Executive Boardroom Commentary

Seismic Design of Structural Silicone Joints in façades

for the protection, safety and well being of occupants

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Past earthquakes have shown the vulnerability of architectural glass in façades and have increased the interest in designing them to resist seismic loads and displacements. Two major concerns related to façade performance during and after a seismic event are highlighted here [1]:

- Hazard to people - Injuries and deaths at street level from shattered storefront and elevated glazed systems are recognized threats.
- Building downtime and costs to repair - Bringing operations and services "back to normal" can be impeded by a breached building envelope due to damages to glazing systems.

In this context, the benefits offered by Structural Sealant Glazing (SSG) systems are widely recognized but still limited. Guidelines are available in current building codes to assess the seismic behavior of the façade systems and to size the structural silicone joints, whose correct design is crucial for performance enhancement.

In this article a design concept for seismic design of SSG-joints is proposed with reference to the performance-based engineering approach defined by Japanese Standard JASS14. Three performance levels associated to different design requirements are defined by the concept, with the final intent of:

- Not threatening the appearance of the façade in its service life for a unique and extreme event;
- Balancing costs and risks, with no compromise on safety.

International Regulations for Seismic Design of Façades

Even if there is increased attention arising on the seismic response of glass façade systems, only limited guidelines are provided by International Building Codes.

In European markets, EN 1998-1 [2] establishes guidelines for design of structures for earthquake resistance and partially deals with curtain walling and partition elements, considered as non-structural elements. Seismic design of façade components basically focuses on a force-based approach: elements needed to resist seismic actions if their failure can cause a risk to people, affect the main building structure or services of critical facilities. No requirements are specified by EN 1998-1 [2] about the capability of the façade elements to accommodate the displacements that the main building structure experiences during the earthquake.

In U.S. markets, ASCE 7-10 [3] specifies that seismic demands for curtain walling components need to focus on both transfer of equivalent static forces and accommodation of relative displacements due to seismic inter-storey drifts, which do represent a key factor in controlling the seismic performance of a façade system.

As exterior wall panels can pose a life-safety hazard, they have to be designed to accommodate the differential displacements Dp caused by the earthquake (Section 13.3.2 of ASCE 7-10 [3]). Additionally, glass in glazed curtain walls, storefronts and partitions have to be designed and installed to accommodate the relative displacement due to the building inter-storey drift Δfallout, which causes glass fallout from the frame. Δfallout has to be determined by engineering analysis or in accordance with AAMA 501.6 [4], which provides an experimental method for determining under controlled lab conditions and by dynamic motion simulation of the seismic drift amplitude Δfallout.

It is worth mentioning that the dynamic test of AAMA 501.6 [4] substantially differs from the static test of AAMA 501.4 [5], which describes a test method to evaluate the performance of curtain wall systems subjected to smaller inter-storey drifts induced either by low-scale earthquake or by wind loads. Indeed, while AAMA 501.4 [5] test method focuses primarily on the seismic serviceability limit state behavior of a wall system, AAMA 501.6 [4] focuses on the seismic ultimate limit state of its glass.

The two different test methods introduce the concept of calibrating the performance requirement to the magnitude of the seismic input, as per design philosophy promoted by NEHRP (National Earthquake Hazard Reduction Program) defining four seismic design performance levels, still at a conceptual stage:

- Operational Level, with essential no damage to cladding elements.
- Immediate Occupancy Level, with moderate damage to non-structural elements and light damage to structural elements in the

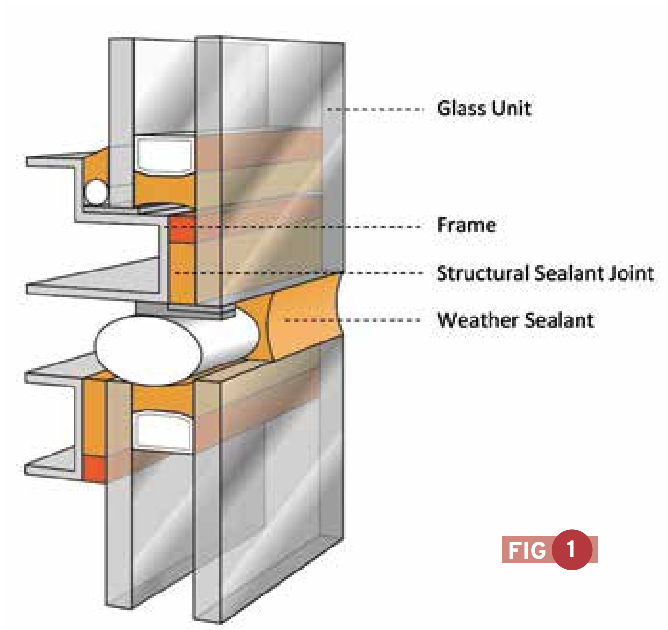

FIG 1

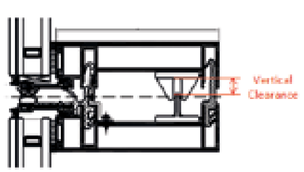

FIG 2

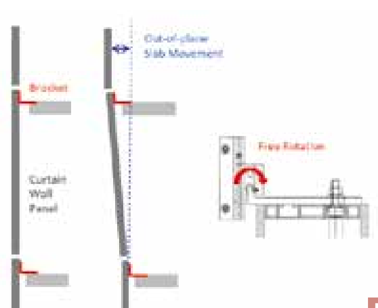

FIG 3

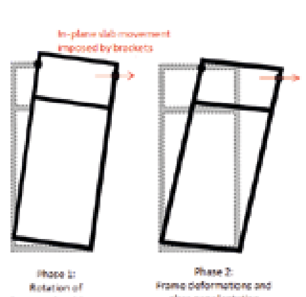

FIG 4

primary structural system of the building.
- Life Safety Level, with moderate damage to structural and non-structural elements.
- Near Collapse Level.

In the Japanese market, JASS 14 [6] is specifically dedicated to façades and curtain walling and provides design criteria for their seismic design. The energy released by the earthquake occurs in the forms of P-waves and S-waves acting in vertical and horizontal directions respectively; façade components need to be verified against equivalent static forces to be applied at their mass center.

Specific focus is given by JASS 14 [6] to the effect of the seismic inter-storey drifts of the main structure, which can introduce deformations into the façade system to be properly accommodated. Based on the building inter-storey height H, JASS 14 [6] sets three different seismic levels diversified by potential hazard and probability of occurrence:
- LEVEL 1 – Maximum inter-storey drift: H/300
- No damages to internal and external components have to occur.
- This seismic grade is related to earthquakes frequently occurring in Japan.
- LEVEL 2 – Maximum inter-storey drift: H/200
- The stress in all external components has not to exceed the allowable standard limits; after the seismic event, the full functionality of the façade is ensured with sealing repairing works admitted.
- This seismic grade is related to the largest scale earthquake happened in the past.
- LEVEL 3 – maximum inter-storey drift: H/100
- Neither the damage of the glass pane nor drop-out of any component is allowed.
- This seismic grade is related to the greatest earthquake to happen in the next 100 years.
-

Please refer to specified codes for a detailed overview about design recommendations provided.

Inter-Storey Drift Effects on SSG Systems
- Typical SSG-systems for unitized curtain wall elements consist of glazed panels bonded to a main aluminum frame by SSG joints (Figure 1). Along mullions and transoms, the panels are provided with stack joints of adequate clearance (Figure 2) designed to ensure free accommodation of any movement that the building structure can experience during its service life; the panel frame is usually hanged to the slab of the main structure by hinge brackets.

- In this section, the typical design concept adopted for standard SSG unitized panels to accommodate seismic slab movements is briefly described.

- Vertical differential movements between slabs
- The upward and downward differential seismic movements of the slabs are usually accommodated by the vertical stack joint along the transoms; adequate vertical clearance should be designed to avoid clashing of the panels (Figure 2). Therefore, no displacement is imposed to the SSG-joints by such movements.
- Horizontal differential movements between slabs (out-of-plane component)
- The out-of-plane differential seismic movements of the slabs due to inter-storey drift are usually accommodated by the brackets, which should allow for free rotation of the panel at the supports (Figure 3). Therefore, no displacement is imposed to the SSG-joints by such movements.
- Horizontal differential movements between slabs (in-plane component)
- The in-plane differential seismic movements of the slabs due to inter-storey drift produce a racking motion of the unit characterized by rigid translation and rotation of the glass panel within the frame, which can deform (Figure 4) [1][7][8].
- As a consequence, differential displacements between glass and frame occur and stress is introduced into the SSG-joints due to such inter-storey movements.
- It should be noted that in-plane movements of the slabs represents the most critical ones for the integrity of the system and it is often demanding to predict their effect accurately. Depending on the design solutions adopted, different rotation points can be identified in the panel racking motion and any component which prevents free rotations can have significant impact in the behavior of the whole system.

Benefits Offered by SSG Systems
Captured glazed systems in unitized curtain walling typically consist of glass panels retained to a main frame by mechanical means able to transfer the required loads (Figure 5). Such systems highly differ from conventional Structural Sealant Glazing (SSG) systems when seismic performances are analyzed.

The benefits offered by SSG systems compared to captured systems in areas prone to earthquake are widely recognized:
- The resilient attachment of the glass panel to the supporting framework by the structural sealant joint has proven to be beneficial in controlling and in some case eliminating breakage normally experienced during a small to moderate earthquake. Since the glass panel is not captured in metal glazing pocket, the opportunity for it to impact the metal surfaces during lateral displacements is minimized, eliminating a primary cause of breakage [10].
- Experimental studies [1] on glass panels retained by mechanical caps have shown that in-plane displacements of slabs produce at first a rigid racking motion of the glass panel as per typical SSG-systems, but mainly limited by the available clearance between glass and capping profiles. Additional inter-storey drifts produce high contact stresses between frame and glass, making it prone to fracture and to fallout under the in-plane compression forces (buckling effect) which are introduced into the capped system but avoided in the SSG one.
- When a glass lite break does occur, the SSG system can retain much if not all of the broken glass due to its continuous attachment along the edges, if a laminated glass panel is used and provided that the structural joints retain sufficient integrity [10].
- Although conventional SSG systems can perform well in an earthquake, consideration could be given to isolate the lite from building frame movements. One method to consider is to structurally adhere the glass panel to a sub-frame and then attach the sub-frame to the primary curtain wall frame with mechanical fasteners in slotted holes, dimensioned to accommodate the required seismic displacements [10].

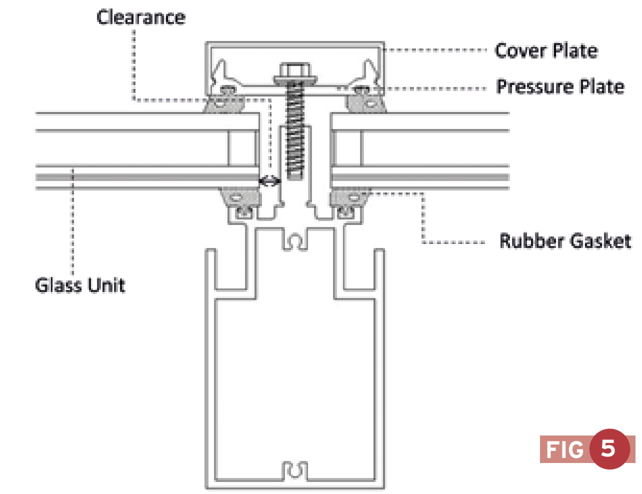

FIG 5

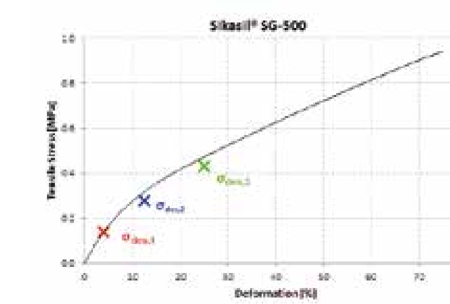

FIG 6

In this context, correct dimensioning of SSG-joints results are crucial to exploit the benefits offered by the system and to properly transfer seismic forces accommodating imposed movements; depending on adhesive properties and joint dimensions, seismic performance requirements associated to different damage levels can be satisfied.

Concept for Seismic Design of SSG-Joints
Even if the benefits offered by SSG systems in CW exposed to earthquakes are widely recognized, no official regulation currently provides clear seismic design criteria for structural sealant joints. In order to answer increasing requests, this section presents a design concept to assess the seismic performance of SSG-joints.

In line with the design philosophy adopted by JASS 14 [6], the utilization limit for the joints is defined depending on the seismic requirements set for the façade.

Three different performance levels associated to corresponding allowable strengths and deformation capabilities of the adhesive joints are proposed.
- LEVEL 1 - Damages to the façade components must not occur and the full functionality of the façade system must not be compromised after the seismic event.

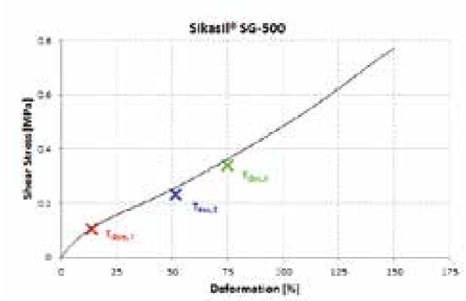

FIG 7

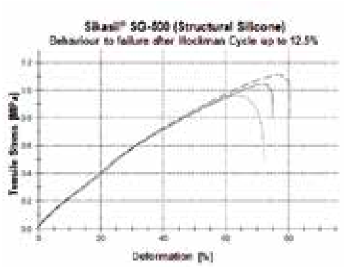

FIG 8

- During and after the seismic event, the stress on the joints is limited by the dynamic tensile and shear strengths $\sigma_{des,1}$ and $\tau_{des,1}$ set for typical wind design; a minimum global safety level of 6 is ensured for the SSG joints.

For structural sealant glazing applications by Sikasil® SG-500, the allowable strength level corresponds to a maximum tensile deformation in the joint of 5% (Figures 6 and 7).

- LEVEL 2 - The full functionality of the façade must be ensured; after the seismic event, some sealing repair works might be needed and inspection of the SSG-joints is required.
- During the seismic event, the movement capability certified for the adhesive is exploited and the allowable strengths $\sigma_{des,2}$ and $\tau_{des,2}$ (Figures 6 and 7) are set to correspond to a joint movement capability of 12.5%.
- The strength values are defined based on statistical analysis of results obtained on a population of minimum 10 samples 12mm x 12mm x 50mm tested in tension and shear.
- After the seismic event, the SSG-joints shall be able to withstand the loads occurring in the future service life of the façade and therefore a minimum safety level of 6 has to be restored.
- Figure 8 shows the behavior of joints 12mm x 12mm x 50mm (structural silicone Sikasil® SG-500) after Hockman Cycles representing an accelerated life cycle simulation consisting of (a) immersion in water for seven days (b) exposure in an oven at 70°C for seven days while under compression (c) automatic compression and extension cycling to 12.5% elongation rate at room temperature and (d) alternate compression and extension up to 12.5% elongation rate at high (70 ± 2° C) and low temperatures (-26 ±2 °C) respectively under conditions described by ASTM C 719.
- The graph proves that the final strength of the joint is not reduced after it has repeatedly experienced stress levels corresponding to 12.5% elongation.
- Therefore, the earthquake associated to Level 2 will not compromise the future performance of the structural joints and a minimum design safety level of 6 will be ensured under future loads.
- LEVEL 3 – Drop-out of any components is not allowed.
- During such unique and extreme event, design focuses mainly on life safety and the demand for the structural joints is to be earthquake-resistant: the allowable strengths $\sigma_{des,3}$ and $\tau_{des,3}$ (Figures 6 and 7) are set to correspond to tensile deformations of 25%.
- After the seismic event, a minimum residual strength must be ensured by the structural joints as the façade could be seriously damaged and substantial repair works are to be accounted for.
- Figure 9 shows the behavior of joints 12mm x 12mm x 50mm by Sikasil® SG-500 after the Hockman Cycles described for Level 2, but associated to compression/elongation rate of 25%. The graph highlights that the final strength of the joint is reduced by repeated stress levels corresponding to 25% elongation; however, after this extreme event a minimum safety level of 2.5 is still ensured.

A proper inter-storey drift Δ associated to each performance level should be set by project specifications or local standard based on proper risk assessments.

In terms of calculation procedure, the design approach proposed allows to evaluate the adequacy of the joint thickness to accommodate the displacement due to seismic racking.

- For European markets where ETAG002 [9] approach applies:

S_i differential displacement to be accommodated by the joint for the seismic performance level i

G_i shear modulus of the adhesive for the performance level i, with

e joint thickness

$\tau_{S,i}$shear stress due to S_i

For performance level 1, G1 is defined according to ETAG002.

For performance level 2, G2 is defined as the secant modulus between the deformation boundary limits [0; $\varepsilon_{des,2}$] covering the shear deformation range 0% < ε ≤ 51.5% (equivalent to tensile deformation range 0% < ε ≤ 12.5%).

For performance level 3, G3 is defined as the secant modulus between the deformation boundary limits [0; $\varepsilon_{des,3}$] covering the shear deformation range 0% < ε ≤ 75% (equivalent to tensile deformation range 0% < ε ≤ 25%).

For Sikasil® SG-500, following values apply: G1=0.50 MPa, G2=0.49 MPA, G3=0.48 MPa.

- For American markets where ASTM C 1401 [10] approach applies:

Where:

ε_i Maximum elongation allowed for the joint for the seismic performance level i, with

$\varepsilon_1 = 0.05$, $\varepsilon_2 = 0.125$, $\varepsilon_3 = 0.25$.

The global utilization level of the joint should be evaluated based on forces and differential displacements which simultaneously apply, limiting the global deformation of the joint to the elongation limit ε_i set for each performance level.

Mock-up test

Seismic mock up tests performed by Permasteelisa Group on four unitized façade panels are used to validate the design concept proposed. Test procedure, system configuration and experimental results are comprehensively provided by [8].

Tests mock up consisted of four unitized panels composed by a single monolithic glass 1452mm x 3752mm bonded to its main aluminum frame by structural sealants; Sikasil® SG-500 joints 10mm x 6mm were used to bond the glass elements of two panels, while Sikasil® SG-550 joints 6mm x 6mm were applied on the other two panels in order to compare the behavior of the two structural sealants.

The following test sequence was implemented, aiming at investigating the seismic behavior of the systems based on the performance requirements set by JASS 14 [6]:

- Air leakage test [11]
- Racking test: an inter-storey drift of H/300 (Δ1 = 12.5mm) was imposed (20 cycles), as per performance Level 1 of JASS14 [6].
- Air leakage test [11]
- Racking test: an inter-storey drift of H/200 (Δ2 = 18.75mm) was imposed (10 cycles), as per performance Level 2 of JASS14 [6].
- Racking test: an inter-storey drift of H/100 (Δ3 = 37.5mm) was imposed (5 cycles), as per performance Level 3 of JASS14 [6].

The following test results were obtained:

- Racking test representative of seismic Level 1 did not cause any damage to the façade panels; the air leakage tests before and after the imposed storey drift Δ1 proved that the functionality of the façade was not altered.
- Racking test representative of seismic Level 2 did not cause any damage to the façade panels; air leakage tests after this test was not repeated as performance level 2 by JASS 14 [6] allows for repair works on sealing joints to restore the tightness efficiency of the system.
- Racking test representative of seismic Level 3 did not cause any damage to the glass panes and no fallout of any component occurred. Failure of the screws located in the transoms and used for panel alignments occurred.
- Test results listed above are mainly provided with focus on behavior of the structural joints. Control transducers were applied to measure the vertical and horizontal displacements of glass and frame in each test phase. The maximum differential displacements recorded during each racking phase are here used as inputs to calculate the joint deformation produced by the inter-storey drifts. Figure 10 summarizes the results obtained in each racking phase with focus on panels bonded by structural silicone Sikasil® SG-500.

The results show that a preliminary design based on the deformation limits set for the adhesive could ensure the resistance of the joint to the seismic inter-storey drifts specified and compliance with the performance requirements set for the façade elements.

Conclusions

Compared to capped systems, SSG systems in unitized curtain walling can provide an effective solution to minimize damages due to an earthquake. Although this is well recognized, no standard provides clear criteria for the design of SSG joints which could be subjected to seismic impacts.

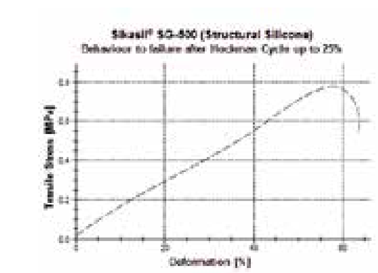

FIG 9

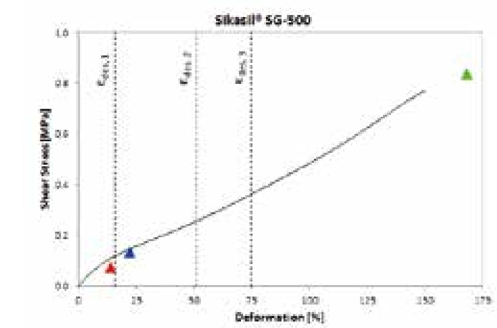

FIG 10

Depending on adhesive properties and joint dimensions, performance requirements associated to different damage levels can be satisfied. In line with the performance-based engineering approach proposed by JASS 14, this article presents a concept to design SSG joints affected by seismic forces and displacement. Three performance levels associated to different design requirements are defined, with the final intent of balancing costs and risks with no compromise on safety and of not affecting the appearance of the façade for a unique and extreme event.

The concept is based on results obtained from small-scale tests carried out on sealant H-specimens and it is validated by full-scale tests performed on mock up panels.

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