NUMERICAL MODELLING OF THE HORIZONTAL CONCRETE FAÇADE SYSTEMS IN RC PRECAST BUILDINGS

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Abstract

In design practice of precast industrial buildings with concrete façade systems, the cladding panels are usually considered only as masses fixed to the main structure without a dedicated calculation of the fastening system. However, recent earthquakes in Italy demonstrated that the behaviour of such systems under seismic loading is poor and this led to profound experimental and numerical investigation of the seismic response with the final aim of improving design procedures. Detailed hysteretic mathematical models of the connections between the panel and the main structure are key components in research and development of robust and safe design procedures.

This paper presents numerical modelling of the fastening system for horizontal concrete cladding panels, typically used in precast industrial buildings in Central Europe. The considered fastening system consists of two main parts: a pair of top bolted connections, which provide the horizontal in- and out-of-plane stability of the panel, and a pair of bottom cantilever connections, which support the panels' weight. The numerical models were developed based on the results of dedicated tests on connections.

The numerical models were built in the OpenSees software framework by combining different material models. The top and bottom cladding connections were analysed separately and showed physically different response behaviours. The typical Coulomb friction model was used to describe the friction in the top connection, whereas the viscous friction model better simulated the variable friction in the bottom connection. The contacts that occur when the gap for sliding of panels closes were simulated by an abrupt increase of the stiffness of the connection.

The new numerical model is validated by single component tests as well as full-scale shake table experiments. Results show a good match between the experiments and the numerical simulations.

Keywords: precast buildings; horizontal cladding panels; connections; numerical modelling

1. Introduction

Reinforced concrete precast structures are one of the most common structural systems in Europe used for industrial as well as commercial purposes, with tens of thousands of visitors on a daily basis. As observed during strong earthquakes that occurred in Italy not long ago, the damage or collapse of reinforced concrete precast buildings could have caused human casualties as well as considerable direct and indirect economic losses due to production disruption [1-3]. Therefore, adequate design of the RC precast buildings is of extreme importance.

In design practice cladding panels were usually considered as non-structural elements, acting only as mass and their stiffness was typically neglected. However, after the latest strong earthquakes in Northern Italy [1, 4] this assumption has been put under question. Several failures of precast structures and cladding panels have drawn attention to the inadequate design of the connections. They were designed to sustain only the out-of-plane forces [5], while the earthquake loads in the in-plane direction were not considered at all.

The comprehensive systematic studies of RC precast structures performed within several large European projects [6, 7] and some parallel researches [8, 9] have improved the understanding of the behaviour of such structural type. However, recent Italian earthquakes have demonstrated that the knowledge about the behaviour of reinforced concrete façade systems was still not adequate. For this reason, the latest EU project SAFECLADDING [10] was devoted to the connections of the façade cladding panels to the main structural system of industrial buildings. At the University of Ljubljana the experimental and numerical investigation of the cladding connections, which are widely used in Central Europe for attaching of vertical [11] and horizontal panels, was performed.

Many important observations about the seismic response of cladding panels have been obtained within the SAFECLADDING project. However, this and other past researches were mainly focused on the investigation of the response of individual connections by monotonic and cyclic tests. Many aspects of the complex system response remained unsolved, though. For this reason, the research was continued within the research project *″Seismic resilience and strengthening of precast industrial buildings with concrete claddings″*, funded by the Slovenian Research Agency.

The central part of this project was devoted to the full-scale shake table experiments on a structure with realistic boundary conditions including main precast structure, RC cladding panels and connections. Within the tests, different parameters such as the orientation of the panels, the type of the cladding to structure connections and the number of the panels were varied. The structure was subjected to the earthquake loading in the horizontal direction parallel to the plane of the cladding panels. For the seismic excitation, an earthquake record modified to match the Eurocode spectrum was used. In total, 19 tests of the specimen with vertical panels and seven tests of the specimen with horizontal panels were performed on the same main structure.

An important part of the project was a formulation of numerical models of the connections. For this purpose, cyclic and dynamic tests of only cladding connections were performed. The response mechanism was first identified and then a robust numerical model was formulated in the OpenSees software framework. In this paper, the numerical model of the connections typically used for attaching of horizontal panels to the main structure in Central Europe is presented and then validated by using it for the simulation of the full-scale shaking table experiment.

2. The fastening system for horizontal concrete cladding panels

RC precast structural system typically consists of an assemblage of cantilever columns tied together by roof beams. Usually, precast concrete cladding panels are attached to the main structural system. The cladding panels can be divided into two categories, according to their geometry.

Vertical cladding panels have the height larger than the width, and horizontal cladding panels have the width larger than the height. Vertical panels are usually attached to the beams, whereas horizontal panels are attached to the columns of the main precast structure. The fastening system presented and studied in this paper is one of the most commonly used fastening systems for attaching of horizontal concrete panels in Central Europe.

2.1 Description of the fastening system

The investigated fastening system consists of a pair of top bolted connections, which provide the horizontal in- and out-of-plane stability of the panel, and a pair of bottom cantilever connections, which is used for supporting the panels' weight.

At the top corner regions of the horizontal panels, the panels are connected to the columns by hammer-head bolts. As presented in Fig. 1, the bolts are anchored into the vertical steel channel, which is built-in into the column, and connected to a box-shaped steel element, which is cast in the panel. The bottom connections that are installed at the bottom corners of the panel (Fig. 2) consist of a special steel box cast into the column, a cantilever bracket installed in the steel box and a steel plate cast into the panel.

The mounting of the horizontal cladding panel is performed in the following order. First, the cantilever bracket is anchored to the column by a diagonal bolt. After that, the panel is placed on the cantilever bracket, and finally, the bolt at the top is fixed inside the channel and tightened to the box profile.

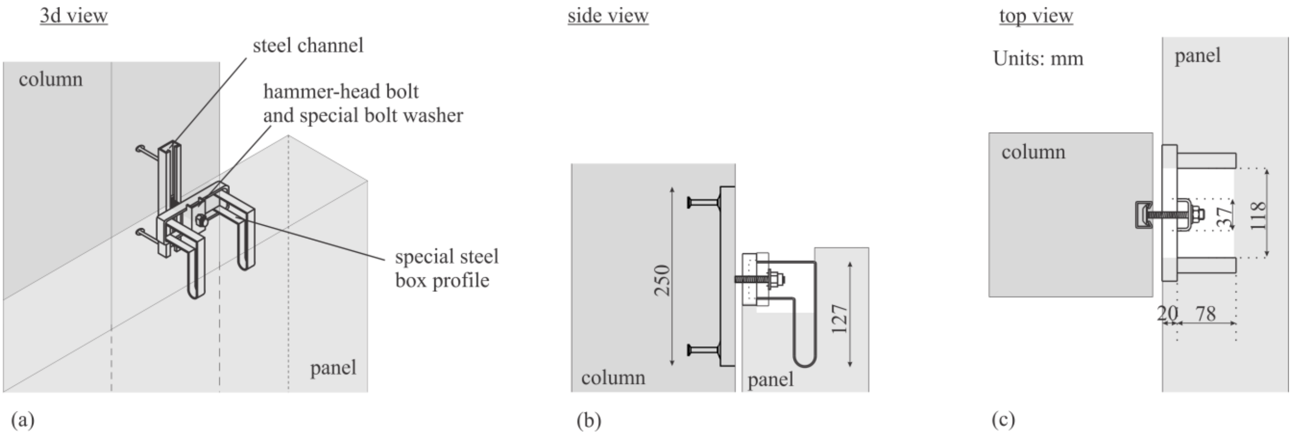

Fig. 1 – The assembly of the top box connection: (a) 3D view, (b) side view, and (c) top view

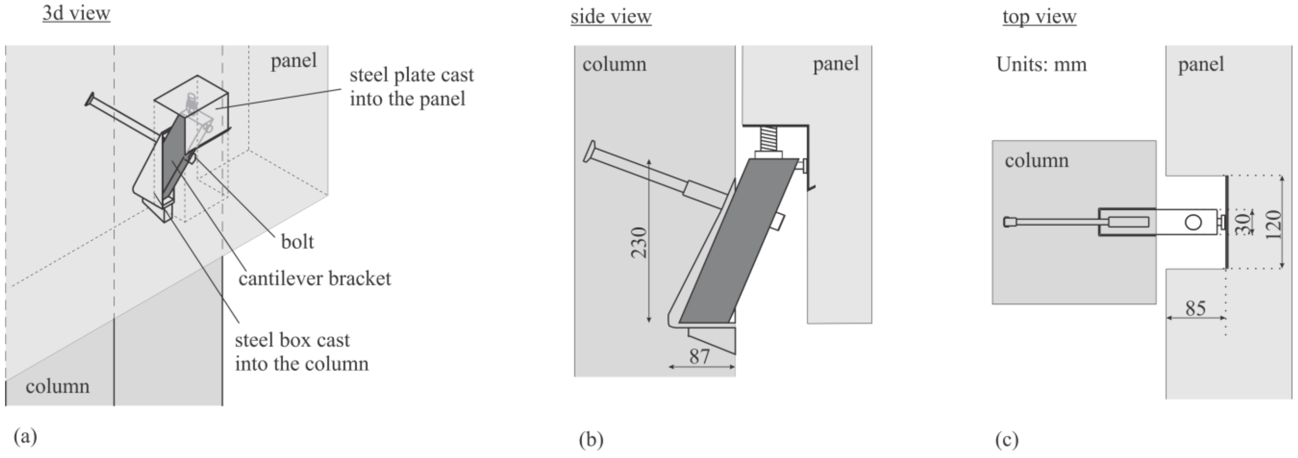

Fig. 2 – The assembly of the bottom cantilever connection: (a) 3D view, (b) side view, and (c) top view

2.2 The response mechanism

The response of the investigated fastening system in the in-plane horizontal direction was identified in two sets of the cyclic and dynamic single component tests. In the first set, only the top bolted connections were tested. In the second set the complete fastening system, which includes top bolted and bottom cantilever connections, was tested. Altogether, four quasi-static cyclic experiments and six dynamic tests were performed. The observed response mechanism was the same as later during the experiments on the shaking table.

The tests have shown that the response of the connections consists of three main stages, as shown in Fig. 3. Stage 1 represents the initial position of the top connection, in which the panel and column are fully connected (there is no relative displacement). When the static friction provided by the tightened bolt is exhausted, the bolt starts to slide along the steel box profile (Fig. 3 Stage 1 – Stage 2). The amount of the activated friction force depends on the tightening torque in the bolt and the coefficient of friction between the steel elements. When the bolt washer reaches the edge of the steel profile, the stiffness significantly increases (Fig. 3 Stage 2). Plastic deformations of the bolt and the channel increase until the displacement capacity of the connection is exhausted. Failure typically occurs due to the deformations of the channel and pulling-out of the bolt (Fig. 3 Stage 3).

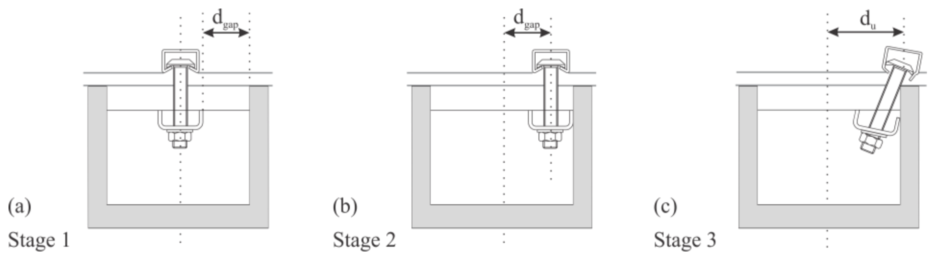

Fig. 3 – The behaviour mechanism of the top bolted connections: (a) initial position, (b) the contact of the connection parts, and (c) the failure of the connection

The response mechanism of the bottom connection is similar, except that initial and sliding frictions are much smaller than in the top connections. After the available gap between the cantilever bracket and the panel is depleted (Fig. 4 Stage 2), the bending stiffness of the cantilever is activated. This event results in a significant increase in the lateral stiffness of the fastening system. From this point on, the cantilever bracket behaves almost elastically with only minor deformations (Fig. 4 Stage 3).

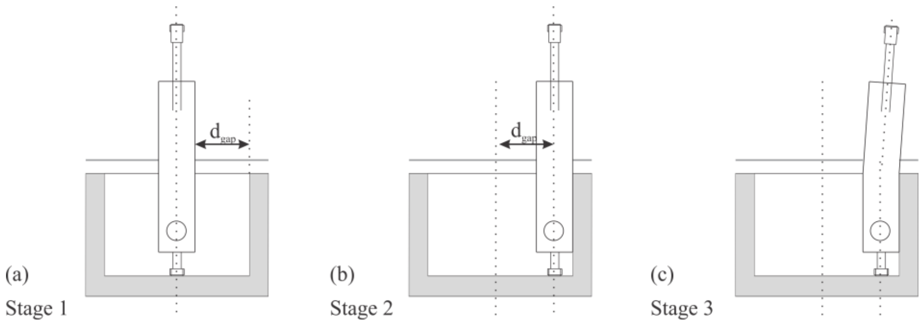

Fig. 4 – The behaviour mechanism of the bottom bearing cantilever connection: (a) initial position, (b) the contact of the cantilever bracket and the panel, and (c) only minor deformations of the connection parts at the end of the test

The component tests have been performed on the pairs of top connections, and on the complete fastening system consisting of a pair of top connections and a pair of bottom connections. In Fig. 5, typical response envelopes with indicated different stages of the response mechanism are presented. As marked in Fig. 5 (b), when the complete fastening system is considered the significant increase in lateral stiffness can be observed twice. Stage 2a in Fig. 5 (b) indicates a moment when there is contact in the top connections, and Stage 2b in Fig. 5 (b) represents the moment when there is contact in the bottom connection.

The tests of the complete fastening system were terminated before the complete failure due to the limited capacity of the actuator. However, at the end of the tests, only limited plastic deformations of the cantilever brackets were observed, whereas the top connections were considerably plastically deformed. It was established that the failure of the complete fastening system occurs when the displacement capacity of the top bolted connections is exhausted. Considering the displacement capacity of the top connections and almost elastic response of the cantilever bracket, it was possible to estimate the failure of the complete fastening system as presented with the hatched line in Fig. 5 (b). The tests showed that the failure occurs approximately 3.5 cm after the gap in top connections is depleted.

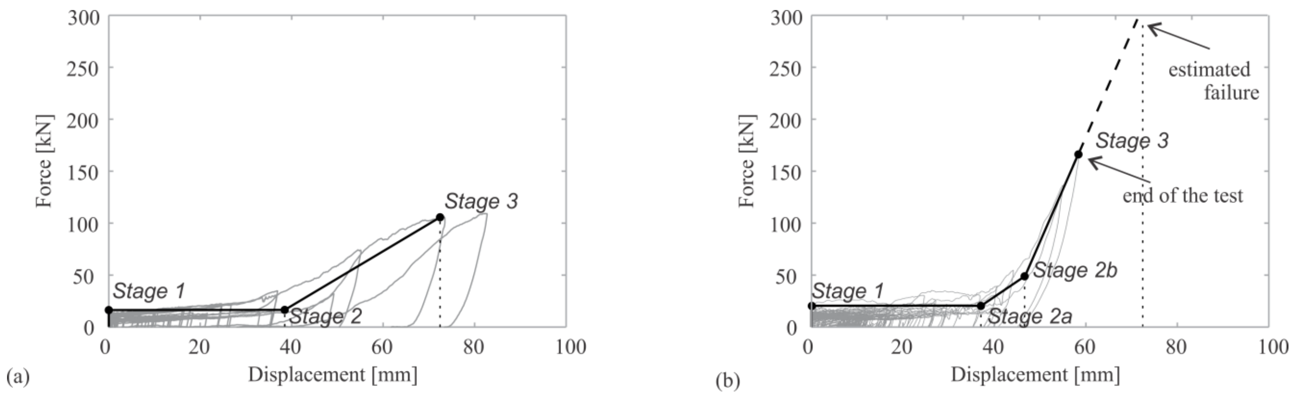

Fig. 5 – Response envelopes of (a) the top connections and (b) the complete fastening system

The response of the connections during the shaking table tests was similar to the mechanism described above. Unlike in single component tests, the cladding connections did not fail in shaking table tests because the relative displacement between the panels and main structure were smaller.

3. Numerical modelling

The response of the connections in the horizontal in-plane direction was modelled in the OpenSees software framework [12] by combining several standard uniaxial material models. The same numerical model was used for the simulation of top and bottom connections´ response during the quasi-static cyclic test.

As presented in Fig. 6 (a), the *ElasticPP* material model was added in parallel to the series combination to the *ElasticPPGap* and *Hysteretic* material models. The *ElasticPP* material model (Fig. 6 (b)) was used to simulate the constant friction between the elements, whereas the *ElasticPPGap* (Fig. 6 (c)) and *Hysteretic* (Fig. 6 (d)) material models were joint in parallel to simulate the instant increase in the lateral stiffness when the gap in the connections closes.

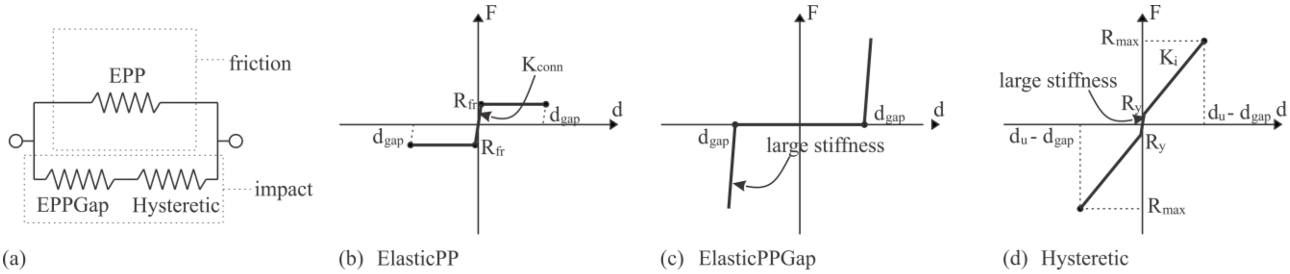

Fig. 6 – The numerical macro model: (a) numerical model of the connection, (b) *ElasticPP*, (c) *ElasticPPGap* and (d) *Hysteretic* material models

The force-displacement and force-velocity responses of the top and bottom connections observed during the dynamic experiments are presented in Fig. 7. The response of the bottom connections during the dynamic tests is somewhat different from the response of the top connection.

As shown in Fig. 7 (a) and (b), the friction in the top connection has typical characteristics of Coulomb friction. The Coulomb friction model assumes that the friction force is the product of the normal force on the contact surface and the constant coefficient of friction between the surfaces.

Since it was not possible to test only the bottom connections, its response behaviour was estimated by subtracting the results of the tests on top connections from the results of the complete fastening system. As shown in Fig. 7 (c) and (d), the friction force in the bottom connection was not constant, and the viscous friction model was identified as more appropriate. It assumes a linear relationship between the friction force and sliding speed.

In general, the response of the bottom connections was viscoelastic (see Fig. 7 (c)). Therefore, for the simulation of the dynamic response of bottom connections, the *ElasticPP* material model was replaced by the parallel combination of *Viscous* and *Elastic* material models, as presented in Fig. 8.

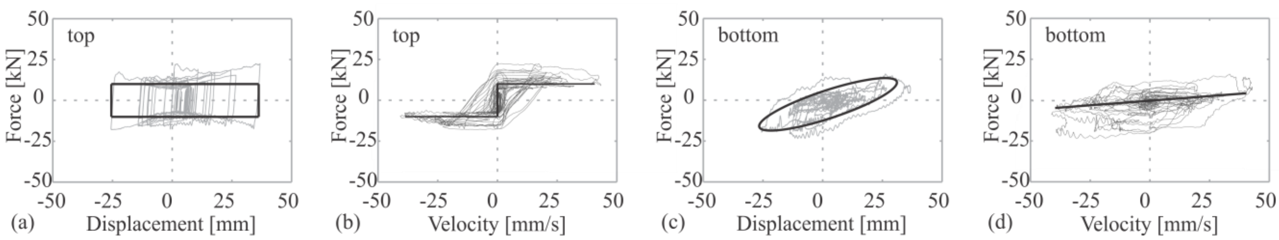

Fig. 7 – Hysteretic responses (grey) and idealized envelopes (black): (a) top connections F-d, (b) top connections F-v (c) bottom connections F-d and (d) bottom connections F-v

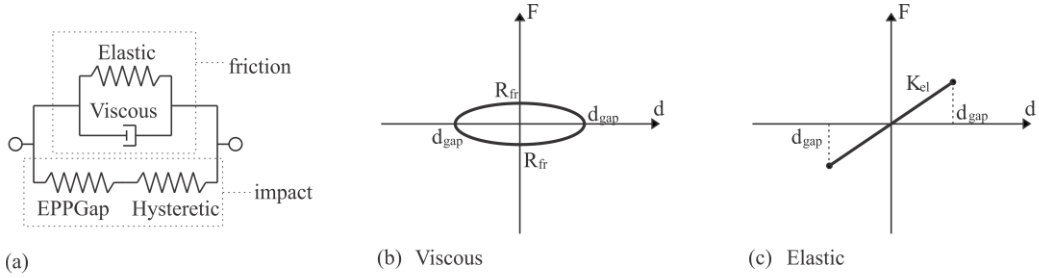

Fig. 8 – The numerical macro model: (a) numerical model of the bottom connections under dynamic loading, (b) *Viscous* and (c) *Elastic* material model

The model used for the numerical simulation of the shake table test is schematically presented in Fig. 9. Since no yielding in the columns was observed during the shake table tests, simple *elasticBeamColumn* elements were used for modelling the cantilever columns. Because the columns were cracked from many previous tests, the cracked cross-section was assumed to be ¼ of the gross cross-section.

Rigid slab and panels were modelled using *elasticBeamColumn* elements with high stiffness. Masses of the elements were lumped in centres of gravity or at the top of the column, as presented in Fig. 9. The models of the connections were such as identified in single component tests.

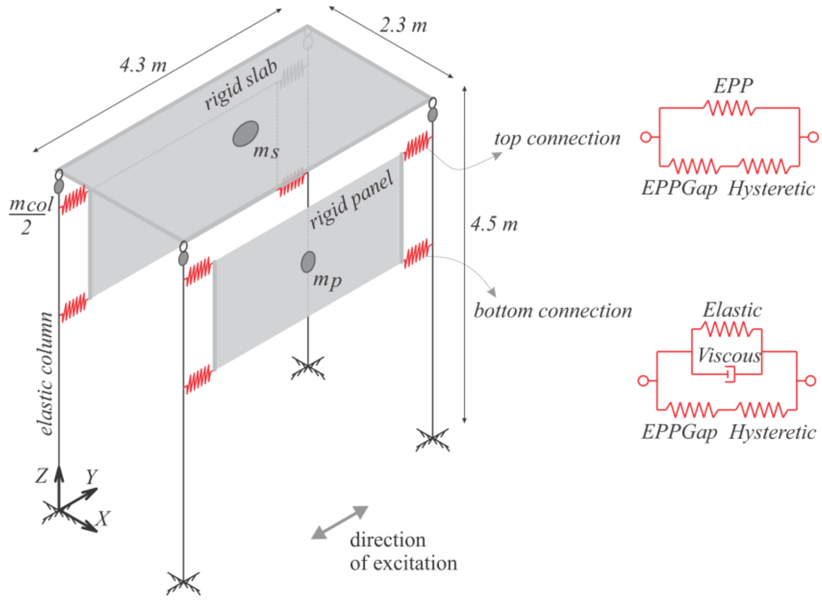

Fig. 9 – Schematic presentation of the numerical model for the shake table test

4. Experimental versus numerical results

In the following paragraphs, the model parameters are presented. Values used in numerical simulations are listed in Table 1. These values are also the recommended values for simulations of such connections.

Size of the gap (d_{gap}): The initial position of the connections depends on the actual construction and the possible residual displacements after the earlier excitations. It was possible to achieve almost ideal position of the connections at the most of the tests on single components. Therefore, d_{gap} is a half width of the available space in the panel reduced by half of the thickness of the cantilever bracket at the bottom or the bolt at the top.

At the shaking table test, the mounting process was not so accurate and additionally, there were some residual displacements in the connections after each excitation. For this reason, the gaps in all the connections were measured prior to each test run performed on the shaking table. The actual (measured) values were used as input data.

Displacement capacity (d_u): The displacement capacity of the fastening system is defined with the displacement capacity of the top connections after the gap in top connections is depleted. Therefore, it consists of the variable gap in the top connections d_{gap}, and the plastic deformation capacity of the bolt, which is about 3.5 cm. If the connections are installed in the middle of the gap, the total displacement capacity amounts to 7.5 cm.

Friction force (R_{fr}): The friction in the top connection depends on the tightening torque in the bolt and the coefficient of friction between the connection parts. It is recommended to use a friction coefficient of 0.4 for this type of connections. During the single component tests, the maximum friction force of 8 kN was observed at each of the top connections, whereas at the test on the shaking table it was somewhat smaller (about 2 kN) due to the uncontrolled tightening and loosening of the bolt during the tests.

In order to estimate the friction force in the bottom connections, the results of the single component tests were used. The friction force of the top connections was subtracted from those observed during the tests of the complete fastening system. The friction force in the bottom connections was estimated to 2 kN.

Damping (c_{visc}): For numerical modelling of friction in bottom connection during the dynamic tests, the damping coefficient of 50 t/s was defined. It was estimated based on the friction force and the velocity measured during the tests.

Stiffness (K_{conn}, K_i, K_L): The stiffness of the connections is very large until the sliding and the friction force in the connections are activated. During the sliding phase, the stiffness is practically zero until the gap is closed. After that, the very large bending stiffness of the connections is activated. With the values proposed in the Table 1, the relative displacements between the main structure and panels could be simulated adequately. To model the response after the contacts, the *Hysteretic* material model was used. Relatively small parameter R_y and large stiffness K_L were used to define the steep unloading branch. Pinching, damage and beta factors should be all set to zero.

Table 1 – Parameters of the model for cladding connections

Material characteristic	Value
Friction force at top connection (component test): $R_{fr,top}$	8 kN
Friction force at top connection (shake table test): $R_{fr,top}$	2 kN
Friction force at bottom connection (cyclic tests): $R_{fr,bottom}$	2 kN
Damping coefficient at bottom connection (dynamic tests): $c_{visc,bottom}$	50 t/s
Initial stiffness of the top connection: $K_{conn,top}$	$2\ 10^4$ kN/m
Initial stiffness of the bottom connection: $K_{conn,bottom}$	$2\ 10^3$ kN/m
Bending stiffness of the top connection: $K_{i,top}$	$1.5\ 10^3$ kN/m
Bending stiffness of the bottom connection: $K_{i,bottom}$	$3\ 10^3$ kN/m
Elastic stiffness of the bottom connection: $K_{el,bottom}$	200 kN/m
Relatively small yield parameter: R_y	0.01 kN
Unloading stiffness after the gap is depleted: K_L	$1\ 10^4$ kN/m

The proposed numerical models simulate the response of the connections with quite high accuracy, as can be observed from Fig. 10 (a) for top connections tests and Fig. 10 (b) and (c) for cyclic and dynamic tests on the complete fastening system.

Experimental and numerical results for the shaking table test are compared in Fig. 11 and Fig. 12. The results correspond to the PGA intensity 0.3 g and the specimen with two panels, mounted at each side of the main structure as shown in Fig. 9. The accuracy is similar also for other test intensities and configurations. However, this model is not able to reproduce the residual displacements in the connections.

It should be noted that the response of the main structural system is also reproduced very well. Therefore, the effect of the panels and the connections on the response of the precast system is simulated accurately and the proposed model is appropriate for the use in further numerical studies.

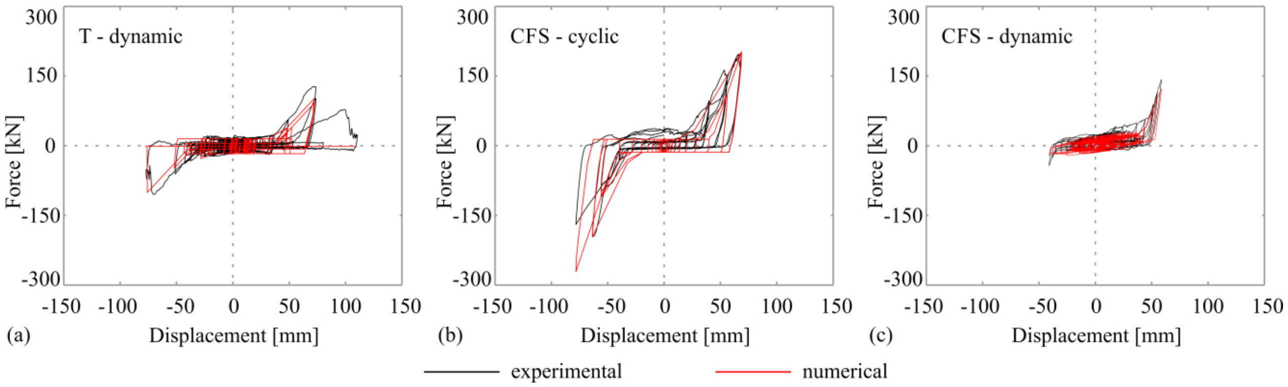

Fig. 10 – The experimental (black) and numerical (red) hysteretic responses of (a) only the top connections, (b) the complete fastening system during the cyclic tests and (c) the complete fastening system during the dynamic tests

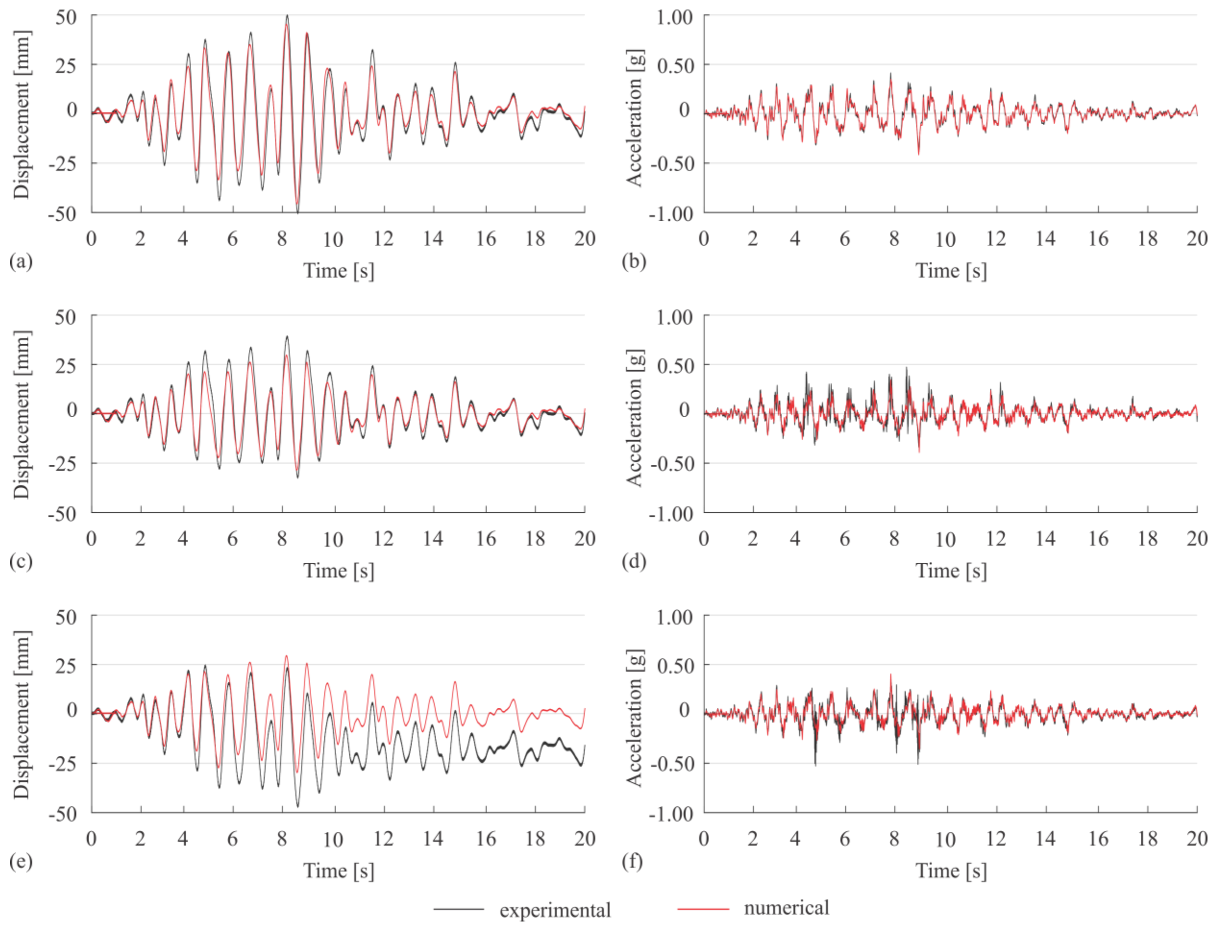

Fig. 11 – Response histories of the specimen tested at the shaking table at PGA 0.3 g: (a) slab displacements, (b) slab accelerations, (c) P1 displacements, (d) P1 accelerations, (e) P2 displacements, (f) P2 accelerations

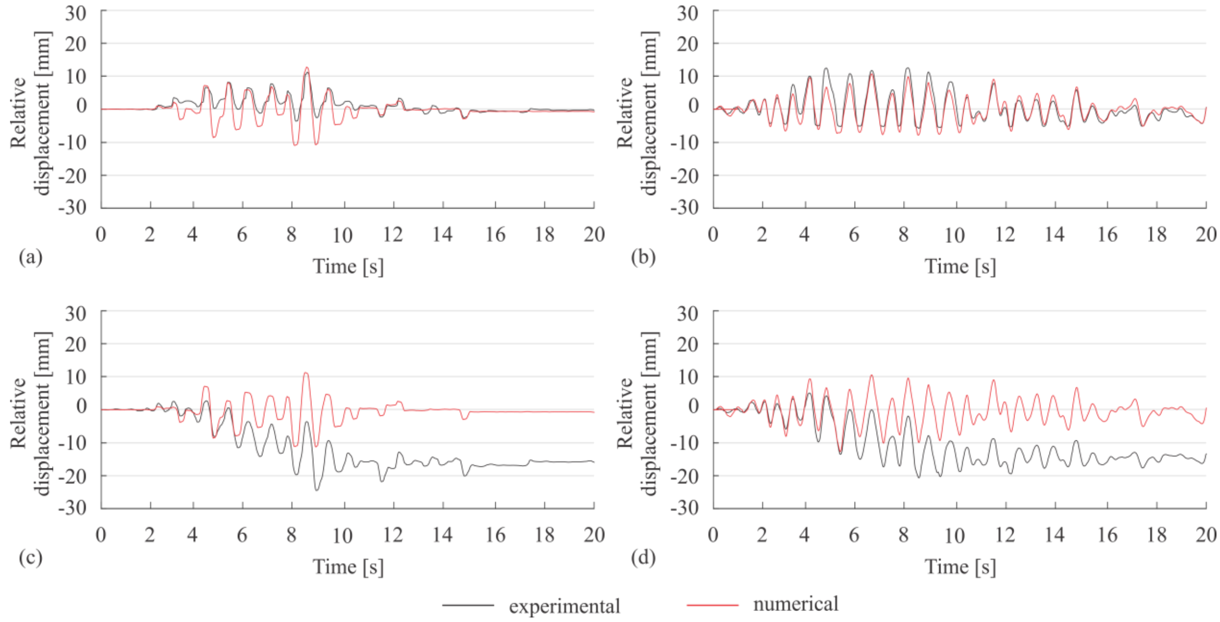

Fig. 12 – Displacements in the cladding connections at the PGA intensity 0.3 g: (a) P1 top connection, (b) P1 bottom connection, (c) P2 top connection, (d) P2 bottom connection

5. Conclusions

In this paper, the numerical model of the most common fastening system in Central Europe for attaching the horizontal RC façade panels to the precast structures is analyzed. The fastening system consists of a pair of top bolted connections, aimed at providing the horizontal stability of the panel, and a pair of bottom cantilever connections that support the weight of the cladding panel.

The numerical models for cladding connections were based on the response of the connections observed during the quasi-static cyclic and dynamic single component tests. The cladding connections were numerically modelled by combining different material models available in the OpenSees software framework.

The analysis showed that the dynamic responses of the top and bottom connections have somewhat different characteristics. The top connection appears to exhibit typical Coulomb friction behaviour, whereas the viscoelastic behaviour better describes the response of the bottom connection. The new numerical model was verified by the single component tests as well as full-scale shake table experiments. Experimental results were reproduced with high accuracy.

The robust and reliable model serves as a key component in the research of the response of the façade panels during strong earthquakes. Models described in this paper can be used in further numerical analysis aimed at investigating the response of the complete structure in which cladding connections and panels are carefully taken into account.

6. Acknowledgements

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7. References

[1] Bournas DA, Negro P, Taucer FF (2013): Performance of industrial buildings during the Emilia earthquakes in Northern Italy and recommendations for their strengthening. *Bulletin of Earthquake Engineering*, **12** (5), 2383-2404.

[2] Magliulo G, Ercolino M, Petrone C, Coppola O, Manfredi G (2014): The Emilia earthquake: Seismic performance of precast reinforced concrete buildings. *Earthquake Spectra*, **30** (2), 891-912.

[3] Savoia M, Buratti N, Vincenzi L (2017): Damage and collapses in industrial precast buildings after the 2012 Emilia earthquake. *Engineering Structures*, **137**, 162-180.

[4] Toniolo G, Colombo A (2012): Precast concrete structures: the lessons learned from the L'Aquila earthquake. *Structural Concrete*, **13** (2), 73-83.

[5] CEN (2004): Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings. Brussels: European Committee for Standardisation.

[6] Toniolo G (2012): European research on seismic behaviour of precast structures. *2012 NZSEE Conference*, Christchurch, New Zealand.

[7] Fischinger M, Zoubek B, Isaković T (2014): Seismic response of precast industrial buildings. *Perspectives on European earthquake engineering and seismology*, Ansal A (Editor), Springer, 1st edition.

[8] Belleri A, Torquati M, Marini A, Riva P (2016): Horizontal cladding panels: in-plane seismic performance in precast concrete buildings. *Bulletin of Earthquake Engineering*, **14** (4), 1103-1129.

[9] Del Monte E, Falsini C, Boschi S, Menichini G, Orlando M (2019): An innovative cladding panel connection for RC precast buildings. *Bulletin of Earthquake Engineering*, **17** (2), 845-865.

[10] SAFECLADDING (2015): "SAFECLADDING project – Improved Fastening Systems of Cladding Wall Panels of Precast Buildings in Seismic Zones." *http://www.safecladding.eu*.

[11] Zoubek B, Fischinger M, Isaković T (2016): Cyclic response of hammer-head strap cladding-to-structure connections used in RC precast building. *Engineering Structures*, **119**, 135-148.

[12] McKenna F, Fenves GL (2010): Open System for Earthquake Engineering Simulation (OpenSees). *http://opensees.berkeley.edu*.

