arms, glass panels and weather sealant (Figure 5b). A special transparent adhesive film was applied to the glass panels to secure the glass fragments for convenience following any glass fracture.



(a) (b)

Figure 5 'a' Support structure assembled into the test rig and 'b' Glass panels installed

A 300 kN, 50 mm stroke hydraulic jack was mounted on the reaction frame (yellow) shown in Figure 5a & 6 and used to laterally load the support structure (blue frame) and the façade system. The loading arm can be locked at any time and adjusted to increase the displacement demand required (Figure 6). The test area was also enveloped with nets to capture any flying glass following fracture and to ensure safety in the lab.

3.2 Instrumentation and Test procedure

The test procedure was as follows:

- The specimen was pulled at the top right hand corner in a step by step manner with displacement increments of 5mm until failure.

- Two systems of measurement were adopted to achieve good confidence in the data acquisition:
  - Displacement measurement with LVDTs (Linear Velocity Displacement Transducers) and
  - Photogrammetry
- Deflections were measured at 11 locations (horizontal, vertical and out-of-plane) with the LVDTs (Figure 6 and the applied load was measured using a load cell (Figure 6).
- Photogrammetry provided displacement data for the target points that were tactically positioned and marked with retro-reflective adhesive labels (Figure 8a). Photographs of the targets were taken before and after a sequence of loading and the relative movement in their positions were interpreted using software based on the principles of triangulation.

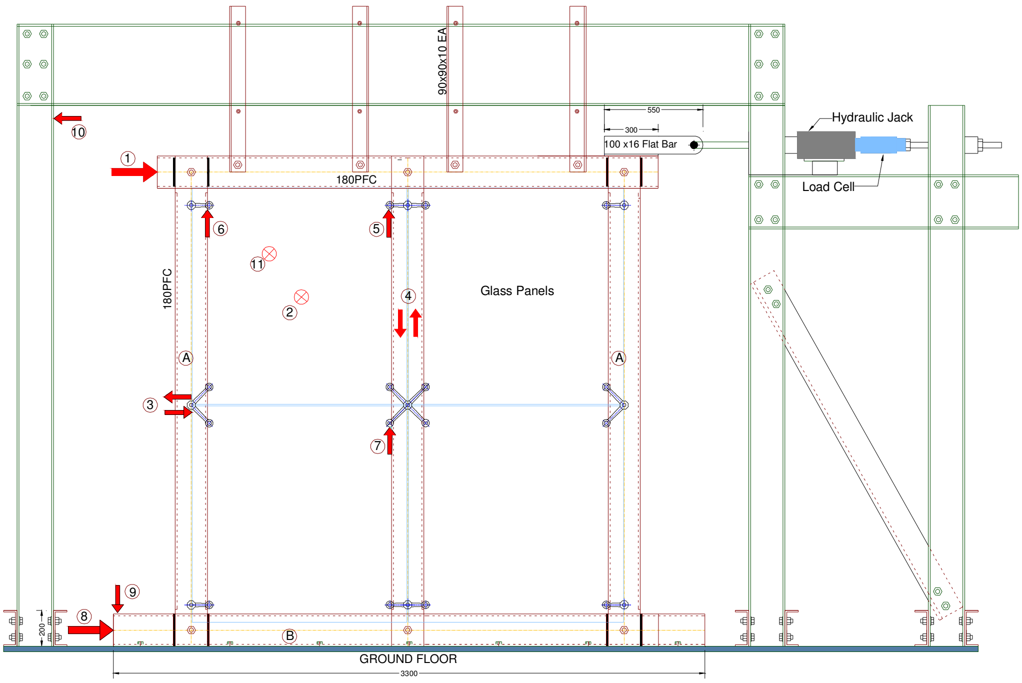


Figure 6 Locations of the LVDTs and the hydraulic jack and the loading bar attachment with the support structure

4 EXPERIMENTAL RESULTS AND DISCUSSION

The load-displacement curve measured at the top of the support structure (LVDT No 1 in Figure 6) from the test is shown in Figure 7. It indicates that the structure performed linearly until failure. A maximum displacement of 58.5 mm was measured with a corresponding 16kN racking load before failure. Surprisingly this resulted in a maximum of 2.1% in-plane drift capacity for the system with minor damage to the sealant and yielding of the spider arms, before catastrophic failure of one of the glass panels. The failure of the system and the glass panel are shown in Figure 8a & 8b respectively. The adhesive films protected the falling glass fragments.

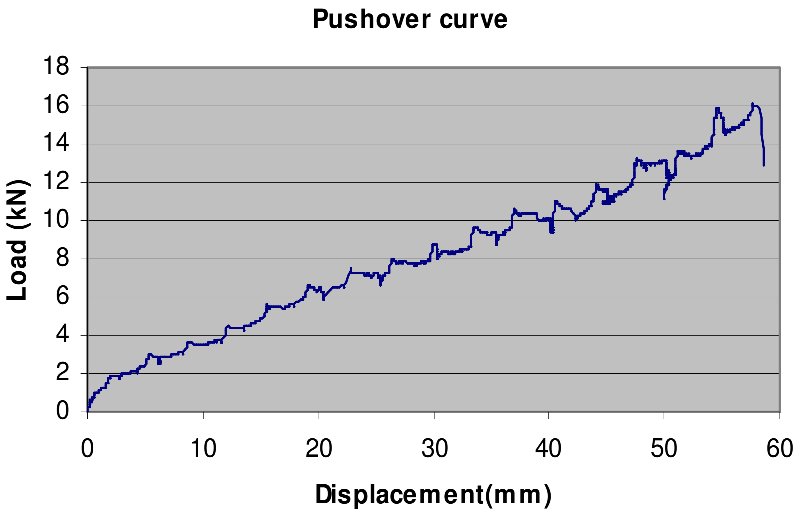
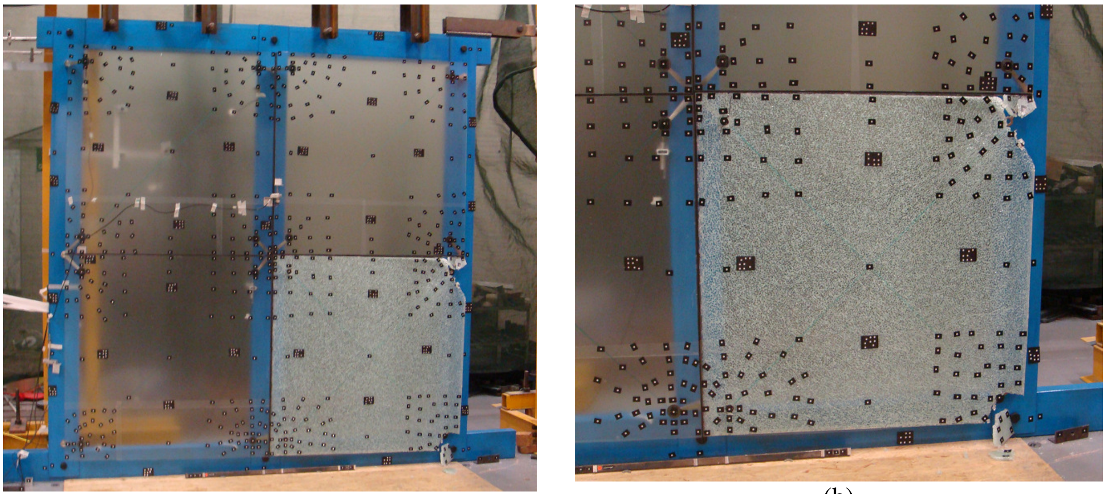


Figure 7 Racking load versus displacement for the PFGFS

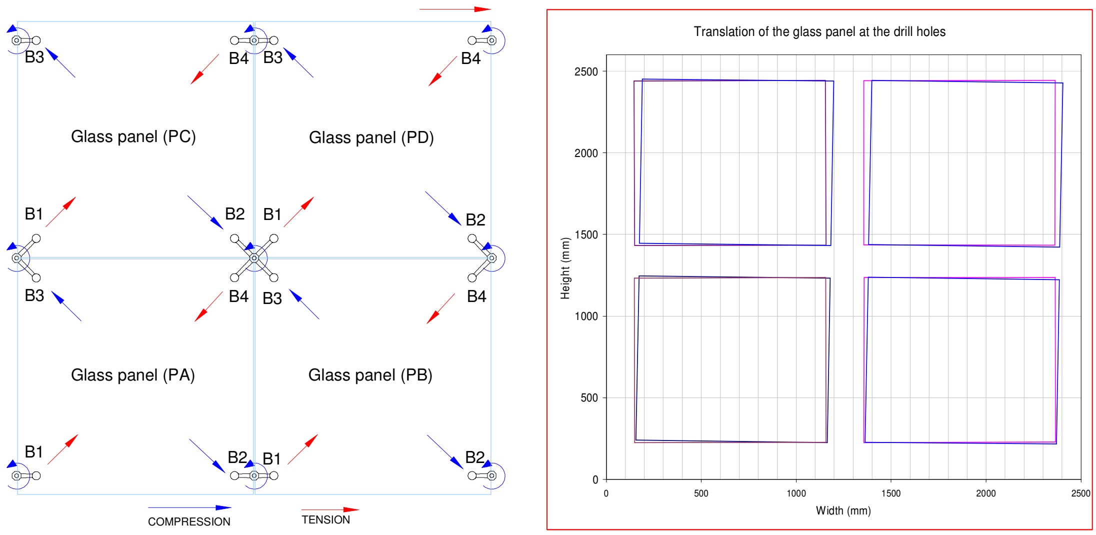


(a) (b)

Figure 8 The system after failure of a glass panel

It was observed during the racking test that the glass panels and the spider arms all rotated as rigid bodies whilst the sealant deformed at the interface. The spider arms used in this experiment had a frictional moment capacity of 200Nm beyond which rotation would occur. A simple truss analysis was carried out to determine the loading actions (tension or compression) in the panels as shown in Figure 9a. The initial (blue) and the final (red) locations of the panels are shown to scale in Figure 9b and these represent the translations that occurred in the glass panels before failure.

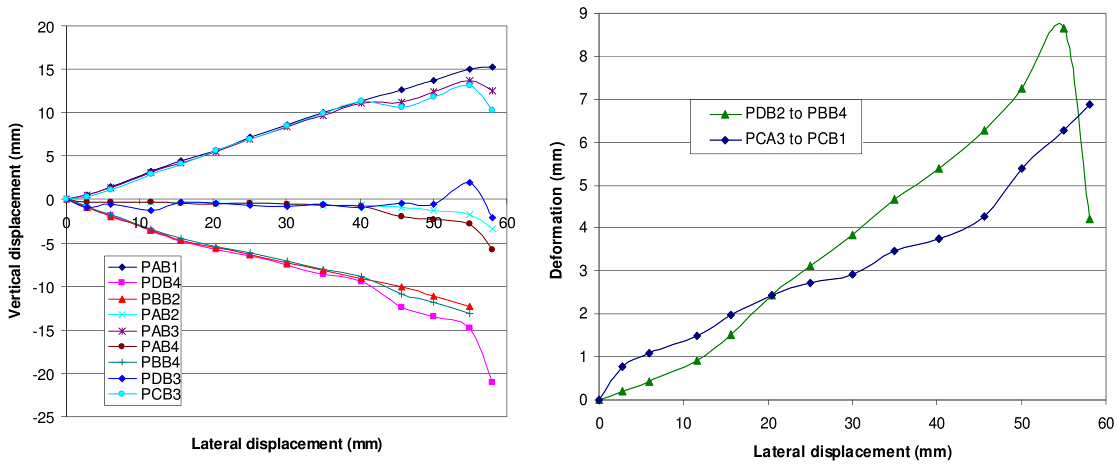
During the first step of loading with a 3mm racking displacement, rotation in a few arms was observed (Figure 10a). The weather sealant prevented the rotation of the arms connected to the PFC at the central interface of the four panels as the sealant was stiff against shear and compressive actions, however, rotations were observed in all the perimeter spider arms (Figure 10a).



(a) (b)

Figure 9 'a' Glass panels and spider arms labelled including the rotational directions 'b' Translation of the spider arms and glass panels

Interestingly the glass panels also displaced in an out-of-plane direction relative to each other. A significant amount of out-of-plane movement was observed between arms PBB4 (Panel PB spider arm B4) to PDB2 and PAB3 to PCB1 (Figure 10b) with a maximum differential movement of approximately 10mm, which induced combined local bending and tensile stresses particularly around the bolt to glass panel (Bolt PBB4) connection resulting in the initiation of cracking and catastrophic failure of the bottom right hand panel as shown in Figure 8.



(a) (b)

Figure 10 'a' Displacement of the spider arms in the vertical direction 'b' Differential out-of-plane movement of the spider arms

The 2x2 panel arrangement allowed the perimeter spider arms and hence the four glass panels to rotate about the four countersunk bolts of the internal central spider arm. These panel rotations allowed the system to move laterally and created the drift capacity despite the stiff sealant. However, a 3x3 panel arrangement would not have the same drift capacity since the internal panel and internal spider arms would be prevented from rotating. The mechanism can be verified using analytical modelling.

5 ANALYTICAL PREDICTIONS

A pilot study was carried out using ANSYS finite element software to study the translation of the glass panels and deformation of the spider arms. Non-linear spring elements COMBIN39 were used to specify the in-plane rotation of the spider arms. Shell elements and beam elements were used to model the glass panels and support structure respectively. The support structure was pin connected at the base and 50mm displacement was applied step by step. The effect of the sealant was ignored in the first model.

The concept of the 3D analytical model is illustrated in Figure 11a and the front view of the model which shows the mesh of glass panel and the bolt head is shown in Figure 11b. The translations and rotations of the glass panels are shown in Figure 11c after the application of a 50mm in-plane lateral displacement. The contour plot in Figure 11c indicates the out of plane deformation of the glass panels due to the out-of-plane deformation of the spider arms. The dark blue contours represent the minimum negative deformation and the red contours represent the positive maximum deformation. Figure 11d expresses the rotation of the spider arms to real scale. Even though the non-linear springs were assigned to have almost the same effect of friction, the stresses developed on the glass panels were small and the out-of-plane deformation was less than a millimetre.

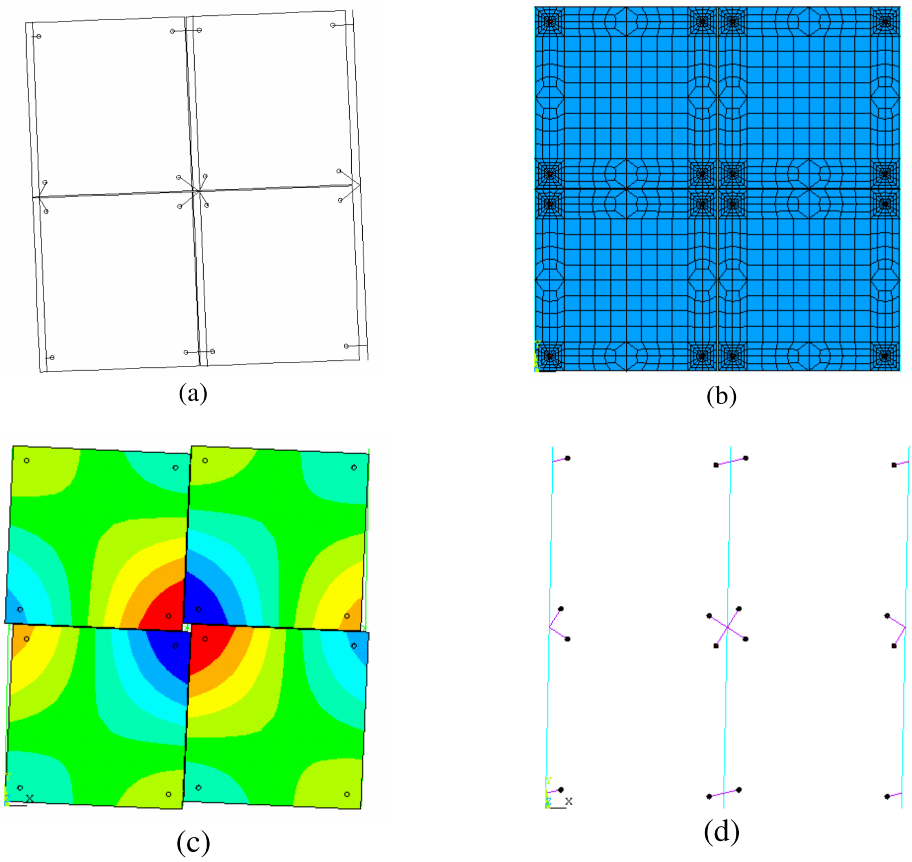


Figure 11 ANSYS finite element modelling and results

6 SUMMARY AND CONCULSION

The maximum drift of 2.1% was much larger than initially anticipated and demonstrated that the 2x2 system was surprisingly flexible. The 2x2 panel arrangement allowed the perimeter spider arms and hence the four glass panels to rotate about the four countersunk bolts of the internal central spider arm. These panel rotations allowed the system to move laterally and created the drift capacity despite the stiff sealant. Therefore, by using low modulus silicon sealant the racking performance of the same system could be increased further. The in-plane drift capacity of similar PFGFS with the same arms with different dimensions of glass panels can be calculated carrying out sensitivity analyses using analytical models. However, a 3x3 panel arrangement would not have the same drift capacity since the internal panel and internal spider arm would be prevented from rotating.

The racking performance of a PFGFS with fixed spider arms are expected to be different from the pin connected as they do not allow the arms to rotate. The next experimental test will be carried out on a typical PFGFS with rigidly connected spider arms. Analytical models are underway to verify these systems and based on that a simplified methodology will be proposed to assess the racking performance of PFGFS. Further rational testing and analytical work is required to assess the drift performance of PFGFS. This is also a part of the on-going research undertaken by the authors to evaluate the vulnerability of glazed façades under in-plane seismic loading.

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