INVESTIGATION ON BOLTED PRECAST COLUMN CONNECTION FOR SEISMIC APPLICATIONS

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ABSTRACT

Precast structures offer several advantages during both production and installation compared with cast-in-situ structures. However, connections between precast elements represent a critical point, where structural continuity is desirable for seismic applications. In fact, the overall structural performance is affected considerably by the cyclic response of the connections between both structural and non-structural elements. Column-to-foundation joints are of primary importance, since they have to guarantee the capacity of the structure to withstand both vertical and horizontal loads without collapsing during a seismic event. Quasi-static oligo-cyclic tests have been carried out on a series of full scale precast column-foundation sub-assemblies to investigate the performance of bolted joints made with column shoes and anchor bolts. Such performance was compared to that of two cast-in-situ columns in terms of ductility, energy dissipation, stiffness and strength degradation. The experimental results showed that the seismic behavior of properly designed bolted joints is equivalent to that of cast-in-situ connections, which allows to consider those as energy dissipative according to current design Codes.

Keywords: Bolted connection; Precast structures; Quasi-static cyclic test; Seismic design

1. INTRODUCTION

Seismic resistant structures shall ensure that in the event of earthquakes human lives are protected, the damage is limited and structures important for civil protection remain operational (CEN 2004b). In order to achieve such requirements, current Codes set specific requirements for both strength and ductility of precast connections so that structures can withstand seismic load reversals without a substantial reduction in global resistance or collapse (CEN 2004b, FEMA 2009, GB 2010, NTC 2008, NZS 2004). In fact, the connections between precast elements play a fundamental role in the overall seismic performance of the structure, with regards to both resistance and deformation capacity. Early precast constructions had inadequate detailing and lacked continuity or redundancy in the structure, which caused many failures during past seismic events. Furthermore, there were no specific design guidelines for precast concrete structures used in seismic areas. For these reasons, precast has seen limited use in earthquake-prone zones. So far, engineers have favored cast-in-situ solutions or used alternatives such as protruding bars or hybrid connections out of habit, despite no clear evidence of their seismic behavior and no usage risks evaluation. On the contrary, precast structures offer better material and product quality control, improved erection speed and cost savings, which make them preferable compared with traditional solutions provided appropriate seismic response.

A wide research program has been carried out by the cooperation between Peikko Group and Politecnico di Milano (Technical University of Milano), in order to investigate the performance of bolted column-to-foundation connections made with column shoes and anchor bolts (Peikko Group Corporation 2009, 2012). The aim of the research was to assess the cyclic behavior of the precast column connections in terms of ductility, energy dissipation capacity, stiffness and strength degradation and to demonstrate that those can be designed as emulative of the monolithic joints, thus combining equivalent performance

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of cast-in-situ structures with the advantages of precast structures.

2. PRECAST BOLTED COLUMN CONNECTIONS

Figure 1a shows a Peikko column-to-foundation connection. HPKM® Column Shoes (ETA-13/0603) are assembled from base and lateral steel plates and anchoring rebars, which are cast at the base of the precast element. Weldings between these components have a nominal strength at least twice that of the anchor bolts. This guarantees the elastic response of the welds. HPM® Anchor Bolts (ETA-02/0006) are ribbed steel bars that are partly casted into the foundation. The external threaded part allows the base plate to be tightened using two washers and two hexagonal nuts. The advantage of using bolted connections is that an immediate connection is made. The system is self-supporting and offers sufficient assembly tolerances to adjust the column to the correct level and vertical position.

The open joint between the column and foundation, including column shoes pockets, is then filled on site with non-shrink cementitious grout. The grout has a design compressive strength at least one class higher than the highest grade of concrete used in the connected elements, so that brittle concrete failures are avoided in the joint.

![Figure 1a](image1.png)

(a) Precast bolted column-to-foundation connection (Peikko Group Corporation 2009, 2012)

![Figure 1b](image2.png)

(b) Chain analogy of the capacity design.

2.1. Capacity design of the connection system

Generally, capacity design is adopted for seismic applications. Capacity design is an approach in which the structural members are proportioned so that energy dissipation under severe deformation is accommodated in suitably designed and detailed locations while all other structural elements are provided with sufficient strength. Column-to-foundation connections can be either designed for over-strength or for energy dissipation (Figure 1b).

In the first case, the connections shall have sufficient over-strength to allow the development of cyclic yielding in the connected dissipative parts. The critical region moves to the column, while the connection remains almost elastic with limited displacements or local deformations. However, the area of the column above the joint is necessarily over-strengthened due to the overlapping of column shoe rebars and column reinforcement. Therefore, a design of the connection that is based on the resistant moment of the column that it supports is not convenient, since it requires relatively large column cross-sections to fit the necessary anchoring bolts and might result in dense reinforcement in the joint.

On the contrary, when the connection represents itself a dissipative zone, the plastic hinging of the
column and/or the buckling of the rebars are avoided while the possible damage is limited to the base of the column at the interface with the foundation, where the anchor bolts represent the “weak” element and act as ductile connectors. Contrary to overdesigned connections, the resistance of energy dissipating joints is dependent on the acting moments as for cast-in-situ ones. For this reason such connections are also called as emulative. The connection can be designed to match the capacity of the column, provided that the local ductility of the connection is enough to satisfy the global ductility demand. In other words, the connection has to be able to sustain the deformations impressed to the structure by the earthquake.

2.2. The emulative precast connection

Special detailing was introduced in Peikko’s standard column connection to improve the performance of the connection in terms of ductility (Jurina et al. 2016) (Figure 2). The effectiveness of the new features is evaluated basing on the comparison between earlier experimental results, where such improvements were not yet included (Bianco et al. 2009, Jurina et al. 2014a, 2014b). HPM®-EQ (Peikko Group Corporation 2016) Anchor Bolts were specifically developed and produced with B500C, which is the highest ductility steel material. The embedded thread is debonded by a heat shrink tube so that the anchor bolt is able to deform freely and the deformation capacity of the steel is not reduced (Jurina et al. 2014b). Loads are then transferred through the ribs and the headed stud as in standard anchor bolts.

![Figure 2. Emulative column-to-foundation connection.](image)

The tightening of the joint under cyclic loading is secured by high strength and anti-lock washers as well as by a type of pre-tensioning of the anchor bolts, which is induced by an additional rotation of the upper nut after snug tightening. An epoxy resin is injected around the anchor bolt inside the over-sized hole of the base plate in order to compensate for the tolerance needed during installation. This helps to significantly reduce the pinching effect, which results in an increased amplitude of hysteresis cycles as experimentally verified.

A high strength fiber-reinforced mortar is used as joint grouting to avoid the spalling of the unconfined
compressed collar of mortar around the column base. Moreover, the surfaces at the base of the column and on the top of the foundation are indented, so that compressed struts can develop between the upper and lower indentations. The shear resistance of the joint relies on both the friction and the mechanical interlocking of the surfaces. Shear is mainly resisted by this mechanism, while anchor bolts are subjected almost exclusively to tension and compression. Finally, additional stirrups around the column shoes limit their mutual displacements and rotations, thus reducing the cracking of the joint.

3. EXPERIMENTAL INVESTIGATION

In order to be considered as emulative, a precast connection has to experimentally show a stable cyclic behavior and an energy-dissipative capacity at least equal to that of a monolithic connection that has the same resistance and conforms to the local ductility provisions of the Code. Several full-scale sub-assemblies consisting of a 2.15 m high precast column and a rigid foundation element and two monolithic columns, which complied with reinforcement detailing for high ductility class as required by CEN (2004a, 2004b), were therefore tested at Politecnico di Milano (Figure 3a). Different layouts of the connection were investigated by changing the number and size of the anchor bolts and by varying the column’s cross-sectional dimensions. Some configurations also underwent three identical tests to assess the replicability of the results. For the sake of brevity, the results presented in the following refer to the connection arrangements shown in Figure 3b, to which monolithic columns were designed to be equivalent.

![Figure 3](image)

3.1. Test setup

Quasi-static oligo-cyclic imposed-displacement tests were performed. Both the typologies of the specimens were tested by applying the same drift pattern with three cycles of equal displacement for each increasing drift level (0.5%, 1%, 2%...) until failure (ACI 2013). The failure criteria were anchor bolt failure or a loss of horizontal resistance greater than 20% from the peak value. Columns were also vertically loaded with a constant axial ratio of about 10%.

3.2. Test results

The precast specimens all showed a localized damage of the grouting, which presented an extensive crack pattern at the end of the test (Figure 4a). Spalling of the mortar was avoided thanks to the steel fibers, which kept the mortar in place around the cracks. It is worth noting that little or no damage was observed for drifts of up to 1%, which is beyond the limit for inter-story drift imposed by the Code (CEN...
Even after a moderate earthquake the column would remain almost undamaged and any possible repair intervention would affect the grouting only. The tests continued until failure to investigate the ultimate capacity of the connection, which resulted at drifts greater than 5%. This highlights the great deformation capacity of the connection, which relies on the anchor bolts. Anchor bolts failed generally below the lower nut or the foundation level since the concentration of the stresses was maximum at the interface between column and foundation as expected. Moreover, the thread of the anchor bolts emerging from the foundation was generally damaged, which is possibly due to tensile and compressive cyclic loading (Figure 4a).

Conversely, cast-in-situ specimens suffered generalized damage with evident spalling at the base of the column and cracks on the foundation surface (Figure 4b). This would lead to higher repair costs. Furthermore, the longitudinal reinforcement buckled and one of the rebars failed in CIP1 (Figure 4b). This indicates that brittle failure could easily occur, especially in absence of proper detailing such as adequate confinement of the critical zone.

All the precast specimens achieved a displacement ductility (ACI 2013) of at least 4, showing great post-elastic deformation capacity (Table 1). In particular, Figure 5a shows the comparison between the force-displacement curves of PC1 and CIP1. It can be noticed that the displacement at failure of the precast specimen is greater than that of the correspondent cast-in-situ one. Moreover, the strength degradation of the precast specimen is extremely limited, fulfilling the threshold (< 20%) recommended by ICBO (1995), while the cast-in-situ column suffered an abrupt loss of resistance after 4% drift due to rebar buckling and spalling.

<table>
<thead>
<tr>
<th>Test</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>CIP1</th>
<th>CIP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+\Delta$</td>
<td>$\Delta_\gamma$</td>
<td>0.8</td>
<td>1.3</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>$\mu_\gamma$</td>
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<td>6.2</td>
<td>4.0</td>
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</tr>
<tr>
<td>$-\Delta$</td>
<td>$\Delta_\gamma$</td>
<td>0.8</td>
<td>0.9</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>$\mu_\gamma$</td>
<td>8.8</td>
<td>6.3</td>
<td>3.5</td>
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The comparison between the backbone curves of all the specimens confirms that the tested precast and cast-in-situ columns are similar in terms of resistance according to the design (Figure 5b). PC2 specimen also showed a greater deformation capacity than PC1, thanks to the presence of more anchor bolts of smaller diameter. The CIP2 specimen was the only one that did not reach failure, even at drifts of more than 9%, and it showed better performance than the equivalent precast PC3 specimen. This was due to the continuous reinforcement between the column and foundation in CIP2, which was designed.
according to the requirements for special moment frames (ACI 2014). Precast and cast-in-situ specimens showed also similar energy dissipation, the precast specimens having even more stable hysteresis cycles. The equivalent damping factor has been evaluated by summing the elastic (2%) and hysteretic components. The result was in general greater than 37.5%, thus fulfilling the requirements in ICBO (1995) for ductile connectors (Figure 6a). Finally, Figure 6b shows that bolted connections can provide also enough stiffness (ACI 2013) as the monolithic joints. It can also be noticed that the decay of initial stiffness is gradual, without any sudden and undesirable stiffness loss.

Figure 5. (a) Comparison of the hysteresis curve of PC1 and CIP1 specimens; (b) Comparison of the backbone curves.

Figure 6. Comparison of the damping factor (a) and the initial stiffness (b).

4. DESIGN GUIDELINE AND SYSTEM BENEFITS

Based on the test results above, HPKM®−HPM®-EQ connection has been approved for use in medium-ductility class structures designed with a behavior factor of up to 4. In fact, the design ductility can be assumed to be equal to 4 for compression ratios of up to 15%, or 3 otherwise. This covers most of the cases for all the structural types identified by the Code (CEN 2004b), for which the connection can be considered energy-dissipative.

If the design requirements are different, such as high ductility class structures and/or higher behavior factors, it is anyhow possible to use Peikko’s standard column connection by adopting an overdesigned solution. However, such requirements are rarely adopted because they might lead to extensive reinforcing detailing and increased displacement demand on both structural and non-structural elements. Peikko’s bolted connections suit different design alternatives depending on the ductility class of the structure. For medium ductility class structures Peikko’s energy dissipating connection represents an
excellent choice. In fact, under specific design conditions it leads to smaller column cross-sections by skipping the over-strength factor, thus leading to concrete volume savings. Substantial savings come also from reduced excavation depth and more slender foundations compared to other systems such as protruding rebars. The behavior of the connection is also less dependent on the reinforcing of the column, thus minimizing the risk of concrete spalling and rebar buckling.

A recommendation document has finally been signed as an outcome of the research program. The document states that Peikko connections can resist seismic loads in a satisfactory ductile and dissipative manner and provides design indications. Such connections are pre-qualified, meaning that the use of standard components and the pre-defined connection system implies that the actual behavior of the precast joint won’t be different from what has been tested.

5. CONCLUSIONS

Peikko addressed the challenges of seismic design and the requirements imposed by the current Codes for precast structures with an extensive research program focusing on the cyclic performance of bolted connections. An innovative connection with partly debonded anchor bolts and improved construction detailing was developed. The experimental results showed that such connection can resist seismic loads with a satisfactory ductility and the same stiffness as cast-in-situ joints.

In fact, the failure of precast specimens always occurred at drift greater than 6%, with a displacement ductility equal to or greater than 4 and a limited strength degradation. The comparison with two monolithic columns proved that bolted connections, if properly designed, are emulative of cast-in-situ joints and energy dissipative, thus avoiding to be oversized. This can lead to substantial savings, both in concrete usage and in the building process, making it a fast precast system for installation on the construction site.

In conclusion, research-based technical documentation, a guided design procedure and easy installation process at the precast factory and on the construction site make the HPKM®–HPM®-EQ connection a safe, reliable and convenient solution for precast concrete structures in seismic areas.

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7. REFERENCES

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