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PROBABILISTIC SEISMIC ASSESSMENT OF UNITISED GLASS CURTAIN WALLS WITH TIMBER FRAMING

Giovanni Milan[1], Jonathan Ciurlanti[1], Danny Bond[1], Simona Bianchi[2], Nebojša Buljan[3], Guido Lori[4], Jamie Dennis[1]

[1] Arup
Amsterdam, the Netherlands
giovanni.milan@arup.com

[2] Delft University of Technology
Delft, the Netherlands
sbianchi@tudelft.nl

[3]RI ISA d.o.o., Permasteelisa Group
Rijeka, Croatia
n.buljan@permasteelisagroup.it

[4]Permasteelisa Group
Vittorio Veneto, Italy
glori@permasteelisagroup.it

Abstract

Unitised glass curtain walls are widely used in the construction industry due to their advantages in terms of quick installation, quality control and overall performance. However, they are associated with a substantial environmental footprint, accounting for a significant contribution of embodied carbon emissions of the building. The urgent need for resilient and eco-friendly buildings is one of the predominant societal challenges of this century. Further research is needed to assess the performance of facades with bio-based materials and low-damage construction details. This paper presents an advanced numerical model of a whole façade system (including frame, glass, and connections) with timber framing (mullions and transoms). The model replicates the setup of dynamic tests carried out at the laboratory of Permasteelisa Group in Vittorio Veneto (Italy). A sensitivity analysis is performed 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). Damage fragility curves based on the inter-story 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.

Keywords: Façade, Earthquake Engineering, Timber, Fragility Functions.

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1 INTRODUCTION

Recent earthquake events, such as those in L'Aquila (2008), Christchurch (2011), and Kaikoura (2016), have underscored the high vulnerability of non-structural elements, including façades, partition walls, ceilings, and equipment. Despite accounting for up to 85% of the total building cost in commercial buildings [1], the seismic design of these elements remains inadequate, often leading to significant overestimations or underestimations of seismic performance. During severe earthquake shaking, the collapse of façades can pose life-threatening risks to building occupants and passers-by. Moreover, façades are particularly susceptible to damage at low-to-moderate seismic intensity levels, which can greatly affect the functionality of the building post-earthquake and result in substantial repair costs and business interruption. These seismic costs can be even higher when dealing with glazed façade systems.

Among glazed façade systems, unitised systems (Figure 1a) are increasingly preferred among the various types of glazed curtain walls (e.g. stick, unitised, structural glazing). Traditionally, these components consist of flat panels made of glass, aluminium, steel, natural stone or terracotta, infilled into metal frames anchored to the structural system by connections at the floor levels. Covering almost the entire building envelope, unitised systems can account for up to 30% of total building costs [2]. 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 accommodate 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, glass cracking and glass fallout [3][4]. 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.

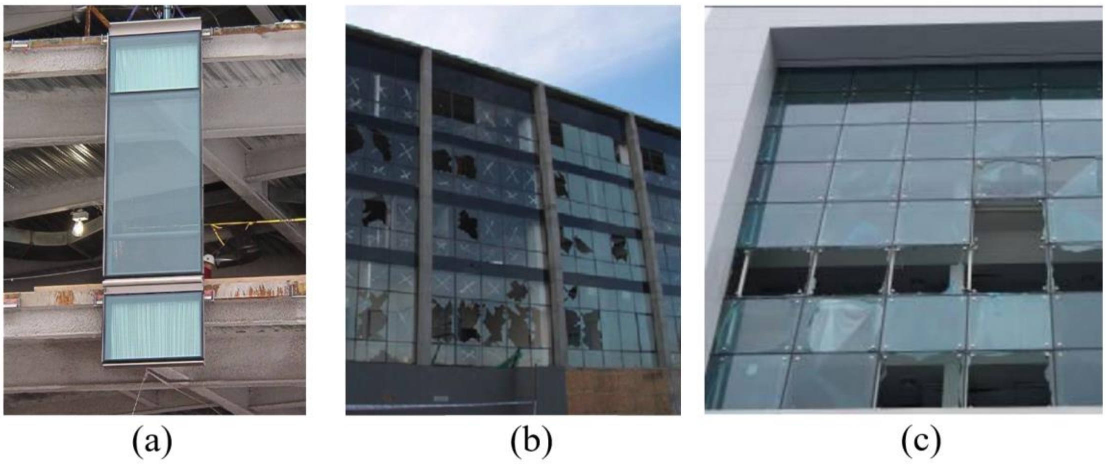

Figure 1 (a) Example of unitised glass curtain walls (by Permasteelisa Group); (b) Seismic damage to glazed façades: 2010 Chile earthquake [3], (c) 2011 Christchurch earthquake [4].

Various experimental studies have been conducted in the past few decades to evaluate the seismic performance of traditional glazing systems. These studies investigated the in-plane movement and drift capacity of glass panels using in-plane monotonic and cyclic racking testing [5][6], and shake table testing [7][8], to study the impact of different glass types, clearance values, and connection systems. The experimental tests demonstrated that unitised curtain wall facades exhibit strong seismic resilience, with failure occurring only at very high drift ratios. The development of fragility curves from the test data supports this conclusion, showing that while non-structural damage – such as water infiltration and silicone sheet damage – can occur at lower drift levels, the overall structural integrity of the facades is preserved even at higher displacements [9]. Advanced numerical simulations [10] also demonstrate the high seismic resilience of unitised systems, with a median inter-story drift in excess of 5% for the fragility function concerning glass fall-out.

While unitised systems exhibit commendable seismic performance, they are associated with a substantial environmental footprint, accounting for 30% of embodied carbon emissions of the building [11]. In particular, the environmental impact of aluminium materials traditionally adopted for framing members has raised concern, with CO_2 net emissions of 26 t/m³ during production and processing [12]. In contrast, timber, which sequesters 1 t/m³ of CO_2 [13], has emerged as a compelling alternative. The shift towards timber framing not only reduces the carbon footprint but also aligns with the growing demand for greener construction practices. Despite the extensive research on aluminium facades, further investigation is required to evaluate the seismic performance of unitised glass curtain walls with timber frames through experimental and numerical studies. This research is essential to provide practitioners with valuable information on both the numerical approach and potential damage mechanisms, supporting 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 static and dynamic 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 and type.

2 NUMERICAL MODELLING

The case study is based on a unitised glass curtain wall façade as installed in a real building and tested at a 1:1 scale during an experimental campaign conducted in 2025 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.

2.1 Experimental setup

The experimental setup consists of three façade units, with each unit measuring 3600 mm in height and 1500 mm in width (Figure 3a). 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 glued laminated wood profiles, using spatial lamination – longitudinal, lateral and layered gluing of wood lamellae, incorporated in a fully unitised curtain wall design – see Figure 2. The material used for the sample was fir for the core and Siberian larch for the ridges, marine grade plywood stiffened the internal lateral face. The mullion cross-sectional dimensions are approximately 180x40mm.

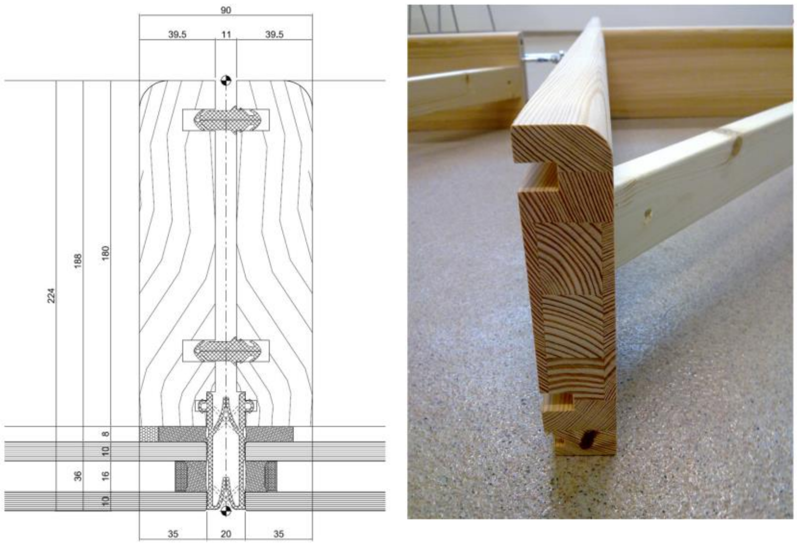

Figure 2: Timber mullion cross section.

The glass is a double-glazed unit with panels measuring 1500x2400x10 mm and is retained to the aluminium frame using structural silicone: Sika SG500, with a cross-section of 25x8 mm (3.125 aspect ratio). A glass spandrel (shadow box) is also present with a size of 1500x1200.

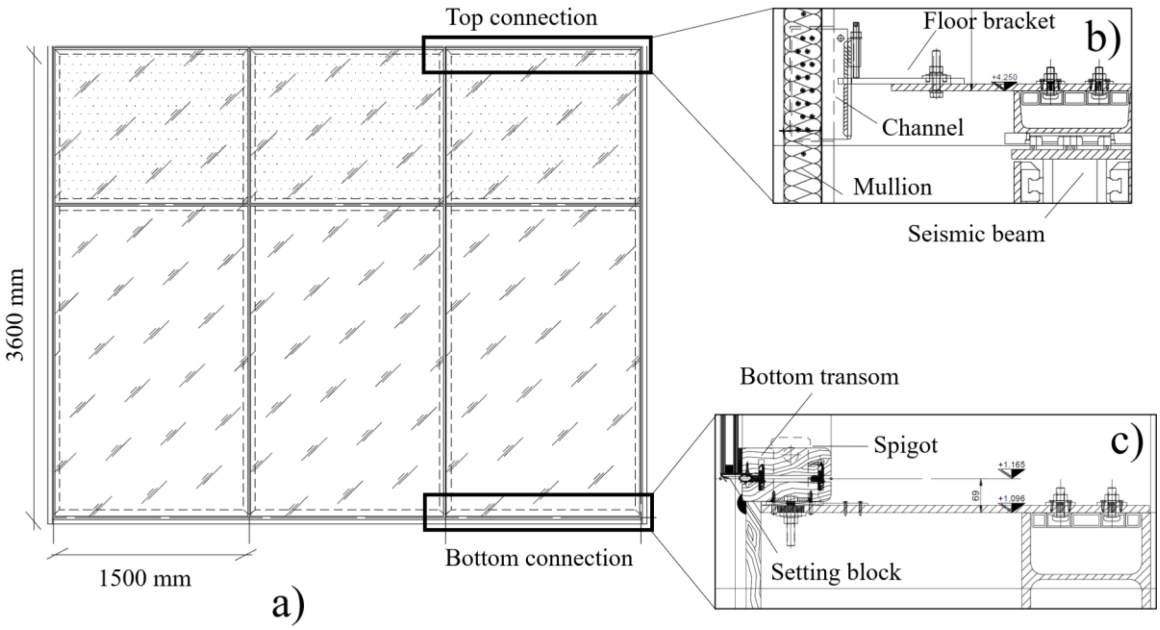

Figure 3: Experimental setup and connections: (a) façade mock-up tested at the laboratory of Permasteelisa Group; construction details for the upper (b) and bottom (c) connection systems.

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 3b) 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 3c) consists of the use of shear keys (spigots) at the corners of the units that allow vertical moments only – see Figure 4. 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 underlying unit.

Figure 4: Bespoke spigots at the corner of the units.

2.2 Numerical approach

A numerical model of the full façade system consisting of the three 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 5a shows the full façade model and all its elements, including the constraints and boundary conditions used in the analysis.

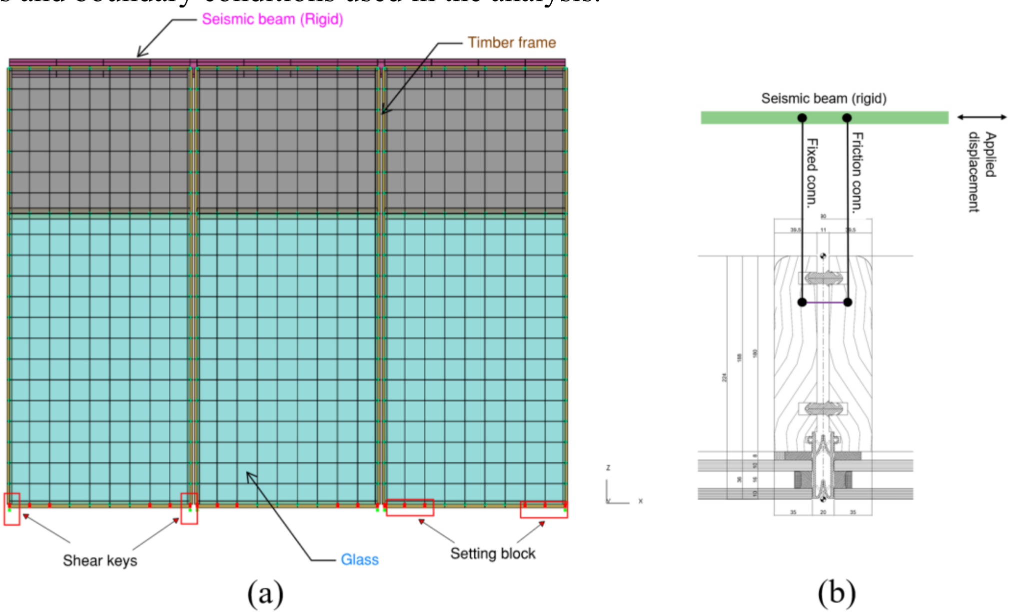

Figure 5: Numerical model developed in LS-DYNA.

The frame members were modelled as beam elements with an equivalent rectangular cross section of 180x39.5 mm. An elastic model was adopted for the timber with an equivalent Young's modulus of 13 GPa. The ultimate bending capacity in the major axis was determined to be 7.2 kNm. These values were derived from four-point bending tests conducted on vertical mullions, courtesy of the Permasteelisa Group. The mullion-transom connections were assumed as fixed connections. For the 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 six degrees of freedom springs with a spacing of 166 mm and an elastic stress-strain relationship that simulated both the axial and shear behaviour. The SikaSil500 material properties (axial and shear design stresses, and Young's and shear modulus) are based on [10].

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 5b). The fixed connection allows for uplifting of the façade only, while the friction connection allows for uplifting and sliding once it overcomes the friction between the hook and the steel bracket. An internal gap of 11 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 12 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.

2.3 Experimental vs numerical comparison

During the experimental campaign, dynamic 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), which specifies the performance evaluation of a curtain wall façade under seismic action. Two additional intermediate levels were included to ensure a gradual increase in shaking intensity until reaching the maximum displacement. This resulted in the following drift amplitudes applied to the façade:

- 12 mm (0.35% inter-story drift ratio) – slightly higher than the H/100 value specified JASS14, indicating no damage to internal and external components.
- 24 mm (0.70% inter-story drift ratio) – exceeding the H/200 value provided by JASS14, where no external components may exceed their allowable stress and sealing must be repaired.
- 36 mm (1.00% inter-story drift ratio) – corresponding to the JASS14 value, ensuring that neither damage of the glass nor dropout of any component is allowed.

The following seismic loading types were adopted in the experimental campaign:

- *Crescendo Tests*: these experiments involved a series of sinusoidal cycles consisting of a succession of four cycles of ramp up intervals followed by four cycles of constant amplitude intervals with frequencies at 0.4 and 0.8 Hz.
- *One far-field record:* (Friuli 1976 earthquake - Peak Ground Acceleration (PGA) = 0.11g, Soil Type C, Station ST33) and one *near-fault record* (Christchurch 2011 earthquake - PGA = 0.17g, Soil Type D, Station CCCC) were selected from a set of spectrum-compatible earthquakes. The testing protocol involved applying inter-story drift time series generated through non-linear dynamic analysis of a multi-story reinforced concrete building for a high-seismicity zone [14].

To verify the accuracy of the numerical model, experimental data from the H/150 displacement level were used to compare the numerical and experimental displacements of both the frame and glass components. Figure 6 shows the time history of the prescribed displacement (input) applied to the seismic beam.

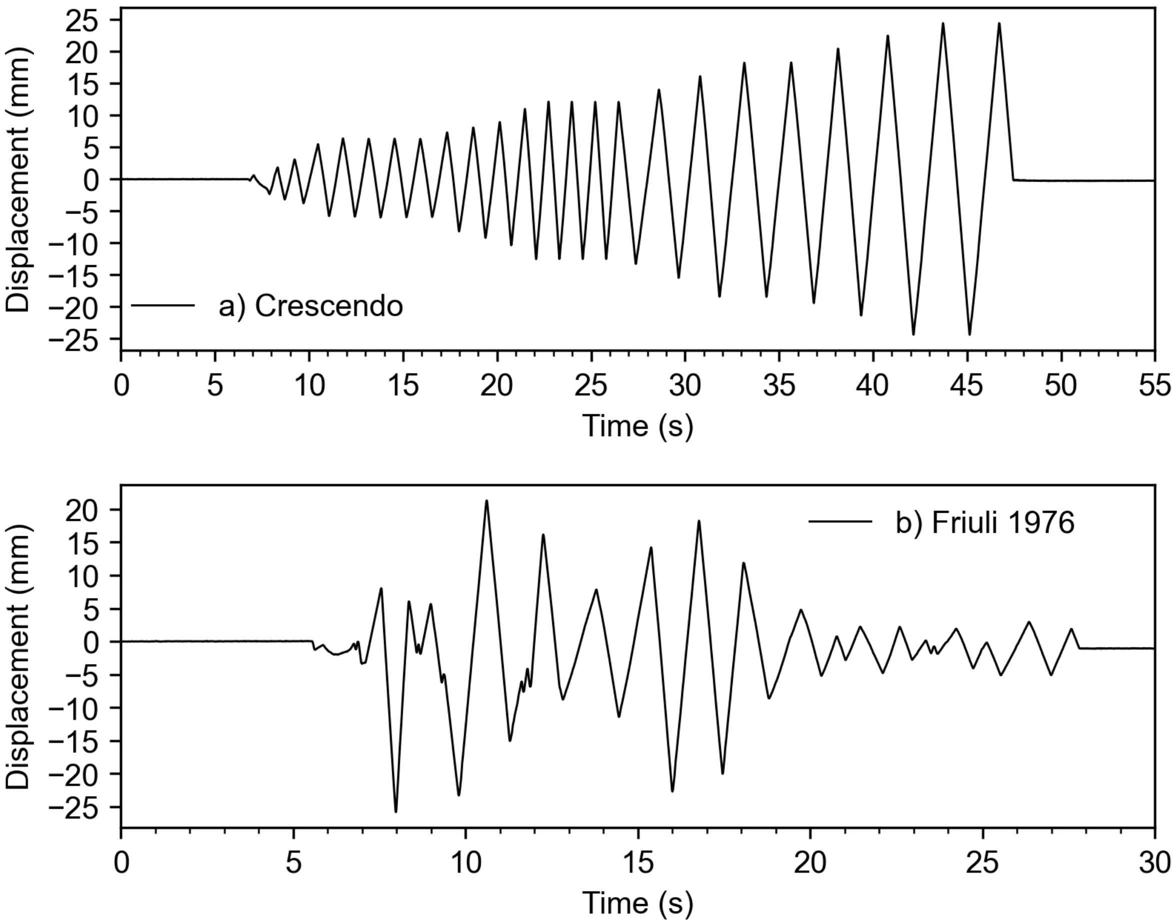

Figure 6: H/150 displacement level applied to the seismic steel beam for the Crescendo test; b) Friuli 1976 earthquake.

During the experiments, several displacement transducers (GEFRAN potentiometers; LZE LVDT; Draw Wires - DW) were installed on the units (see Figure 7) 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 approximately 20% for the peak uplift at corners. Figure 7 shows an example of the time-history results for the bottom right corner of the middle unit in the vertical direction for Friuli 1976 record for inter-story drift of 0.70% (H/150 displacement level).

In addition to displacement transducers, strain gauges were employed to monitor the in-plane behaviour of the glass near the corners, in proximity to the setting blocks. For the Friuli 1976 seismic record (corresponding to an H/150 displacement level), the maximum recorded strain was approximately 13 μm/m. This value is consistent with the numerical model's prediction of around 15 μm/m at the same location.

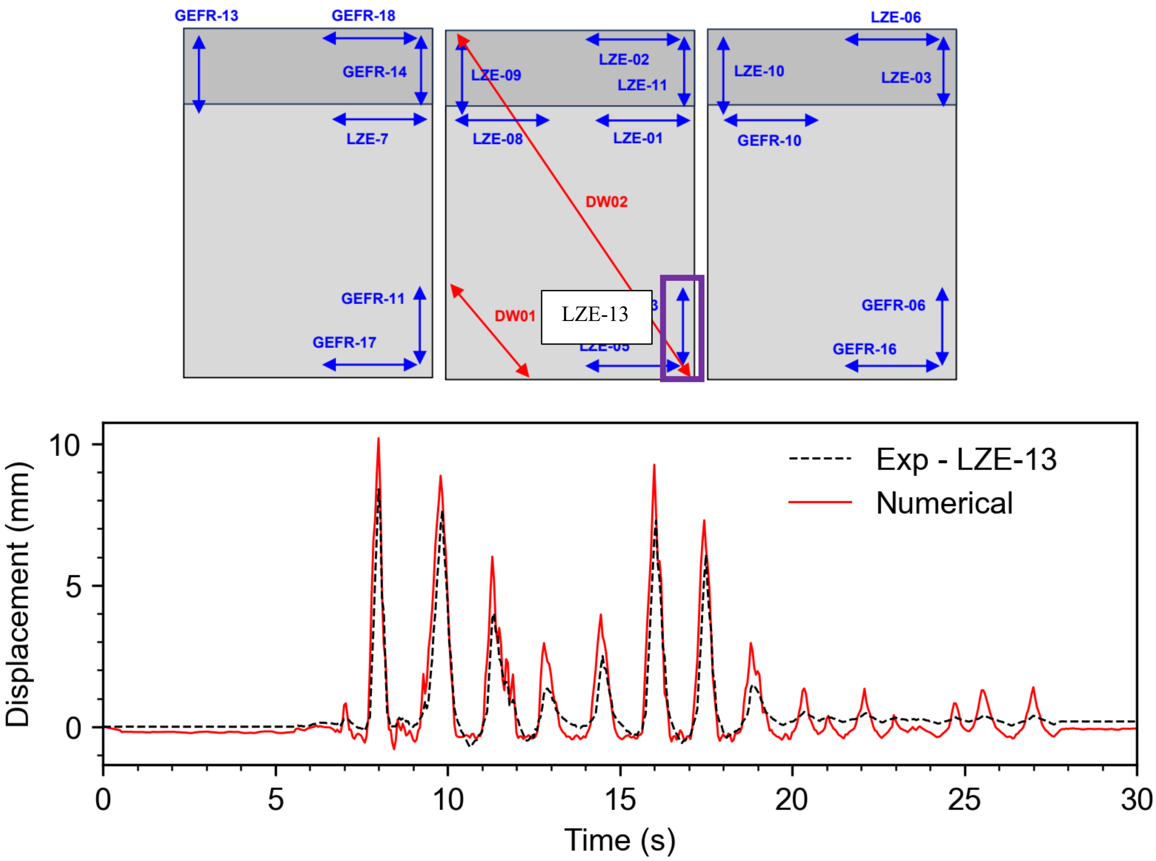

Figure 7: Comparison between experimental vs numerical results on frame members for Friuli 1976 record at H/150 displacement level.

After validating the model, the Utilisation Factor (U_t) of the different façade components was derived to provide insights into the hierarchy of structural strength within the façade. 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, 0.35 and 0.44 were found as U_t values for the structural silicone for Crescendo and Friuli respectively. The higher value for Friuli possibly indicates the importance of dynamic effects for the silicone response. U_t values of 0.013 and 0.017 were obtained for the glass panel instead, and 0.05 and 0.07 for the timber frame. Although these U_t values do not indicate failure for inter-story drift of 0.70% (H/150 displacement level), the results suggest that the structural silicone is governing in the overall performance of the façade.

It is worth adding that as part of the test campaign, a monotonic test was performed on a single unit to check the governing failure mechanism for the façade system. It was observed that the for large displacements, no visible damage was observed for the silicon, timber and glass. However, for approximately 4.3% drift, the unit experienced the disengagement of the spigots due to excessing uplift at corners. Hence, an additional utilization factor was introduced to monitor the uplift of the corners with the respect to the maximum allowable limit (i.e., the spigot height) of approximately 77mm ($U_t=d_{max}/d_{limit}$).

3 SENSITIVITY ANALYSIS

A probabilistic 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 Latin Hypercube Sampling (LHS) technique was utilised to sample the random variables and create a large set of numerical models. Each random variable is assigned a probability distribution (which may be a continuous - or discrete -valued distribution), and each Cumulative Distribution Function (CDF) is divided into a number of equiprobable bands equal to the number of analyses to be carried out. The number of simulations required does not depend on the number of variables. The combination of values for the variables is set up such that every band of the CDF is sampled exactly once (in the case of discrete variables, each value is sampled a number of times in proportion to its probability mass [15].

The probability distributions and coefficients of variation for these parameters are listed in Table 1, based on literature data [10] and engineering judgement. It is worth adding that correlation coefficient equal to 0.8 (based on engineering judgment) between strength and stiffness of silicone was accounted for in the sampling.

Parameter	Mean	Coefficient of Variation	Distribution
Glass Young modulus	70 GPa	0.03	Normal
Spigot disengagement limit	77 mm	0.05	Normal
Timber bending capacity	7.2 kNm	0.2	Normal
Timber Young modulus	13 GPa	0.2	Normal
Silicone shear modulus	0.50 MPa	0.1	Normal
Silicone axial modulus	1.5 MPa	0.1	Normal
Silicone design shear stress	105 kPa	0.1	Normal
Mullion-mullion gap	11 mm	0.05	Normal
Silicone width	8-35 mm	-	Uniform

Table 1: Probabilistic distributions implemented in the sensitivity analysis.

The study was conducted for three fixed inter-story drift levels (1%, 1.5%, and 2%) that represent typical design choices for the primary structure of a building. For each inter-story drift level, 100 probabilistic numerical models were identified, thus a total of 300 cases to investigate. Numerical analyses were performed considering one full load cycle (e.g., for 1% drift ratio: 0, 1%, −1% and 0) with low frequency excitation (0.15Hz) to avoid dynamic effects.

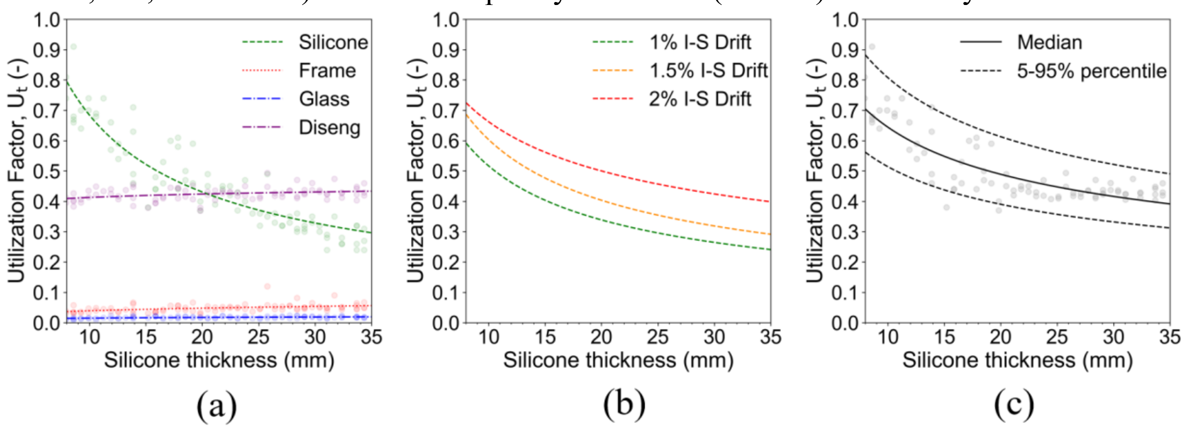

Figure 8: Results in terms of Utilization Factor (Ut) vs Silicone thickness; (a) governing mechanism at 2% inter-story drift, (b) influence of inter-story-drift, and (c) 5/95 percentile values at 2% inter-story drift.

Overall, the probabilistic parametric analysis provides insights into how uncertainties in the input parameters affect façade performance under seismic loading. As illustrated in Figure 8a, the results show U_t as a function of the silicone bite. The probabilistic analysis results were used to identify a regression (median) curve (Figure 8c) and to evaluate this curve for all the inter-story drift levels considered (Figure 8b). As expected, the utilization factor decreases as the silicone bite increases. However, for silicone thicknesses greater than 20mm (at 2% inter-story drift), spigot disengagement becomes the governing factor.

It is also worth noting that the disengagement U_t shows high sensitivity to drift compared to the silicone utilization factor. The values for glass and frame remain nearly constant with varying silicone thickness. Importantly, the frame utilization factor is less than 0.1, due to the moment-resisting connection between the transom and mullion, which causes the unit to be dominated by rigid body rotation. A pin connection, typically assumed for aluminium frames, would contribute to higher distortion of the frame.

4 FRAGILITY ASSESSMENT

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 [16] 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_{ti}) 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 case, the fragility functions were developed using inter-story drift ratio as proxy for the seismic intensity measure (IM). Regarding the response, the maximum utilisation factor from each mechanism was adopted, given the governing mechanism could either be the silicone or the spigot disengagement depending on the combination of silicone thickness and drift level. In order to correctly treat the results of the analyses where the utilization factor is greater than 1 (e.g., exceedance of spigot uplift or exceedance of silicone design stress), a censored regression [17] has been undertaken when estimating the regression coefficients.

In addition to the 1%, 1.5%, and 2% inter-story drift levels, two additional stripes of 5% and 6% drift have been analysed using Latin hypercube sampling to assess the behaviour of the façade closer to failure (i.e., closer to U_t equal to 1). The cloud method typically assumes a linear relationship between the logarithm of response and intensity measure (IM) and homoscedasticity of the residuals (i.e., dispersion is not a function of the IM), which may not hold over the full range of intensity levels. Furthermore, the aleatory variability in the low response is much lower than the high response counterpart. Therefore, removing the 1% stripe helps to create a set of data that is more likely to be homoscedastic, making the analysis more reasonable when focused on higher levels of response.

In summary, the adopted drift ratio stripes for the fragility function regressions are: 1.5%, 2%, 5% and 6%. Each stripe consists of 100 realisations of the LHS sampling with a total of 400 realisations.

The regression analysis for fragility functions was carried out in terms of both the inter-story drift ratio (IM) and silicone thickness parameter (S_t). In this case, the median of the fragility function ($E[lnR_F|IM]$) is modelled by a linear regression equation on the logarithms of both IM and S_t, with parameters b_0, b_1 and b_2, whilst the standard deviation or dispersion ($\beta_{R_F|IM}$) is estimated by the standard error of the regression:

$$E[lnR_F|IM] = b_0 + b_1 ln(IM) + b_2 ln(S_t) \quad (1)$$

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

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

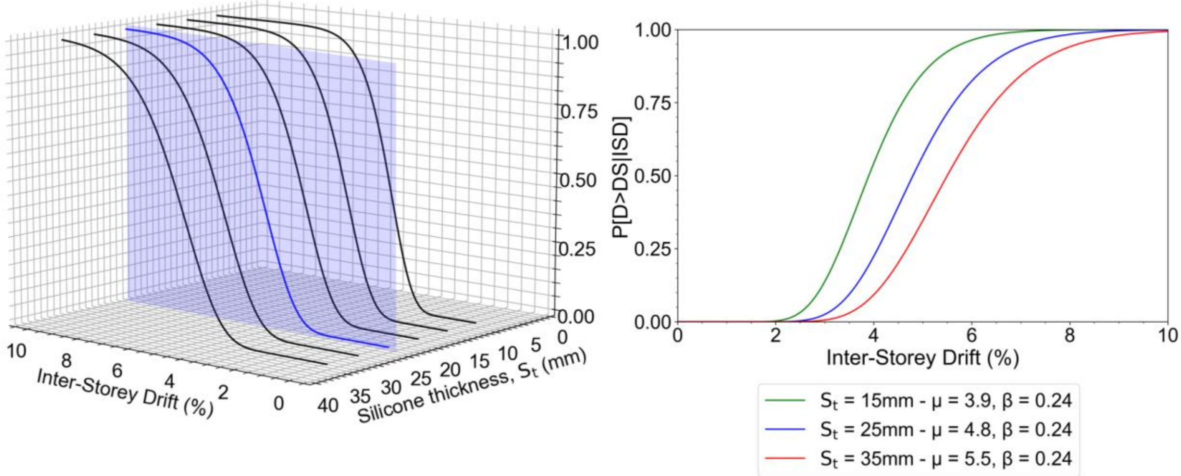

Figure 9: 3D fragility function and respective 2D cut sections for 15, 25 and 35mm of silicone bites.

In essence the fragility function is a 3D surface (Figure 9) where the probability of the silicone reaching its maximum allowable stress level is both a function of the inter-story 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, when governed by silicone response is herein interpreted as probability of glass fallout from a design perspective. 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-story 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-story drift ration 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. It is worth noting that the median for 25mm of silicone thickness is in line with the experimental findings for which the inter-story drift ratio for collapse is higher than 4%.

Parameter	Inter-story drift ratio
Median at 15mm of silicone thickness	3.9%
Median at 25mm of silicone thickness	4.8%
Median at 35mm of silicone thickness	5.5%
Dispersion	0.24

Table 2: Median and dispersion of fragility functions.

5 CONCLUSIONS

In this paper, an application of detailed numerical modelling, parametric analysis, and fragility function development to the seismic performance of a timber unitised curtain wall system is summarised. The numerical modelling approach, incorporating representations of the glass, silicone, and timber framing system, is validated against test experiments carried out by Permasteelisa Group, showing good benchmark in terms of peak displacements at the corner units. Consequently, a sensitivity analysis is carried out through generation of three suites of 100 unique analysis models varying key parameters of the model (e.g., silicone and timber properties) by use of the Latin Hypercube Sampling 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 sensitivity analysis show that the silicone bite is the governing parameter of unitised curtain walls for inter-story drift values up to 2% , with the associated utilisation factor varying between approximately 0.8 for an 8 mm bite and 0.3 for a 35 mm bite. For larger drift values, the spigot disengagement at corner units becomes the dominant failure mode, making the spigot heigh a significant parameter. 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.

Overall, this study has demonstrated the feasibility of adopting an advanced numerical probabilistic approach to assess the seismic performance of unitised systems. The sensitivity analysis outcomes can support design engineers in making more informed decisions regarding various design inputs, their influence on seismic performance, and the acceptable probability of not meeting relevant performance criteria. The development of fragility functions highlights the high seismic resilience of unitised systems and their strong dependence on silicone bite. The results also support the feasibility of using timber framing systems as a sustainable alternative to metal ones. These curves can be integrated within a risk assessment framework to estimate repair costs and downtime for building envelopes.

A number of possibilities for future work in this area are also identified. These could focus on parameterising the geometry of the façade (e.g., aspect ratio) to allow a wider applicability of the outcomes for design engineers, further exploration of the importance of various structural details (e.g., gasket), 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. In addition, it is recommended to further investigate the out of plane behaviour of the unitised system, as well as the combined in-plane and out-of-plane behaviour. Finally, in terms of fragility function developments, it is recommended to assess the sensitivity of using different loading protocols (e.g., a set of earthquake records that cover the entire spectrum of seismic intensity).

6 ACKNOWLEDGEMENTS

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