Seismic performance of Point Fixed Glass Facade Systems through Finite Element Modelling and proposal of a low-damage connection system

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Abstract. Among glazed curtain walls, the growing interest in Point Fixed Glass Facade Systems (PFGFS), simply known as "Spider Glazing", is mainly due to their aesthetics, architectural attractiveness and high transparency they can provide when compared to more traditional framed glass facades. PFGFS are in fact punctually attached to the structure by using spider arms and bolted fittings. However, some PFGFS solutions have shown an unexpected moderate seismic vulnerability in recent earthquake events, as a consequence of inadequate connection detailing. As part of current seismic design philosophy, high structural and non-structural damage is accepted under a design-level earthquake. This inevitably leads to high post-earthquake losses in terms of both repair costs and business interruption for the damaged buildings. Therefore, nowadays the need for research efforts towards the development of low-damage technologies for the overall building system, including structural and non-structural components, is increasingly recognized.

This paper aims at investigating the seismic performance of PFGFS through numerical studies at both local-connection level, by advanced non-linear FEM modelling implemented in ABAQUS software, and at global-facade system level, through a simplified lumped plasticity macro-model developed in SAP2000 program. Non-linear static (PushOver) analyses have been carried out to assess the overall in-plane capacity of the facade. Based on the numerical outcomes obtained for a PFGFS consisting of traditional connections (i.e., available on the market), a novel low-damage system has been proposed. This solution comprises horizontal slotted holes for the bolted connection of the spider arms to the supporting structure. A parametric analysis, involving the variation of the slotted hole length, has been finally performed to study the effectiveness of the proposed solution. Results highlight the improvement of the in-plane capacity of the PFGFS, specifically an increase of the maximum allowable inter-storey drift ratio from 1.17% for the traditional system to 2.49% for the low-damage connection.

Keywords: Non-structural components, Glass Facade Systems, Numerical Modelling, Seismic Performance, In-Plane Drift Capacity.

1. INTRODUCTION

Earthquakes that occurred worldwide in the last years have further highlighted the high vulnerability of non-structural components (e.g., architectural elements, mechanical and electrical equipment, contents). Specifically, post-earthquake surveys and reconnaissance on damaged buildings have pointed out how non-structural components can lose functionality even under low-intensity earthquakes, and eventually reach collapse under moderate-to-strong ground motion intensities, leading to a life-safety threat for both occupants as well as pedestrians around the building, [Perrone *et al.*, 2019]. As a result, nowadays it is well acknowledged that such components can highly increase building repair costs, as well as daily inactivity and business interruption (downtime), leading to unsustainable socio-economic (direct and indirect) losses. This justifies the growing research effort, in the last years, towards the implementation of integrated low-damage buildings (both for structural as well as non-structural components) to achieve the goal of a more resilient society against seismic hazard, [Pampanin, 2015; Bianchi *et al.*, 2021]. Specifically, the crucial need for including non-structural components in the design/assessment/loss analysis of buildings is justified when considering the large investment associated with them. For example, Taghavi and Miranda [2003] pointed out that the investment related to non-structural components is 82%, 87% and 92% of the total construction building cost for offices, hotels, and hospitals, respectively. Moreover, such a high value could further increase in the case of Glazed Facade Systems (GFS), being such components among the most expensive.

GFSs are growing in interest due to their high transparency and elegancy. Among GFSs, a relatively novel solution is the Point Fixed Glass Facade System (PFGFS), which allows greater transparency with respect to traditional solutions. GFSs are featured by curtain walls in which mullions and transoms are used. If PFGFSs are used, punctual supports are provided exclusively by spider elements (described in the following section), enhancing the elegance and transparency of the building envelope. Even though recent studies have proved the enhanced performance of PFGFSs with respect to traditional GFSs, recent earthquakes, specifically the 22nd February 2011 Christchurch Earthquake, New Zealand, have proved the vulnerability of such a system under strong earthquakes. Figure 1 shows the extended damage of the building envelope of a modern building in the city of Christchurch, [Baird *et al*, 2011a].

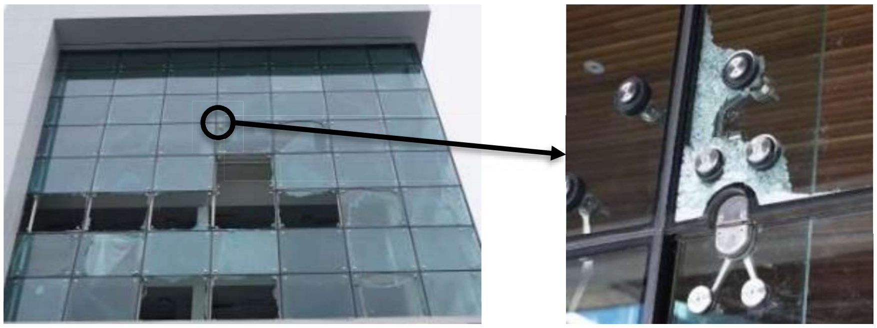

Figure 1. Example of damage in a PFGFS in a modern building located in Christchurch (left), and particular of the damage, due to tensile stress concentration, of the glass panel around the fixing zone (right), [Baird *et al.* 2011].

The main objective of this paper is to investigate the seismic performance of PFGFSs considering the connection systems currently available on the market and to propose an innovative solution, able to improve the seismic performance when the system undergoes moderate-to-severe earthquakes. To achieve these goals, firstly, detailed non-linear 3D Finite Element Models (FEM) is implemented in the software ABAQUS to investigate the local (connection-level) behaviour of the system. After that, using the results from the micro-modelling investigations, a refined lumped-plasticity macro-model is implemented in the software SAP 2000 to define the overall seismic performance of the facade. Finally, an innovative low-damage connection system is proposed, and a comparison (with respect to the traditional connection details) is carried out to investigate the benefits of implementing the latter.

2.DESCRIPTION OF PFGFSs AND THEIR PERFORMANCE

In this paragraph, a brief description of PFGFSs is provided (further information can be found in Inca *et al.* [2019]). PFGFSs generally consist of four components: the supporting structure, glazing support attachments, bolted fixings, and glass panels. The supporting structure generally consists of a light metallic frame to which the spider elements are attached. It is worth noting that using such a component is not mandatory, and the spider elements can be attached directly to the building structure through T-shaped supporting plates. In this case, larger glass panels are used, but as a counterpart, they become much more vulnerable to the in-plane actions [Sivanerupan, 2010]. Figure.2 schematically shows an example of PFGFS.

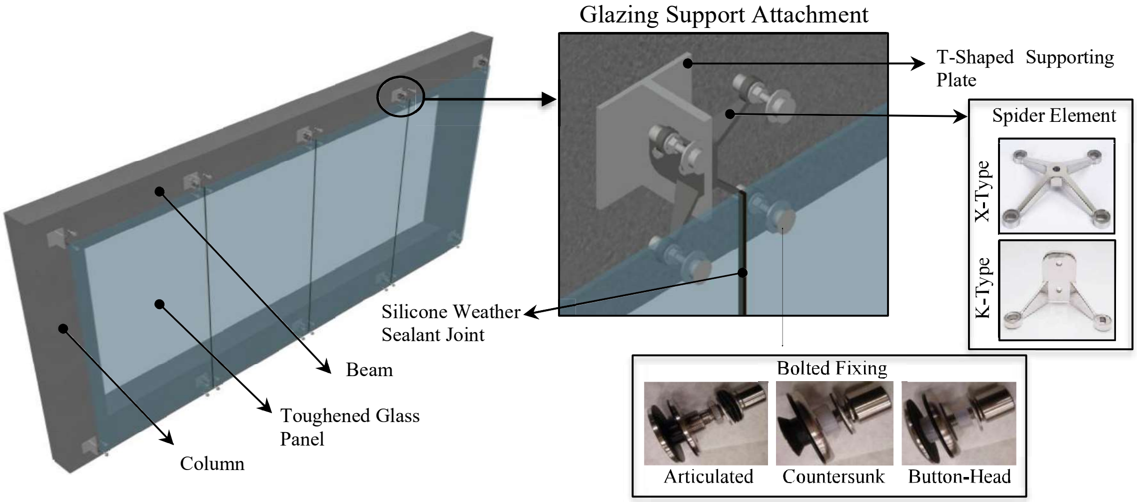

Figure 2. Schematic representation of a PFGFS without supporting structure

The spider elements (e.g., the glazing support attachments), allow to transfer the load to the supporting structure (if used) or directly to the building structure itself. Nowadays, two types of spider elements are available on the market, specifically, the pinned "X-Type" and the sliding "K-Type". The details of such components lead to different capacities in accommodating the in-plane movement of the facade (major details in the following). Further, several bolted fixings are available. These elements are located nearby the corner of the glass panels, and they allow the transfer of the load to the spider element. Bolted fixings can be featured by an articulated system as well as by a fixed one. In the former case, a "spherical joint" allows a higher performance of the facade as a greater rotation and displacement of the glass panel to the fixing can be accommodated without causing excessive stress concentrations. In case a fixed system is used, "countersunk bolts" as well as "button head bolts" are available. In these latter cases, the load is transferred through the bolt to the glass interface, and the system is less performing when compared to the articulated one. Finally, considering the glass panels, toughened or laminated glass is generally used. The main difference is related to the strength of the glass panel itself. In case of laminated glass, two or more panels are bonded together through an intermediate layer (generally polyvinyl butyral, PVB). The resulting "overstrength" should be carefully taken into account in the design phase, as it could affect the correct "hierarchy of strength" and the connection system could become the "weakest link" leading to the potential fallout of the facade, thus resulting in a life-safety threat, [Baird *et al.*, 2011b; Diaferia *et al.*, 2011]. Toughened glass is less resistant, and it is characterized by the property of fragmenting into small pieces in case of rupture.

As pointed out previously, PFGFSs are a relatively novel type of glazed facade. For this reason, limited investigations are available in literature. At the Swinburne University of Technology, Melbourne, Australia, two full-scale displacement-control monotonic tests have been carried out to assess the in-plane capacity of such systems, [Sivanerupan *et al.*, 2014]. The two specimens, featured by the use of X-Type and K-Type spider elements, consist of four 1200x1200mm toughened glass panels 12mm thick, with a silicone weather sealant joint of 8mm. The tests have been carried out pushing the system until the failure of the first glass panel. Further, numerical investigations have been implemented and benchmarked against the experimental results, [Sivanerupan *et al.*, 2016]. The experimental tests, as well as the numerical investigations, pointed out that PFGFSs tend to accommodate the in-plane movement through three main mechanisms, and the difference between the X-Type and the K-Type solution is related only to the first. If X-Type elements are used, the first mechanism is related to the in-plane rigid-body rotation of the spider element itself, while, in case of K-Type, rigid-body translation of the spider element at the base slotted hole connection to the supporting plate is observed. The second mechanism is a rigid body translation related to the built-in standard gaps between the bolts and the holes within the spider arms, as well as between bolts and glass panels. The last mechanism is related to the deformation and yielding of the spider arms, which facilitate the out-of-plane movement of the panels. The out-of-plane movement, together with the diagonal tensile stresses around the bolted connection, bring to a rapid increment of tensile stresses, leading to a brittle failure of the glass panels. The results of the experimental tests highlighted a better performance of the facade system featured by K-Type elements (maximum allowable drift of 5.25%) with respect to the one in which X-Type elements were used (maximum allowable drift of 2.01%). Considering the superior behaviour of K-Type elements, this work focuses on such components as a basis solution to further improve their performance, moving towards a low-damage system.

3.DETAILED FEM MODELLING OF PFGFSs COMPONENTS

This chapter describes the Finite Element Modelling (FEM) approach implemented in the software ABAQUS to assess the behaviour of the PFGFS components, namely the frictional behaviour of the spider element, the bending of the spider arms, the silicone weather sealant joints, and the bolted fixings.

3.1 THE SPIDER ELEMENT

Firstly, a refined 3D non-linear FEM has been developed in ABAQUS to capture the frictional behaviour of the spider element to the supporting plate, as well as the flexural behaviour of the spider arms. After that, the results from the ABAQUS analyses have been used to calibrate a simplified, yet accurate, system of frame/link elements for implementing the macro-model of the overall facade system.

In order to assess the frictional behaviour of the spider element to the supporting plate, simplified assumptions have been considered, allowing a reduction of the computational effort. Specifically, the T-shaped supporting plate has been simplified considering only the part to which the spider elements are attached. Further, this plate has been constrained by fixed support, modelling a rigid connection to the building structure. Finally, in order to study the frictional behaviour, the spider arms have been removed from the model. Figure 3 (left) shows the real connection between the structure and the glazing support attachment (a), as well as the simplified system considered in the analyses (c). The simplified model consists of three parts: i) the supporting plate, ii) the spider element(s), and iii) the bolts. The overall model has been implemented using the quadratic brick element C3D20R featured by 20 nodes with reduced (2x2x2) Gauss integration points.

Two materials have been used into the model: i) the stainless steel AISI 316 modelled as an elastic material and used for the supporting plate as well as the spider element(s), and ii) the stainless steel A4 modelled as an elastic-plastic material and used for bolts. The parameters for implementing the correct material characteristics of bolts depend on their resistance class (CR). Specifically, CR 50, 10mm diameter bolts have been used. The material properties used to implement the plasticity are: the yielding stress σy (210 MPa), the ultimate stress σu (500 MPa), as well as the ultimate strain εu (11.40%).

The frictional behaviour among the parts has been modelled through tangential and normal behaviour within the contact surfaces. For the first one, a frictional coefficient μ for steel-to-steel contact has been selected (μ = 0.30, according to the Italian Building Code [NTC, 2018]). The normal behaviour has been modelled as Hard Contact. Further information about the modelling of frictional interaction are available in the ABAQUS Standard user's manual [2009]. After that, a relative movement between the supporting plate and the spider element(s) has been applied until the gap closure, i.e., when the bolt shanks get in contact with the plate holes. Figure 3 (right) shows the force-displacement curves representative of the frictional behaviour for two assemblies consisting of one (Type A), as well as two (Type B) spider elements. Further, a particular of the mesh used in such analyses is shown. Focusing on the force-displacement curves, it is worth noting how forces increase in the connection until the critical frictional-force is achieved, then the sliding is triggered. After that, the sliding continues until the gap closure, where it is possible to note a sudden increase in stiffness. In this condition, there is a rapid increment of forces which cause a sudden increase of tensile stresses in the glass panels until the failure. These results allow to define multi-linear links for modelling the frictional behaviour into the proposed macro-model of the overall facade system.

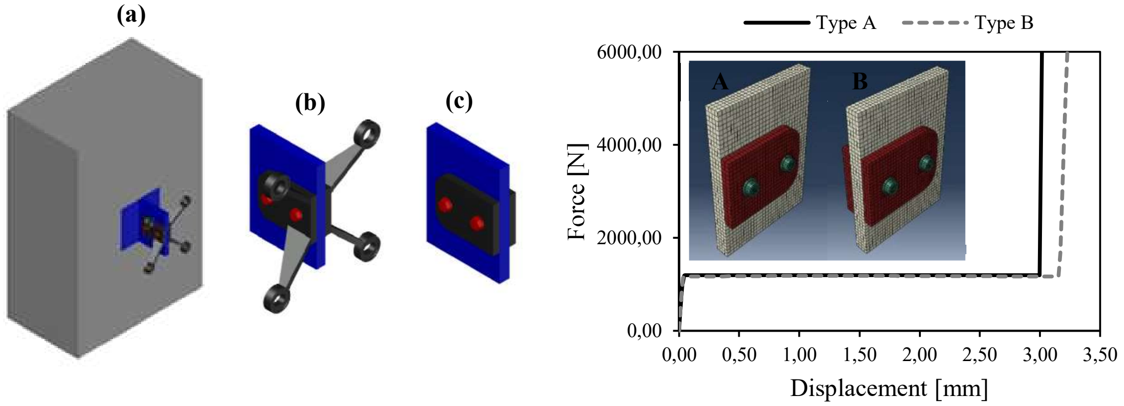

Figure 3. Left: (a) Schematic representation of the real connection, together with the simplified models used for the assessment of the (b) flexural behaviour, as well as of the (c) frictional behaviour; Right: force-displacement curves representing the frictional behaviour of the glazing attachment systems together with the particular of the mesh.

Once the frictional behaviour of the connection had been assessed, the second task focused on the assessment of the flexural behaviour of the spider arms. Specifically, to reach this goal, the aforementioned model was enriched by modelling the spider arms, Figure 3 (left, b) and Figure 4 (left).

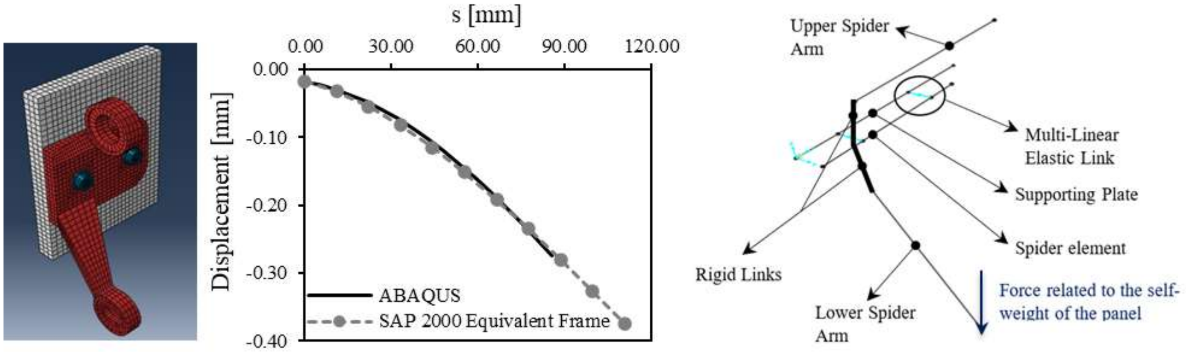

Figure 4. Left: ABAQUS model used to assess the flexural behaviour of spider arms; Centre: calibration of the equivalent frame for spider arms; Right: simplified lumped-plasticity macro-model for the glazing support attachment.

This model allows assessing the flexural behaviour of the spider arms under a vertical force, representing the self-weight of the glass panel. The analysis aims at calibrating the cross-sectional area properties of the equivalent frame to be used in SAP 2000, for modelling the complex geometry of the spider arms. In fact, such an element is featured by variable cross-sectional area properties. Using the results of the ABAQUS model, an iterative procedure has been carried out benchmarking such results with the analyses carried out on a simplified model consisting of the equivalent frame/link elements system. Figure 4 (centre) shows the comparison of the analyses carried out both in ABAQUS as well as in SAP 2000 in terms of the deformed shape of the spider arm when the self-weight force from the glass panel acts. The frame element used for modelling the spider arms consists of a simple rectangular section 30.5mm width and 13.5mm height. Finally, Figure 4 (right) shows the simplified system, used for modelling the glazing attachment system into the lumped-plasticity macro-model. Such an equivalent system consists of frame elements for supporting plate and spider(s) (the same cross-sectional area properties of the real element have been considered), the equivalent frame elements for the spider arms, and multi-linear links for modelling the frictional behaviour. Finally, it is worth noting that in such work, only monotonic (pushover) analyses have been carried out. This justifies the use of multi-linear links as acceptable for modelling the monotonic in-plane behaviour of the facade system. In case cyclic analyses were needed, refined link properties should be accurately calibrated to capture the actual hysteretic behaviour.

3.2 THE SILICONE WEATHER SEALANT JOINT

This paragraph focuses on the behaviour of the silicone weather sealant joint. Specifically, a refined non-linear ABAQUS model has been implemented, and the material characteristics have been calibrated with the experimental results on such a component, as widely investigated in Sivanerupan *et al.* [2016]. The experimental tests have been carried out on 100x100mm specimens consisting of two toughened glass panels (12mm thick) with an 8mm thick silicone weather sealant joint. The specimens have been tested subjecting the silicone to tension, compression and to shear forces.

The refined 2D non-linear model implemented in ABAQUS, used to simulate the experimental tests, consists of both linear (implemented for modelling glass) as well as non-linear (for modelling silicone) shell elements. Glass has been modelled as an elastic material, while silicone has been modelled as an elastic-plastic material for loads cases simulating tension as well as shear, while as a hyperelastic material in case of compression. By means of iterative procedures, the material properties have been defined by calibrating the numerical analyses against the experimental tests. Figure 5 (left) shows the force-displacement curve considering the load cases (i.e., tension, compression, and shear) for an 8mm thick silicone weather sealant joint.

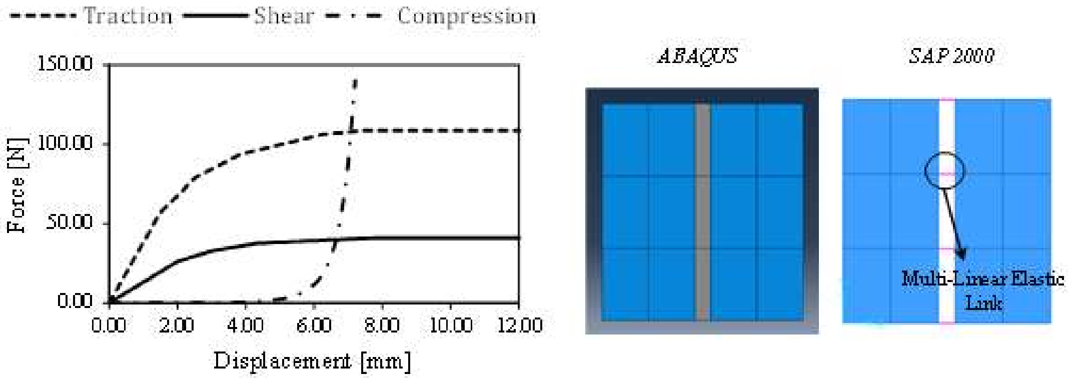

Figure 5. Left: Force-displacement curves representative of the silicone weather sealant joint behaviour; Right: refined non-linear model implemented in ABAQUS together with the simplified one developed in SAP 2000.

Finally, the results of the ABAQUS analyses have been used to calibrate a simplified, yet accurate, model in SAP 2000. Specifically, multi-linear elastic links have been used to replace the complex non-linear shell elements used in ABAQUS. This approach allows for a less computational expensive and more practical analysis. Figure 5 (right) shows the refined non-linear model in ABAQUS as well as the simplified one developed in SAP 2000.

3.3 THE BOLTED FIXINGS

This paragraph focuses on the connection between the glass panel and the spider arm through the bolted fixing. Specifically, countersunk bolts ("fixed" systems) have been adopted in this case. As pointed out previously, higher-performance facade systems could be implemented using "articulated fixings". Nevertheless, the complexity related to the definition of a reliable model of the ball-joint requests further research efforts, and it is out of the scope of this work.

Firstly, a refined 3D non-linear model has been implemented in ABAQUS. The model is similar to those implemented for studying the frictional behaviour of the supporting plate to the spider element connection, and for the flexural behaviour of the spider arm. Also, as in the previous 3D models, the C3D20R hexahedral element has been used for implementing the numerical ABAQUS model. In order to evaluate the frictional behaviour of the bolted fixing to spider arms, the overall model, Figure 6 (left), has been used focusing on the spider arms end. Specifically, a relative displacement between the bolted fixing and the spider arms has been applied until the gap closure, in order to evaluate the force-displacement curves representative of the frictional behaviour. Two analyses have been performed to capture the differences between the two connections. The former analysis focuses on the frictional behaviour of the bolted fixing to the upper spider arm. In this case, the connection consists of a circular hole, and the same relative movement is allowed both vertically as well as horizontally. In the second case (lower connection), there is a horizontally slotted hole, which allows only horizontal movement.

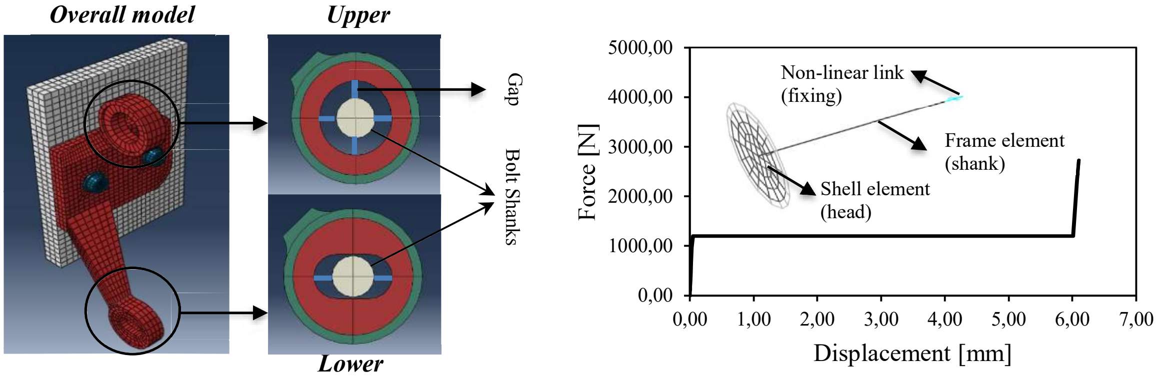

Figure 6. Overall model implemented in ABAQUS with particulars of the upper and lower connection of the bolted fixing to the spider arm (left); force-displacement curve representative of the frictional behaviour of the bolted fixing to the spider arm together with the schematic representation of the simplified model of the bolted fixing.

Finally, as in the previous cases, the results from the ABAQUS micro-model have been used to implement the simplified, yet refined, lumped-plasticity macro-model of the overall facade system. Specifically, such analyses have been used to calibrate a frame/shell/link elements system able to capture the behaviour of the bolted fixing. The simplified model of the bolted fixing consists of shell elements used to model the bolt head, a frame element for modelling the bolt shank, and a multi-linear link for modelling the frictional behaviour of the bolted fixing to the spider arm. Figure 6 (right) shows the force-displacement curve representing the frictional behaviour of the lower connection, together with a schematic of the simplified model implemented for the bolted fixing.

4.SIMPLIFIED MACRO-MODEL OF THE OVERALL FACADE

In this paragraph, the seismic assessment of the overall performance of a PFGFS using traditional K-Type element is assessed and discussed. Referring to the detailed 3D non-linear analyses carried out in ABAQUS at a local (connection) level, a macro-model has been developed in SAP 2000. The PFGFS is coupled with a portion of a Moment-Resisting Frame (MRF) system, modelled through frame elements. Considering the facade, the spider elements, together with the bolted fixings, are modelled by an equivalent frame/non-linear link system. The silicone weather sealant joint is modelled through multi-linear elastic links. Finally, the glass panels are modelled with shell elements. Referring to the glass panels, it is worth noting that a refinement of the mesh has been provided around the bolted fixings. Figure 7 (left) shows the implemented macro-model in SAP 2000, together with the refinement of the mesh.

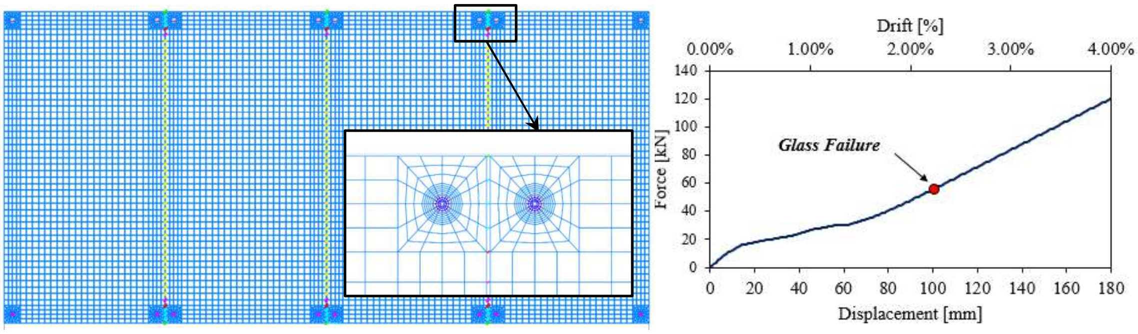

Figure 7. Schematic representation of the traditional as well as innovative solution (left); and stress distribution in bolts for the two configurations.

Non-linear static (pushover) analysis has been performed to define the force-displacement capacity curve of the PFGFS, Figure 7 (right). The principal tensile stresses of the glass panels have been monitored during the analysis in order to assess the glass failure. The failure of the first panel is assumed when the maximum principle tensile stress, f_g, reaches the maximum allowable stress, $f_{g,d}$, according to DT-210 guidelines [CNR, 2013]. These guidelines provide such value according to several parameters (i.e., glass panel dimensions, aspect-ratio, etc.). For the PFGFS assessed herein, four 2000x3800mm, 12mm thick toughened glass panels are considered, and the maximum allowable tensile stress, according to DT-210, the maximum allowed principle tensile stress, $f_{g,d}$, is 82 MPa. The silicone weather sealant joint thickness is 8mm.

The maximum allowable drift value for this PFGFS is 1.17%. It is worth noting that such a value is lower than the5.25% drift capacity observed in the experimental investigations, [Sivanerupan *et al.*, 2014, 2016]. This was expected as the performance of PFGFSs depends on several factors. First, in Sivanerupan *et al.* [2014, 2016], spider elements with vertically slotted holes, enabling for a better performance, rather than with circular holes, were adopted. Further, in those tests, square panels with a length of 1200mm were used. In this case, rectangular glass panels 2000x3800 are adopted, and using larger panels allows for a reduced maximum allowable tensile stress [CNR DT-210, 2013]. These aspects justify a lower performance of the facade systems studied in this work with respect to the tests carried out at Swinburne University.

5. PROPOSAL FOR AN INNOVATIVE LOW-DAMAGE CONNECTION

With the aim of improving the seismic performance of PFGFSs, alternative high-performance attachment systems have been proposed in the last years. Specifically, such components consist of spider elements including vertically slotted holes. These holes allow the connection to slide until the gap closure, so that longer holes lead to an improvement of the in-plane capacity. Nevertheless, strong earthquakes cause bolts yielding during the sliding, and preload losses are expected. If preload losses occur, the bolt is no longer able to counteract the vertical settlement of the facade through the frictional behaviour at the connection level. For this reason, even though the glass panel does not reach rupture, the connection level damage, and the related vertical settlement, lead to potential high economic losses.

For this reason, an innovative low-damage system able to overcome the issues pointed out previously is herein proposed and analytically-numerically investigated. In the low-damage system, horizontally (rather than vertically) slotted holes are introduced, and the supporting system, together with the spider elements, are attached to the structure by rotating themselves 90 degrees. Figure 8 (left) compares the traditional solution (consisting of K-Type spider elements) with the proposed innovative one. A further key difference among the two solutions is the supporting plate. In the former case (traditional solution) a "T-shaped" plate is adopted, while in the low-damage system, a "C-shaped" plate incorporating vertical stiffeners is used. The stiffeners are adopted to reduce the potential high deformations related to the self-weight of the glass panels. As outlined before, the innovative solution is developed to overcome the issues related to the vertical settlement. In fact, even though the preload loss occurs, bolts are still able to support the glass panels through their axial stiffness. Furthermore, as demonstrated by the analyses carried out in ABAQUS, bolts yielding does not occur if the innovative solution is adopted. Specifically, two analyses have been carried out on the attachment systems by applying the same relative displacement, until the gap closure, between the supporting plate and the spider element. Figure 8 (right) shows the analyses results in terms of Von Mises stress distribution. In the traditional case, bolts deform in flexure-shear, yielding locally. If an innovative solution is adopted, the maximum stress developed at the gap closure is about 80 MPa, far from reaching yielding (σy = 210 MPa).

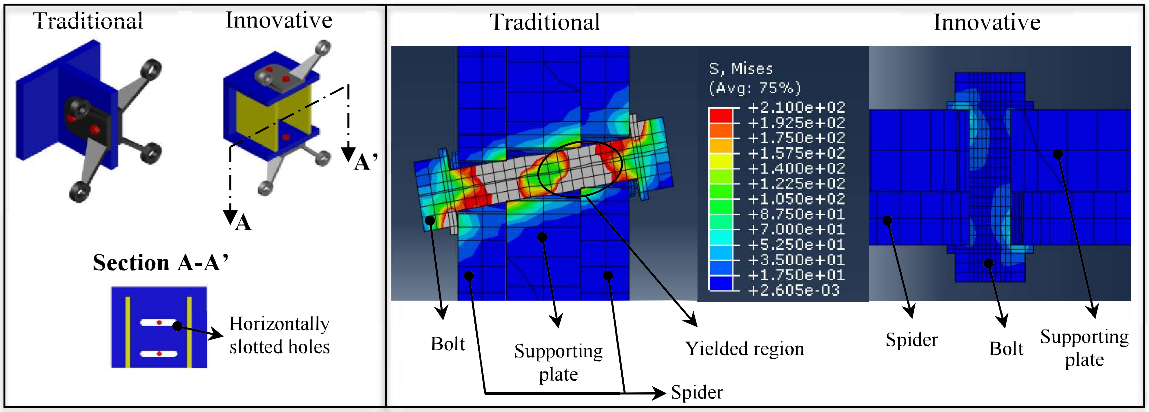

Figure 8. Schematic representation of the traditional as well as innovative solution (left); and stress distribution in bolts for the two configurations.

In addition, a parametric study has been carried out by varying the dimension of the horizontally slotted holes (from 13mm to 80mm). Firstly, ABAQUS FEM analyses have been carried out to define the force-displacement curves at the connection level for implementing the new macro-models of the overall facade. Results in Figure 9 (left) show an improvement of the in-plane capacity of the facade. In fact, using larger horizontally slotted holes enables to reach greater in-plane displacement before the gap closure (which leads to a rapid increment of the tensile stresses) occurs. Nevertheless, it is worth noting that such results refer to a facade system consisting of four rectangular, 2000x3800mm panels. Considering that the maximum allowable tensile stress for glass depends on the panels' dimension and aspect-ratio, [CNR DT-210, 2013], if glass panels with different dimensions are used, such analyses should be repeated. Using 80mm horizontally slotted holes increases the maximum allowable drift to 2.49% (larger than the 1.17% drift achieved by the traditional solution with 13mm circular hole). It is worth noting that the maximum allowable drift defined for the traditional solution (1.17%) is lower when compared to the value of 5.25% observed in the experimental investigations, [Sivanerupan *et al.*, 2014, 2016]. This was expected as the performance of PFGFSs depends on several factors. First, in Sivanerupan *et al.*, [2014, 2016], spider elements with vertically slotted holes, enabling for a better performance, rather than circular holes, have been adopted. Further, in those tests, square panels with a length of 1200mm were used. In this case, rectangular glass panels 2000x3800mm are adopted, and using larger panels allows for a reduced maximum allowable tensile stress [CNR DT-210, 2013]. These aspects justify a lower performance of the facade systems studied in this work with respect to the tests carried out at the Swinburne University.

Finally, another crucial difference between the traditional and the innovative (low-damage) solution is the way they accommodate the in-plane movement of the PFGFS. When a traditional connection system is used, the PFGFS accommodates the in-plane movement through a rocking motion related to the glass panels. If a low-damage system is adopted, instead, the facade is horizontally isolated from the structure, leading to several advantages, such as reduction of the in-plane actions without increasing the system stiffness, [Brueggeman *et al.*, 2000]. Figure 9 (right) schematically shows the difference between the two mechanisms for accommodating the in-plane movement.

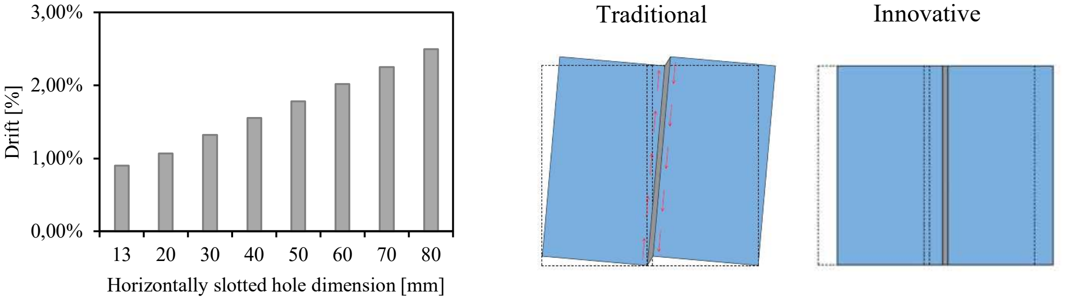

Figure 9. Left: Maximum allowable drift of the innovative system varying the dimension of the horizontally slotted holes; Right: movement accommodation of the facade using traditional or innovative connection systems.

6.CONCLUSIONS

This work assessed the seismic performance of Point Fixed Glass Facade Systems (PFGFSs). Firstly, refined 3D non-linear FEMs have been implemented in ABAQUS to assess the complex local (connection) level behaviour, as well as the behaviour of the silicone weather sealant joint. After that, results from the micro-modelling analyses have been used to define a refined lumped-plasticity macro-model of the facade into the software SAP 2000. The macro-model consists of frame elements, multi-linear springs, and shell elements, and it allows to assess the overall in-plane capacity of the facade. Nowadays, PFGFSs are considered more performing with respect to traditional glazed facade, especially if high-performance attachment details, consisting in vertically slotted holes, are used. Nevertheless, post-earthquake surveys have highlighted the vulnerability of such a system, in fact, traditional attachments have shown yielding and preload losses after strong earthquakes. This compromises the ability to counteract vertical settlements through the frictional mechanism at the connection level, leading to potential high economic losses. Therefore, an innovative low-damage connection system, consisting of horizontally slotted holes, has been proposed and numerically investigated. Refined 3D models have been implemented even for the innovative attachment system, together with the macro-model to assess the overall in-plane capacity of the facade. A parametric study confirmed that the dimension of the horizontally slotted holes strongly affects the in-plane capacity of the facade. Specifically, the maximum allowable drift increases from 1.17% (in case of traditional connection system) to 2.49% when a horizontally slotted hole connection (80 mm length) is used. Currently, a research effort by the authors is focusing on defining other parameters that mostly affect the overall capacity of PFGFSs consisting of the innovative low-damage connection system (e.g., the glass panel size, the silicone weather sealant joint thickness, etc.).

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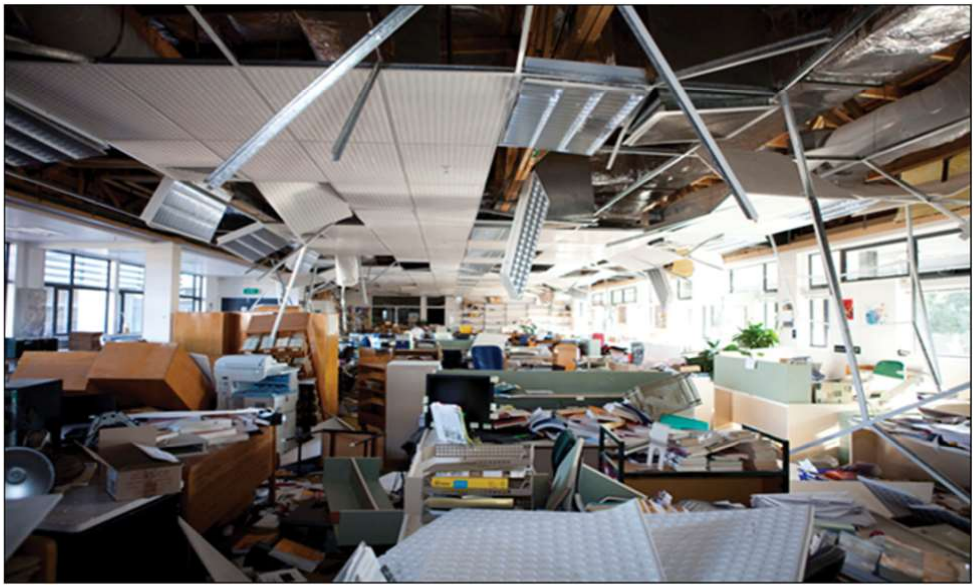

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