FULL-SCALE SHAKE TABLE TESTS OF CLADDING PANELS

Tatjana ISAKOVIC¹, Blaz ZOUBEK², Matej FISCHINGER³

ABSTRACT

The seismic response of cladding panels, mounted to reinforced concrete precast buildings using hammer-head straps, typical for Central European design practice, has been analyzed within extensive full-scale shake table experimental campaign. These fastenings are intended to isolate the panels from the main structure. After several failures, during the recent earthquakes in Italy, many doubts about their capabilities were expressed. Several questions have been raised: a) how they respond to realistic dynamic excitations, b) what is the maximum seismic demand they can sustain, c) whether they are able to isolate panels from the main structural system. To obtain the answers, full-scale shake-table tests have been performed considering two types of straps a) relatively short straps, typical for the design practice, b) longer, which were intended to improve the panels’ isolation from the main structure. Two extreme types of panels were tested: a) panels, which were allowed to rock, b) panels, which were fixed to the foundations. The response of fixed and rocking panels was qualitatively different. The rocking panels followed the movements of the main structure. Displacements of the fixed panels were considerably smaller. In all examined cases the stiffness of the panels did not considerably influence the response of the main structure. In general, the overall response of fixed panels was more predictable. Longer straps were beneficial only for fixed panels. They considerably increased the displacement demand on rocking panels. The capacity of the straps in terms of PGA considerably depends on the flexibility and overstrength of the main structure.

Keywords: full-scale shake table tests; rocking cladding panels; fixed cladding panels; hammer-head straps; one-story precast structures

1. INTRODUCTION

Majority of industrial facilities in many European countries are housed in reinforced concrete precast buildings. The damage of the main structure as well as the non-structural components, such as cladding panels, can cause enormous direct and indirect financial losses. This was confirmed in the recent earthquakes in Italy (2009, 2012). In spite of their importance, the knowledge about their seismic response is still limited, due to their complicated behavior. The design practice and the codes need to be improved. One of the components that should be studied in more details are cladding panels. Despite the previous extensive research campaigns performed within the European SAFECLADDING project (Dal Lago et al. 2017, Khajehdei et al. 2014, Negro et al. 2017, Pscyharis et al. 2014, Zoubek et al. 2016) and many important findings in tests on single components (Zoubek et al. 2016), their seismic response has not been completely revealed and explained. In those studies, it has been demonstrated that their seismic response primarily depends on the types of their fastenings to the main structure. In the study, presented in this paper, fastenings, which are typical for Central Europe, were experimentally analyzed. They were intended to isolate the panels from the main structure and to avoid considerable influence of the panel stiffness to the overall response.

¹Professor, University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia, tatjana.isakovic@fgg.uni-lj.si
²Dr, Schimetta Consult Ziviltechniker Ges.m.b.H., Innsbruck, Austria, Blaz.Zoubek@Schimetta.at
³Professor, University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia, matej.fischinger@fgg.uni-lj.si
Many doubts about their capabilities were expressed after the failures, observed during the recent earthquakes in Italy. The main questions that have been raised were several, and mostly related to the system response of cladding panels, e.g.: a) how the fastenings respond to an earthquake when they are used in real structures, b) what is the maximum seismic demand they can sustain, c) whether they are able to isolate panels from the main structural system of a building.

To answer these questions, the full-scale shake-table experiments were needed. For the first time they were performed within the research project “Seismic resilience and strengthening of precast industrial buildings with concrete claddings” (http://claddings.fgg.uni-lj.si/) funded by the Slovenian National Research Agency in cooperation with IZIIS, Skopje, Macedonia using their large shake table. Vertical as well as horizontal panels have been studied. In this paper only the tests of the vertical panels are presented and analysed.

Following the results of the previous research (Zoubek et al. 2016) it was decided to study two different types of vertical panels with extremely different boundary conditions at their basement: a) panels, which were allowed to rock at the basement, and b) panels, which were fully fixed to the foundations.

Both types of panels were connected to the main structure by means of hammer-head straps, which are typical for the design practice in Central Europe. The straps of two different lengths were used: a) in one set of experiments, the length of the straps, which is typical for the design practice was provided (210 mm); b) in the second set of tests longer straps (290 mm) were used in order to increase the displacement capacity of connections and to improve the isolation of the panels from the main structure.

The description of the tested specimens and the performed tests are presented in Section 2. The main observations of these experiments and important parameters, which influence the response of cladding panels, connections, and the main structural system of precast structures are presented in Sections 3 and 4 for the rocking and fixed panel, respectively. In Section 5 the response of rocking and fixed panels is compared and the discussion and interpretation of the results is provided.

2. DESCRIPTION OF THE SPECIMENS AND THE TESTING PROGRAM

2.1 The full-scale specimen

The tested full-scale one-story specimen is presented in Figure 1. The main structural system consisted of four columns, which were linked by the solid slab.

Figure 1. The full-scale specimen
The total height of columns was 4.5 m (see Figure 2). The dimensions of their cross-section were 30 cm x 30 cm. The longitudinal reinforcement consisted of 8 bars of diameter φ16 mm (see Figure 2). Square and diamond stirrups φ8/5 cm were provided at the length of 75 cm and 195 cm at the bottom and at the top of columns, respectively. In the middle part of the columns the distance between the stirrups was 10 cm. Dimensions of the columns’ foundations were 1 m x 1 m, and their height 50 cm. Each foundation was fixed to the shake table by four dywidags. The dimensions of the slab were 4.3 m x 2.3m. To provide the realistic mass of the structure and the realistic period of vibration, the thickness of the slab was 36 cm. Each column was connected with the slab by one dowel of diameter 25 mm. Dowels were placed centrically into the columns. The elastomeric pads were provided between the slab and the columns. In all elements concrete C 40/50 and reinforcement B 500 B was used.
2.2 The vertical cladding panels’ configurations and their fastenings

The total height of each panel was 5.65 m. Their width and thickness was 1.8 m and 15 cm, respectively.

Four basic configurations of vertical panels were tested. They are summarized in Table 1.

Two extreme boundary conditions at the bottom of the panels were tested. In tests V1-R and V2-R (see Table 1) free rocking of the panels were enabled. In tests, V3-F and V4-F panels were fully fixed to steel foundation plates.

Following the limitations of the shake table regarding the maximum overturning moment and the corresponding total mass of the structure, one panel at each side of the main structural system was provided. The specimens were excited in the horizontal direction in parallel to the plane of the panels. In majority of tests the panels’ configurations were symmetric. Two additional asymmetrical panels’ configurations V1e-R and V2e-R were also tested. In these tests, only one panel was attached to the main structure. In this way the mass eccentricity and consequently the excitation of the specimens in the transverse direction was also provided.

Cladding panels were connected to the slab by means of two hammer-head straps, which are typically used in the design practice in Central Europe (see Figure 3). The straps of two different lengths were tested. In tests V2-R, V2e-R, and V3-F the straps of typical length 210 mm were provided. (see Figure 3).

Table 1. Configurations of cladding panels.

<table>
<thead>
<tr>
<th>Test</th>
<th>No. of panels</th>
<th>Boundary conditions of cladding panels at the foundation level</th>
<th>Length of hammer-head straps [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1-R</td>
<td>2*</td>
<td>Free movements (Rocking of the panels)</td>
<td>290</td>
</tr>
<tr>
<td>V1e-R</td>
<td>1</td>
<td>Free movements (Rocking of the panels)</td>
<td>290</td>
</tr>
<tr>
<td>V2-R</td>
<td>2*</td>
<td>Free movements (Rocking of the panels)</td>
<td>210</td>
</tr>
<tr>
<td>V2e-R</td>
<td>1</td>
<td>Free movements (Rocking of the panels)</td>
<td>210</td>
</tr>
<tr>
<td>V3-F</td>
<td>2*</td>
<td>Fixed</td>
<td>210</td>
</tr>
<tr>
<td>V4-F</td>
<td>2*</td>
<td>Fixed</td>
<td>290</td>
</tr>
</tbody>
</table>

*Note: One panel was attached at each side of the main structure in its longitudinal direction (see Figures 1 - 2)*

Figure 3. Fastenings of the panel to the slab: a) short hammer-head straps, b) long hammer-head straps

In tests V1-R, V1e-R and V4-F somewhat longer straps (290 mm) were used in order to ensure larger displacement capacity of the panels’ connections (see Figure 3). In this way the larger relative displacements between panels and the structure can be accommodated. It has been expected also to provide better isolation of the panels from the main structure and to reduce the influence of the panels’ stiffness to the response of the main structural system.
2.3 Earthquake loading and the testing program

The accelerogram Petrovac E-W (ESMD 2017), which was recorded during the Montenegro 1979 earthquake, was used to define the earthquake excitation for all tests. This accelerogram was modified to match the EC8 spectrum corresponding to soil type B. The accelerogram (scaled to intensity of 1g) and the corresponding acceleration spectrum is presented in Figure 4.

![Figure 4. a) The applied accelerogram (normalized to 1g), and b) the corresponding acceleration spectrum](image)

The loading program and maximum applied accelerations are documented in Table 2 for all tests (summarized in Table 1). For each panels’ configuration, free-vibration tests were performed at the beginning and at the end of the test in order to define the frequency/period of the structure. In all tests the specimen was excited in the horizontal direction in parallel to longitudinal direction of the main structure (in parallel to the plane of panels).

<table>
<thead>
<tr>
<th>Test</th>
<th>No. of tests and applied maximum accelerations</th>
<th>Period of the structure after the tests [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1-R</td>
<td>4/ PGA = 0.1g, 0.2g, 0.3g, 0.4g</td>
<td>0.67</td>
</tr>
<tr>
<td>V1e-R</td>
<td>3/ PGA = 0.1g, 0.3g, 0.4g</td>
<td>0.77</td>
</tr>
<tr>
<td>V2-R</td>
<td>3/ PGA = 0.2g, 0.4g, 0.5g</td>
<td>0.73</td>
</tr>
<tr>
<td>V2e-R</td>
<td>2/ PGA = 0.2g, 0.4g</td>
<td>0.74</td>
</tr>
<tr>
<td>V3-F</td>
<td>4/ PGA = 0.1g, 0.2g, 0.4g, 0.5g</td>
<td>0.74</td>
</tr>
<tr>
<td>V4-F</td>
<td>3/ PGA = 0.2g, 0.4g, 0.5g</td>
<td>0.65</td>
</tr>
</tbody>
</table>

3. RESULTS OF THE TESTS ON ROCKING PANELS

3.1 Main observations of tests V1-R and V1e-R on rocking panels and long straps

3.1.1 Response of panels and the main structure

The panels rocked around their bottom corners. The measured maximum uplift of the panels’ corners regarding the shake table amounted up to 28 mm. No considerable relative horizontal displacements at
the bottom of the panels (regarding the shake table) were observed. Displacement response history of the slab and the displacement response history of the top of the panels, parallel to the plane of panels are compared in Figure 5a and 5b, for panel P1 and P2, respectively. The presented results were recorded in the test with maximum seismic intensity of 0.4g.

Figure 5. Horizontal displacements of a) the slab and panel P1, b) the slab and panel P2 (test V1-R: rocking panels, long straps, maximum seismic intensity of 0.4 g)

Figure 6. Relative displacements of a) panel P1, and b) panel P2 compared to the displacements of the slab (test V1-R: rocking panels, long straps, maximum seismic intensity of 0.4 g)
The period of vibrations of panels and the main structure were similar (with an exceptions of cycles, where the displacements of the panels were relatively small). This period was mainly affected by the properties of the main structure. Stiffness of panels did not have considerable influence to the overall response (see the discussion in Section 5).

The top horizontal displacements of the panels P1 and P2 (see Figure 3) were different in spite of symmetric configuration of the specimen. In some parts of the response, the displacements of panels (particularly those of the panel P1) were larger than the displacements of the main structure (slab). The absolute maximum horizontal displacements are summarized later-on in Table 3.

In spite of different displacement response history of the panels, the magnitude of their relative displacements regarding the slab, and consequently the demand on the straps, were not drastically different (see Figures 6a and 6b). Maximum relative displacement between panels and the slab were 70 mm and 57 mm for panels P1 and P2, respectively.

3.1.2 Response of fastenings

No failure of the panels’ fastenings was observed, even in the tests of largest intensity of 0.4g. In the horizontal plane the hammer-head straps were rotating around the bolt, which was used to fixed them to the channel mounted in the slab (see Figure 3). No sliding of the straps along this channel was observed.

During the large intensity tests, the straps were deformed in the horizontal as well as in the vertical direction (see Figure 7). The type of deformations of the straps in the horizontal direction was the same as it was predicted before the tests, according to the experiments, performed at UL on single components of panels’ fastenings (Zoubek et al. 2016).

Due to the vertical movements of the panels caused by their rocking, the straps were deformed also in the vertical direction. As long as the rotation of the straps in the horizontal plane were small and the strap was not deformed, vertical relative displacements between the head of the strap and the channel of the panel were enabled. When horizontal and vertical relative displacements between the panel and the slab considerably increased, the heads of the straps were deformed in the horizontal direction and consequently they were stacked into the panels’ channels. When the panels started to move downward, they deformed the stacked strap also in the vertical (downward) direction (see Figure 7 b).

![Figure 7. Deformations of the hammer-head straps](image)

3.2 Main observations of tests V2-R and V2e-R on rocking panels and short straps

The response of the rocking panels, which were connected to the slab by means of the short straps (tests V2-R and V2e-R), was qualitatively similar to that of the panels with long straps. However, the response was more predictable and the horizontal and vertical displacements of the panels were smaller. In general, maximum values of horizontal displacements did not considerably exceed the maximum displacements of the slab (as it was the case in structures with long straps). The relative horizontal displacements between panels and the slab were also smaller comparing to the tests with long straps. The maximum values of all displacements are summarized in the next subsection.

The straps were deformed in the same manner as in the tests V1-R and V1e-R (for more details see previous subsection). There was no failure observed even in the test with the largest seismic intensity of 0.5g.
3.3 Comparison of the tests with long and short straps

In all tests with rocking panels the response was qualitatively similar. However, the response was considerably more controllable, when the short straps were used to fasten the panels to the slab (V2-R, V2c-R). In these cases, the demand on the panels and the straps was considerably reduced. It can be concluded that in spite of the increased displacement capacity of the long straps, the response was not improved, since the displacement demand on panels was considerably increased. To illustrate this observation, the absolute values of displacements in tests V1-R (long straps) and V2-R (short straps) for seismic intensity of 0.4g are summarized in Table 3.

Table 3. Maximum displacements in tests V1-R (rocking panels, long straps) and V2-R (rocking panels, short straps)

<table>
<thead>
<tr>
<th></th>
<th>Test V1-R (rocking panels, long straps)</th>
<th>Test V2-R (rocking panels, short straps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal displ. of the slab [mm]</td>
<td>94</td>
<td>84</td>
</tr>
<tr>
<td>Horizontal displ. of the panel P1 [mm]</td>
<td>135</td>
<td>93</td>
</tr>
<tr>
<td>Horizontal displ. of the panel P2 [mm]</td>
<td>107</td>
<td>77</td>
</tr>
<tr>
<td>Horizontal relative displ. between panel P1 and the slab [mm]</td>
<td>70</td>
<td>39</td>
</tr>
<tr>
<td>Horizontal relative displ. between panel P2 and the slab [mm]</td>
<td>57</td>
<td>48</td>
</tr>
<tr>
<td>Vertical displ. of panel P1 [mm]</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td>Vertical displ. of panel P2 [mm]</td>
<td>27</td>
<td>22</td>
</tr>
</tbody>
</table>

4. RESULTS OF THE TESTS ON FIXED PANELS

4.1 Main observations of tests V4-F on fixed panels and long straps

4.1.1 Response of panels and the main structure

In tests V4-F panels were fully fixed to the foundations. No considerable displacements in any direction were observed at the bottom of the panels even at the largest seismic intensity of 0.5g. The top horizontal displacements of the panels parallel to their plane were considerably smaller than in the tests on rocking panels (see Figure 8). Like in the tests on rocking panels the horizontal displacements of panels P1 and P2 were different in spite of the symmetric configuration of the specimen. However, these differences were not as significant as in the case of rocking panels.

The magnitude of the relative displacements between the panels and the slab was similar to the magnitude of the slab’s displacements. This is illustrated in Figure 9, where the relative top displacements of the panels are compared with the displacements of the slab. The periods of vibration of panels was significantly shorter than that of the slab. Based on all presented results, it can be concluded that hammer-head straps isolated the panels from the main structure.

4.1.2 Response of fastenings

The hammer-head straps were deformed only in the horizontal plane in the similar manner as it is illustrated in Figure 7a. No deformations in the vertical direction were observed. In spite of considerable deformations, the straps accommodated the relative displacements between the panels and the slab without failure even in the strongest test with seismic intensity of 0.5g.
4.2 Main observations in tests V3-F on fixed panels and short straps

In test V3-F, the panels were fastened to the slab using the short straps, the response was qualitatively the same as in test V4-F. The maximum displacement demand of the straps was somewhat decreased comparing to test V4-F (10 – 20 %), however it exceeded the capacity of the straps. The failure of the straps occurred at the seismic intensity of 0.5g.
4.3 Comparison of the tests with long and short straps

The maximum displacements observed in tests V3-F and V4-F are summarized in Table 4. The horizontal displacements of the panels, the slab and the relative displacements between them were similar in both tests. Since the displacement capacity of the shorter straps was considerably smaller, the failure of the straps was obtained. The longer straps improved the response. In all tests on fixed panels the relative top horizontal displacements between the slab and the panels, transverse to their plane, were smaller than the provided gap between panels and the slab (3 cm and 7 cm in the case of short and long straps, respectively).

Table 4. Maximum displacements in tests V3-F (fixed panels, short straps) and V4-F (fixed panels, long straps)

<table>
<thead>
<tr>
<th></th>
<th>Test V3-F (fixed panels, short straps)</th>
<th>Test V4-F (fixed panels, long straps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal displ. of the slab [mm]</td>
<td>72</td>
<td>82</td>
</tr>
<tr>
<td>Horizontal displ. of the panel P1 [mm]</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Horizontal displ. of the panel P2 [mm]</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Horizontal relative displ. between panel P1 and the slab [mm]</td>
<td>58</td>
<td>71</td>
</tr>
<tr>
<td>Horizontal relative displ. between panel P2 and the slab [mm]</td>
<td>62</td>
<td>70</td>
</tr>
</tbody>
</table>

5. COMPARISON OF THE RESPONSE OF ROCKING AND FIXED PANELS

The response of rocking and fixed panels was considerably different. It is evident from Tables 3 and 4 that the top horizontal displacement demand on rocking panels was about 10 times larger than that of the fixed panels.

The vibrations of the rocking panels were mainly controlled by the main structure. The movements of the fixed panels were considerably smaller and the period of vibration considerably shorter than that of the main structure. In spite of the qualitatively different response of fixed and rocking panels, the maximum relative displacements between the panels and the main structure were not considerably different.

When the long straps were used, the maximum relative displacements were almost the same (about 70 mm at seismic intensity of 0.4g). In both cases, considerable deformations of the hammer-head straps were observed at large intensity tests. In the case of rocking panels, the hammer-head straps were deformed in the horizontal as well as vertical direction. In the case of fixed panels, the straps were deformed only in the horizontal direction.

When short straps were used, the maximum relative displacements were somewhat larger in the structure with fixed panels (62 mm versus 48 mm in rocking panels at 0.4 g). In this structure, the capacity of the straps was exhausted at the seismic intensity of 0.5g. In all other cases the straps were able to accommodate the displacement demand at quite large seismic intensities (0.5g and 0.4g).

The longer straps were beneficial only in structures with fixed panels. In the case of the rocking panels the use of longer straps significantly increased the displacement demand on panels, which in some cases exceeded the displacements of the main structure.

In spite of the failure of the straps in test V3-F (fixed panels, short straps), it can be concluded that the fixed panels configuration might be more appropriate for two reasons: a) The hammer head straps are deformed only in the horizontal plane (contrary to the rocking panels, where the vertical deformations can be also expected), b) the response of fixed panels is less susceptible to various coincidences caused by the imperfections during the construction (it is more predictable).

In all tested structures, the stiffness of the panels did not considerably influence the response of the main structure. This is illustrated in Figure 10, where the displacement response history of the main structure recorded during the tests V1-R (rocking panels, long straps), V2-R (rocking panels, short straps), V3-F (fixed panels, short straps), and V4-F (fixed panels, long straps) is compared. In spite of extremely different panels’ configurations, the periods of vibrations and the displacements of the main
structure are similar.

![Graph showing displacements over time for different slab configurations](image)

Figure 10. Displacements of the slab in the longitudinal direction, recorded in tests V1-R (rocking panels, long straps), V2-R (rocking panels, short straps), V3-F (fixed panels, short straps), and V4-F (fixed panels, long straps)

6. CONCLUSIONS

The extensive full-scale shake table experimental campaign on cladding panels mounted to one-story precast building was performed. Two types of panels were tested: a) panels, which were allowed to rock at the basement, and b) panels, which were fully fixed to the foundations. All panels were attached to the main structure using the hammer-head straps. In basic set of experiments, the straps, which are typically used in the design practice, were studied. In the second set of experiments, longer straps were used in order to improve the displacement capacity of the connections.

The response of fixed and rocking panels was qualitatively different. The response of rocking panels was considerably affected by the movements of the main structure. The response of the fixed panels was significantly different from that of the main structure. In spite of the qualitatively different response, the stiffness of both types of panels did not significantly affect the movements of the main structure.

The magnitude of the relative displacements between the panels and the main structure were in both cases similar. In all tests the hammer-head straps were able to accommodate these displacements even at the large seismic intensities of 0.5g. The only exceptions were short straps, which were used to attach the fixed panels. They failed at the seismic intensity of 0.5g.

In structures with rocking panels considerable deformations of the hammer-head straps were observed in the vertical as well as in the horizontal direction. In structures with fixed panels the straps were deformed only in the horizontal plane in the direction of the excitations.

Long straps improved the response only in structures with fixed panels. In the case of rocking panels, the use of longer straps was not beneficial, since the displacement demand of the panels were considerably increased. In some cases, their displacements even exceeded the displacements of the main structure.

In spite the short straps failed, when they were used to attach fixed panels, it can be concluded that fixed panels might be more appropriate for two reasons: a) The hammer head straps are deformed only in the horizontal plane (contrary to the rocking panels, where considerable vertical deformations can be also expected), b) the response of fixed panels is less susceptible to various coincidences caused by the imperfections during the construction (it is more predictable).

The straps were able to accommodate the seismic demand corresponding to relatively large seismic intensity. Note, however, that this observation cannot be simply generalized to all precast buildings. In more flexible structures, the capacity of the straps can be exhausted at much lower seismic intensities, since the displacements of the structure, and consequently the relative displacements between the main structure and the panels can be considerably increased. This can be in particular critical in typically very flexible multistory precast buildings as long as the special measures are not applied to limit the displacements of their main structure.

Due to the limitations of the shake table the interaction between more panels mounted at the same side of the structure was not possible to test. Based on the observed response, it can be concluded that in structures with fixed panels, this interaction might not be so important, since the panels move only in
the horizontal direction and their displacements are relatively small. However, in structures with rocking panels, which moves also in the vertical direction, more considerable interaction between panels can occur. It can importantly influence the overall response, since it can affect the stiffness of the panels and the interaction between their straps. This influence will be analyzed in the future analytical studies.

7. ACKNOWLEDGMENTS

The test campaign was funded by Slovenian National Research Agency within the project “Seismic resilience and strengthening of precast industrial buildings with concrete claddings”. The experiments were performed at shake table at IZIIS, Skopje, Macedonia. The specimens were casted at Kolektor CPG – construction plant Laže. The authors express their gratitude to Igor Bužinel for his devoted cooperation in the construction of specimens, their transportation, and assembly of the specimens. We are particularly grateful to prof. dr. Golubka Nečevska Cvetanovska, prof. dr. Roberta Apostolska, prof. dr. Lidija Krstevska and prof. dr. Zoran Rakičević for their help during the planning of the experiments and their execution.

8. REFERENCES


