

Experimental investigation on the influence of silicone sealant on the seismic behaviour of precast façades

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Abstract Silicone sealant is usually interposed between panels of precast façades. In ordinary cladding panel configurations, relative sliding between panels occurs under lateral actions. The shear drifts and consequent stresses arising in the silicone strips may lead to a significant increase of the load demand in the cladding panel connections and affect the seismic behaviour of the structural system. This paper presents the results of experimental tests and numerical analyses carried out to clarify the role of the silicone sealant on the seismic response of precast structures with cladding panels. An experimental campaign including monotonic and cyclic tests on both silicone strips applied to small concrete blocks and two panel sub-assembly sealed with silicone, has been developed at Politecnico di Milano. Furthermore, cyclic and seismic pseudo-dynamic tests on a full-scale prototype of precast building with cladding panels sealed with silicone, have been performed at the Joint Research Centre of the European Commission. The results of the experimental tests are presented and compared with the results of numerical simulations. Some recommendations for seismic design of precast frame structures with cladding panels, considering the effect of silicone sealant, are finally provided.

Keywords Precast structures · Cladding panels · Silicone sealant · Seismic design

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1 Introduction

Silicone sealant is a common completion material of precast façades. It is used to fill and seal the joints in between cladding panels and between panels and other components, with silicone strips placed either only at the external side of the panel or at both external and internal sides. Silicone is not a structural product. It can deform at large shear strain without damage providing negligible stiffness. For this reason, it is usually not intended to collaborate with the structural system.

Scarce information about the mechanical behaviour of silicone is available in the literature. Meunier et al. (2008) performed experimental tests on silicone strips and observed that the material is characterised by a similar behaviour under shear and tension and a stiffer behaviour in compression. In ASTP STP-1243 recommendations, Lacasse et al. (1995) evaluate the cyclic fatigue of silicone sealant strips subjected to tension. Carbary and Ryan (2004) showed the effects of weather condition and ageing on the bond properties of silicone sealant. Experimental testing on the influence of ageing on the bond properties of silicone has also been performed by Ding and Liu (2005). The mechanical behaviour of silicone sealant under seismic excitation has been studied by Behr (1998) and Broker et al. (2012) with reference to silicone applied to glass and through testing on sub-assembly specimens. Roland (2006) pointed out that the mechanical behaviour of rubber polymeric materials is influenced by the strain rate, with both strength and stiffness increasing with the strain rate.

In ordinary cladding panel configurations of precast façades, sliding between panels occurs under lateral actions. This leads to a shear drift of the silicone sealant strips and a consequent increase of the load demand on the panel connections. This effect is generally negligible for multi-storey braced buildings, owing to the expected low values of the inter-storey drifts. However, for unbraced precast frame structures the seismic shear drift of silicone strips may be significantly larger due to the relevant flexibility of the structural system. The corresponding high shear stresses arising in the silicone strips may lead to a significant load increase in the cladding panel connections and affect the seismic behaviour of the structure.

The seismic behaviour of precast concrete structures with cladding panels has been widely investigated within the three-year SAFECLADDING research project supported by a grant of the European Commission within the Programme FP7-SME-2012 (Colombo et al. 2014). This research activity included solutions for existing and new precast structures with isostatic, integrated, and dissipative connection systems of the cladding panels (Biondini et al. 2012, 2013; Toniolo and Colombo 2012; Dal Lago 2015). The influence of the silicone sealant interposed between panels has been also investigated (Biondini et al. 2014a).

This paper presents the results of experimental tests and numerical analyses carried out to clarify the role of the silicone sealant on the seismic response of precast structures with cladding panels. An experimental campaign including monotonic and cyclic tests on both silicone strips applied to small concrete blocks and two panel sub-assembly sealed with silicone, has been developed at the Laboratorio Prove e Materiali (LPM) of Politecnico di Milano. Furthermore, cyclic and seismic pseudo-dynamic tests on a full-scale prototype of precast building with cladding panels sealed with silicone have been performed at the European Laboratory of Structural Assessment (ELSA) of the Joint Research Centre (JRC) of the European Commission. The results of the experimental tests are presented and discussed and compared with the results of numerical simulations. In this way, the

mechanical behaviour of silicone sealant is assessed at different structural levels and its influence on the overall seismic performance of precast structures is identified. Some recommendations for the seismic design of precast frame structures with cladding panels, considering the effect of silicone sealant, are finally provided.

2 Local tests

Several local tests on silicone strips applied to small concrete blocks have been carried out under both monotonic and cyclic loading by means of a uniaxial testing machine at the LPM of Politecnico di Milano. The specimens are made by four silicone strips applied at the interface edges of three concrete blocks, as shown in Fig. 1. Different specimen geometries, with lengths: $L = 60, 90,$ and 120 mm and sides: $s = 10, 15,$ and 20 mm of the square cross-section of the silicone strips, respectively, have been tested. Figure 2 shows three specimens with strip length to side ratio $L/s = 6$ and 9 . The test protocol for the cyclic tests is based on imposed displacements with constant amplitude increased every three cycles with steps of 4 mm up to failure. The tests have been performed under velocities of 0.010 and 0.025 mm/s, corresponding to strain rates between 0.05 and $0.25\%/s$. The complete series of tests is described in Table 1.

Monotonic and cyclic experimental results are shown in Fig. 3 for some of the tests performed on the three different specimen geometries in terms of shear stress τ versus shear strain γ , defined as follows:

$$\gamma = \frac{d}{s} \quad (1)$$

$$\tau = \frac{V}{4sL} \quad (2)$$

where d is the applied drift and V is the measured shear force.

The monotonic behaviour exhibits a large displacement capacity of silicone, with an elastic behaviour up to about 50–80% of drift and a post-elastic nonlinear behaviour characterised by the development of inclined ties with out-of-plane deformation. The main stages of the monotonic behaviour are illustrated in Fig. 4 for the test M16 (see Table 1).

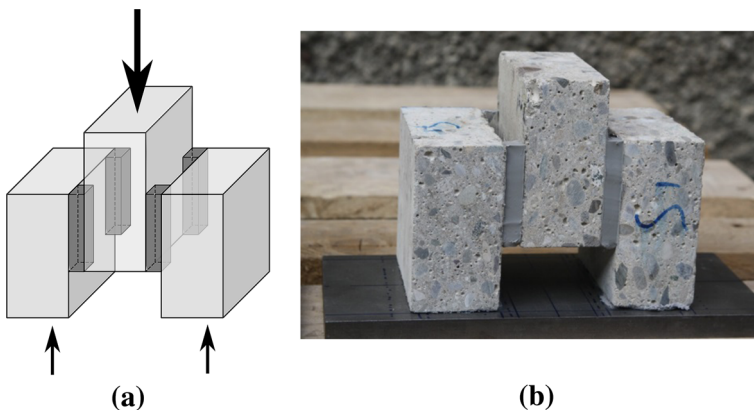


Fig. 1 Test specimen: **a** concept and **b** view of the assembled specimen

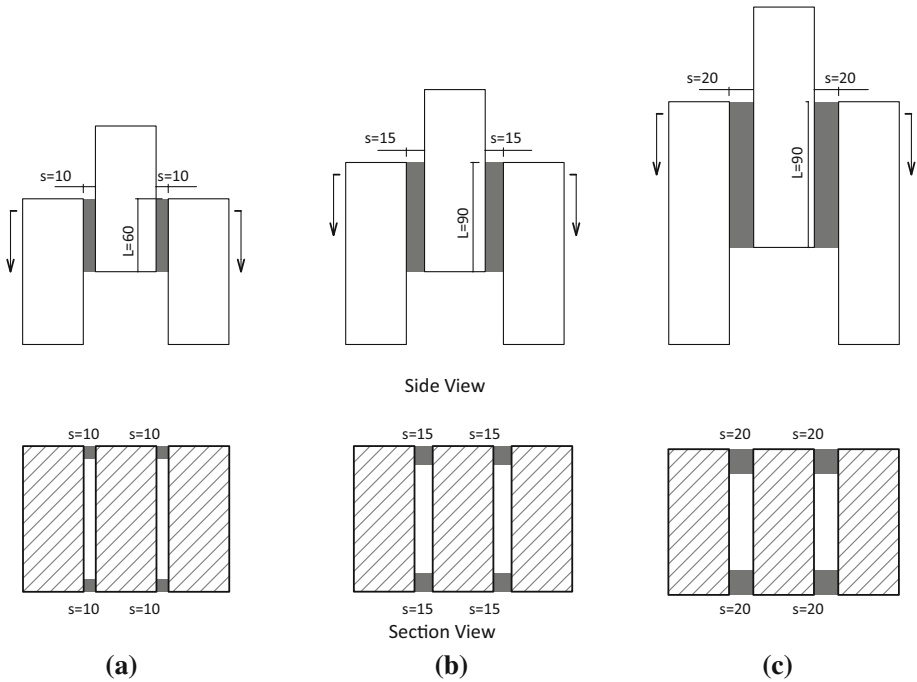


Fig. 2 Three tested specimen geometries with strip length to side ratio $L/s = 6$: **a** 60/10; **b** 90/15; **c** 120/20 (all dimensions in mm)

Failures occurred between 150 and 300% of drift with two different mechanisms. For the tests with low strain rates, failure of the inclined ties occurred (Fig. 5a). For the higher strain rates, a combined tensile failure and detachment from the concrete support has been noticed, according to sliding surfaces that form at large drifts (Fig. 5b).

The cyclic behaviour is characterised by an earlier softening branch, with the attainment of earlier failure in terms of ultimate drift with respect to the monotonic response. The cycles show a relevant stiffness degradation tendency for increasing values of the imposed drift.

The experimental results show a large scatter in initial elastic modulus, shear strength and ultimate shear strain, even for identical specimens, as typical for materials that are not subjected to severe production monitoring and control. The results indicate also a significant dependency of the behaviour of silicone on the strain rate. Figure 6 shows that an increase in the strain rate leads, on the average, to a logarithmic increase of the initial shear modulus and the shear strength, and a decrease of the ultimate shear strain. It is worth noting that the strain rates considered in the experimental tests (between 0.05 and 0.25%/s) correspond to quasi-static actions. Since much higher strain rates may occur during seismic events, further experimentation is needed to mechanically characterise the silicone for seismic applications. The effect of ageing on the shear strength exhibits a remarkable variability, as shown in Fig. 7. This confirms the large scatter of the structural properties of silicone and indicates that, once polymerisation is complete, little increase of strength occurs in the short term.

Table 1 Local tests on silicone sealant

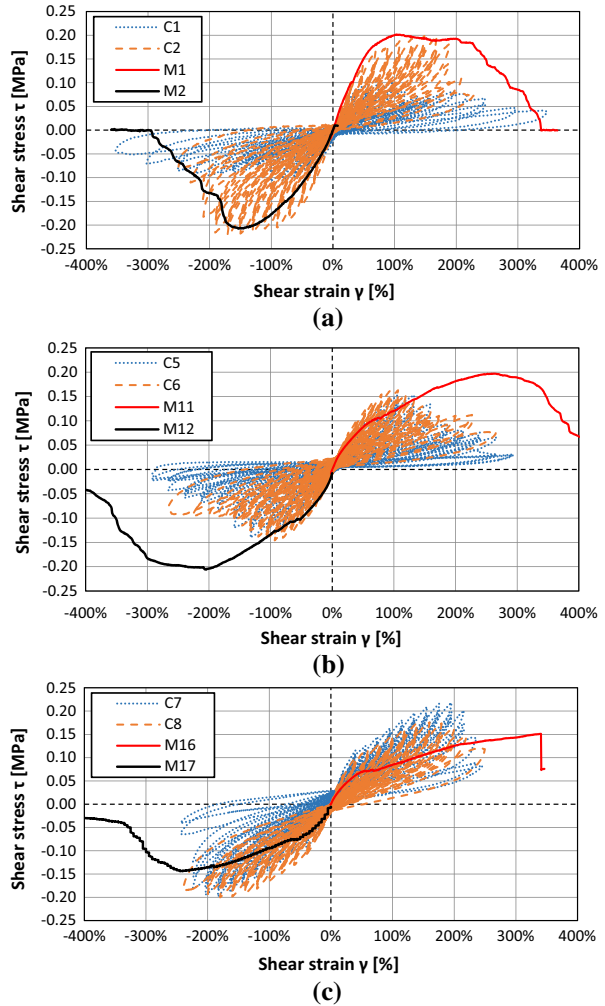
Test type	Test id	Specimen geometry		Velocity (mm/s)	Strain rate (%/s)	Age (days)
		Side s (mm)	Length L (mm)			
Cyclic	C1	10	60	0.025	0.250	105
	C2	10	60	0.025	0.250	116
	C3	10	90	0.025	0.250	25
	C4	10	90	0.025	0.250	10
	C5	15	90	0.025	0.167	5
	C6	15	90	0.025	0.167	10
	C7	20	120	0.025	0.125	116
	C8	20	120	0.025	0.125	117
Monotonic	M1	10	60	0.025	0.250	67
	M2	10	60	0.025	0.250	67
	M3	10	60	0.010	0.100	5
	M4	10	60	0.010	0.100	5
	M5	10	90	0.010	0.100	12
	M6	10	90	0.010	0.100	12
	M7	10	90	0.025	0.250	34
	M8	10	90	0.025	0.250	6
	M9	15	90	0.010	0.067	46
	M10	15	90	0.010	0.067	12
	M11	15	90	0.025	0.167	26
	M12	15	90	0.025	0.167	26
	M13	20	120	0.010	0.050	46
	M14	20	120	0.010	0.050	46
	M15	20	120	0.010	0.050	46
	M16	20	120	0.025	0.125	26
	M17	20	120	0.025	0.125	26

3 Sub-assembly test

The experimental campaign has been extended at the structural level by means of a cyclic test on a two-panel sub-assembly, with silicone sprayed at the panel interface, carried out at the LPM large scale testing facility at Politecnico di Milano. The aim of this sub-assembly test is to investigate the cyclic behaviour of long strips of silicone and to observe the influence of the sealing on the interaction of adjacent panels.

The uniaxial test setup is shown in Fig. 8a. It consists of two solid concrete panels 129 cm wide and 323 cm high (aspect ratio ≈ 2.50), and with thickness of 16 cm. Each panel is connected to the supporting beam with a hinge placed at the middle of the panel base. At the height of 2.70 m the panels are linked to the top beam of a peripheral articulated steel frame, used to transmit imposed displacements to the sub-assembly, by means of a hinged connection made with round holes hosting steel pins. Three recesses are

Fig. 3 Local tests: monotonic and cyclic shear stress τ versus shear strain γ relationships for the specimens with silicone strip length to side ratio $L/s = 6$: **a** 60/10; **b** 90/15; **c** 120/20



provided along the lateral sides of each panel, at 1/4, 2/4, and 3/4 of the clear distance between the top and bottom hinges, to eventually host dissipative panel-to-panel connections. Such connections are not installed in the test described in this paper (see Biondini et al. 2014b; Dal Lago 2015 for additional details). The articulated steel frame is made of two HEA steel columns hinged at both the foundation steel beam and the top steel beam made by two UPN profiles enclosing the panels. The top beam is connected to the horizontal jack fixed to a reaction braced steel frame. A restraining system is installed at the top beam level to prevent out-of-plane displacements.

Preliminary testing performed prior to the application of silicone confirmed that under imposed top displacements the panels rigidly rotate around the base pins with negligible lateral stiffness. Silicone strips with cross-section of about 10/15 mm by 10/15 mm,

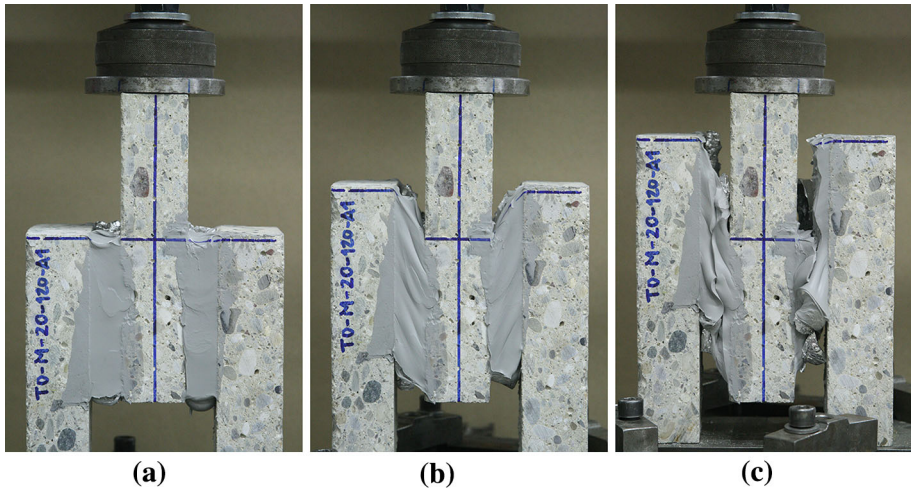


Fig. 4 Some stages of the monotonic response for the local test M16 (see Table 1): **a** undeformed specimen; **b** 200% shear deformation; **c** failure

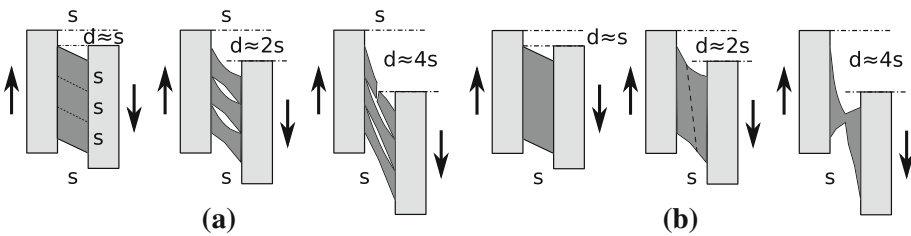


Fig. 5 Failure mechanisms for the local tests: **a** lower strain rates, with failure of the inclined ties of silicone strips; **b** higher strain rates, with combined tensile failure and detachment from the concrete support

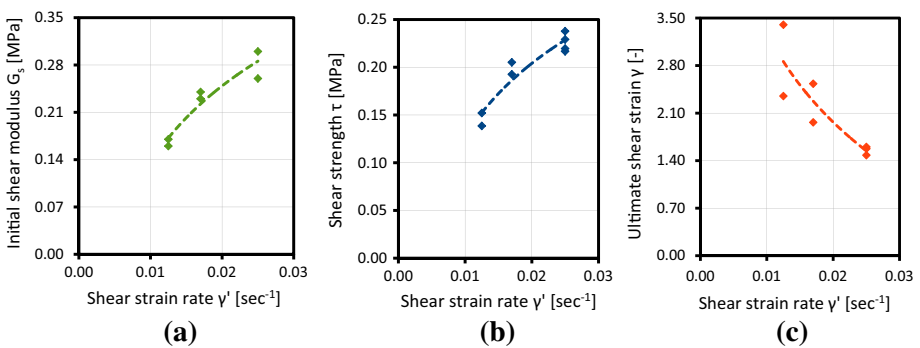


Fig. 6 Local tests: effect of the strain rate on **a** initial shear modulus, **b** shear strength and **c** ultimate shear strain

depending on imperfections in panel position and silicone depth, have been placed at both sides of the panel interface along the joint with the exception of the upper part because of the presence of the rig beam. The test has been performed after a period of ageing of

Fig. 7 Local tests: effect of the ageing time on the shear strength

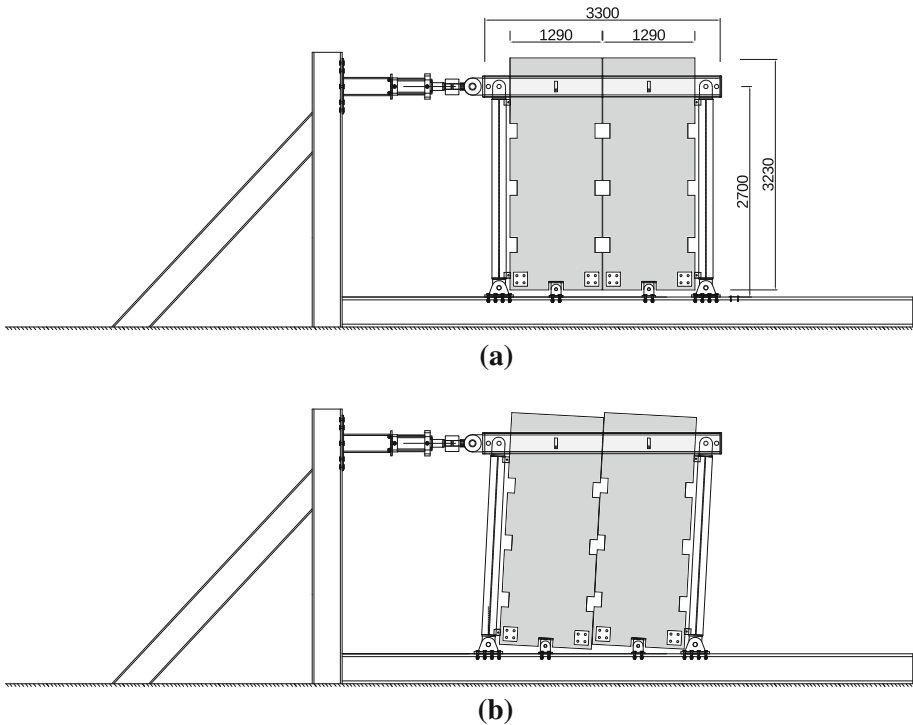
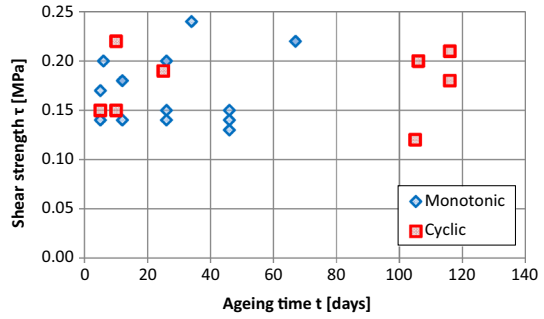


Fig. 8 Two-panel sub-assembly: **a** test setup and **b** displaced configuration (dimensions in mm)

12 days. Small samples sprayed at the same time of the application to the structure and cut before the test showed that the polymerisation of silicone was correctly attained.

The cyclic test protocol consists of a series of three-cycles with top displacement amplitudes of 6, 11, 22, 42, and 85 mm, corresponding to about 0.2, 0.4, 0.8, 1.6, and 3.2% of panel drift. The cyclic frequency of the actuator has been set to the higher strain rate adopted in the local tests (0.25%/s) and kept constant. Figure 8 shows a view of the two-panel sub-assembly in the undeformed configuration (Fig. 9a) and at maximum imposed top displacements (Fig. 9b, c).

The results of the test are shown in Fig. 10 in terms of base shear versus panel-to-panel relative displacement diagram (Fig. 10a) and shear stress versus shear strain diagram

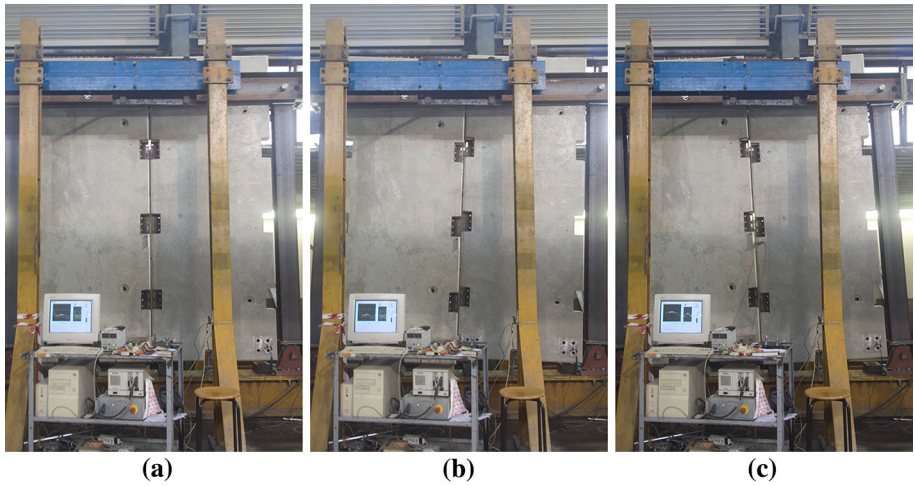


Fig. 9 View of the two-panel sub-assembly: **a** undeformed configuration; **b, c** configuration at maximum imposed top displacements

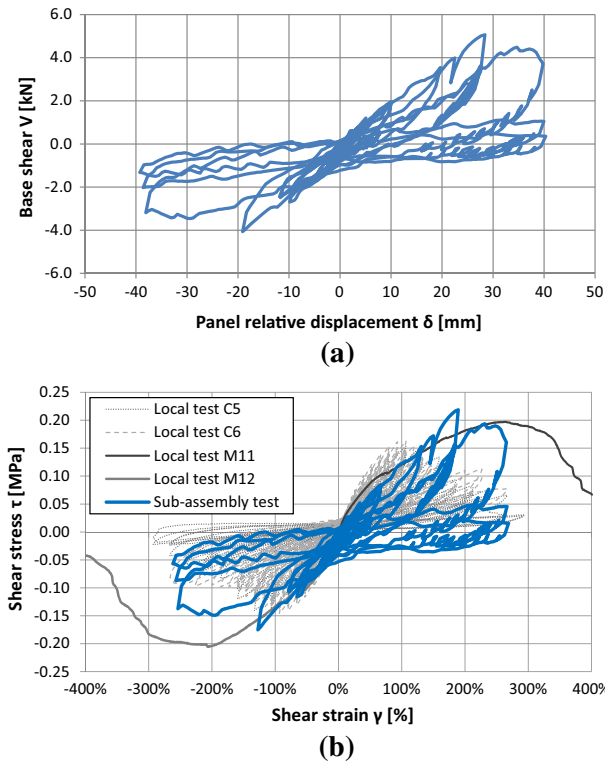


Fig. 10 Sub-assembly cyclic test: **a** base shear versus panel-to-panel relative displacement; **b** shear stress versus shear strain diagram compared with the results of local tests

(Fig. 10b). The cyclic response is characterised by a significant stiffness degradation and progressive damage, in accordance to the cyclic behaviour observed during the local tests. In particular, Fig. 10b shows the good agreement between the sub-assembly structural response and the local test results. The approximate initial elastic tangential modulus is about 0.25 MPa. The energy dissipation is negligible compared to the energy potentially dissipated by reinforced concrete resisting structural members. As shown in Fig. 11, failure occurred after formation of inclined ties and out-of-plane deformation (Fig. 11a) for both detachment from the support and tear at mid-span (Fig. 11b).

4 Full scale prototype tests

Cyclic and pseudo-dynamic tests on a full-scale prototype of a precast building with cladding panels have been carried out at the ELSA Laboratory by the JRC team within the SAFECLADDING European research project. The Politecnico di Milano research group contributed to both the design of the prototype and the numerical structural analyses to predict the building seismic response and properly define the testing programme. The prototype has been produced and installed by Styl-Comp company, partner of the research project. The structure is a dry-assembled single-storey precast frame representing a typical industrial building widespread in Southern Europe.

4.1 Structural prototype

The structural prototype has been tested with different configurations of horizontal and vertical cladding panels and different connections systems, including isostatic, integrated, and dissipative systems, under cyclic and pseudo-dynamic load protocols performed at different levels of seismic action. A complete description of the structural prototype, test setup, and testing programme, can be found in Negro and Lamperti Tornaghi (2016). The large number of tests performed included a structural configuration with vertical panels

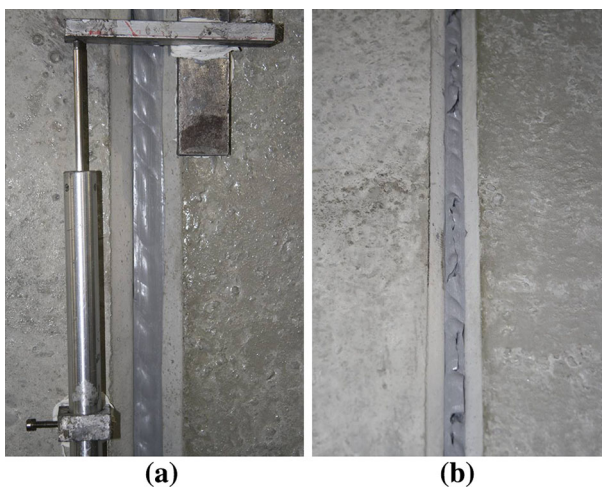


Fig. 11 Sub-assembly cyclic test: **a** formation of inclined ties and out-of-plane deformation; **b** failure for both detachment from the support and tear at mid-span

sealed with silicone. Figure 12 shows two views of the structural prototype with vertical cladding panels. This structure consists of two longitudinal two-bay frames with 8.00 m of span each, columns with 7.00 m of clear height, a 5.00 m single span slab roof and 6+6 solid vertical panels 2.49×8.40 m with thickness of 0.16 m. The panels have a recess at the base to accommodate a hinged connection and three recesses along the lateral sides to accommodate panel-to-panel dissipative connectors (see Dal Lago 2015 for details). The dissipative devices have not been installed in the tests presented in this paper. The connection system of the panels includes a steel shear connector at the top and a steel cylindrical hinge at the bottom placed along the vertical mid-axis of each panel, as shown in Fig. 13. The bottom hinge prevents the rotation around the vertical axis, and two push-pull connections have been left acting at the top of panels as additional safety rods.

Silicone strips with thickness of 10 mm have been sprayed along both the exterior and interior sides at the interface between panels, as shown in Fig. 13. The total length of the strips is 7.5 m along the exterior sides, with 8.4 m of panel height except the three recesses 0.3 m each, and 6.1 m along the interior sides, starting from the bottom side of the top beam with an additional clearance of 1.4 m from the top side of the panel. The test has been performed after a period of ageing of 10 days, due to the tight testing programme and consequent strict schedule of the laboratory. Small samples sprayed at the same time of the application to the structure and cut before the test showed that the polymerisation of silicone was correctly attained.

4.2 Experimental results

Pseudo-dynamic tests have been performed on the structural prototype with vertical panels, without and with silicone sealant, under the accelerogram shown in Fig. 14 with peak ground acceleration (PGA) scaled to 0.10 g. The accelerogram is recorded from Tolmezzo earthquake and modified in the frequency content to make it compatible with the elastic response spectrum given by Eurocode 8 for soil type B (CEN-EN 1998-1:2004).

The results of the tests are shown in Fig. 15 in terms of time history of both top displacement (Fig. 15a) and base shear (Fig. 15b), and base shear versus displacement

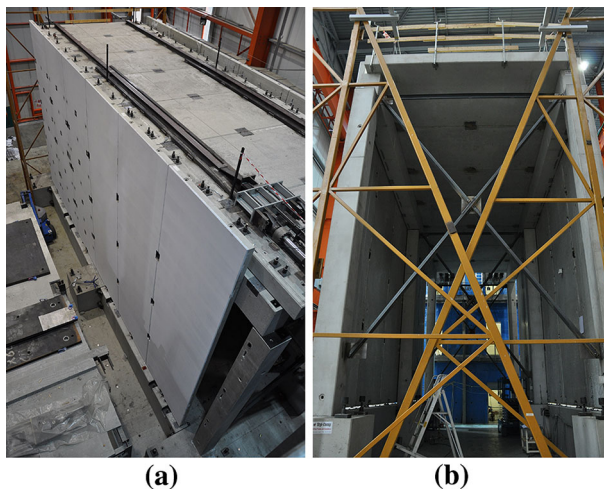


Fig. 12 Full scale structural prototype with vertical panels: **a** top view; **b** frontal view

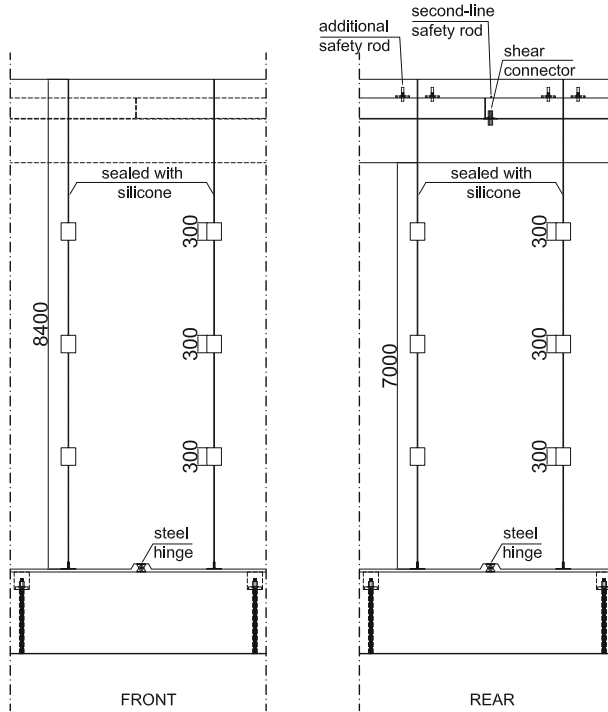


Fig. 13 Configuration of the panel connections and sealing with silicone (measures in mm)

Fig. 14 Modified Tolmezzo accelerogram used for pseudo-dynamic tests

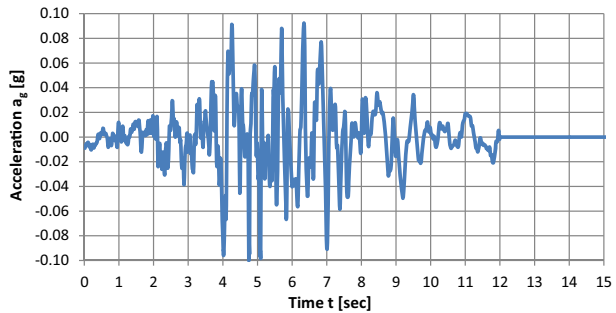


diagram (Fig. 15c). These results indicate a similar structural response of the prototype without and with silicone, with dominant flexural behaviour of the frame system. The sealing between adjacent panels leads to an increase of the elastic stiffness by about 50%, with slightly reduced top displacements and slightly enlarged base shear forces.

Cyclic tests have been also performed on both configurations, without and with silicone sealant. The test protocol consists of a sequence of three cycles repeated at displacement amplitudes of ± 8.4 ; 11.7; 16.4; 23.0; 32.1; 45.0; 63.0 mm. The test on the configuration with silicone has been performed after the pseudo-dynamic test in order to prevent an early damage of the sealing. The results shown in Fig. 16 confirms the similar behaviour observed in the pseudo-dynamic tests. A relevant cyclic degradation observed at the maximum displacement amplitude indicates that silicone attained its strength and entered a

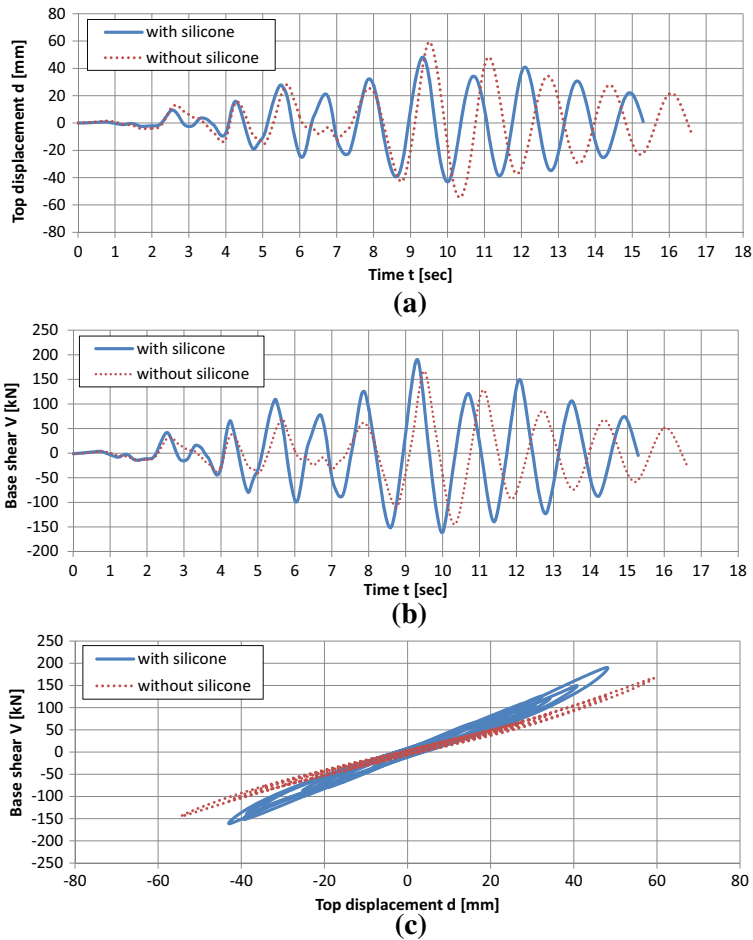


Fig. 15 Full scale prototype. Pseudo-dynamic tests (PGA = 0.10 g): comparison of the results without and with silicone in terms of time history of **a** top displacement and **b** base shear, and **c** base shear versus top displacement diagram

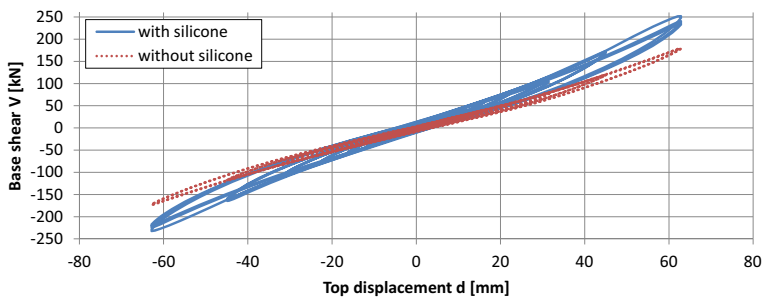


Fig. 16 Full scale prototype. Cyclic tests: comparison of the results without and with silicone in terms of base shear versus top displacement diagram

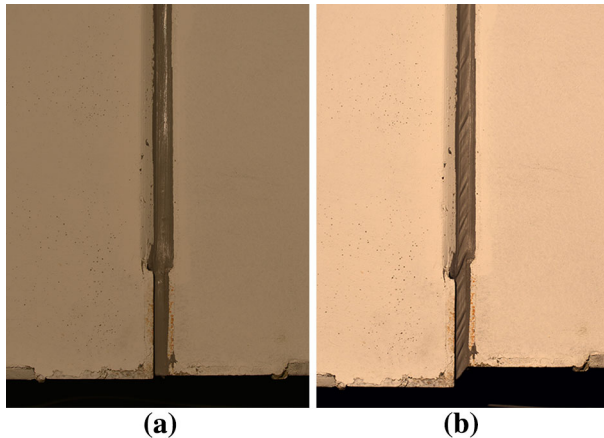


Fig. 17 Full scale prototype. Cyclic test with silicone: detail of a sealed joint at the base of the panels **a** before the test, and **b** with deformed silicone strips at 0.9% of overall structure drift, corresponding to about 150% of shear deformation of silicone

softening branch. Figure 17 shows a detail of a sealed joint at the base of the panels before the test (Fig. 17a), and with deformed silicone strips at 0.9% of drift (Fig. 17b).

4.3 Numerical results

A numerical modelling has been elaborated to simulate the dynamic non-linear response of the precast structural prototype with vertical cladding panels subjected to the pseudo-dynamic tests. The frame members have been modelled using beam elements. Columns have been modelled using beam elements with distributed plasticity based on bending moment versus curvature relationships under axial force. The envelope curve of the hysteresis diagrams have been evaluated based on the constitutive laws of the materials. The Mander model is assumed for concrete taking the confinement effects into account (Mander et al. 1988). A bi-linear elastic-hardening behaviour is adopted for the reinforcing steel. The hysteresis rules are established based on the Takeda model (Takeda et al. 1970). The base pocket foundations have been considered as perfect clamped connections. The beam-to-column and roof-to-beam dowel connections have been modelled as perfect hinges around the corresponding transverse horizontal axis and clamped around the other axes through master-slave coupling links. Elastic behaviour is assumed for beams and roof members, since they are not involved in the lateral load resisting system of the hinged frame structure. The cladding panels have been modelled using elastic shell elements.

Figure 18 shows the results of the non-linear time-history analysis carried out to simulate the pseudo-dynamic test without silicone. The comparison of numerical versus experimental results indicates a good accuracy of the model in terms of maximum values of top displacement and base shear and confirms the almost elastic response of the frame structural system under $PGA = 0.10$ g.

In order to simulate the pseudo-dynamic test with silicone, elastic links are used to couple the panel-to-panel vertical displacements. The links are concentrated at mid-height of the panel interfaces, since the stiffness of the silicone strips is much lower than the stiffness of the concrete panels and this assumption is not expected to significantly affect the overall structural response of the system. The stiffness of the elastic links is evaluated as follows:

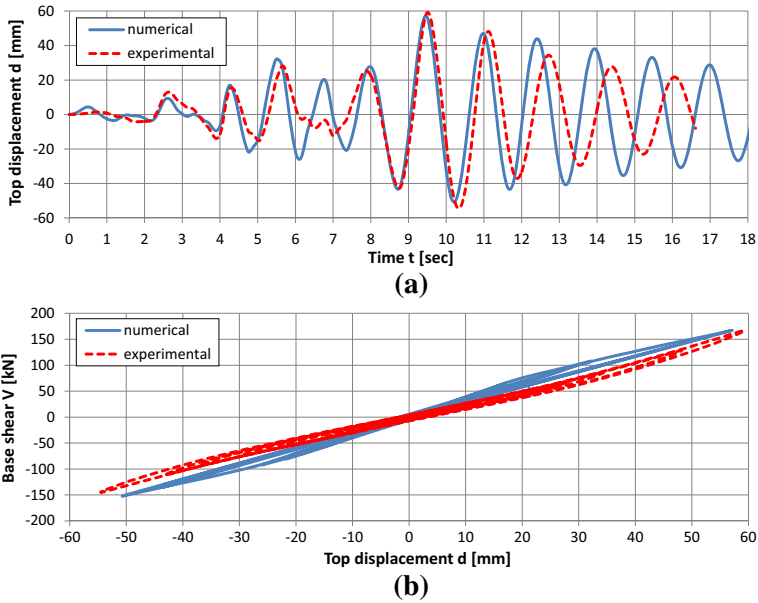


Fig. 18 Full scale prototype. Numerical simulation of the pseudo-dynamic test without silicone sealant (PGA = 0.10 g): comparison of numerical versus experimental results in terms of **a** top displacement time history and **b** base shear versus top displacement diagram

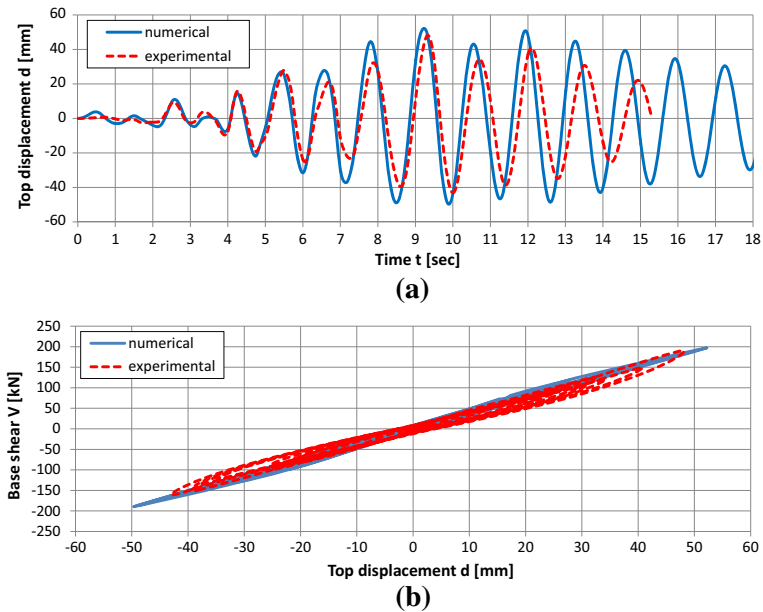


Fig. 19 Full scale prototype. Numerical simulation of the pseudo-dynamic test with silicone sealant (PGA = 0.10 g): comparison of numerical versus experimental results in terms of **a** top displacement time history and **b** base shear versus top displacement diagram

$$K_{\text{eq}} = \frac{G_s t_s H_s}{b_s} = \frac{0.25 \times 10 \times 13.6}{10} = 3.4 \text{ kN/mm} \quad (3)$$

where b_s is the depth of the silicone strips, taken as the mean clear panel distance, t_s is the width of the strips ($t_s = b_s = 10$ mm), H_s is the total length of the silicone strips at each panel interface, computed by summing up the length of all strip segments along both the external and internal layers ($H_s = 13.6$ m), and G_s is the mean initial elastic shear modulus of silicone, estimated as $G_s = 0.25$ MPa on the basis of the results of local and sub-assembly tests.

The results of the non-linear time-history analysis carried out is shown in Fig. 19. The comparison of numerical versus experimental results confirms the good accuracy of the model in the estimation of the maximum values of both the top displacement and base shear, as well as the validity of the assumptions made in the modelling of the panel-to-panel elastic links.

It is worth noting that the structural model has been developed for the prediction of the nonlinear dynamic response of the prototype structure in all tests performed in the experimental campaign (36 tests; see Dal Lago 2015). However, plasticisation of the column base rebars was not observed during the pseudo-dynamic tests considered in this paper.

5 Concluding remarks and design recommendations

The mechanical behaviour of silicone sealant and its influence on the seismic response of precast structures with cladding panels have been experimentally assessed at different structural levels, including local tests on small specimens of silicone sprayed in between concrete blocks, sub-assembly tests on panels sealed with long silicone strips, and full scale prototype testing on a precast building with vertical cladding panels sealed with silicone. In particular, the basic features of the silicone behaviour under imposed shear strains have been identified. Silicone exhibits high flexibility with mean shear elastic modulus of 0.25 MPa, elastic behaviour up to about 100 ÷ 150% of shear strain, low shear strength up to 0.25 MPa, and large deformation capacity with a pseudo-plateau branch up to about 200% of strain and a final softening branch. A relevant stiffness degradation has been observed in cyclic tests.

Based on the results of experimental tests and numerical analyses, it can be concluded that the silicone sealant placed in between cladding panels of precast frame structures can influence the seismic performance at the serviceability limit state and increase the load demand on the panel connections. However, it is worth noting that the stiffening contribution is limited and not reliable, since the variability of the mechanical characteristics of this type of product is large. Moreover, silicone is not suitable to sustain the large drifts typically associated with the ultimate limit state. Therefore, it is recommended to disregard the influence of the silicone sealant when it involves possible beneficial effects on the seismic performance of the structure. On the contrary, the effects of the panel sealing have to be considered when they are on the unsafe side, like for example in the evaluation of the design forces for the panel connections. To this purpose, capacity design based on the equilibrium of single panels can be applied with reference to the strength of the silicone strips. Further experimental research would be required to investigate the effects of ageing and higher strain rates, consistently with the expected strain rates under seismic actions.

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