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Seismic testing and multi-performance evaluation of full-scale unitized curtain walls: research overview and preliminary results

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Abstract. Unitized curtain walls are glazing facade systems widely used in modern architecture for mid and high rise buildings, due to their benefits in terms of lightness, quality control, ease of construction and quick installation. However, recent earthquake surveys have shown damages to these non-structural elements. Slight-to-moderate damage can cause loss of facade functionality, moderate-to-major damage can provoke severe post-earthquake economic losses and pose a life-threatening danger to both building occupants and pedestrians. Despite recent studies on the seismic behavior of unitized curtain walls, research in this field is still limited and experimental investigations typically neglect the study of the overall facade performance as well as the identification of the full sequence of damage states and the ultimate resistance of the facade components.

This paper presents the extensive experimental campaign carried out at the laboratory of Permasteelisa Group, in Vittorio Veneto (Italy), to investigate the seismic behaviour of full-scale unitized curtain walls from a holistic and multi-performance perspective. The research aims at providing information about the serviceability performance and the ultimate limit state of alternative facade designs. The tests involve various facade configurations consisting of dry (gasket) vs. wet (structural silicone) glazing systems with different construction details for glass, frame and joints (dimensions and type). The testing sequence consists of displacement-control dynamic cyclic loading and/or time histories at increasingly seismic intensity levels, accounting for in-plane, out-of-plane and vertical movements. Air infiltration tests, water leakage tests and wind resistance tests are performed before and after the low-intensity seismic tests to study the post-earthquake facade serviceability. This paper discusses the research objectives, the specimen details and the test setup, and provides preliminary experimental results.

Keywords: Glass facades, Structural silicone, Experimental testing, Seismic loads, Serviceability.

1. INTRODUCTION

Unitized curtain walls are widely used by architects and system manufacturers especially for high-rise buildings (Figure 1a), due to their multiple advantages such as lightness, ease of construction, weather tightness, thermal performance and quality of detailing. Unitized systems enable straightforward processing through serial production and pre-assembly of the facade units under controlled working conditions, therefore allowing for improved quality of assembly, reduced fabrication lead-time and rapid installation.

(a) (b) (c)

Figure 1. (a) Application of unitized curtain walls to high-rise buildings - GIOIA 22 tower in Milan, Italy (by Permasteelisa S.p.A.). Seismic damage to glazed facades: (b) 2010 Chile earthquake [FEMA E-74, 2011], (c) 2011 Christchurch earthquake [Baird *et al.*, 2011]

These non-structural components consist of glass panels within metal frames anchored to the main load-bearing structure by means of connections at the floor levels. During earthquakes these glazed facades are affected directly by inter-storey drift ratios and possible displacement incompatibilities (mainly in-plane) as well as by inertia forces (mainly out-of-plane). Seismic movements can initially (if small) be sustained by the facade through internal gaps and deformations, then, if deformations become larger, local stresses concentrate in specific parts of the system and damage develops. Past earthquake events have repeatedly shown damages to unitized curtain walls (Figure 1b) and the damage mechanisms observed were: (a) gasket degradation, leading to air and/or water infiltrations; (b) glass breaking, not compromising life-safety whilst allowing even further air leakage, water infiltration and other indirect damages; (c) glass fallout, posing potential life safety hazard and causing huge economic consequences [Baird *et al.*, 2011]. Glass breaking was often due to the presence of an insufficient movement capacity of the panels. Another typical damage consisted of warping of the aluminum frame and its total or partial disconnection from the structure in case of inadequately designed connections.

Different experimental studies have been conducted to assess the seismic performance of glazing systems over the past decades. These studies focused on the investigation of the in-plane movement and drift capacity of the glass panels through in-plane monotonic and cyclic racking testing [e.g., Memari *et al.*, 2004; Caterino *et al.*, 2017] as well as through shake table testing [e.g., Wang *et al.*, 2015; Lu *et al.*, 2016], in order to study the influence of different glass typologies, clearance values and connection systems. Bi-directional tests were also performed [e.g., Behr *et al.*, 1995; Lu *et al.*, 2016] to properly identify the damage patterns and study the in-plane/out-of-plane action. It is worth noting that also the out-of-plane behaviour of glazed facades may limit the overall seismic performance, as observed in the experimental campaign carried out by Bianchi *et al.* [2021]. Furthermore, recent experimental tests performed by Arifin *et al.* [2020] aimed at studying the post-earthquake serviceability of glazed curtain walls in terms of water tightness, observing that this property was lost at a median inter-storey drift ratio as low as 0.35%. In most cases, experimental results were also used to calibrate finite element models (solid elements/shells) able to describe the facade in-plane behaviour [e.g., Memari *et al.*, 2011] or macro-models (lumped plasticity) to be used in numerical simulations of building systems [Casagrande *et al.*, 2019].

Despite previous works on the seismic performance of unitized curtain walls, research in this field is still limited and, particularly, research efforts are needed to study the facade performance from a multi-performance perspective. Towards this goal, an extensive experimental campaign is currently ongoing at the laboratory of Permasteelisa Group, in Vittorio Veneto (Italy), to investigate the overall performance of full-scale unitized curtain walls subjected to increasingly earthquake intensity levels. Air infiltration, water leakage and wind resistance tests are performed before/after the low-intensity seismic tests to study the post-earthquake facade serviceability. This paper discusses the research objectives, the specimen details and the test setup, and provides preliminary experimental results.

2. RESEARCH MOTIVATION

A series of full-scale mockup performance tests must be carried out before starting the production and the on-site assembly of a facade, in order to verify that the final product complies with the project specifications. The facade system can in fact be accepted only if it fulfills all the performance requirements. When dealing with seismic performance, specimens are typically subjected to specified horizontal displacements representing the earthquake and the seismic safety of the facade architectural components is assessed through visual inspection. Nevertheless, both the post-earthquake serviceability and the ultimate performance should be analyzed to properly identify the behaviour of the facade and its components. To this end, the proposed research aims at evaluating the performance of unitized curtain walls from a multi-performance perspective. Moreover, the following main objectives are pursued:

i. *Influence of facade detailing on the seismic behaviour*. Experimental tests are carried out on specimens consisting of dry-glazed (with rubber gasket, DG) and wet-glazed (structural silicone glazing, SSG) systems, different glass units (panel dimensions, double-pane or triple-pane glass) and joints (aspect ratio, type of silicone). This allows to investigate the influence of alternative details on the facade response. By comparing the performance of all the alternative solutions, adequate strategies/materials/elements can be proposed to enhance the facade behaviour.

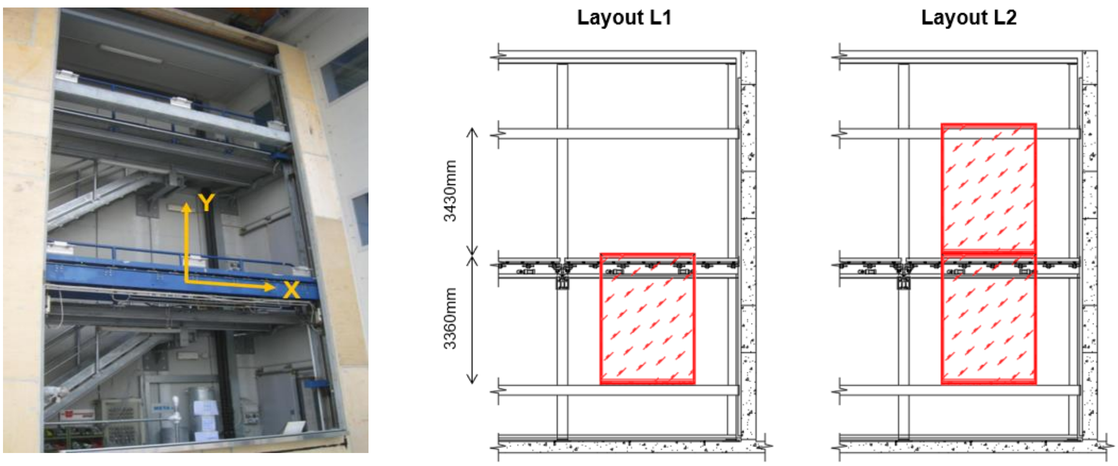
ii. *Calibration of numerical modelling*. Numerical simulations represent the main tool for a designer to validate the facade performance prior to the experimental testing, especially in case of bespoke curtain wall manufacturing. However, enhanced modelling strategies should be developed to support the numerical study of unitized curtain walls. The research aims at developing finite element models (FEM) able to describe either the local (joint/connection) response or the global (facade) behaviour. Furthermore, equivalent spring models for both joints and facades (lumped plasticity models) are developed based on FEM and experimental results. These models could be useful to assess the expected facade seismic response at early design stage.

iii. *Investigating the facade modes of failure*. As mentioned above, during the seismic testing protocol required for a specific building project, the only intent is to prove that the facades comply with the project requirements. The ultimate resistance and the different mode of failures of the facade are generally unknown. For this reason, in addition to the serviceability performance at lower seismic intensities, the experimental campaign aims at collecting relevant information regarding the maximum seismic levels that the facade is able to resist prior to its structural failure. This would allow to identify design and application issues related to the structural and infiltration performances that might arise during their life cycle. Therefore, this study could provide useful indications on how to improve the existing guidelines/codes in terms of displacement verifications and seismic (displacement) demands to be considered in order to verify the façade functionality and safety.

3. EXPERIMENTAL CAMPAIGN

3.1 TEST FACILITY

The experimental campaign is carried out at the Permasteelisa laboratory in Vittorio Veneto, Italy, where full-scale facades up to about 10m width and height can be tested. The specimens can be anchored to the available steel support structure at three levels: two upper and lower fixed beams and an intermediate moving beam (Figure 2a). By means of a hydraulic actuator able to apply a maximum displacement of ± 75 mm in the in-plane horizontal (X) and vertical (Y) directions and ± 50 mm in the out-of-plane (Z) direction, a range of velocities (11-60mm/s) can be applied to impose the displacement history at low-to-higher frequencies (0.25-1Hz). The actuator is interfaced with a digital controller and a control panel to apply the desired displacement. Specimens can be tested in two different layouts (Figure 2b): (a) L1, to test single-storey glazed units or units in a row; (b) L2, to test facades on two levels. L1 allows to study and compare the behaviour of alternative facade systems. Although not representing a real scenario where different inter-story drift ratios are expected at the two floor levels, L2 is generally used in performance tests to study the facade movement at the horizontal joint and verify compliance with the project requirements.



(a) (b)

Figure 2. (a) Seismic performance test facility, highlighting the blue "seismic beam" and the in-plane X horizontal and Y vertical directions. (b) Possible testing layouts for the facade specimens (assuming one unit at each level)

3.2 SPECIMEN CONFIGURATIONS

Four full-scale unitized curtain walls are available for the experimental testing (Figure 3), each designed for a specific building project. *Facade T1* is composed of two SSG modules of 3430mm height and 1267.5mm width and one large dry-glazed module of 2535mm width. *Facade T2* is a full DG system comprising four identical units, all characterized by 3500mm height and 2700mm width. *Facade T3* is a SSG system consisting of eight units of 3850mm height, four with 1500mm width and four with 2250mm width. *Facade T4* is another SSG system consisting of eight units of 3850mm height, four with 1500mm width and four with 2691mm width. In addition to the units dimensions, the four alternative facades are characterized by different aluminum profiles (material type, cross-section of mullions and transoms, male-female joint connection), glass panels (double or triple panes), thermal bridging solutions, presence or absence of openings in the units, type and dimension of gasket and structural sealant. Moreover, the systems can be tested in layout L1 or L2 assembled in their original configuration and/or a modified experimental arrangement, i.e. joint modifications in order to transform a DG system into a SSG module or to test different conditions of structural silicone (material type and aspect ratio). This system variability creates a set of parametric configurations to be tested and compared in terms of performance during the entire experimental campaign, therefore allowing to investigate the influence of the construction details on the facade behaviour.

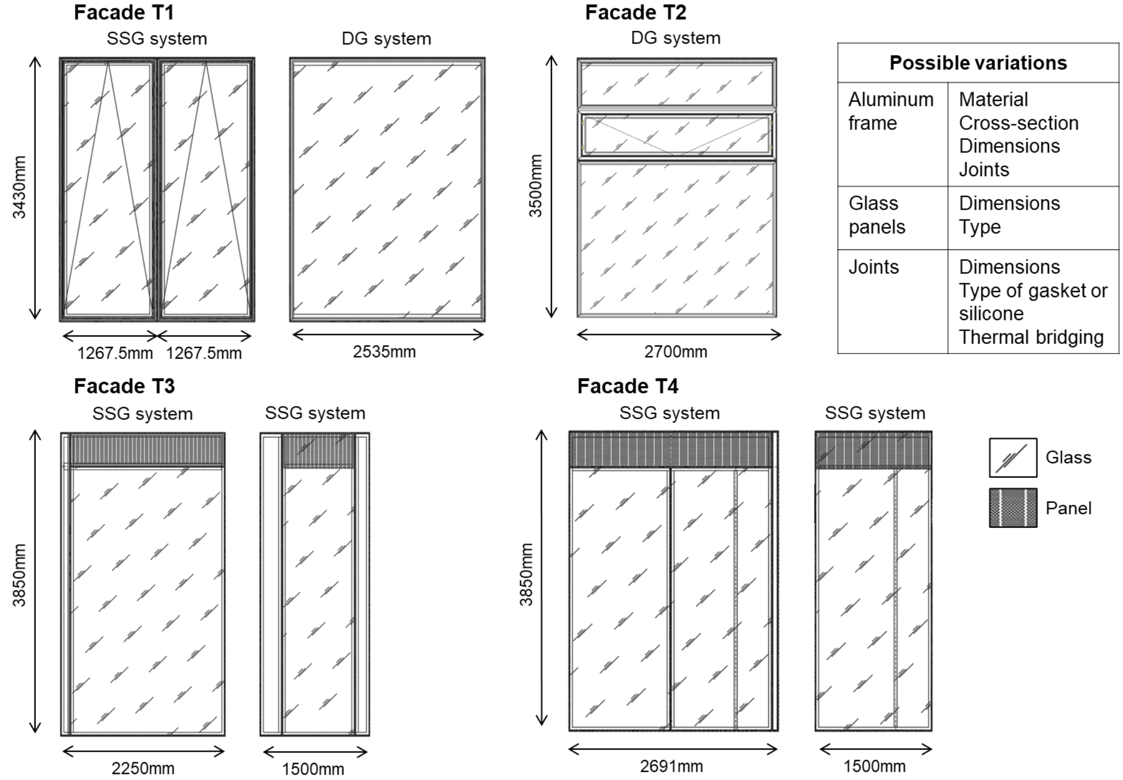


Figure 3. Facade types available for testing

3.3 TESTING PROTOCOL

The testing protocol involves a series of experiments applied on the same test chamber, in order to assess the facade overall performance in terms of air infiltration, water penetration, wind resistance and seismic resistance. Air infiltration test is carried out under static pressure to determine the air leakage through the facade specimen at specified differential pressures induced across the assemblies [EN 12153, 2000]; the air leakage rates are compared against the acceptable rates identified for the specific project. Water penetration test is performed under static pressure by applying a differential pressure across the curtain wall assembly, while simultaneously applying water spray on the exterior facade surfaces [EN 12155, 2000]; the water leakage is checked through simple visual inspection. Wind resistance test is carried out based on both serviceability and safety requirements by applying positive and negative pressure increments to the specimen, then the pressure is dropped to zero [EN 12179, 2000]; frontal deflections are recorded on both glass and frame to verify that the deformation limits are not exceeded. During the experimental campaign, air permeability test, water leakage test and wind resistance test are performed before and after the low-intensity seismic tests to study the facade functionality.

Concerning the seismic resistance test, this is typically applied following a code-compliant procedure [e.g. JASS14, 1996] which involves the application of in-plane horizontal drift levels, representing earthquakes with different return periods. To properly analyse the seismic response of unitized curtain walls, seismic displacements are applied in all the directions of the moving beam (horizontal X and vertical Y in-plane, Z out-of-plane) at increasingly intensity levels. Moreover, to study the failure mechanism for specific facade configurations, the displacement demand is increased till the maximum displacement capacity of the test rig (± 150 mm, to be achieved by modifications to the existing seismic beam).

Based on the discussion above, Table 1 shows a typical test matrix to be followed during each experiment.

Table 1. Test matrix

ID	Type	Description
1	Air	Pre-seismic: Air infiltration test (procedure for fixed joints and openings, pressure/suction)
2	Water	Pre-seismic: Water penetration test (pressure/suction)
3	Wind	Pre-seismic: Wind resistance test at serviceability level (pressure/suction)
4	Seismic	Seismic level 1 (H/300 displ. for X, Z directions, 30-50% intensity Y direction): cyclic loading or real time-history (separately and/or simultaneously in all the directions)
5	Air	Seismic level 1: Air infiltration test (procedure for fixed joints and openings, pressure/suction)
6	Water	Seismic level 1: Water penetration test (pressure/suction)
7	Wind	Seismic level 1: Wind resistance test at serviceability level (pressure/suction)
8	Seismic	Seismic level 2 (H/200 displ. for X, Z directions, 30-50% intensity Y direction): cyclic loading or real time-history (separately and/or simultaneously in all the directions)
9	Air	Seismic level 2: Air infiltration test (procedure for fixed joints and openings, pressure/suction)
10	Water	Seismic level 2: Water penetration test (pressure/suction)
11	Wind	Seismic level 2: Wind resistance test at serviceability level (pressure/suction)
12	Seismic	Seismic level 1 (H/100 displ. for X, Z directions, 30-50% intensity Y direction): cyclic loading or real time-history (separately and/or simultaneously in all the directions)
13	Wind	Seismic level 3: Wind resistance test at safety level (pressure/suction)
14	Seismic	Seismic level 4 (failure test): monotonic or cyclic loading (in-plane X direction)

4. PHASE 1 - PRELIMINARY RESULTS

4.1 SPECIMEN DETAILS

The first experiments were conducted on *Facade T1*, which was assembled in two different configurations: (a) SSG units only and (b) overall *Facade T1*, both tested in layout L1 as shown in Figure 4 (a,b).

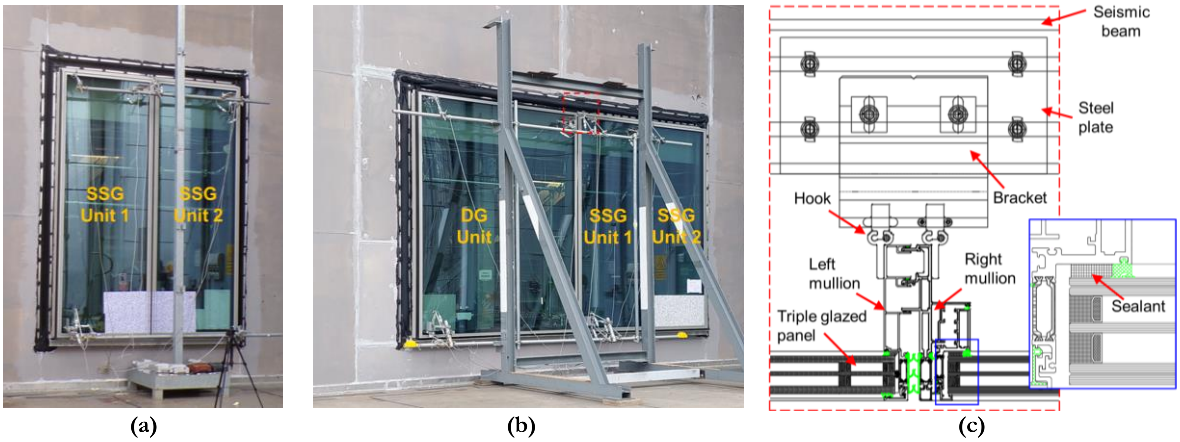


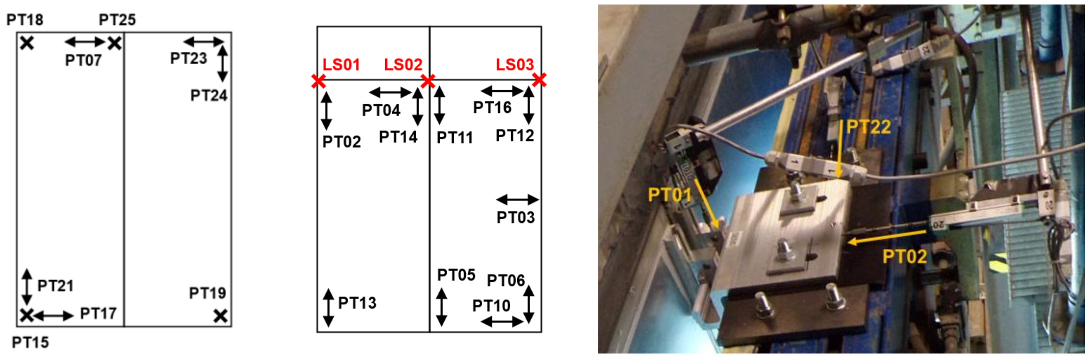
Figure 4. Facade specimens tested in the first experimental phase: (a) SSG units of *Facade T1* in layout L1, (b) *Facade T1* in layout L1. (c) Joint detailing of *Facade T1*

The facade framing consists of aluminum (type 6063 T6) extruded profiles, where mullions and transoms are connected through screwed joints while mullions of different units by male-female joints, including thermal breaks and anti-buckling local components. Figure 4c shows the typical joint detailing of the dry (with rubber gasket) and wet (with structural sealant) triple-glazing units. The SSG units embed DOWSIL™ 993 structural glazing silicone with dimensions of 26mm bite and 8mm thickness for both mullions and transoms. The fastening system to the main steel structure consists of hooks, brackets and adjusting bolts for the connection to the upper (moving) beam, while brackets and bolts for connecting the starter sill to the lower (fixed) beam. The starter sill is, in turn, connected to the bottom transom of the units by means of screwed allignment blocks and shear keys. Each unit requires two hooks for the upper anchorage to the structure. These hooks have different constraints in the horizontal in-plane direction: one hook is fixed (by using screws) while the other hook is free to move; this constraint scheme is applied to allow the unit to accommodate thermal and building differential movements. In addition to the rotation, the hooking connections also allow to accommodate construction tolerances. Vertical tolerance is accommodated using adjusting bolts, while horizontal tolerance is provided by the clearance between the hook and the steel plate.

It is worth noticing that, in order to perform the other performance tests (air/water/wind) on the same testing chamber, after the assembly of the facade units by their uplifting through a crane and subsequent fastening to the support steel structure, wooden panels were installed and connected to the glazed units by a waterproofing shealth to make the full mock-up airtight (as shown in Figure 4).

4.2 MONITORING SYSTEM

Instrumentation layouts were properly designed for both specimens to capture the in-plane and out-of-plane facade movements under cyclic loading. The monitoring system of the first configuration (SSG units) included a total of 24 potentiometers (PT, 50mm or 100mm stroke) and 3 laser sensors (LS, 200mm or 500mm detection). These sensors were used to record the vertical and horizontal displacements of glass panels and framing system (Figure 5), as well as the displacements of the upper central bracket/hook, the lower central bracket and the seismic beam.



(a) (b) (c)

Figure 5. Monitoring system used for Specimen 1 (SSG units): (a) glass panels (external view), (b) frame system (internal view), (c) upper bracket connection

The monitoring system of the second configuration (*Facade T1*) included additional sensors: 6 linear transducers (200mm stroke), 4 draw wires (50mm measurement range) and 6 bi- or tri- directional accelerometers (± 6g). The displacement sensors were placed following a similar configuration as per Specimen 1, but focusing on the large dry glazed unit and the internal SSG unit. Draw wires were used to monitor the diagonal and corner elongations of the frame, while accelerometers measured the accelerations at the centre of the panels, at the bracket connections and on the seismic beam. Measurements were acquired through the same data acquisition device and controller and adjusted by applying calibration factors to consider the measurement accuracy. A second order Butterworth low-pass filter was applied to the recorded acceleration data to eliminate noise outside of the range of response.

In addition to videos recording front/elevation/joint views, two cameras (Pentax K70) were used to capture multiple scans and acquire repeated point clouds during the seismic testing. These set of recordings enabled to detect deformations at specific locations of the glass panels through Digital Image Correlation.

4.3 TESTING SEQUENCE

The first experimental phase served as validation of the proposed testing protocol involving air infiltration, water leakage, wind resistance and seismic resistance tests. As the calibration of the numerical modeling of both specimens (with DG vs. SSG units) was one of the main objectives of this phase, cyclic tests were only performed at two different seismic intensities, namely: a) *Seismic Level 1*, corresponding to 10 cycles at ± 12mm displacements (around 0.35% drift), signal frequency of 0.24Hz, applied separately in the horizontal directions X (in-plane) and Z (out-of-plne), plus ±6mm for the vertical Y direction for Specimen 2 only; b) *Seismic Level 2*, simulated by 10 cycles at ± 24mm displacements (0.70% drift), signal frequency range of 0.24-0.45Hz, applied separately in both horizontal directions X and Z (and increased to ± 36 mm in the X direction for Specimen 2, for which ± 12mm was also applied in the vertical Y direction). All the other performance tests (air infiltration test up to a pressure of 600 Pa, water penetration test up to a pressure of 900 Pa, wind resistance test up to a pressure of 1500/1900Pa for pressure/sunction) were carried out in the pre-seismic and post-seismic conditions for Specimen 2 (after *Seismic Level 1* only, representing the serviceability limit state for the specific project), while the air permeability test was only performed for Specimen 1. It is worth noting that, due to the presence of the openings in the SSG units, the air permeability test was also conducted after the application of tape at the internal perimeter of the frame (simulating the case of fixed joints) in order to investigate the influence of the openings. A wind test at safety level (wind load amplified by a safety factor of 1.5) was finally performed after *Seismic Level 2* for Specimen 2.

4.4 PRELIMINARY RESULTS

The displacements recorded on the facade components (glass panels, internal frame, connection systems) allow to study the global behaviour of the specimens under cyclic dynamic motions. Focusing on Specimen 1 (SSG units only), the rotational behaviour of the facade units is evident when the horizontal in-plane displacement is applied to the seismic beam (Figure 6). To adapt to the inter-storey drift, the whole facade unit first rotates rigidly, then the aluminum frame undergoes deformations by rotations in the corners, the structural silicone sealant between the glass and the aluminum frame deforms in shear to accommodate the inter-storey drift and the glass panel rotates as a result of forces imposed by the structural silicone. By elaborating the displacement data (+X direction) and accounting for geometrical considerations, it is found that the glass panels rotates by 0.12-0.30° while the frame by 0.21-0.40° (diagonal elongations of 1.6-2.0mm) during Seismic Level 1-2, where the rotations are measured referring to the component diagonal. When the horizontal -X displacement is analyzed, it is observed a reduced rotation of the glass panels when compared to the +X direction for both Seismic Level 1 and 2 (rotations become 0.01-0.18°) and a sliding of the glass on the support blocks is also recorded. As highlighted in a previous study by Galli (2011), this behaviour is due to the alignment screw in the bottom transom representing a restraint in the horizontal translation: (a) during the positive motion, it enables the mixed rotational and deformational behaviour of the unit, (b) during the negative motion, it induces a total deformational behaviour of the unit (rhomboidal shape).

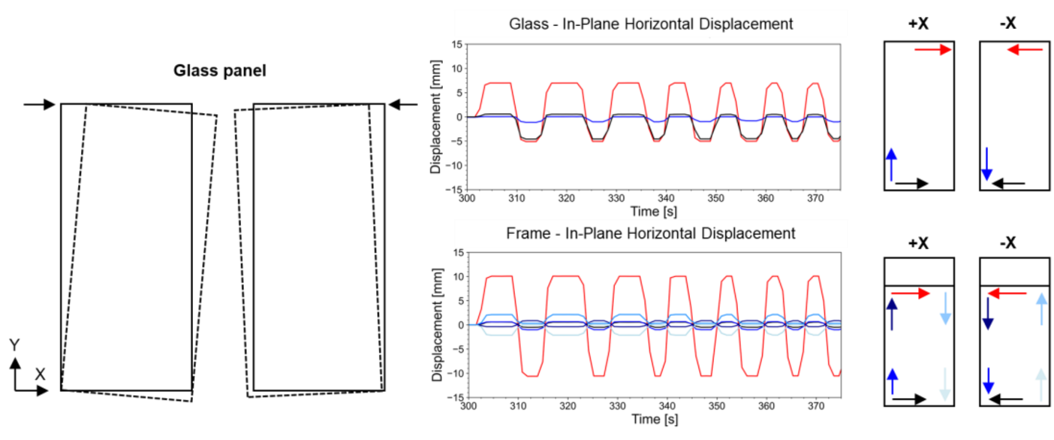


Figure 6. Rotations of the glass panel during Seismic Level 1, ± 12mm X direction, and displacements recorded

During the seismic motion, the aluminum frame deforms and its male-female mullions are slightly able to slip vertically relative to each other. It should be highlighted that the vertical measurements at the bottom corner of the frame could be used (indirectly) to calibrate spring models describing the behaviour of the sill/transom connection (free to uplift whilst resisting to the movement in the negative direction). The same consideration applies to the measurements at the hook/bracket, useful to calibrate spring models to simulate the connection to the seismic beam. In addition to the independent dynamic behaviour of facade attached to the main frame structure, the hook-bracket system contributes in reducing the seismic displacements of around 25% from the beam to the glass. When referring to the out-of-plane Z direction, the rotation of the units is facilitated by the hook and the clearance in the sill/transom. A maximum tilt of around 0.20-0.40° is recorded on the glass panels for both the positive and negative directions. It is finally highlighted that negligible residual displacements are recorded (less than 1mm in all directions) meaning that the frame behaved in the elastic domain, while glass-frame relative displacements achieve a maximum of 4.9mm (glass/frame clearance is 8mm). Table 2 summarizes the displacements measured for Specimen 1.

Table 2. Displacements (max/min) recorded for Specimen 1 (SSG units)

	Glass		**Frame**		**Glass**		**Frame**	
	X dir. (±12mm)	Z dir. (±12mm)	X dir. (±12mm)	Z dir. (±12mm)	X dir. (±24mm)	Z dir. (±24mm)	X dir. (±24mm)	Z dir. (±24mm)
Displ. [mm]	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min
IP_H_Top	9.4/9.4	0.0/0.1	10.6/10.1	0.2/0.0	20.8/19.2	0.2/0.1	20.5/20.0	0.1/0.3
IP_H_Bot	4.6/0.6	0.0/0.0	0.5/0.6	0.1/0.0	5.5/1.5	0.0/0.0	0.5/1.2	0.0/0.2
IP_V_Top	0.9/2.8	1.2/1.1	0.4/2.1	0.2/0.3	1.1/6.5	3.2/2.2	5.5/0.8	0.9/0.3
IP_V_Bot	1.1/0.1	1.2/1.1	2.1/0.7	0.2/0.1	3.9/0.4	1.7/2.7	0.5/5.3	0.1/0.7
OOP_Top	0.5/0.3	11.8/12.2	0.6/0.3	6.4/6.5	1.2/0.4	22.1/24.5	0.8/0.2	12.6/12.6
OOP_Bot	0.0/0.7	0.4/0.3	-	-	0.4/0.7	0.7/0.9	-	-

Note: 1) IP = In-Plane, OOP= Out-Of-Plane, H = Horizontal, V = Vertical; 2) max/min refer to the local axes of the sensors.

Regarding Specimen 2 (*Facade T1*), the following main conclusions can be drawn. Although characterized by different geometrical dimensions, Specimen 2 allows to compare the behaviour of the DG and SSG units. The different rotations of the glass panels in the positive and negative direction are still observed for both units, although more limited than the previous test. For smaller X displacements, the glass panels undergo rotations less than 0.1° while for higher displacements the SSG units rotate more than the DG unit (0.52° for SSG, 0.46° for DG). Vertical displacements at the bottom corners of the glass panels are higher for the larger DG unit (16.1mm) when compared to the smaller SSG unit (7.3mm), as shown in Table 3.

Table 3. Displacements (max/min) recorded for Specimen 2 at Seismic Level 2 (DG vs. SSG)

	Glass - DG		**Frame - DG**		**Glass - SSG**		**Frame - SSG**	
	X dir. (±36mm)	Z dir. (±24mm)	X dir. (±36mm)	Z dir. (±24mm)	X dir. (±36mm)	Z dir. (±24mm)	X dir. (±36mm)	Z dir. (±24mm)
Displ. mm]	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min	Max/Min
IP_H_Top	33.5/32.5	1.9/1.2	26.7/29.2	0.3/0.4	32.4/33.5	0.4/0.2	23.5/29.4	0.5/0.3
IP_H_Bot	2.5/6.9	0.7/0.3	1.4/5.0	0.2/0.1	4.1/5.1	0.6/0.1	2.2/2.6	0.4/0.0
IP_V_Top	-	-	21.1/3.5	1.2/3.1	-	-	8.8/1.1	1.1/0.8
IP_V_Bot	1.5/16.1	4.1/2.4	3.1/19.7	2.9/0.5	0.8/7.3	2.9/3.3	2.2/9.5	1.0/1.3
OOP_Top	1.9/0.6	23.6/25.2	2.4/8.7	21.6/19.6	4.3/4.8	23.5/26.7	1.4/1.7	22.2/18.9
OOP_Bot	0.3/0.6	1.0/0.9	0.3/0.1	0.6/0.7	0.4/1.2	1.0/1.1	-	-

Note: 1) IP = In-Plane, OOP= Out-Of-Plane, H = Horizontal, V = Vertical; 2) max/min refer to the local axes of the sensors.

Focusing on the frame behaviour, higher vertical displacements are recorded for the larger unit, also experiencing defomations in the out-of-plane direction (8.7mm), while the different behaviour in the positive/negative direction is due to the sill/transom and hook/bracket connections, as previously discussed. Referring to the draw wire located at the corner of the large frame, a maximum elongation of 2mm is found which confirms the rotational behaviour of the corner instead of a full rigidity. Residual displacements are below 2mm thus the frame still behaved in the elastic domain, and the frame/glass relative displacements are less than 7mm (higher in the vertical direction). When the out-of-plane Z and vertical Y motions are analyzed, a similar behaviour is found for the SSG and DG units.

Although Specimen 2 experienced an inter-storey drift of 1% (representing the design drift level for the building project), the facade behaved very well due to its detailing and internal gaps and no potential damage mechanism was observed. The only negligible damage noticed during the disassembly phase was the distortion of the anti-buckling components located between the vertical mullions. Concerning the post-earthquake serviceability of the specimens, the facades maintained their performance after Seismic Level 1 (0.35% drift level). Specifically, performance tests on Specimen 2 highlighted that: (a) the air leakage - measured per unit length of openings, $m^3/h\ m$ - was negligible in case of pressure, while higher losses were measured in the suction phase for the no tape scenario (with openings), probably due to the units subjected to other performance tests before the planned campaign; overall, the air tightness was preserved and the facade maintained the same class A4; (b) no water penetration was observed after Seismic Level 1; (c) frontal deflections slightly increased for the frame when the wind test was performed in the post-earthquake scenario. For the wind test at safety level, despite the expected noise in the suction phase due to the presence of the openings, out-of-plane displacements reached 5mm and 7mm for glass and frame, respectively, that are deflection values which highly satisfy the deflection limits (around 18mm for the glass and 16mm for the frame) as defined in UNI EN 13830 (2022).

5.CONCLUSIONS

The paper describes the experimental campaign currently ongoing at the laboratory of Permasteelisa Group, in Vittorio Veneto (Italy), to investigate the serviceability and ultimate seismic performance of unitized curtain walls. The research project aims at pursuing multiple objectives, namely: (a) the study of the influence of various facade details on the overall behaviour (b) the calibration of proper numerical modelling (distributed and lumped plasticity), (c) the study of the damage mechanisms developing until failure. The paper describes the alternative facade designs available for testing, consisting of various architectural features for glass/frame/joints, to be compared from a holistic perspective. The paper discusses the testing protocol involving seismic tests at increasingly intensity levels, and air permeability, water resistance and wind resistance tests at the lower intensities. Preliminary results are provided for two specimens composed of structural silicone sealant and dry glazed units. Experimental data are elaborated to investigate the seismic response of the facade units in all the directions, by deriving max./min. displacements and accelerations, rotations, frame elongations, residual displacements and relative glass-frame displacements. Both specimens behaved well and maintained their serviceability performance in the post-earthquake scenario (drift level of 0.35%). As further investigation, the whole facade will be converted into a fully structural silicone glazed system and tested either following the same protocol, for comparison purposes, or until failure.

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