

SENSITIVITY ANALYSIS AND RISK ASSESSMENT OF UNITISED GLASS CURTAIN WALLS

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Abstract: *Unitised glass curtain walls are pre-assembled façade systems broadly used in the construction industry, especially for mid-to-high rise buildings, due to their advantages in terms of quick installation, quality control and overall performance. However, glass façades are not adequately designed for seismic loads despite the fact that they usually represent one of the largest portions of the capital investment of a building. Recent earthquake disasters have highlighted the vulnerability of these components, which can result in loss of functionality, severe direct and indirect economic losses, and human injury / loss of life for building occupants and pedestrians. Although research studies have focused on improving the seismic performance of glass façades and assessing their dynamic behaviour through experimental testing, numerical modelling for more accurate simulations remains limited and further research is needed. This paper presents an advanced numerical model of a whole façade system (including frame, glass, and connections) using LS-DYNA, which is able to capture the complex behaviour of the façade components and joints. The model is validated against full-scale experimental results from quasi-static cyclic tests carried out at the laboratory of Permasteelisa Group in Vittorio Veneto (Italy). After the initial validation of the numerical approach, a sensitivity analysis is performed for assessing the influence of different façade design parameters on the seismic response, e.g. the variation of material properties (e.g., frame stiffness and strength) and construction details (e.g., structural silicone bite). Finally, damage fragility curves based on the inter-storey drift ratio are derived using cloud analysis. The results demonstrate the high correlation between the seismic performance of the façade and its design parameters, such as the structural silicone bite.*

Introduction

Recent earthquake events, such as those in L'Aquila (2008), Christchurch (2011) and Kaikoura (2016), continue to highlight the high vulnerability of Non-Structural Elements (NSE), i.e., façades, partitions, ceilings, equipment, egress systems, and contents. Although they represent a significant portion of the capital investment in commercial buildings, generally 70%–85% of the total building cost (Taghavi and Miranda 2003), their seismic design is still not adequate, leading to large overestimations or underestimation of the seismic demand. Under larger earthquake shaking, façade collapse can pose life-threatening risks to building occupants and passers-by. However, façades are also particularly susceptible to damage at low-to-moderate seismic intensity levels, and such damage can greatly affect the functionality of the building after an earthquake and result in significant repair costs and business interruption. These seismic costs can be even higher when dealing with glazed façade systems.

Among glazed façade systems, unitised glass curtain walls (Figure 1a) are a widely used typology in the construction industry, especially for mid-to-high rise buildings, due to their advantages in terms of quick installation, quality control and overall performance. These components consist of glass panels infilled into metal frames anchored to the structural system by connections at the floor levels. These façades are generally classified as drift-sensitive, with the inter-story drift ratio being the primary engineering demand parameter affecting their seismic behaviour. During seismic shaking, the façade system is able to sustain initial movements through internal gaps and deformations. If deformations become larger, local stresses concentrate in specific parts of the system, leading to damage. Past earthquakes have repeatedly shown damage to unitised glass curtain walls (Figure 1b, c), with observed mechanisms including gasket/silicone degradation,

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glass cracking and glass fallout (Miranda *et al.* 2010; Baird *et al.* 2011). While gasket or silicone degradation and glass cracking do not pose a direct risk to life safety, they allow for air and water infiltration and other indirect damages. Glass fallout, on the other hand, can pose a potential life safety hazard and cause significant economic consequences if the connection between glass and frame is insufficient.



Figure 1. (a) Example of unitised glass curtain walls installed in a high-rise building – GIOIA 22 tower in Milan, Italy (by Permasteelisa Group); Seismic damage to glazed façades: (b) 2010 Chile earthquake (FEMA E-74), (c) 2011 Christchurch earthquake (Baird *et al.*, 2011).

Various experimental studies have been conducted in the past few decades to evaluate the seismic performance of glazing systems. These studies investigated the in-plane movement and drift capacity of glass panels using in-plane monotonic and cyclic racking testing (e.g., Memari *et al.* 2004, Caterino *et al.* 2017), and shake table testing (e.g., Wang *et al.* 2015, Lu *et al.* 2016, Bianchi *et al.* 2021), to study the impact of different glass types, clearance values, and connection systems. Bi-directional tests were also performed on plane or corner configurations to identify damage patterns and study the in-plane and out-of-plane action (e.g., Behr *et al.* 1995, Lu *et al.* 2016). In most cases, experimental results were used to calibrate finite element models or macro-models to be used in numerical simulations of façade systems (e.g., Memari *et al.* 2011, Aiello *et al.* 2019, Casagrande *et al.* 2019). However, due to the high variability in system detailing (including the type of gasket or silicone, framing, glass, and connection system), such studies only offer a general understanding of the behaviour and expected damage states of glazed façades.

To fully understand the behaviour of each component and the overall façade, it is necessary to conduct specific testing and advanced numerical calibration (Bianchi and Pampanin, 2022). Such data and simulations can also be valuable in the development of fragility curves. Despite non-structural or façade damage being the main source of loss in most buildings during earthquakes, the identification of fragility curves for use in the Performance-Based Earthquake Engineering (PBEE) approach (Moehle and Deierlein 2004, Porter 2003) is still a critical task. Therefore, further research is required to investigate the seismic performance of unitised glass curtain walls through experimental and numerical investigation, in order to provide practitioners with valuable information (both the numerical approach and potential damage mechanisms) to support early-stage design decisions.

Toward this goal, a research study was carried out to demonstrate the effectiveness of an advanced numerical modelling approach using LS-DYNA, which is capable of capturing the complex behaviour of the façade components and joints. The numerical model was calibrated using experimental data obtained from quasi-static cyclic tests carried out at the laboratory of Permasteelisa Group in Vittorio Veneto, Italy. Once the numerical approach was validated, a probabilistic sensitivity analysis was conducted to assess the influence of different features on the seismic response, such as varying material properties and construction details. Finally, fragility curves for various façade damage mechanisms were obtained through cloud analysis, which demonstrated a high correlation between the seismic performance of the system and design parameters such as silicone bite (thickness) and type.

Numerical Modelling

The case study is based on a unitised glass curtain wall façade system as installed in a real building and tested at a 1:1 scale during an experimental campaign conducted in 2011 at the laboratory of Permasteelisa Group. An advanced numerical model of the façade was created to simulate all relevant system components and its structural/construction details. The model was then calibrated and validated using the experimental data, as discussed below.

Experimental test setup

The experimental setup consists of four façade units, with each unit measuring 3800 mm in height and 1500 mm in width (Figure 2a). The façade system is a structural silicone glazed curtain wall, which utilises wet connections without any mechanical restraint. This façade is composed of three primary components: the frame, the glass and the silicone. The frame comprises vertical mullions and horizontal transoms made of aluminium type 6063 T6 (EN 1999-1-1:2007, BS EN 755-2:2016), with cross-sectional dimensions of approximately 140x50x3 mm. The glass is a monolithic panel measuring 1452x3752x12 mm and is retained to the aluminium frame using structural silicone. Two types of structural silicone are investigated: Sika SG500, with a cross-section of 10x6 mm, and Sika SG550, with a cross-section of 6x6 mm.

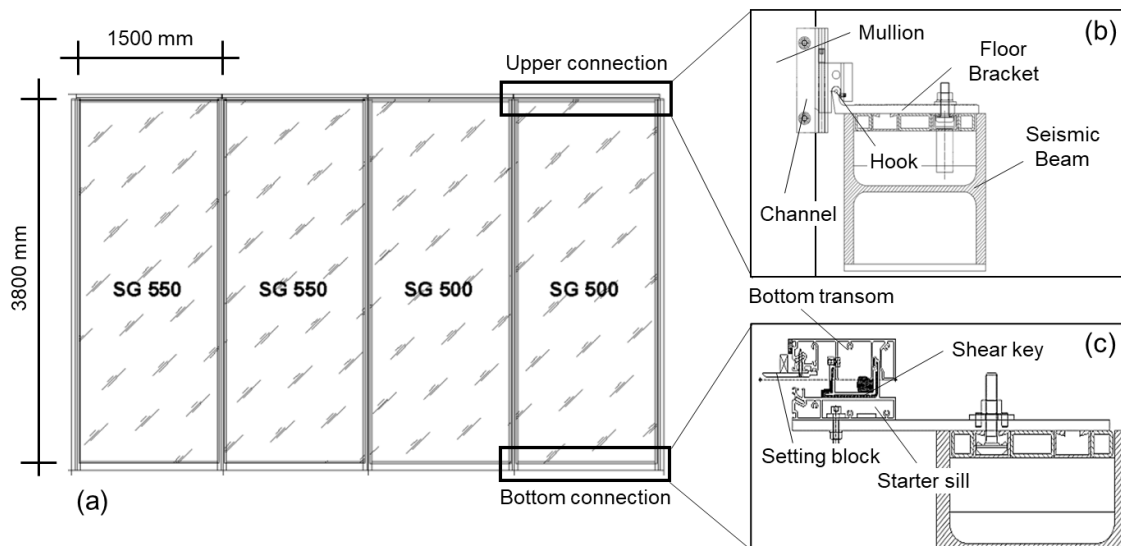


Figure 2. Experimental setup and connections: (a) façade mock-up tested at the laboratory of Permasteelisa Group; construction details for the upper (b) and bottom (c) connection systems (modified after Galli 2011).

To connect each façade unit to the external steel structure, two bracket connections are used for each of the upper and bottom connections. The upper connection (Figure 2b) consists of a slider directly bolted to the mullion allowing for vertical movements of the façade. A hook is used to suspend the façade from the floor bracket, creating a hinge connection. The floor bracket is responsible for supporting all loads: self-weight, horizontal and vertical actions. The bracket is finally bolted to a steel beam, which emulates the floor slab of a building. This steel seismic beam is used to induce a prescribed displacement to the façade through a hydraulic actuator. The bottom connection (Figure 2c) consists of the bottom transom resisting on shear keys (sleeve) that allow vertical moments only. A setting block is used to support the dead load of the glass panel, and a starter sill is employed to simulate the connection with the façade below. The starter sill is connected to the bottom transom via an alignment screw that is positioned at 1/3 from the right bottom corner of each façade module. This screw is installed in a slotted hole which allows for both the uplifting of the façade and the rotation during horizontal displacements.

Numerical approach

A numerical model of the full façade system consisting of the four units was developed in LS-DYNA to replicate the experimental test setup described above. The numerical model was used to evaluate the in-plane performance of the façade, while out-of-plane effects were neglected in this study. Figure 3a shows the full façade model and all its elements, including the constraints and boundary conditions used in the analysis.

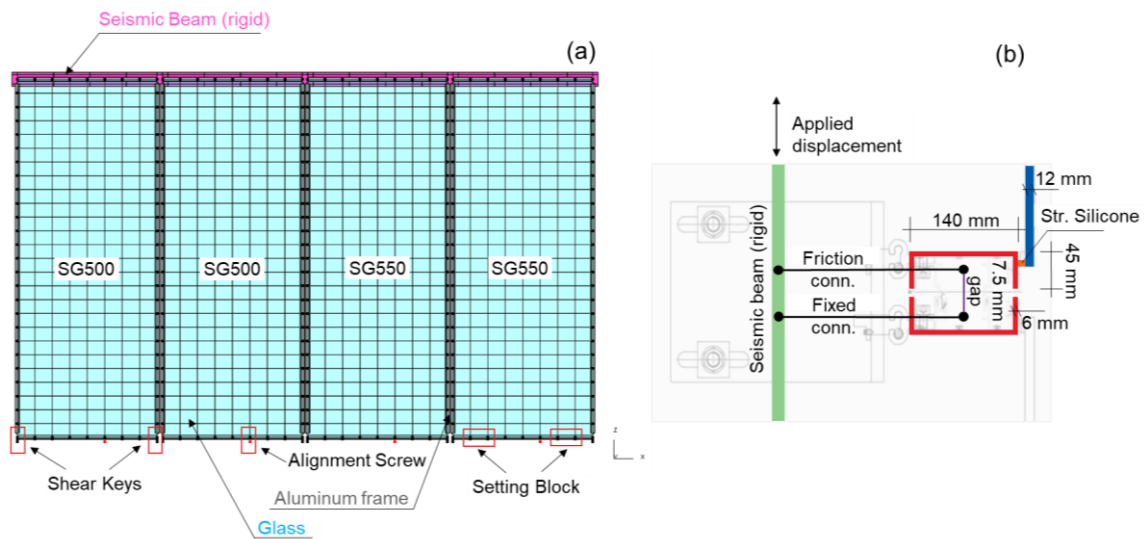


Figure 3. Numerical model developed in LS-DYNA.

The frame members were modelled as beam elements with an assumed equivalent C-shape cross section with dimensions of 140x45x6 mm (without internal stiffening plates). This cross-section geometry was chosen to have an equivalent moment of inertia to the real cross section. A plastic kinematic material model without hardening was implemented for the aluminium (EN 1999-1-1, BS EN 755-2:2016) with a characteristic stress of 150MPa, and the mullion-transom connections were assumed as pinned connections. To model the single pane laminated glass, shell elements were adopted with an elastic material model considering a characteristic stress of 60MPa. The glass was connected to the frame members solely through the structural silicone, which was described by discrete connections with a spacing of 166 mm and an elastic stress-strain relationship that simulated both the axial and shear behaviour. To obtain design stresses (axial and shear), Young's modulus, and shear modulus for both SikaSil500 and SikaSil550, the manufacturer's specifications were consulted.

The connection between the façade and the seismic beam was modelled using discrete link elements to represent both a friction and a fixed connection (Figure 3b). The fixed connection allows for uplifting of the façade only, while the friction connection allows for uplifting and sliding once it overcomes the steel-to-steel friction between the hook and the steel bracket. An internal gap of 7.5 mm was considered between the vertical mullions of two adjacent façade units. The constraints at the base corner of each unit allow for uplifting only due to the presence of the shear keys, while a maximum displacement of 10 mm was considered in the vertical direction (before resisting) to account for construction tolerances between the bottom transom and the starter sill. The setting block was modelled using discrete connections and as above mentioned, is responsible for carrying the dead load of the glass. The alignment screw, positioned 550 mm from the right bottom corner of each unit, allows for a maximum of 20 mm vertical displacement while the rotation is free. The starter sill was considered rigid and not explicitly modelled in this study.

Experimental vs Numerical comparison

During the experimental campaign, quasi-static cyclic tests were conducted to assess the in-plane performance of the unitised glass façade. Prescribed horizontal displacements were directly applied to the seismic beam. The maximum displacement was calculated using the Japanese Standard JASS14 (1996) to simulate different earthquake intensity levels. This regulation specifies the performance evaluation of a curtain wall façade under seismic action. Three different displacement amplitudes were applied to the façade:

- H/300, corresponding to 12.50 mm (0.33% of inter-story drift ratio)
No damage on internal and external components.
- H/200, corresponding to 18.75 mm (0.50% of inter-story drift ratio)
All external components must not exceed the allowable stress. Sealing must be repaired.
- H/100, corresponding to 37.50 mm (1.00% of inter-story drift ratio)
Neither damage of the glass nor dropout of any component is allowed.

The goal was to test the façade against the inter-story drift, which is the primary source of damage for this type of façade system. At least five full cycles are required, and force-based verifications are not requested from the code procedure.

To verify the accuracy of the numerical model, experimental data from the H/200 displacement level were used to compare the numerical and experimental displacements of both the frame and glass components. Figure 4 shows the time history of the prescribed displacement (input) applied to the seismic beam.

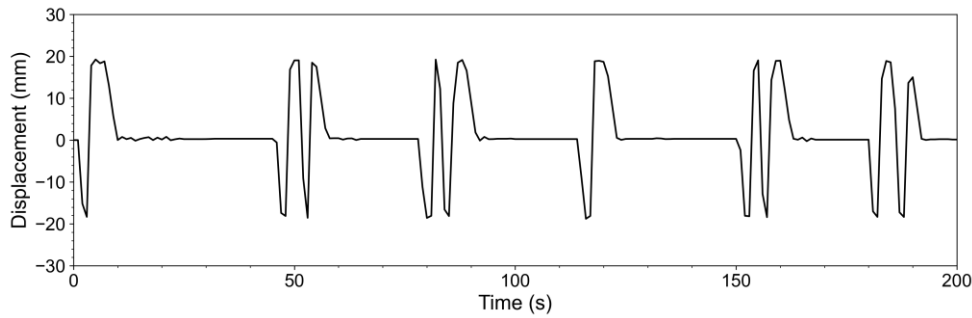
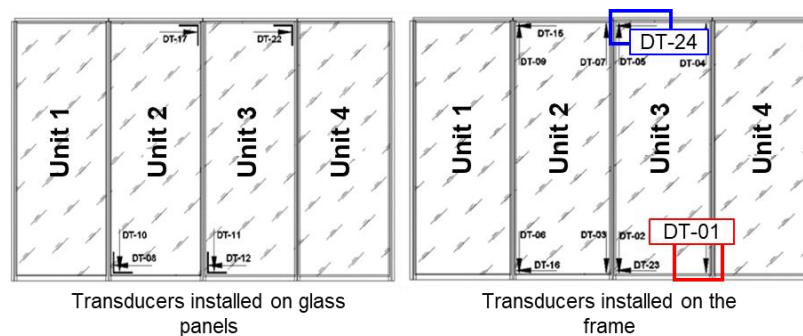


Figure 4. H/200 displacement level applied to the seismic steel beam.

During the experiments, several displacement transducers (DT) were installed on the central units (Unit 2 and 3 in Figure 5) of the façade, to measure both absolute and relative horizontal and vertical displacements of the glass and frame. Corner displacements were used to compare experimental vs. numerical results, and a good agreement was found in terms of peak values and displacement patterns. The maximum difference between the experimental and numerical results was found to be 15–20% for both frame and glass. Figure 5 shows an example of the time-history results for specific sensors. It is worth noticing how the uplifting in the vertical direction (monitored through DT01) is well captured from the numerical model.

The Utilisation Factor (U_t) is an indicator for evaluating the performance of a façade in the elastic range. This factor compares the maximum stress experienced by each façade component (i.e., frame, glass, and silicone) during the seismic motion to the design stress level ($U_t = \sigma_{max} / \sigma_k$). If U_t equals 1, it means that the component, i.e. glass, frame and silicone, has reached its maximum allowable stress level. Safety factors were not taken into account in assessing the design stress level, while only characteristic material values were used for the evaluation. In this numerical study, 0.24 and 0.26 were found as U_t values for the two configurations SG500 and SG550, respectively; while U_t values of 0.04 and 0.02 were obtained for the aluminium frame and the glass panel. Although these U_t values do not indicate failure for inter-story drift of 0.50% (H/200 displacement level), the results suggest that the structural silicone is governing in the overall performance of the façade when wet connections are considered.



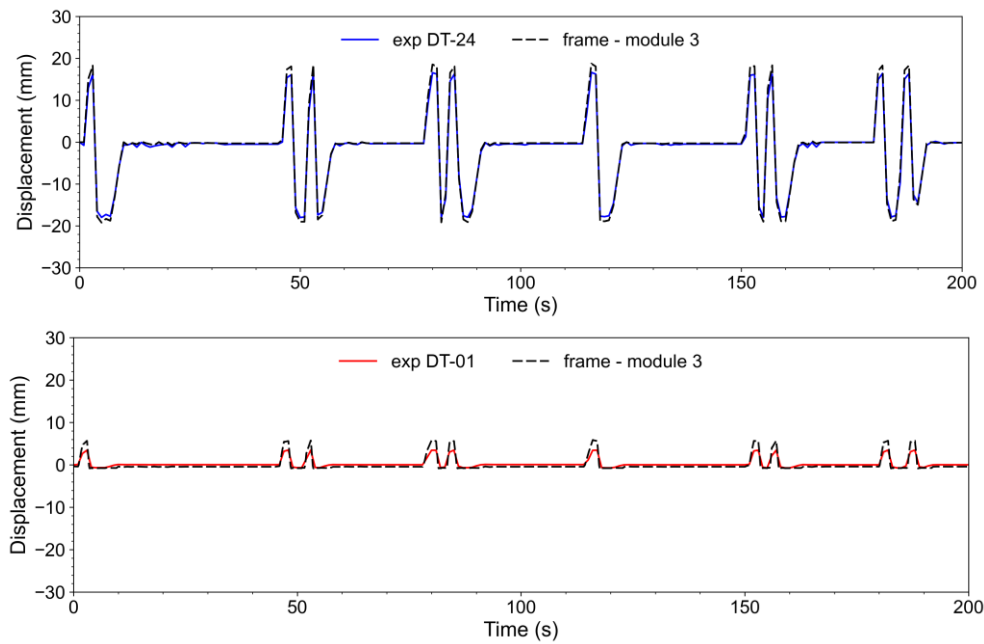


Figure 5. Comparison between experimental vs numerical results on frame members.

Parametric Analysis

After validating the numerical model against experimental results, a probabilistic parametric analysis was conducted to assess the performance of the façade and the parameters mostly influencing the overall behaviour. To account for the epistemic uncertainties, material properties (strength and stiffness) and structural details (frame connection and internal gaps) were treated as uncertain input parameters. The probability distributions and coefficients of variation for these parameters are listed in Table 1, based on literature data (BS EN 572-2:2012) and engineering judgement. To perform the sensitivity analysis, the Latin Hypercube Sampling (LHS) technique (Helton and Davis 2003) was utilised to sample the random variables and create a large set of numerical models. It is worth noting that the parametric study does not consider aleatoric uncertainties related to the seismic event.

Parameter	Mean SG500	Mean SG550	Coefficient of Variation	Distribution
Glass Young modulus, E_G	70 GPa		0.03	normal
Aluminium Young modulus, E_A	69.5 GPa		0.08	normal
Silicone Shear Modulus, K_v	0.50 MPa	0.63 MPa	0.1	normal
Silicone Axial Modulus, K_r	1.50 MPa	1.87 MPa	0.1	normal
Silicone Design Shear Stress, τ_v	0.105 MPa	0.13 MPa	0.1	normal
Frame connection, K_{conn}	1kNm/rad		0.1	normal
Mullion-mullion gap, Δ_g	7.5 mm		0.05	normal
Silicone Width, w	2-35 mm		-	uniform

Table 1. Probabilistic distributions implemented in the sensitivity analysis.

The study was conducted for three fixed inter-storey drift levels (1%, 1.5%, and 2%) that represent typical design choices for the primary structure of a building. For each inter-storey drift level, 100 probabilistic numerical models were identified, thus a total of 300 cases to investigate for each structural silicone type (SG500 and SG550). Numerical analyses were performed considering one full load cycle (e.g., for 1% drift ratio: 0, 1%, -1% and 0) with low-velocity excitation, to avoid dynamic effects.

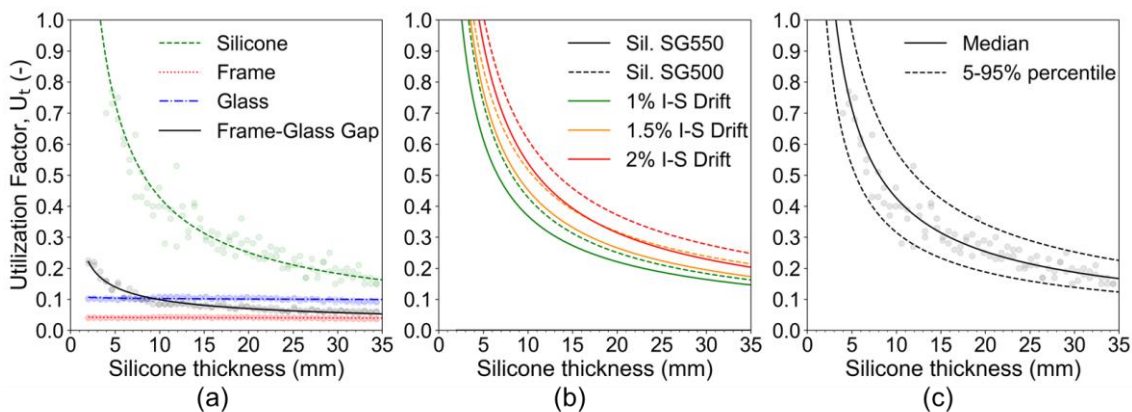


Figure 6. Results in terms of Utilization Factor (U_t) vs Silicone thickness; (a) governing mechanism for SG500 at 1% inter-storey drift, (b) comparison between SG500 and SG550, and (c) 5/95 percentile values for SG500 at 1% inter-storey drift.

Overall, the probabilistic parametric analysis provides insights into how the uncertainties in the input parameters affect the façade performance under seismic loading. Figure 6a illustrates the results in terms of U_t as a function of the silicone bite. The probabilistic analysis results were used to identify a regression (median) curve (Figure 6c) and to evaluate this curve for all the inter-storey drift levels considered and both silicone configurations (Figure 6b). As expected, the utilisation factor decreases as the silicone bite increases. Lower bite values simulate a condition where a dry glazed system with a gasket is used instead of silicone. The values for glass and frame remain nearly constant. This indicates that the structural silicone represents the first failure mechanism that can occur for the façade. Furthermore, the graph also displays the variation of the frame-glass clearance. This condition simulates the potential impact of glass on the frame, which can have a significant impact on the results when dry systems are considered. This highlights the possibility of glass cracking for the façade.

Damage Fragility Functions

For the development of fragility functions, which describe the probability of reaching or exceeding a given damage or collapse state under increasing levels of ground shaking intensity, a model for the probabilistic relationship between ground motion intensity and the structural response of the system is needed. The cloud method (Jalayer 2003) has been employed using Maximum Likelihood regression. A lognormal cumulative distribution function was adopted as functional form of the fragility. Once the maximum response of the facade (R_F) is obtained from all n realizations, each utilization factor (U_{t_i}) is plotted against the intensity measure (IM) and the statistical parameters corresponding to the lognormal distribution of $R_F|IM$ can be extracted.

In this framework, the median of the fragility function $E[\ln R_F|IM]$ is modelled by a linear regression equation on the logarithm of the intensity measure, with parameters b_0 and b_1 , whilst the standard deviation or dispersion $\beta_{R_F|IM}$ is estimated by the standard error of the regression:

$$E[\ln R_F|IM] = b_0 + b_1 \ln(IM) \quad (1)$$

$$\beta_{R_F|IM} = \sqrt{\frac{\sum_i^n (\ln U_{t_i} - E[\ln R_F|IM])^2}{n-2}} \quad (2)$$

In this case, the fragility functions were developed using inter-storey drift ratio as proxy for the seismic intensity measure (IM). Regarding the response, given the silicone is shown to be the governing component (see previous section), the silicone shear stress has been used to estimate the utilization factor for each realization (U_{t_i}). In order to correctly treat the results of the analyses where the stresses exceed the expected design stress of the silicone (i.e. utilization factor greater than 1), a censored regression (Stafford 2008) has been undertaken when estimating the regression coefficients in the above equations.

The adopted drift ratio stripes are consistent with the parametric analysis presented above: 1%, 1.5% and 2%. Each stripe consists of 100 realisations of the LHS sampling with a total of 300 realisations.

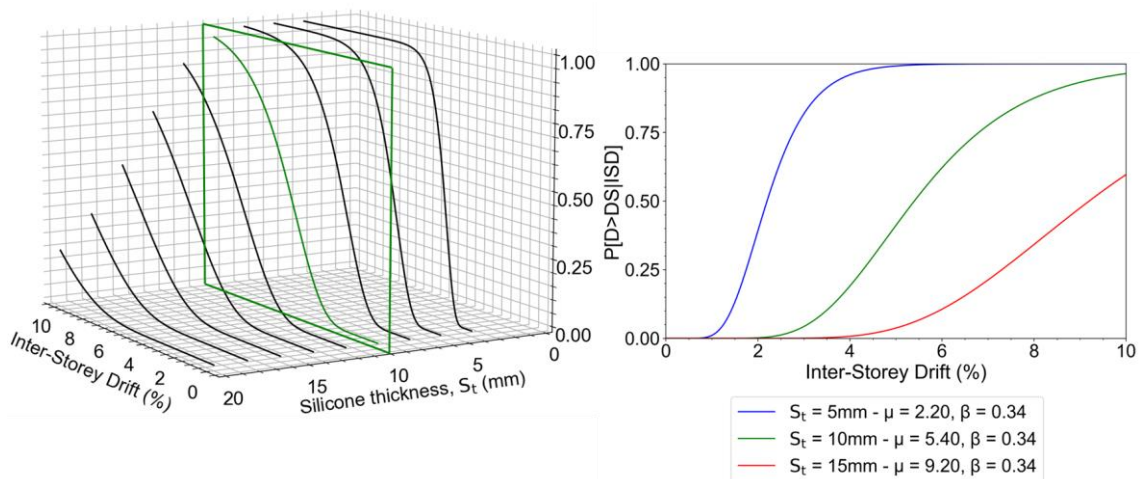


Figure 7. 3D fragility function and respective 2D cut sections for 5, 10 and 15mm of silicone bites for SG500.

The large pool of analysis results with parametric variations also allowed explicit regression analysis to be carried out for fragility functions in terms of both the inter-storey drift ratio (IM) and silicone thickness parameter (S_t). In this case, the median of the fragility function is modelled by a linear regression equation on the logarithms of the intensity measure (IM) as well as the silicone thickness parameter (S_t), with parameters b_0 , b_1 and b_2 , whilst the standard deviation or dispersion is estimated by the standard error of the regression:

$$E[\ln R_F | IM] = b_0 + b_1 \ln(IM) + b_2 \ln(S_t) \quad (3)$$

$$\beta_{R_F | IM} = \sqrt{\frac{\sum_i^n (\ln U_{t_i} - E[\ln R_F | IM])^2}{n-3}} \quad (4)$$

The parameters b_0 , b_1 and b_2 are the estimated regression coefficients obtained by performing a multivariate linear regression.

In essence the fragility function is a 3D surface (Figure 7) where the probability of the silicone reaching its maximum allowable stress level is both a function of the inter-storey drift ratio and the silicone thickness. The underlying assumption is that the dispersion is independent of the silicone thickness. It is worth noting that the probability of reaching or exceeding the utilization factor of 1 is herein interpreted as probability of glass fallout from a design perspective, despite the fact that some countries do not allow connections with only structural silicone (CSTB 3488), for safety reasons. This is conservative due to: a) the design stress rather than failure stress is adopted to calculate the utilization factor, b) the utilization factor is calculated based on the maximum observed stress on any portion of the silicone joint. In reality, one may expect that the silicone strength is locally exceeded without necessarily leading to the complete detachment and consequent fallout of the glass panels.

The multivariate regression approach has been validated against the univariate regression (regression only on inter-storey drift ratio for a batch of realizations with the same silicone thickness) and leads to negligible difference in terms of median and dispersion compared to the respective multivariate regression (on both inter-storey drift ratio and silicone thickness, plotted for the same silicone thickness as the univariate one). Regression results in Table 2, shows that the probability of glass fallout is strongly dependent on the silicone bite and decreases as the silicone bite increases. As expected, the SG550 shows higher (1.25x higher in average) median of fragility functions compared to SG500, for all silicone bites, due to its superior mechanical properties. The difference in dispersion is negligible.

Parameter	SG500	SG550
Median at 5 mm of silicone thickness	2.2%	2.7%
Median at 10 mm of silicone thickness	5.4%	6.8%
Median at 15 mm of silicone thickness	9.2%	11.6%
Dispersion	0.34	0.35

Table 2. Median and dispersion of fragility functions for SG500 and SG550.

Conclusions

In this paper, an application of detailed numerical modelling, parametric analysis, and fragility function development to the seismic performance of a unitised curtain wall system is summarised. The numerical modelling approach, incorporating representations of the glass, silicone, and framing system, is validated against experimental data provided by Permasteelisa. A parametric study is carried out through generation of three suites of 100 unique analysis models varying key parameters of the model (silicone bite or thickness) by use of the LHS method. By comparing key performance metrics of each component to their allowable design values (e.g. silicone shear stress) a utilisation factor could be calculated and its relationship with the input parameters assessed. Results from the parametric analysis show that the silicone bite is the governing parameter of unitised curtain walls adopting wet connections only, with the associated utilisation factor varying between approximately 1 for a 5 mm bite and 0.2 with a 35 mm bite when subjected to a seismic demand equal to 1% inter-storey drift with SG500. Functions for the utilisation factor against silicone bite are also developed considering 1.5% and 2.0% drift, and with the SG550 silicone type. Utilisation factors are found to be lower for SG550, and of course increased with increased inter-storey drift. Utilisation factors are also relatively insensitive to the other parameters varied throughout the studies.

A benefit of the probabilistic type of approach is the possibility to switch over from a deterministic approach and define confidence intervals for the utilisation factor. This was presented based on the 5th and 95th percentile. Finally, fragility functions for exceedance of silicone design stress (conservatively interpreted as probability of glass fallout) against inter-storey drift ratio are developed using cloud analysis. The results shows that the probability of glass fallout is strongly dependent on the silicone bite and decreases as the silicone bite increases – e.g. As expected, the SG550 shows higher median of fragility functions for all silicon bites (1.25x higher in average) compared to SG500 given the higher mechanical properties. The difference in dispersion is instead negligible.

Overall, this study has demonstrated the feasibility and possible value in a probabilistic approach to façade seismic performance assessment using advanced numerical methods. The deeper insights provided may allow design engineers to make more informed decisions regarding the various design inputs, their influence on the seismic performance, and the acceptable probability of not meeting their relevant performance criteria.

A number of possibilities for future work in this area are also identified. These could focus on parameterising the geometry of the façade to allow a wider applicability of the outcomes for design engineers, calibration of the model at higher drift levels where non-linearity and damage can be explicitly assessed (pending availability of appropriate test data), further exploration of the importance of various structural details, an association of consequence functions to the fragility curves in terms of repair cost and repair time, and an evaluation of the loss of functionality for non-seismic performance criteria such as air and water tightness resulting from various levels of seismic performance.

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