Challenging Glass 5 – Conference on Architectural and Structural Applications of Glass
Belis, Bos & Louter (Eds.), Ghent University, June 2016.

ISBN 978-90-825-2680-6

Performance-Based Concept for Design of Structural Silicone Joints in Façades Exposed to Earthquake

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Façade failure due to seismic event represents a potential hazard to people and can cause serious damages to buildings with consequent high-cost remedial works. As a result, interest in the design of buildings and façades to resist seismic loads and displacements has increased. Current standards and literature recognize the benefits offered by Structural Sealant Glazing (SSG) systems to enhance the performance of unitized curtain walls exposed to earthquake but no precise criteria are available for the seismic design of the structural silicone joints. This paper proposes a design concept to evaluate the effect of forces and displacements imposed to the structural joints due to panel seismic racking; referring to the design philosophy developed by Japanese Standard, the concept is engineered based on three performance levels associated to different design requirements which aim at balancing costs and risks with no compromise on safety. Tensile and shear tests performed on sealant H-specimens and Hockman cycle tests simulating accelerated life cycles at different deformation rates are used to exploit the deformation capability of the joints correlated to residual strengths. Results from static racking tests on full-scale façade panels are used to validate the proposed design concept.

Keywords: Silicone joint, Seismic design, Performance level, Earthquake, SSG system, Inter-storey drift

1. Introduction

Past earthquakes have focused the attention on the performance of façades and architectural glazing, revealing their seismic vulnerability. Two major concerns related to their performance during and after a seismic event exist (Beher 2009):

- 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.

As a result, interest in the design of buildings and façades to resist seismic loads and imposed displacements has increased.

In this context, the benefits offered by Structural Sealant Glazing (SSG) systems to enhance the performance of unitized curtain walling exposed to earthquake 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 to ensure transfer of seismic loads and accommodation of seismic inter-storey drifts.

This paper proposes a design concept to evaluate the effect of forces and displacements imposed to the SSG joints due to seismic panel racking, with reference to the performance-based engineering approach developed by Japanese Standard JASS14. Three performance levels associated to different design requirements are defined in 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.

2. Seismic Design Requirements for Glazed Curtain Walling in Building Codes

Even if an increased attention is arising on the seismic response of glass façade systems, only limited guidelines are provided to design and evaluate architectural glazing systems exposed to earthquake. This section provides a brief overview on the seismic design criteria set by three main international standards. For complete information, direct reference to the mentioned codes is recommended.

2.1. EN 1998

EN 1998-1 provides rules for seismic design of structures for earthquake resistance; Section 4.3.5 covers the seismic design of curtain walling and partitions -classified as non-structural elements- specifying that they have to be verified to resist seismic actions if their failure can cause risks to people, affect the main building structure or services of critical facilities.

The effect of the seismic action on non-structural elements as well as their connection and attachments can be determined by applying a horizontal force F_a defined by Equation 1.

$$F_a = \left(S_a W_a \gamma_a\right) / q_a \tag{1}$$

Where:

F_a	horizontal seismic force acting at the mass center of the element in the most unfavorable direction
S_a	seismic coefficient applicable to the non-structural element
W_a	weight of the element
γ_a	importance factor of the element
q_a	behavior factor of the element

The seismic coefficient can be calculated by Equation 2.

$$S_a = \alpha \cdot S\left[3 \cdot \left(1 + z/H\right)/\left(1 + \left(1 - T_a/T_l\right)^2\right) - 0.5\right] \geq \alpha \cdot S \tag{2}$$

With:

α	ratio of the design ground acceleration a_g to the acceleration of gravity g
S	soil factor
T_a	fundamental vibration period of the non-structural element
T_l	fundamental vibration period of the building in the main relevant direction
z	height of the non-structural element above the level of application of the seismic action
H	building height measured from the foundation or from the top of a rigid basement

No requirements are provided by EN 1998 about the capability of the non-structural elements to accommodate the displacements that the main structure experiences during the earthquake.

2.2. ASCE 7-10 and AAMA 501.6

Chapter 13 of ASCE 7-10 establishes minimum seismic design criteria for non-structural components which are permanently attached to structures; architectural glass elements in building envelopes are commonly classified as part of such a group.

The seismic demands of ASCE 7-10 for non-structural components focus on:

- Transfer of equivalent static forces

  Horizontal and vertical seismic design forces $F_{p,H}$ and $F_{p,V}$ act at the center of gravity of the elements; the magnitude of such forces can be determined according to Equations 3÷6.

$$F_{p,H} = \pm \frac{0.4 a_p S_{DS} W_p}{R_p / I_p}\left(1 + 2\frac{z}{h}\right) \tag{3}$$

$$F_{p,V} = \pm 0.2 S_{DS} W_p \tag{4}$$

With:

$$F_{p,H} \geq 0.3 S_{DS} I_p W_p \tag{5}$$

$$F_{p,H} \leq 1.6 S_{DS} I_p W_p \tag{6}$$

Where:

$F_{p,H}$ horizontal seismic design force
$F_{p,V}$ vertical seismic design force
a_p component amplification factor varying from 1.0. to 2.5
S_{DS} spectral response acceleration at short period
W_p component weight
R_p component response modification factor varying from 1.0 to 3.5
I_p component importance factor varying from 1.0 to 1.5
z height of the point of attachment of the component with respect to the building base
h average roof height of the structure relative to the base

All façade components and supports have to be designed to withstand the simultaneous action of the seismic forces $F_{p,H}$ and $F_{p,V}$. Please refer to ASCE 7-10 for exceptions and specific details.

- Accommodation of relative displacements due to seismic inter-storey drifts

The magnitude of the relative displacements occurring within the main building structure during an earthquake is a key factor to consider in controlling the seismic performance of the facade system fixed to it.
As exterior wall panels can pose a life-safety hazard, they have to be designed to accommodate the differential displacements D_p caused by the earthquake and determined according to Section 13.3.2 of ASCE 7-10. Additionally, glass in glazed curtain walls, storefronts and partitions have to be designed and installed to accommodate the relative displacement due to building inter-storey drift given by Equation 7:

$$\Delta_{fallout} \geq \max\left[1.25 I_e D_p ; 13mm\right] \quad (7)$$

Where:

$\Delta_{fallout}$ seismic inter-storey drift causing glass fallout from frame
I_e importance factor of the building

Following exceptions apply:

a) Glass with sufficient clearance from its frame (such that physical contact between the glass and frame will not occur at the design drift) does not need to comply with the requirement above, if Equation 8 is satisfied.

$$D_{clear} \geq 1.25 D_p \quad (8)$$

where D_{clear} is the differential horizontal inter-storey drift measured over the height of the glass panel under consideration, which causes initial glass-to-frame contact. For rectangular glass panels within a rectangular frame (Figure 1):

$$D_{clear} = 2c_1\left(1 + \frac{h_p c_2}{b_p c_1}\right) \quad (9)$$

With:

h_p height of the rectangular glass panel
b_p width of the rectangular glass panel
c_1 average of the clerarance (gaps) on both sides between the vertical glass edges and the frame
c_2 average of the clearance (gaps) on top and bottom between the horizontal glass edges and the frame

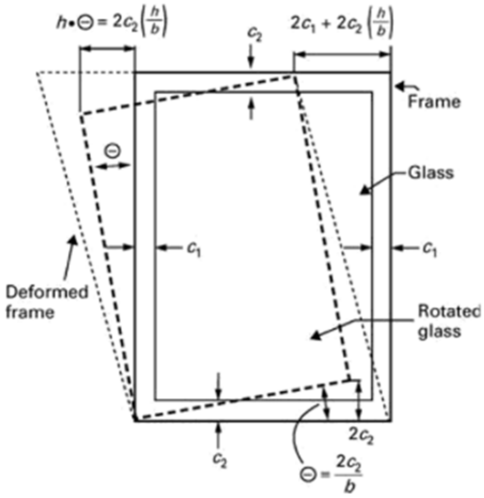


Fig. 1 Illustration showing the definition of clearance terms (Beher 2009).

b) Fully tempered monolithic glass in Risk Categories I, II and III located no more than 3m above a walking surface does not need to comply with the requirement above.

c) Annealed or heat-strengthened laminated glass in single thickness with interlayer no less than 0.76mm that is captured mechanically in a wall system glazing pocket and whose perimeter is secured to the frame by a wet glazed gunable curing elastomeric sealant perimeter bead of minimum 13mm bite does not need to comply with the requirement above.

$\Delta_{fallout}$ has to be determined by engineering analysis or in accordance with AAMA 501.6.

AAMA 501.6 provides an experimental method for determining under controlled lab conditions and by dynamic motion simulation the seismic drift amplitude $\Delta_{fallout}$ causing fallout of the architectural glass from a wall system. The test should be conducted on full-scale elements that simulate closely the components of the overall curtain wall system; mounting conditions for the test panels have to replicate the support conditions of the full-size assembly. In-plane racking displacements have to be imposed to the panel supports according to the Crescendo Test sequence described in Figure 2. The Crescendo sequence consists of a concatenated series of ramp up intervals and constant amplitude intervals of four sinusoidal cycle each, performed at a frequency of 0.8 Hz for racking displacements up to ±75mm or less and 0.4 Hz for racking displacements greater than ±75mm. The Crescendo test has to run continuously until completion, which occurrs when one of the following conditions exists:

- glass fallout;
- the drift index over the height of the glass panel is at least 0.10;
- the dynamic racking displacement of ±150mm is reached.

It is worth to mention that the dynamic test of AAMA 501.6 substantially differs from the static test of AAMA 501.4, 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 test method focuses primarily on the seismic serviceability limit state behavior of a wall system, AAMA 501.6 focuses on the seismic ultimate limit state of its architectural 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:

- Operational Level, with essential no damage to non-structural (i.e. cladding) elements.
- Immediate Occupancy Level, with moderate damage to non-structural elements and light damage to structural elements in the primary structural system of the building.
- Life Safety Level, with moderate damage to structural and non-structural elements.
- Near Collapse Level.

Although these levels are still somehow conceptual, they can guide designers and cladding specifiers choosing the most appropriate seismic design approach for the specific project.

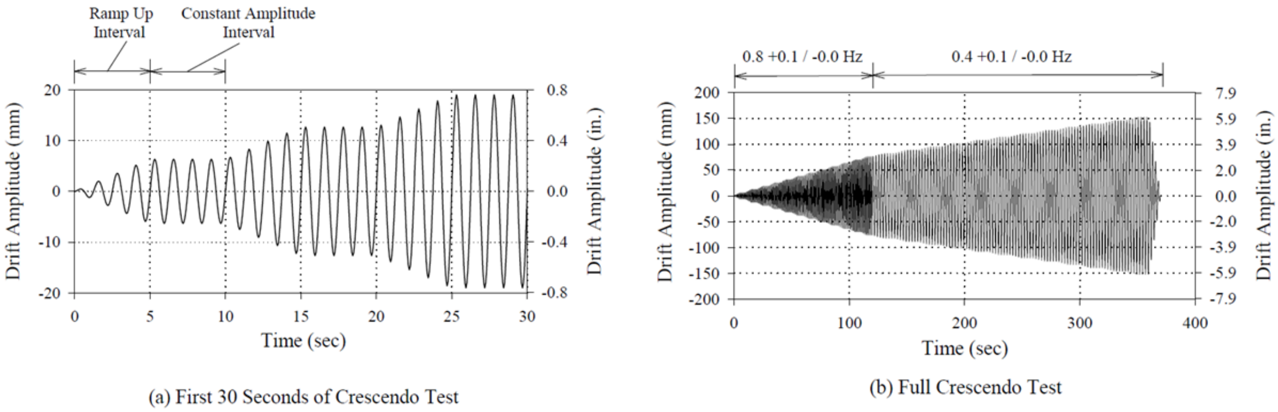


Fig. 2 Displacement time history for the Crescendo test (AAMA 501.6).

2.3. JASS 14

Japanese Architectural Standard Specification 14 (JASS 14) 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 form of seismic waves distributed into two main components:

- P-wave (or Primary wave) acting in vertical direction in fast conveyance;
- S-wave (or Secondary wave) acting in horizontal directions in slower conveyance.

To take into account the different energy of P-waves and S-waves, JASS 14 determines vertical and horizontal seismic forces to be applied to the center of mass of the components and proportional to seismic coefficients S_P and S_S:

$$F_{P,V} = WS_p \tag{10}$$

$$F_{P,H} = WS_s \tag{11}$$

With:
$F_{P,V}$ vertical seismic force acting at the mass center of the element
$F_{P,H}$ horizontal seismic force acting at the mass center of the element
W weight of the element
S_P seismic coefficient in vertical direction
S_S seismic coefficient in horizontal direction

Specific focus is given by JASS 14 to the effect of the seismic inter-storey drifts of the main building to which the façade is fixed: the differential displacements of the slabs of the main structure can introduce deformations into the façade system that should be properly accommodated.

Based on the building inter-storey height H, JASS 14 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 the drop-out of any component is allowed.
  This seismic grade is related to the greatest earthquake to happen in the next 100 years.

2.4. Comparison

EN1998 provides rules for design of structures for earthquake resistance and briefly deals with curtain walling elements, considered as non-structural elements. For their seismic design, only a verification based on a force-check is recommended; no requirements about the capability of the non-structural elements to accommodate the seismic displacements imposed by the main building structure are defined.

American Standard ASCE 7-10 provides design criteria for earthquake resistant structures and deals in Chapter 13 with seismic requirements for non-structural components which curtain walling and glazed façade systems are part of. It requires that façade components and supports are able to transfer the seismic forces acting on masses and recognizes that inter-storey drifts caused by earthquake are highly important factors to consider in the performance evaluation of the façade elements; for glazed curtain walling it specifically requires for controlling the drift value $\Delta_{fallout}$ (causing the fallout of the glass pane from its frame) based on engineering analysis or by the dynamic Crescendo test prescribed by AAMA 501.6.

Japanese JASS 14 is specifically dedicated to design of curtain walling elements and provides a comprehensive approach for their seismic design. In addition to a force-based check, it focuses on the effect of the inter-storey drift of the main structure on the behavior of the façade panels. JASS 14 sets three performance levels associated to different design requirements, inter-storey drift magnitude and probability of occurrence introducing a performance-based engineering approach for seismic design of facades.

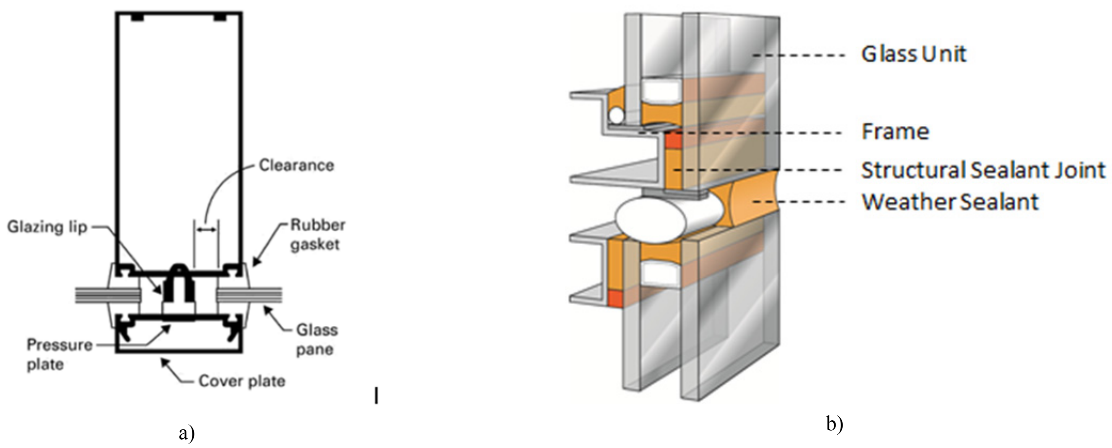


Fig. 4 Example of a) Captured glazed system (Beher 2009) and b) Structural Sealant Glazing system.

3. Benefits Offered By SSG Systems in Areas Prone to Earthquake

Captured glazed systems in unitized curtain walling typically consist of glass panels retained to a main frame by mechanical means able to transfer the loads acting on the glass panels themselves (Figure 4a). Such systems highly differ from conventional Structural Sealant Glazing (SSG) systems which are composed by glass panels bonded to the main frame by structural silicone joints now responsible for the load transfer (Figure 4b); thanks to the aesthetic advantage SSG systems offer in increasing the façade transparency by an apparently frameless solution, they quickly gained popularity over captured systems since their introduction more than 50 years ago.

Typical units of both captured and SSG systems in unitized curtain walling are fixed to the building structure by hinge connections and stack joints designed to allow the panels to accommodate all vertical and horizontal out-of-plane differential displacements that the main structure can experience during a seismic event, without introducing significant stresses into the façade components (Nardini et al. 2015). Vice versa, accommodation of seismic in-plane inter-storey drifts (horizontal in-plane differential displacements) results more critical to be controlled within the system and they usually cause racking of the units characterized by rigid translations and rotations of the glass panels within the frame, which can deform under the movements imposed by the slabs (Figure 3a) (Memari et al. 2004, Beher 2009, Galli 2011).

In this context, 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 (ASTM C 1401, 2009).
- Experimental studies (Beher 2009) 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 (ASTM C 1401, 2009).
- 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 (ASTM C 1401, 2009).

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

a) b)

Fig. 3 a) Broken glass and bent mullions in flexible building which experienced large interstorey drift in Northridge (California) earthquke in 1994 b) Glazing damage in building in central Chile following 2010 earthequake (FEMA E-74, 2012).

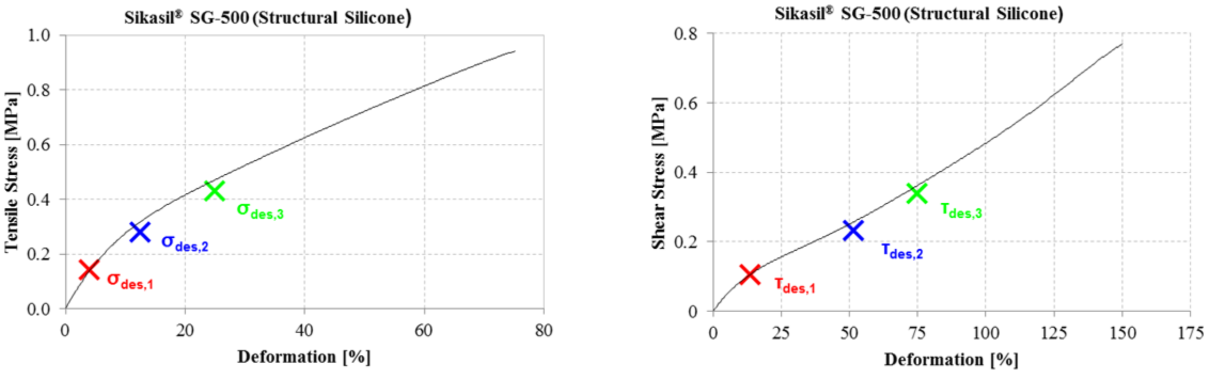
4. Concept for Seismic Design of SSG-Joints In Unitized Curtain Walling

Even if the benefits offered by SSG systems in CW exposed to earthquake are widely recognized, no official regulation currently provides clear seismic design criteria or performance levels to ensure for structural sealant joints. In order to answer to 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, 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.
  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 5a and 5b).



a) b)

Fig. 5 a) Tensile Strength and b) Shear strength associated to different performance levels.

- 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 (ASTM C 719, 1998) is exploited and the allowable strengths $\sigma_{des,2}$ and $\tau_{des,2}$ (Figures 5a and 5b) 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; Figures 6a and 6b show the stress vs. strain average curves obtained by the tests and representative of the tensile and shear behavior of structural silicone Sikasil® SG-500; $\sigma_{des,2}$ and $\tau_{des,2}$ (Figures 5a and 5b) represent the characteristic strengths giving 75% confidence that 95% of the test results will be higher than the values adopted at the tensile deformation rate of 12.5% (equivalent to shear deformation rate of 51.5%).

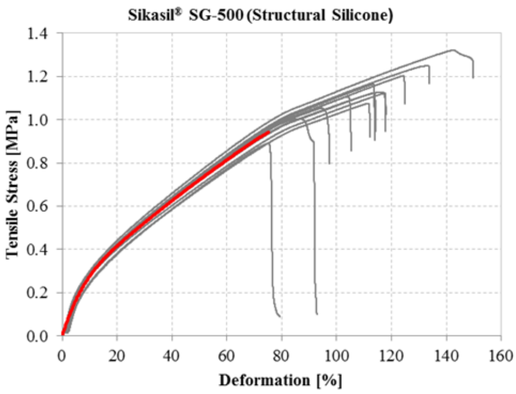
  After the seismic event, the SSG-joints shall be able to withstand the loads occurring in the future service life of the façade and therefore a minimum safety level of 6 has to be restored.

  Figure 7a 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.
  If compared to Figure 6a, 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.

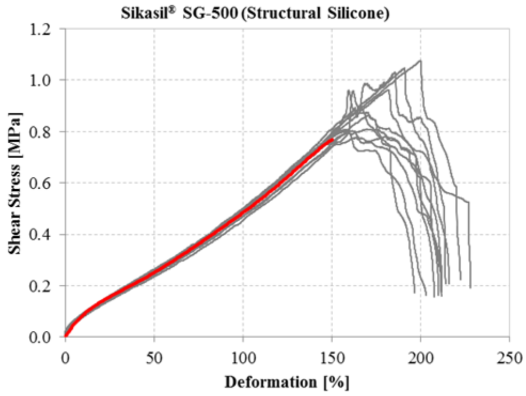
- LEVEL 3 – Drop-out of any components is not allowed.
  During such unique and extreme event, design focuses mainly on life safety and the demand for the structural joints is to be earthquake-resistant: the allowable strengths $\sigma_{des,3}$ and $\tau_{des,3}$ (Figures 5a and 5b) are set to correspond 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 7b shows the behavior of joints 12mm x 12mm x 50mm by Sikasil® SG-500 after the Hockman Cycles (ASTMC C 719, 1998) described for Level 2, but associated to compression/elongation rate of 25%. If compared to Figure 6a, 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.

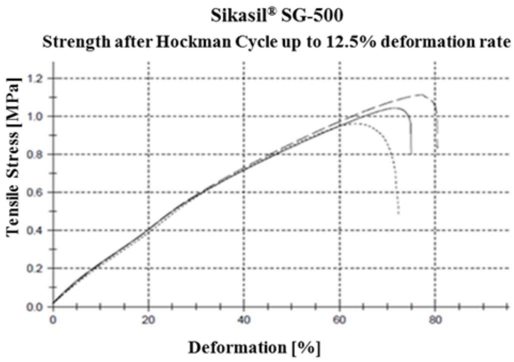


a)

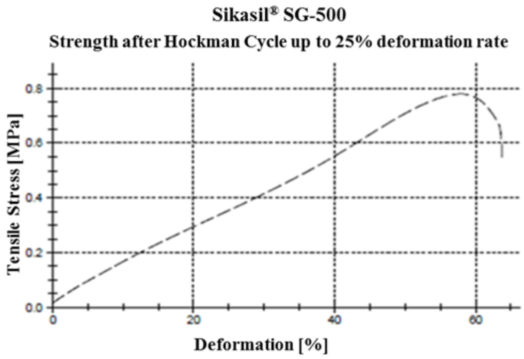


b)

Fig. 6 a) Tensile Stress and b) Shear stress vs. strain: average curves.



a)



b)

Fig. 7 Residual tensile stress after Hockman cycle at deformation rates of a) 12.5% and b) 25%.

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 based on:

- Equations 12, according to ETAG002 approach for European markets:

$$\tau_{S,i} = \frac{S_i G_i}{e} \leq \tau_{des,i} \qquad (12)$$

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, G_1 is defined according to ETAG002.
For performance level 2, G_2 is defined as the secant modulus between the deformation boundary limits [0; $\varepsilon_{des,2}$] covering the shear deformation range $0\% < \varepsilon \leq 51.5\%$ (equivalent to tensile deformation range $0\% < \varepsilon \leq 12.5\%$).
For performance level 3, G_3 is defined as the secant modulus between the deformation boundary limits [0; $\varepsilon_{des,3}$] covering the shear deformation range $0\% < \varepsilon \leq 75\%$ (equivalent to tensile deformation range $0\% < \varepsilon \leq 25\%$).

For Sikasil® SG-500, following values apply: G_1=0.50 MPa, G_2=0.49 MPA, G_3=0.48 MPa.

- Equation 13, according to ASTM C 1401 approach for American markets (Figure 8):

$$e = \frac{S_i}{\sqrt{2\varepsilon_i + \varepsilon_i^2}} \tag{13}$$

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 the relevant forces (§2) and differential displacements which simultaneously apply, limiting the global deformation of the joint to the elongation limit ε_i set for each performance level. Detailed analytical procedure to analyze the global stress level of the joint is given by (Nardini et al. 2015).

Fig. 8 Shear deformation of the joint.

5. Seismic Mock Up Test

Seismic mock up tests performed by Permasteelisa Group on four unitized façade panels are here used to validate the performance-based concept proposed in § 4.

Test procedure, system configuration and experimental results are comprehensively provided by (Galli 2011).

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 (§ 2):

- Air leakage test (EN 12153, 2000).
- Racking test: an inter-storey drift of H/300 (Δ1 = 12.5mm) was imposed (20 cycles), as per performance Level 1 of JASS14.
- Air leakage test (EN 12153, 2000).
- Racking test: an inter-storey drift of H/200 (Δ2 = 18.75mm) was imposed (10 cycles), as per performance Level 2 of JASS14.
- Racking test: an inter-storey drift of H/100 (Δ3 = 37.5mm) was imposed (5 cycles), as per performance Level 3 of JASS14.

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 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; please refer to (Galli 2009) for complete information about the tests and their results.

Control transducers were properly 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 13 summarizes the results obtained in each racking phase (and seismic level) with specific 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.

The seismic tests performed by Permasteelisa on the full-scale panels include static racking tests which conservatively neglect the dynamic behavior of the façade. As part of future investigation, a F.E.M. simulation of the tested CW panels will be used to better evaluate the performance limits of the structural joints for the dynamic racking test sequence defined by the Crescendo test of AAMA 501.6.

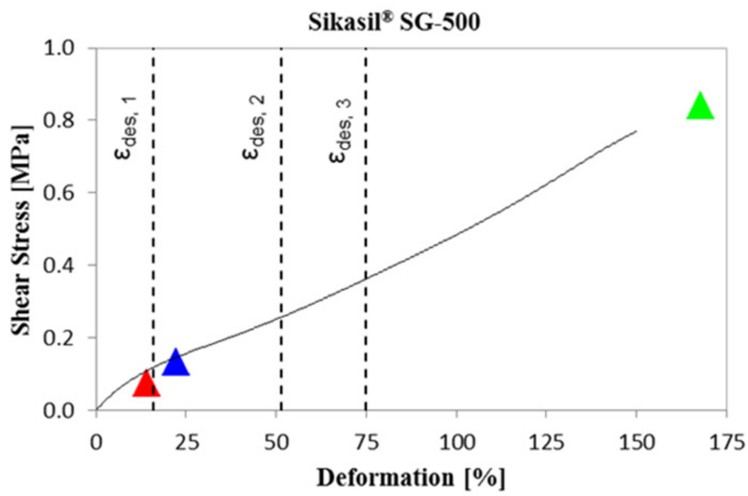


Fig. 13 Seismic mock up results: shear stress level in the SSG joints depending on performance level.

6. Conclusions

Even if the benefits offered by Structural Sealant Glazing systems in unitized curtain walling exposed to earthquake are widely recognized, current available standards provide very poor guidelines to assess the seismic performance of structural sealant joints.

This paper proposes a design concept to check the adequacy of SSG-joints to withstand seismic forces and accommodate imposed movements caused by panel racking due to seismic inter-storey drift, which is recognized by American standard ASCE-07 and Japanese Standard JASS 14 as an highly important factor to consider in controlling the seismic behavior of the whole façade system.

In line with the performance-based engineering approach outlined by JASS 14, the design concept proposed defines three performance levels associated to different design requirements and different deformation levels for the SSG-joints.

Small-scale tests on silicone samples -including tensile and shear tests on H-specimens and Hockman cycle tests to simulate accelerated life cycles- are the investigation base to assess the boundary deformation limits provided for the SSG-joints. Full scale seismic tests on mock up panels validate the concept.

As a result, the appearance of the façade in its service life is not threatened by a design developed for a unique and extreme event, balancing costs and risks with no compromise on safety.

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