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EXPERIMENTAL RESEARCH OF TYPICAL CLADDING PANEL CONNECTIONS IN INDUSTRIAL BUILDINGS

Tatjana ISAKOVIĆ[1], Blaž ZOUBEK[2], Jože LOPATIČ[3] and Matej FISCHINGER[4]

ABSTRACT

The seismic behaviour of the existing cladding panel connections, which are typical for European industrial buildings, is far from being clarified, particularly in the plane of the cladding panels. Some of these connections that are typically used in the practice were experimentally investigated. Three typical cladding-to-structure connections were analysed: (a) sliding connection with hammer-head strap, (b) angle connection, and (c) cantilever connection. In this way the connections of vertical as well as horizontal panels were addressed. Before the experiments there was no data available at all about their seismic response. Thus, the most of performed tests were cyclic. To be able to compare the cyclic and monotonic response, a limited number of monotonic tests was also performed. It was observed that the strength of the sliding connections, subjected to the cyclic load was considerably smaller than that registered and expected under the monotonic load. Response of these connections in the vertical direction was predominantly sliding. Angle and cantilever connections responded in a different manner than the sliding connections, and their strength under the cyclic load was considerably larger, particularly that of the cantilever connections.

INTRODUCTION

The behaviour of the existing cladding panel connections, which are typical for European industrial buildings, is far from being completely understood. Furthermore, supported by the observations after the recent earthquakes in Italy, it was concluded that these connections performed in a different way as it had been foreseen in the design. The claddings and the existing connections to the main structure cannot accommodate large displacements of the columns, which are needed to develop the energy dissipation foreseen in the design. Consequently the connections can be loaded with the large seismic forces proportional to the total mass of the structure. Neither the mechanism of this response nor the seismic capacity (strength and deformability) of the traditional cladding connections has been known, prior to the investigations that are presented in the paper.

To clarify these issues experimental studies of cladding panel connections that are typically used in industrial buildings in Europe has been performed in the frame of the extensive European FP7 project SAFECLADDING. At the first glance, the existence of the numerous (seemingly different)

[1] Prof. dr., University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia, tatjana. isakovic@fgg.uni-lj.si
[2] B. Sc., University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia, blaz.zoubek@fgg.uni-lj.si
[3] Assoc. Prof. dr., University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia, joze.lopatic@fgg.uni-lj.si
[4] Prof. dr., University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia, matej.fischinger@fgg.uni-lj.si

systems made this selection difficult. However, a detailed overview of the cladding connections, used in the most seismically prone regions of Europe, proved that quite limited number of types can sufficiently represent the behaviour of the large class of connections.

Three most common types were experimentally tested: 1) sliding connections - consisting of two channels, which are linked by hammer-head strap, 2) angle connections - consisting of channels connected by steel angles, 3) cantilever connections - consisting of bolted channel and steel corbel. First type is typically used to connect vertical panels to the main structural system of building, while the third type is specific for horizontal panels. All types of the tested connections as well as the basic features of the experimental set-up are described in section “Description of the tested connections and the set-up of the experiments”.

Majority of the preformed experiments were cyclic; however a limited number of monotonic tests were also performed in order to be able to make the comparison. Altogether 30 tests were performed. In most of them, the connections were subjected to the horizontal load (displacements) in the plane of the panel. In certain number of tests the vertical response of the sliding connections was simulated. There was no data at all available about this type of the response, prior to the experiments.

In general, the mechanism of the response of all tested connections subjected to cyclic load had not been known before these experiments. Therefore, one of the main results of these investigations was the identification of the main phases of the response. The observed behaviour and the main mechanism of the cyclic response are presented in section “Results”.

DESCRIPTION OF THE TESTED CONNECTIONS AND THE SETUP OF THE EXPERIMENTS

Since there are a large variety of panel-to-structure connections available, a survey of the most typical types, used in the practice, was accomplished prior to the experiments. Typical mechanical connections, which are used to attach cladding panels to structural system of precast buildings, first of all depend on the orientation of the panels. In most of the European countries both, vertical as well as horizontal panels are widely used. In the past vertical panels were more popular, while nowadays the horizontal panels are more common, since they simplify construction of different types of windows and doors. Thus the typical connections of both types of panels were included into the plan of experiments: a) sliding connections - consisting of two channels, which are linked by hammer-head strap, b) angle connections - consisting of channels connected by steel angles, c) cantilever connections - consisting of bolted channel and steel corbel. They are presented in Figure 1. Two types of channels were used for sliding connections: hot rolled and cold formed channels.

(a) (b) (c)

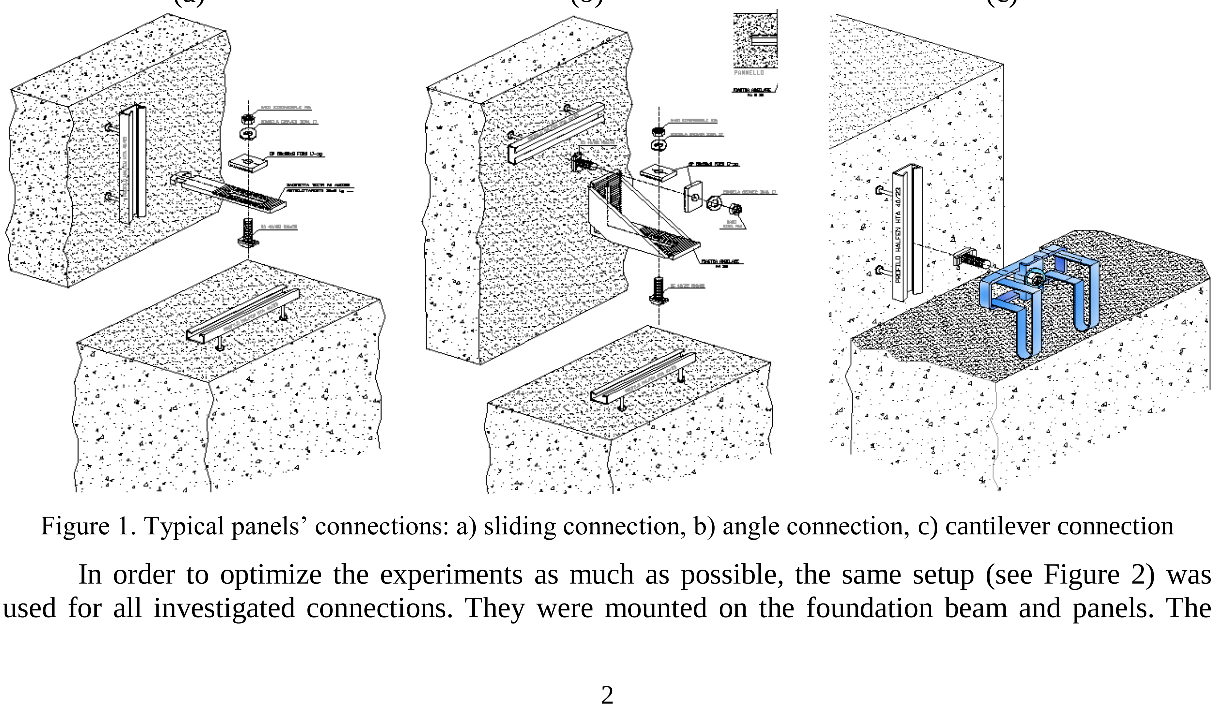


Figure 1. Typical panels’ connections: a) sliding connection, b) angle connection, c) cantilever connection

In order to optimize the experiments as much as possible, the same setup (see Figure 2) was used for all investigated connections. They were mounted on the foundation beam and panels. The inverted T foundation beam was fixed to the lab's floor. Panel was placed at one side of the foundation beam. It was connected to the actuator (see Figure 3) and mounted on rollers in order to be able to slide it in parallel to the foundation beam. Special attention was devoted to the construction of rollers (see Figure 4) in order to reduce the amount of friction to a minimum possible level, since it could considerably influence the results of the tests. A construction, using special ball bearings, provided movements of the panels with almost no friction. The force and displacement capacity of the used actuator were 250 kN and ± 20 cm, respectively.

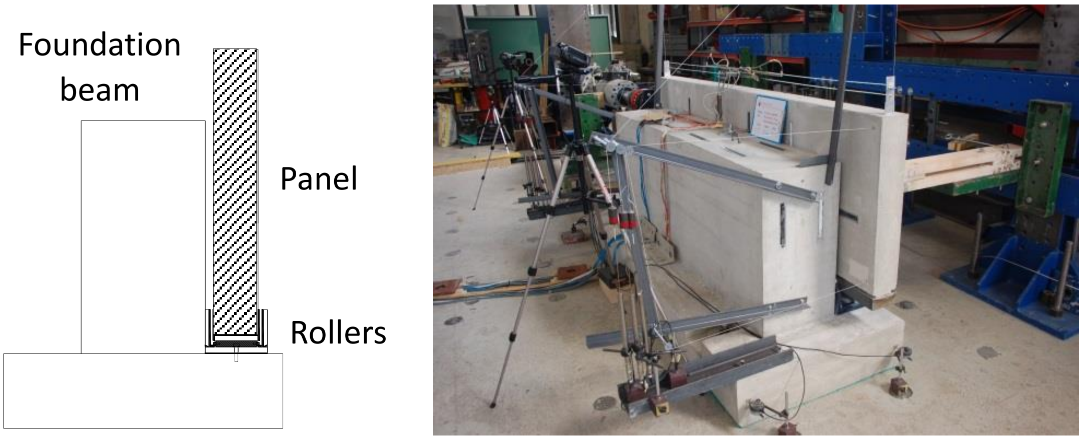


Figure 2. General setup of the experiments

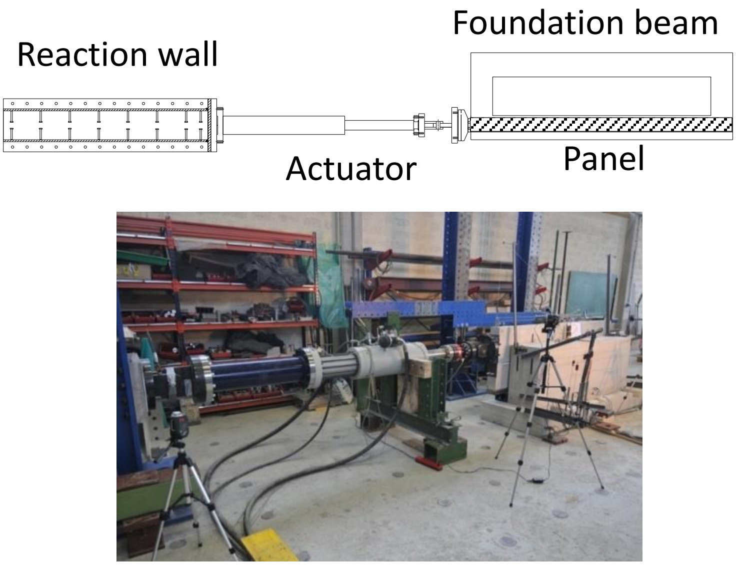


Figure 3. The connection of the panel and the actuator

Figure 4. The connection of the panel and the foundation beam – frictionless rollers

All together 30 tests were performed, 7 monotonic and 23 cyclic tests. In general three types of cyclic tests were accomplished:

1. Uniaxial shear tests (see Figure 5a): The load was applied in the horizontal direction in parallel to the longitudinal axis of the panel. The direction of the load was perpendicular to the channel mounted in the panel and perpendicular to the hammer-head strap. The uniaxial shear tests were performed on all investigated connections (including angle and cantilever connections).

2. Biaxial shear tests (see Figure 5b): The specimens were loaded in two horizontal directions perpendicularly and in parallel with the longitudinal axis of the panel. The hammer-head strap was loaded in shear and tension simultaneously. The hammer head strap was loaded in its strong direction. These tests were performed on sliding and angle connections.

3. Uniaxial sliding tests (see Figure 5c): The load was applied in the horizontal direction in parallel to the longitudinal axis of the panel. The channel mounted in the panel was loaded in parallel to its longitudinal axis. The hammer-head strap was loaded perpendicularly to its weak direction. These tests gave information of the response of the sliding connections in the vertical direction. This type of test was performed only on sliding connections.

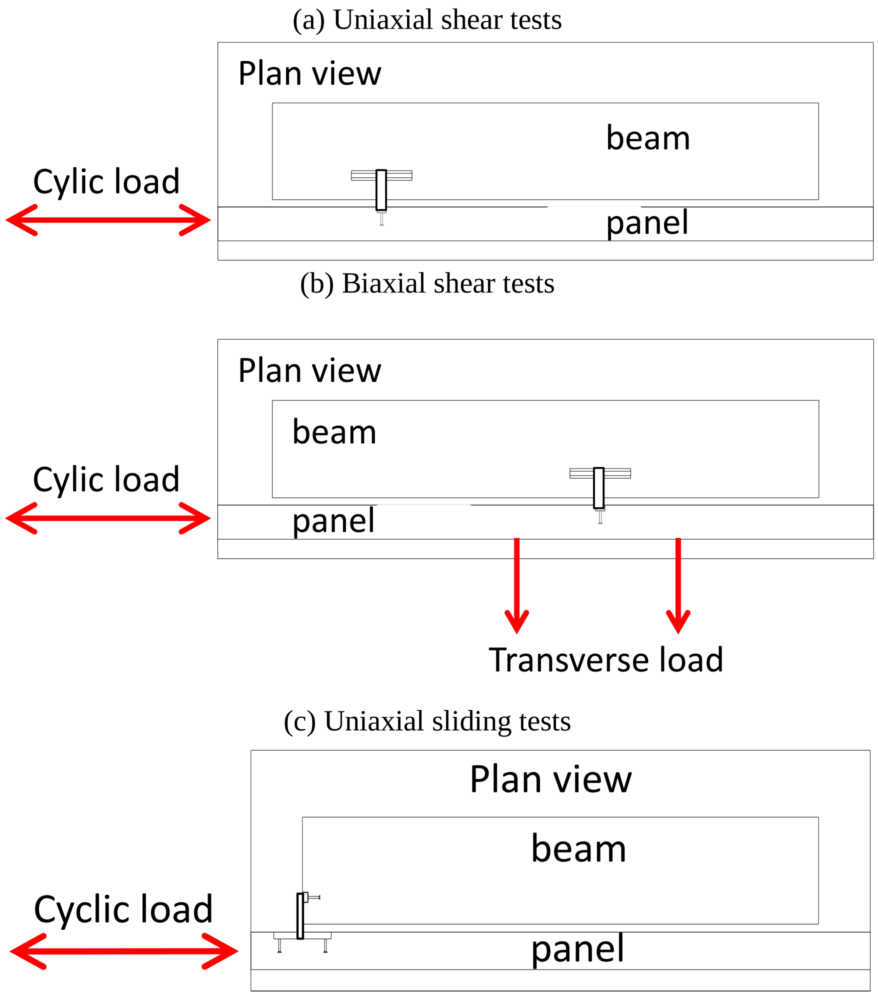


Figure 5. Types of the preformed cyclic tests

The cyclic load was applied according to the recommendations in provided in FEMA 461. The amplitudes were increased exponentially. Two full cycles per each amplitude were applied. The exceptions were sliding tests, were the half-cycle load was applied instead of the full cycles.

RESULTS

Shear tests of sliding connections

The mechanism of the response of the sliding connections subjected to cyclic load had not been known at all before the experiments, described in this paper. Therefore, one of the main results of these investigations was the identification of the main phases of the response, which are summarized in Figure 6. In order to make this presentation clearer, the main steps are explained on the example of the connection loaded only in one direction.

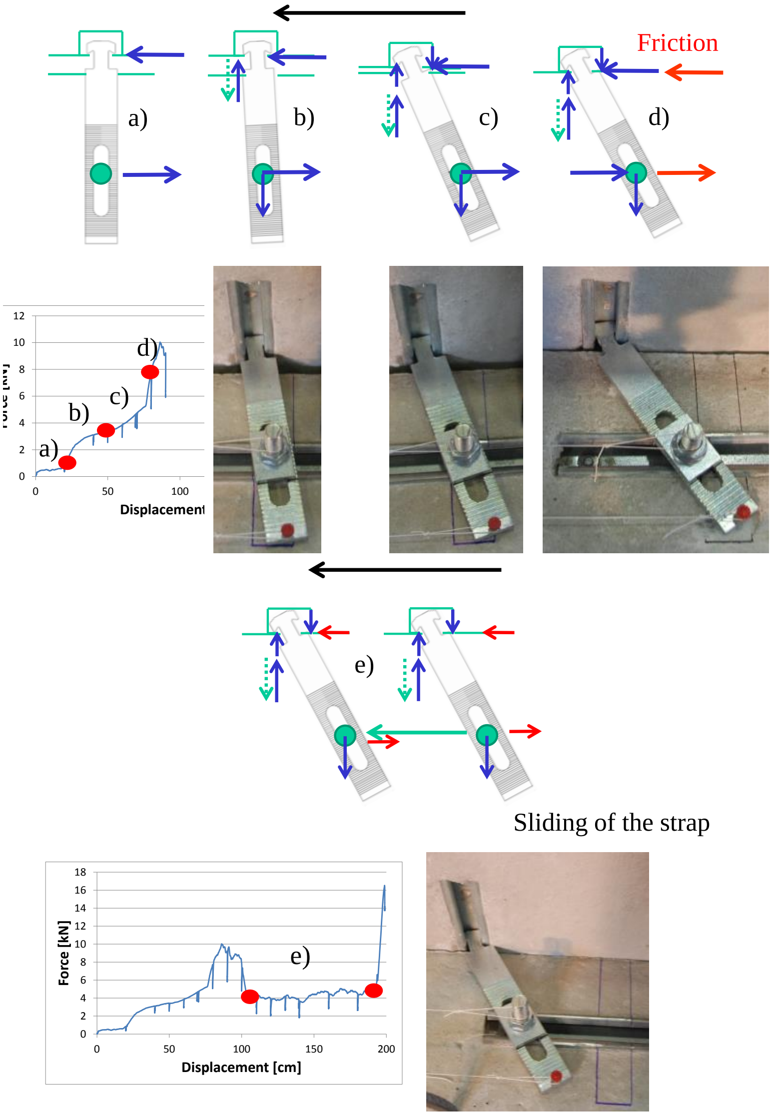
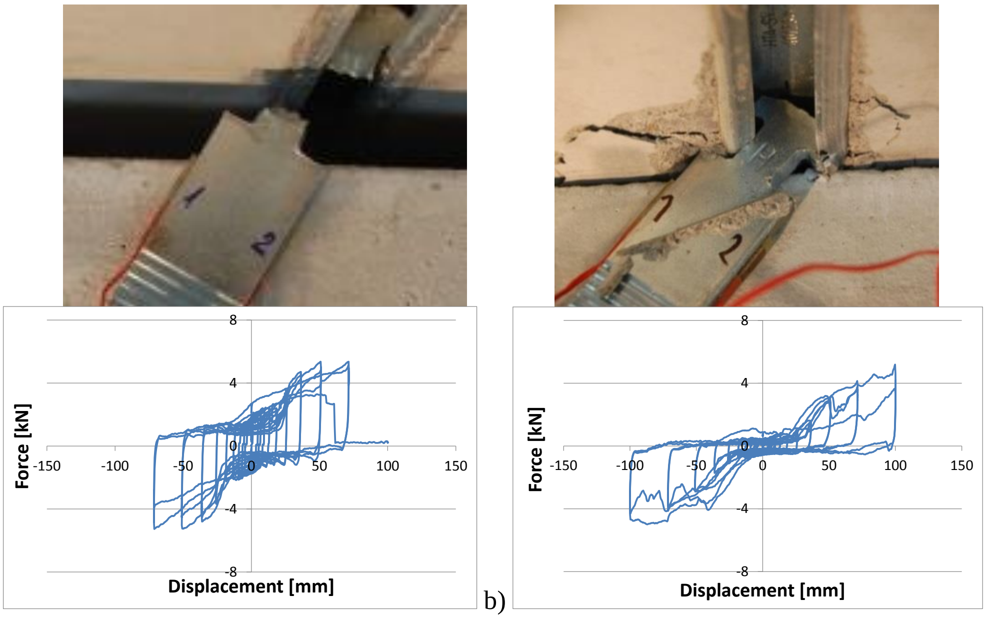


Figure 6. The main steps of the response of sliding connections

In the beginning the strap can rotate without restrictions (a). The displacements of the panel and the rotations of the strap increase simultaneously. When the displacements of the panel are large enough (in the investigated cases these displacements were around 20 - 30 mm) the head of the strap is stacked in the channel. Consequently the force in the connection is increased (b). Plastic deformations of the head of the strap increases (c). When the displacements are large enough the gap between the panel and the beam is closed (d). The force almost instantly considerably increases, due to the activated friction between the panel and the beam. All these phases are visible in the force-displacements diagram, presented in Figure 8. They are marked by red spots.

In some experiments considerable sliding of the strap (screw) were also observed (e). In such cases the force in the connections is reduced or it is kept constant as long as the strap reaches the end of the channel. When the strap reaches the end of the channel the force again considerably instantly increases. It should be noted that the sliding of the strap (screw) was observed only in monotonic tests, and in the cyclic tests, were the torque moment applied to the screw at the beginning of the experiment, was small (almost 0 Nm).

The response of connections, which included two types of channels: a) hot rolled, and b) cold formed, channels were investigated. The strength of both connections as well as the maximum displacements were quite similar, however the type of failure was completely different. The failure of the strap occurred in the connections, which included hot rolled channels (see Fig. 7a). In the connections with cold formed channels the failure of the channel (channel lips) was obtained (see Fig. 7b). The strap was pulled out form the channel, mounted in the panel. It is a general observation that investigated hot rolled channels were stronger than cold formed channels.



a) b)

Figure 7. Typical cyclic response of the sliding connections a) with hot rolled channels, b) with cold formed channels

At the small displacements amplitudes the force in both types of the connections was smaller than the maximum force detected during the test. The force in the connections with hot rolled channels was a bit larger. Anyway, it can be concluded that the response was in both cases almost pure sliding, as long as the head of the strap was not stacked in the channel, mounted in the panel. After that the force was increased, but not significantly. In general the maximum strength was in both cases relatively small.

Additional increase of the force was observed when the gap between the panel and beam was closed, due to the large rotation of the strap. In such cases the friction between the panel and the beam additionally increased the strength. This however was not very significant in cyclic tests, but was quite important in monotonic shear tests (please see a description and an explanation in further paragraphs). At cyclic shear tests, the failure of the connection was obtained almost immediately after the friction between the panel and the beam was activated.

The response of both types of the investigated connections was quite symmetric in both pull and push direction. The strength of the connections with hot rolled channels was in the range 5 kN – 6.5 kN. The strength in the connections with cold formed channels was in the range 4 kN – 8.5 kN. The exceptions were connections were considerable sliding of the strap was observed. In such cases the response was highly asymmetric. Typically the strength was larger in the push direction. The values as large as 12 kN were measured. In the pull direction this value was considerably smaller. Maximum displacements were in the range 70 mm – 100 mm. Again the exceptions were experiments where considerable sliding of the strap was observed. In such cases the maximum displacements were in the range 170 mm – 200 mm.

In the majority of the cyclic shear tests, the sliding of the strap was not significant. The exceptions were the tests were the torque moment applied to the screw at the beginning of the test was very small. In these experiments the displacements of the strap were quite large (due to the sliding). In majority of these tests the displacements were quite close or even exceeded the displacement capacity of the actuator, which was ± 200 mm.

During the biaxial cyclic shear tests, the same type of the failure was obtained as that obtained in uniaxial tests. The strength of the both types of the connections was increased. However, this increase was not significant; the strength was in the range 7 kN – 10 kN in both types of the investigated connections. The strength was increased because the initial force, applied perpendicularly to the panel, acted in the opposite direction than the force, which was generated due to the interaction between the strap and the panel. In some biaxial experiments maximum displacements were somewhat smaller than in uniaxial tests; they were in the range 50 mm – 100 mm.

The type of the failure in the monotonic tests was different than that in cyclic tests (see Figure 8). The connection between the washer and the strap failed. The strength was considerably larger than in the cyclic tests. It was around 30 kN and 40 kN during the uniaxial and biaxial tests, respectively. This was expected in accordance of the producer’s reports (ETA-09, 2010). The maximum strength was obtained at the end of the test after considerable sliding of the strap, as that illustrated in Figure 6(d). When the strap reached the end of the channel, it was additionally supported, and the force in the connection was instantly increased. Maximum displacements in these tests were typically equal to the displacement capacity of the actuator (200 mm). In some cases this value was even exceeded.

The response, identified during the performed experiments, was in a very good agreement with the damage observed during the last earthquakes in Italy, where several examples of the failure of cladding panel connections were observed (see Figure 9).

Sliding tests of sliding connections

Sliding tests were performed in order to study the response of the sliding connections in the vertical direction. There were some doubts that this response is not sliding, first of all due to the imperfections during the construction. Before the tests were performed there were no data at all about the response in this direction. The producers did not provide them even for the monotonic load.

The response of both types of connections (with hot rolled and cold formed channels) was tested. Uniaxial cyclic and monotonic tests were performed. The response of both types of connections was similar. It was essentially sliding as long as the gap between the beam and the panel was not closed. The displacements were in the range 90 mm – 150 mm when the gap was closed, depending on the length of the channels, initial size of the gap and the initial position of the screw. When the gap was closed the force in the connection was considerably increased. It was in the range 25 kN – 34 kN in both types of the investigated connections. There were no considerable differences between cyclic and monotonic tests (see Fig. 10).

Two exceptions were observed in the case of the cold formed channels, were the channel was filled with the flexible foam instead with the styrofoam. In such cases gaps between the ends of the channel and the surrounding concrete were formed during the concreting. Due to these gaps, the strap was pulled out from the channel with quite small forces of about 7 kN.

In other cases the failure of the channels (in the beam or in the panel) was observed, accompanied by considerable damage of the concrete near the channels and considerable deformations of the strap and in many cases also of the screw.

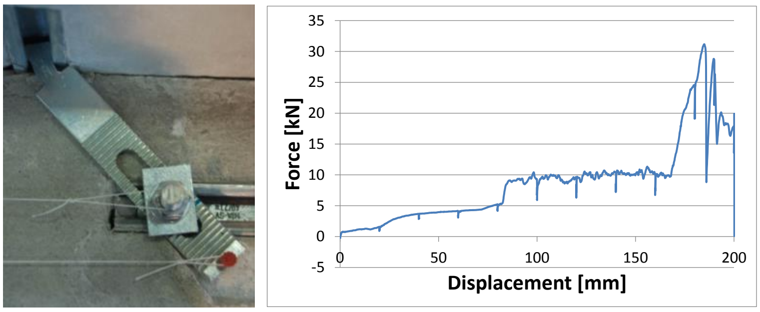


Figure 8. Typical monotonic response of the sliding connections


Figure 9. Typical damage of the sliding connections, observed during the latest earthquakes in northern Italy

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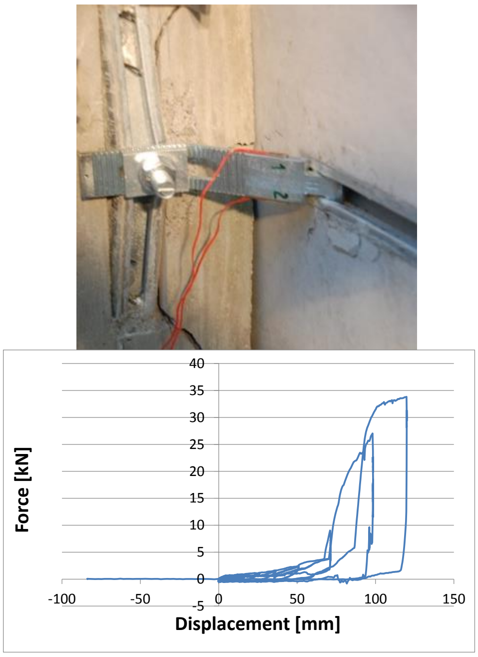

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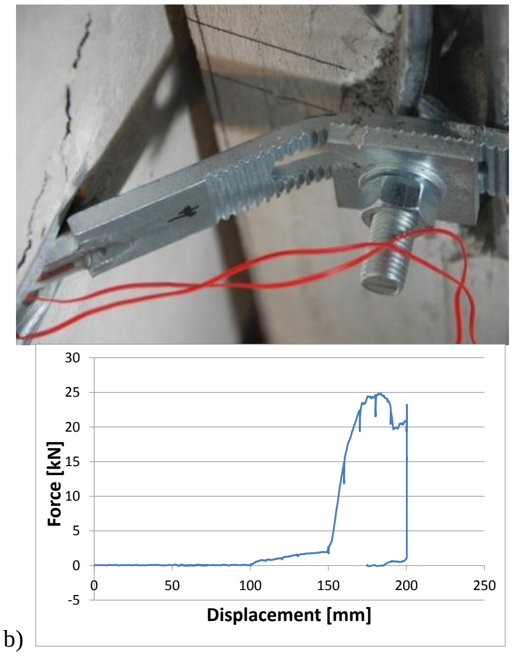

Figure 10. Typical response of the sliding connections in the vertical direction a) cyclic, b) monotonic

Angle connections

Similarly to the sliding connections, there was no data at all available about their cyclic response, prior to the experimental campaign, described in this paper. Therefore, the results of these tests are quite important for proper understanding of the mechanisms that are developed during the seismic excitations of these connections. They are summarized in the next paragraphs.

Only the shear cyclic tests of the angle connections were performed. They were uniaxial as well as biaxial. There were no considerable differences between them, neither regarding the strength nor regarding the type of failure (see Figure 11). Only the maximum displacements were somewhat smaller in the biaxial tests (e.g. 56 mm and 40 mm in uniaxial and biaxial tests, respectively).

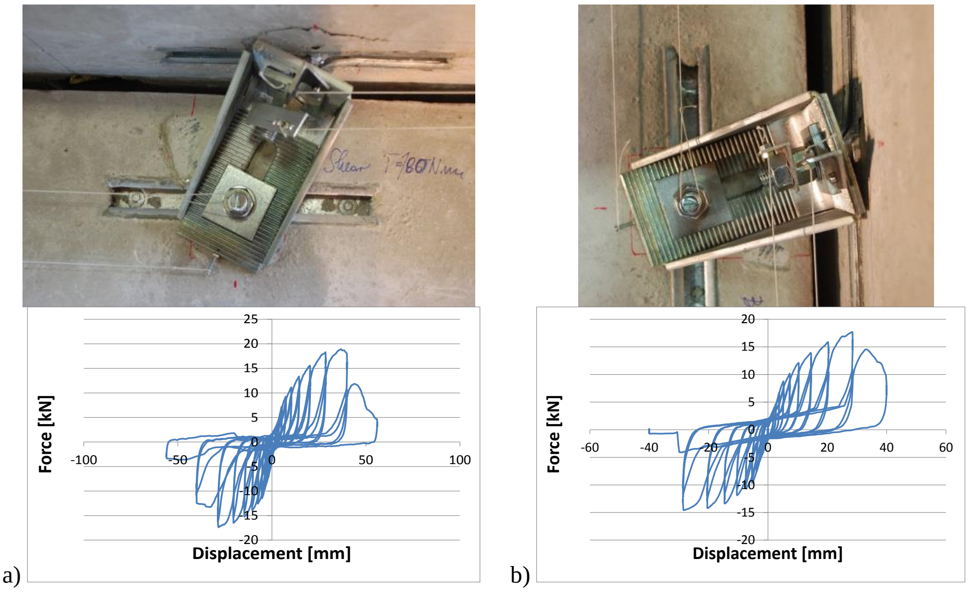

Figure 11. Typical response of angle connections: a) uniaxial tests, b) bi-axial tests

During small displacement cycles only the rotations of the angle were visible. When the displacements were increased, some deformations of the angle were also noticed; however they were remained moderate throughout the experiment. Considerable cracking of the concrete and deformations of the channel, mounted in the panel, were obtained at cycles, where the displacement amplitude was around ±14 mm.

Further increase of displacements resulted in an increase of the damage of the concrete around the channel, mounted in the panel, and an increase of plastic deformations of this channel. Rotations of the angle, around vertical as well as horizontal axis, were also more pronounced when the displacement amplitude was increased.

Considerable deformations of the channel, mounted in the panel were obtained at the moment of the failure. The strength was around 18 kN. In all cases failure of the channel mounted in the panel was observed (channel lips). The screw was pulled out from the channel.

In all experiments but one, there was no considerable sliding of the angle observed. In the case, where the sliding occurred, the strength in the push direction was as large as in other experiments. In the pull direction it was somewhat reduced to 13 kN. In this case only the maximum displacements were considerably increased to about 110 mm.

Cantilever connections

The cyclic response of cantilever connections typical for horizontal panels was also investigated for the first time. Two tests were performed; both of them were uniaxial. Contrary to the previous tests, the connections were tested in pairs (two connections per test).

At the beginning of the tests the force of about 10 kN was registered (see Figure 12). The stiffness of the connections was large. At very small displacements amplitudes the sliding of the screw was initiated. Consequently the force in the connections was increasing slowly. When the screw, together with the surrounding steel frame, reached the concrete edge, the force increased abruptly and reached the maximum values between 60 kN – 75 kN. The maximum displacements were around ±60 mm.

When the screws reached the concrete edge, deformations of the channels as well as deformations of the screw were considerably increased. In last cycles deformations of channels and screws were large. Concrete around the channels was considerably damaged. Finally, the screws were pulled out from the channels. Channels failed due to the large deformations of their lips. Contrary to the connections with the hammer head strap, this type of connection increased the gap between the beam and the panel, pushing the panel away from the beam.

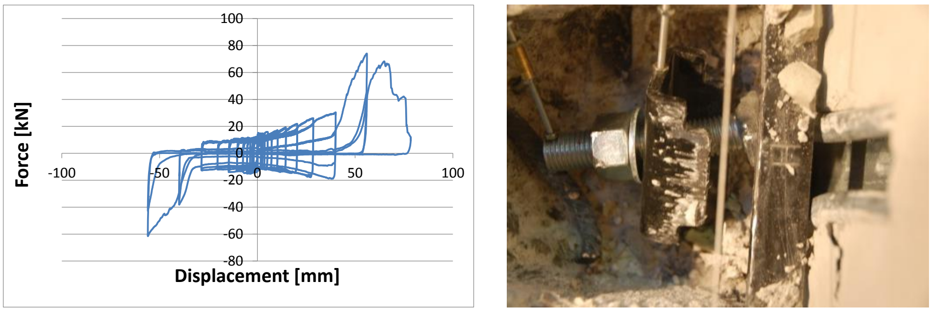

Figure 12. Typical response of cantilever connections (a pair of connection was tested)

CONCLUSIONS

The mechanism of seismic response of tested connections had not been known before the presented experiments were accomplished. Thus, one of the main results of these studies was the identification of the main phases of this response. Three types of typical panels' connections were tested: a) sliding connections, b) angle connections, and c) cantilever connections. In this way the connections of both, vertical as well as horizontal panels were addressed.

When the sliding connections (typically used to attach vertical panels to the main structural system of precast buildings) were subjected to the shear cyclic load, the type of the failure depended on the type of the channels, which are used to construct the connection. If the cold formed channels are used, the failure of the channel mounted in the panel will most likely occur. If the connection is constructed using hot rolled channels, the failure of the strap will be more probable. In spite of different types of failure, the cyclic strength and deformability of both types of connections was similar, and considerably smaller than that observed during the monotonic tests.

The response of sliding connections in vertical direction was essentially sliding as long as the gap between the panel and the beam was not closed. In majority of the cases the failure of the channels (in the beam or in the panel) was observed. It was accompanied by considerable damage of the concrete around the channels, considerable deformations of the strap and in many cases also considerable deformations of the screw.

The failure of channels mounted in the panel was typically observed in other two types of investigated connections. The screw was typically pulled out from the channel. The response was considerably different than that of sliding connections. The strength was larger, particularly that of the cantilever connections, which are typically used to attach horizontal panels to main structural system of industrial building.

ACKNOWLEDGEMENTS

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