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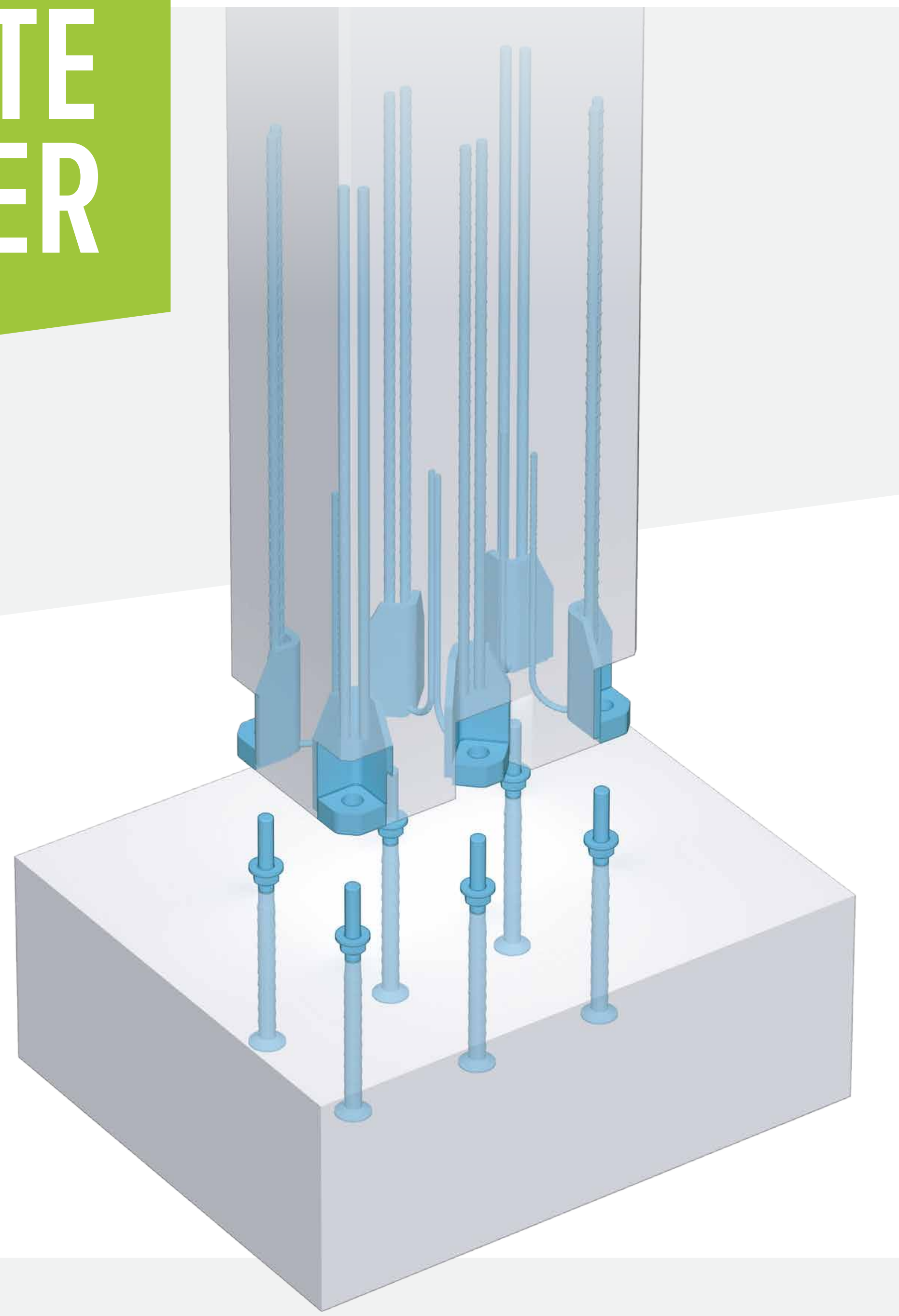

BOLTED COLUMN CONNECTION FOR SEISMIC APPLICATIONS

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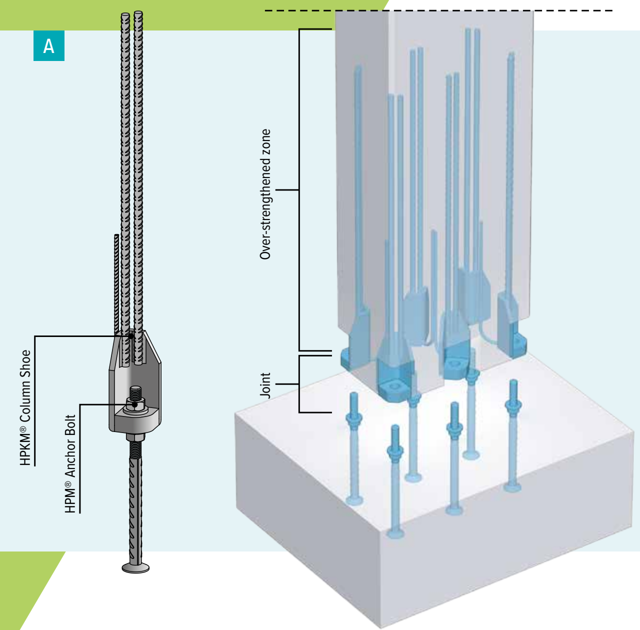


FIGURE 1. (A) PEIKKO'S BOLTED COLUMN-TO-FOUNDATION CONNECTION (ADAPTED FROM [16], [17])

INTRODUCTION

The connections between precast elements play a fundamental role in the overall performance of the structure, especially if seismic applications are considered. In fact, precast connections represent a critical link where structural continuity is needed. Early precast constructions had inadequate detailing and lacked continuity or redundancy in the structure, resulting in poor seismic performance. Furthermore, there were no 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 favoured cast-in-situ solutions or used alternatives such as protruding bars or hybrid connections out of habit. However, there is not always clear evidence of their seismic behaviour, and usage risk evaluations are lacking. In addition, precast structures offer several advantages during both production and installation compared with traditional solutions, such as better material and product quality control, improved erection speed and cost savings.

In the last two decades, numerous studies have been performed regarding the cyclic behaviour of precast joints in order to support the development of modern Codes [5], [8], [9], [14], [15]. The major aim is the mitigation of seismic risk through a performance-based design approach where accepted damage levels are considered as limit states. Specific requirements for both strength and ductility of connections have been imposed so that structures can withstand seismic load reversals without a substantial reduction in global resistance.

With regard to such design needs and considering customers' interests, Peikko initiated a wide-ranging experimental research program in 2008 in cooperation with Politecnico di Milano (the Technical University of Milan) to investigate the performance of bolted column-to-foundation connections made with HPKM® Column Shoes [16] and HPM® Anchor Bolts [17]. The aim of the research was to develop a precast connection that emulates monolithic joints with the same performance in terms of ductility, energy dissipation capacity, stiffness and strength degradation, thus combining compliance with the Codes with the advantages of precast structures.

PEIKKO'S BOLTED COLUMN CONNECTION

Peikko's Bolted Column Connection consists of HPKM® Column Shoes and HPM® Anchor Bolts (Figure 1a). HPKM® Column Shoes [16] are assembled from base and lateral steel plates and anchoring rebars, which are cast at the base of the precast element. Weldings between such components have a nominal strength at least twice that of the anchor bolts. This guarantees the elastic response of the welds. HPM Anchor Bolts [17] are ribbed steel bars, which are partly cast into the foundation. The external threaded part allows the base plate to be tightened using two washers and two hexagonal nuts.

The open joint between the column and base structure, including column shoe pockets, is filled 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.

The main advantage of using bolted connections is that an immediate connection is made. The column can be installed on the construction site without temporary bracing, simply by levelling and tightening the nuts. Peikko's Column Connection offers sufficient assembly tolerances to adjust the column to the correct level and vertical position. The construction process is fast and safe, and the final look of the connection is very similar – if not identical – to conventional cast-in-situ solutions.

The part of the column above the joint is overdesigned so that plastic hinging is developed exclusively inside the grouted joint. This is due to the column shoes, which are stronger than the bolts, and to the overlapping of column shoe rebars with column reinforcement, which results in a column cross-section flexural resistance much higher than that of the joint.

B

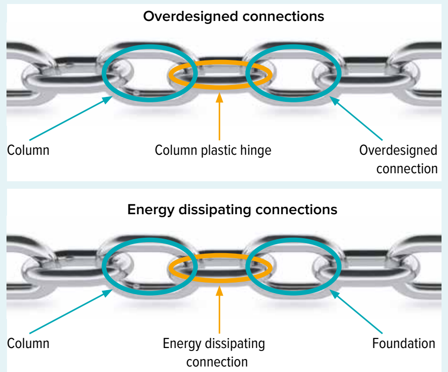


FIGURE 1. (B) CHAIN ANALOGY OF THE DESIGN ALTERNATIVES.

DESIGN ALTERNATIVES FOR THE CONNECTION SYSTEM

Generally, the Codes allow two different approaches to designing precast column-to-foundation connections (Figure 1b). Firstly, connections can be overdesigned so that the critical region moves to the connected column. The connection remains almost elastic with limited displacements or local deformations, representing a "strong" link in the hierarchy of resistances. This means that the resistance of the column connection is dependent on the resistant moment of the column that it supports. However, the area of the column above the joint is over-strengthened due to the overlapping of column shoe rebars and column reinforcement. As a consequence, overdesigned column connections require relatively large column cross-sections to fit the necessary anchoring bolts. This is not economically efficient and may result in dense reinforcement in the joint.

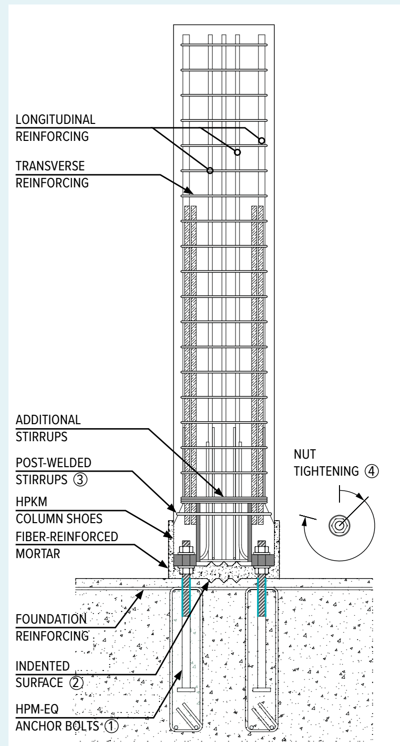
The second alternative is represented by energy dissipating connections, which are located in the critical region but also comply with the prescribed local ductility criteria. In this case, the plastic hinging of the column and/or the buckling of the rebars are avoided while the possible damage is limited 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. In contrast to overdesigned connections, the resistance of energy dissipating connections is dependent on the acting moments as for cast-in-situ joints. Since the joint dissipates energy itself, it can be designed to match the capacity of the column while respecting the capacity design in the overall structure. Under specific conditions, this leads to a smaller and adequately reinforced column cross-section.

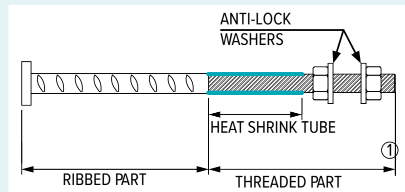
PEIKKO'S COLUMN CONNECTION FOR SEISMIC APPLICATIONS

To be considered "ductile", a connection must show experimentally a stable cyclic behaviour 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. Special detailing shown in Figure 2 was then introduced in Peikko's standard Column Connection for this purpose [11]. The effectiveness of the new features is evaluated basing on the comparison with earlier experimental results, where such improvements were not yet included [3], [12], [13].

HPM®-EQ Anchor Bolts [18] were specifically developed and produced with B500C – the highest ductility steel material. The embedded thread is now 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. Different debonding materials were tested. The heat shrink tube was the best option for keeping the highest ultimate deformation of the steel during push-pull tests on anchor bolts [13]. Loads are then transferred through the ribs and the headed stud as in standard anchor bolts.

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





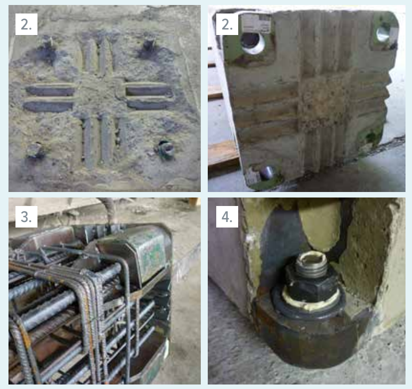


FIGURE 2. PEIKKO'S COLUMN CONNECTION FOR SEISMIC APPLICATIONS.

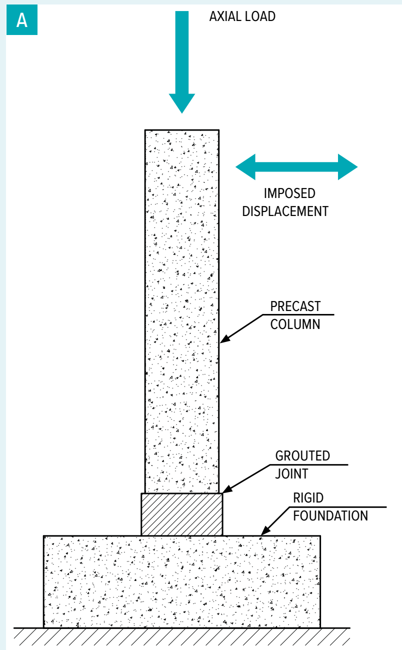


FIGURE 3. **(A)** TEST SETUP AND **(B)** GENERAL VIEW OF THE SPECIMEN IN THE LAB.

induced by an additional rotation of the upper nut after snug tightening. In particular, anti-lock washers are made of two parts with a wedged internal surface where the angle is greater than that of the threads. The possible slippage of the two parts results in an increase in the thickness of the washer that is greater than the pitch of the thread, thus keeping the connection tightened. The additional rotation assures the proper functioning of the connection, which is anyhow guaranteed by a certain tolerance of the pre-tension force value.

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. Any movement of the anchor bolt inside the hole is prevented. This helps to significantly reduce the pinching effect, which is due to mutual displacement of the anchor bolt and column shoe. The beneficial effect results in an increased amplitude of hysteresis cycles as experimentally verified.

A high strength fibre-reinforced mortar is used as joint grouting to avoid the spalling of the unconfined compressed collar of mortar around the column base. This limits damage and hence post-earthquake repair intervention. 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. This results in avoiding column slippage. The shear resistance of the joint under cyclic loading is increased by relying on both the friction and the mechanical interlocking of the surfaces. Shear is mainly accounted for 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. The equal displacement of the column shoes under cyclic loading is guaranteed. For example, in a column with four column shoes, two shoes will be compressed and two tensioned alternatively. The presence of stirrups helps to redistribute such forces among the shoes.

EXPERIMENTAL INVESTIGATIONS

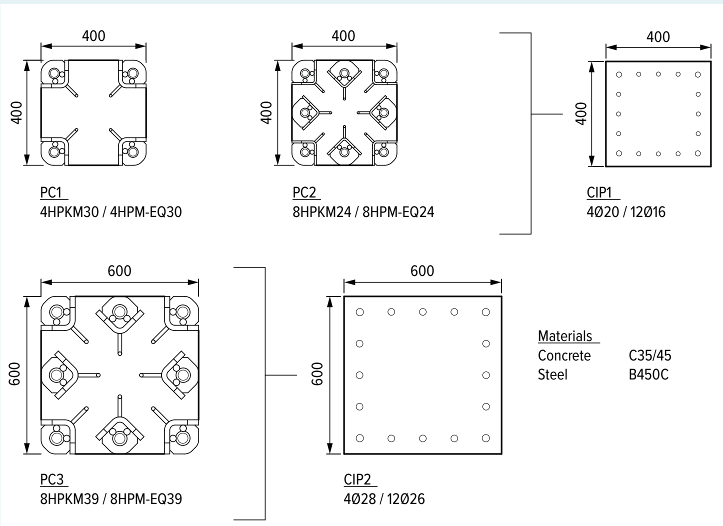
In order to assess the performance of such an innovative connection for seismic applications, several full-scale sub-assemblies have been tested at Politecnico di Milano. The specimens consisted of a 2.15 m high column and a rigid foundation element. Different layouts of the connection were investigated 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.

The main aim of the research activities was to compare the cyclic performance of emulative connections to that of cast-in-situ joints in order to demonstrate that the connection possesses stable cyclic deformation and energy-dissipation capacity according to Eurocode requirements. Two monolithic columns, which complied with reinforcement detailing for high ductility classes as required by [4] and [5] were therefore tested. Such columns were designed to have the same resistance as three of the precast specimens.

TEST SETUP

Quasi-static oligo-cycles imposed-displacement tests were performed. All 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 [2]. 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% (Figure 3).

FIGURE 4. COLUMN CROSS-SECTIONS AND MATERIAL DETAILS OF THE SPECIMENS.



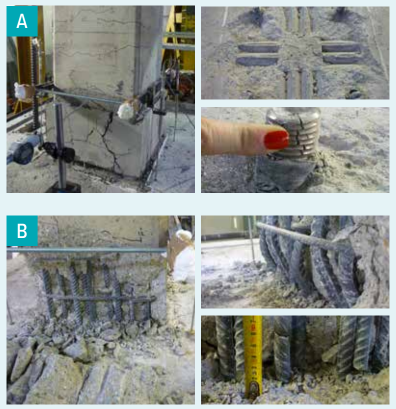


FIGURE 5. **(A)** PC1 SPECIMEN AND FAILED ANCHOR BOLTS WITH DAMAGED THREAD; **(B)** CIP1 SPECIMEN WITH BUCKLING AND FAILURE OF LONGITUDINAL REBARS.

TEST RESULTS

For the sake of brevity, the presented results refer to the last part of the research program carried out during 2015. The precast connection arrangements and the equivalent cast-in-situ concrete cross-sections considered herein are shown in Figure 4.

The precast specimens all showed localized damage in connection to the grouting, which presented an extensive crack pattern at the end of the test (Figure 5a). Spalling of the mortar was avoided thanks to the steel fibres, 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 interstorey drift imposed by the Code [5]. Even after a moderate earthquake, the column remains almost undamaged and any possible repair intervention would affect the grouting only.

In order to investigate the ultimate capacity of the connection, the tests continued until failure, which always occurred for 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. This indicates that the concentration of the stresses is 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 5a).

Test		PC1	PC2	PC3	CIP1	CIP2
+Δ	Δ_y	0.8	1.3	1.5	1.0	1.8
	μ_Δ	8.8	6.2	4.0	4.0	>5.0
−Δ	Δ_y	0.8	0.9	1.7	1.2	1.8
	μ_Δ	8.8	6.3	3.5	3.3	>4.4

TABLE 1. DUCTILITY VALUES FOR POSITIVE AND NEGATIVE DISPLACEMENTS.

Conversely, cast-in-situ specimens suffered generalised damage with evident spalling at the base of the column and cracks on the foundation surface (Figure 5b). This would lead to higher repair costs. Furthermore, the longitudinal reinforcement buckled and one of the rebars failed in CIP1 (Figure 5b). This indicates that brittle failure could easily occur, especially in the absence of proper detailing, such as adequate confinement of the critical zone.

DATA ANALYSIS

One of the most important seismic design parameters is the displacement ductility, which is the ratio between the ultimate displacement and the yielding displacement of a structural member. This ratio measures the ability of the connection to undergo large-amplitude cyclic deformations in the elastic range without a substantial reduction in strength [2]. All the precast specimens achieved a displacement ductility of at least 4, showing great post-elastic deformation capacity (Table 1).

In particular, Figure 6a shows the comparison between the force-displacement curves of PC1 and CIP1. It can be noticed that the deformation capacity 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 [10], while the cast-in-situ column suffered an abrupt loss of resistance after 4% drift due to rebar buckling and spalling.

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 6b). The PC2 specimen also shows a greater deformation capacity than PC1 thanks to the presence of more anchor bolts of a 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 is possibly due to the continuous reinforcement between the column and foundation in CIP2, which was designed according to the requirements for special moment resisting frames [1].

Another parameter to be taken into account when comparing precast and cast-in-situ specimens is the energy dissipation capacity. The equivalent damping factor has been evaluated by summing the elastic (2%) and the hysteretic components. Both typologies resulted in similar equivalent damping factor values, the precast specimens showing even more stable hysteresis cycles. The result was in general greater than 37.5%, thus fulfilling the requirements in [10] for ductile connectors (Figure 7a). Finally, Figure 7b shows that bolted connections are also as stiff [2] as monolithic joints. It can also be noted that the decay of initial stiffness is gradual, without any sudden and undesirable stiffness loss.

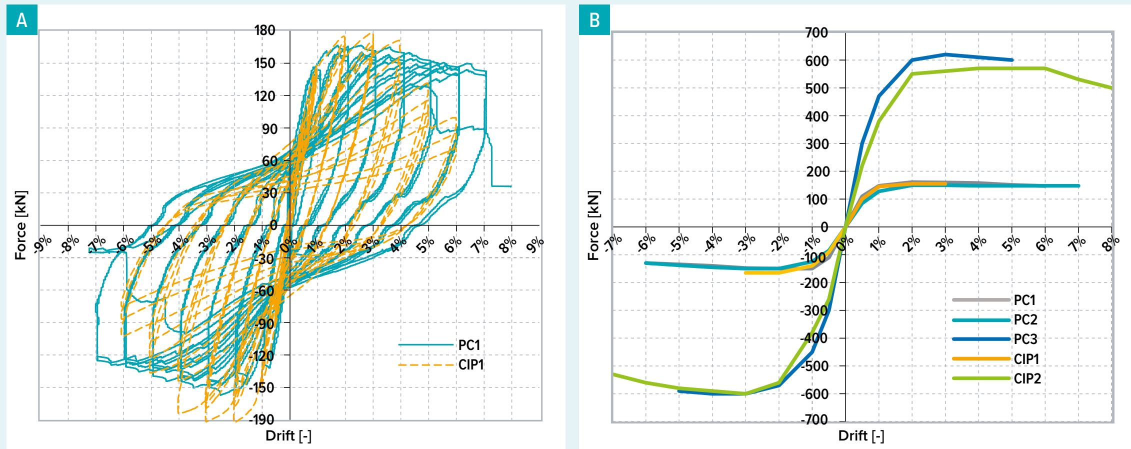
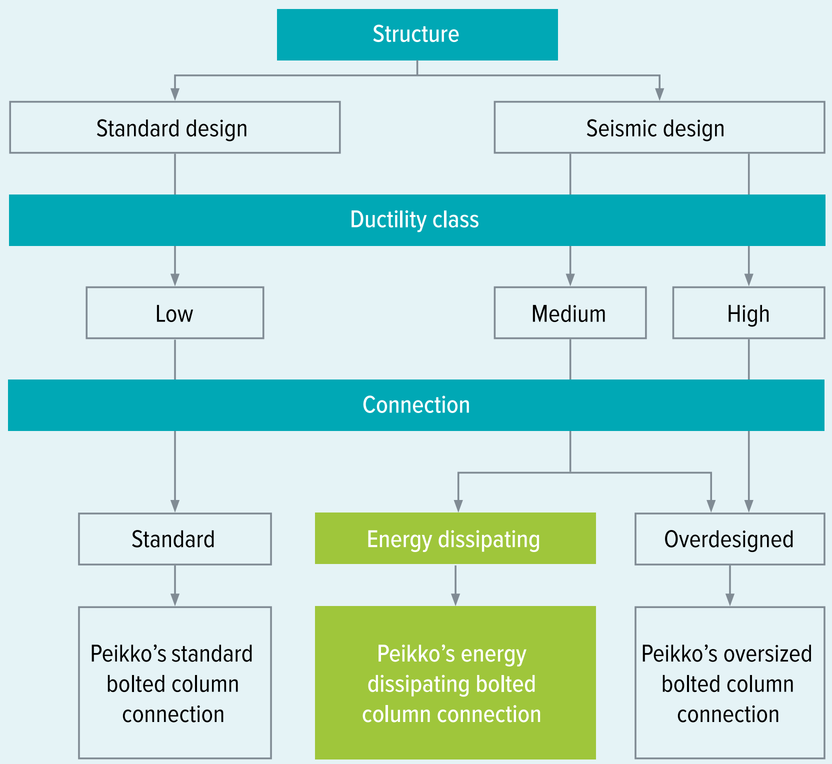


FIGURE 6. **(A)** COMPARISON OF THE HYSTERESIS CURVE OF PC1 AND CIP1 SPECIMENS; **(B)** COMPARISON OF THE BACKBONE CURVES.

FIGURE 8. FLOWCHART SHOWING THE DIFFERENT DESIGN OPTIONS FOR BOLTED COLUMN CONNECTIONS.



DESIGN GUIDELINE

Peikko's Column Connection for seismic applications has been approved for use in mediumductility class structures designed with a behavioural factor of up to 4 according to [5]. In fact, the design ductility of the HPKM®–HPM®-EQ connection can be assumed to be equal to 4 for compression ratios of up to 15%, or 3 otherwise, based on the test results above. This covers most of the cases for all the structural types identified by the Code, for which the connection can be considered energy-dissipative. If the American approach is adopted, the connection can be used in intermediate moment resisting frames according to [1].

Moreover, the static performance of Peikko's Column Connection and its single components is fully covered by European Technical Approvals ETA-13/0603 [7] and ETA-02/0006 [6].

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If the design requirements are different, such as high ductility class structures and/or higher behaviour factors according to [5] and special moment resisting frames according to [1], it is 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.

Figure 8 shows the different design options for precast structures with bolted column connections. Depending on the ductility class requirements, the connection can be designed as standard, energy dissipating or overdesigned. For medium ductility requirements, the HPKM®–HPM®-EQ connection is an excellent choice.

TECHNICAL DOCUMENTATION

The safety of Peikko's Column Connection for precast concrete structures in seismic zones has been validated by serious research, which was carried out under the supervision of a highly-respected third party. The Politecnico di Milano has issued a signed recommendation document as an outcome of the research program (Figure 9a). This document describes the tests performed, comments the results and provides indications regarding the design of such connections.

The recommendation document and the technical manual for Peikko's Column Connection for seismic applications (Figure 9b, [18]) are both available at www.peikko.com. To ensure proper detailing and design, Peikko also offers clear design guidance and the latest expert know-how for seismic precast frame connections.

SYSTEM BENEFITS

The use of Peikko's Column Connections for seismic applications offers several advantages compared with other solutions. For energy dissipating connections, the design is made more efficient by skipping the over-strength factor and matching the capacity of the column. This can lead to smaller column cross-sections than the overdesigned ones, thereby resulting in concrete volume savings of up to 20% .

A further 50% can be saved in costs thanks to the reduced excavation depth for foundations and the self-supporting connection. In fact, the foundation height is limited by using anchor bolts with headed studs. This is particularly beneficial compared with the protruding bar system. Column installation on the construction site is also quick and easy, with no need for temporary bracings.

The HPKM®–HPM®-EQ connection improves the overall efficiency on site and makes for faster construction. This is particularly important when there are several different workgroups and simultaneous processes. Moreover, because precast structures are made in factories, there is a high standard of quality control and workmanship, effectively eliminating problems that often arise when using an unskilled workforce.

From the structural point of view, the system is reliable thanks to clear design guidelines and a standard installation procedure. There is no way the system would behave differently from the way it was assessed during testing. The behaviour of the connection is also less dependent on the reinforcing details of the column than cast-in-situ joints. This means limited influence of transverse reinforcement and no rebar buckling. Furthermore, since deformations are lumped at joint level, no significant damage is expected to occur in the column, thus eventually limiting the cost of a post-earthquake repair intervention.

FIGURE 9. (A) RECOMMENDATION DOCUMENT AND (B) TECHNICAL MANUAL.

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 bolted connections. The cyclic performance by HPKM® Column Shoes and HPM®-EQ Anchor Bolts has been widely investigated. The experimental results showed that such connections can resist seismic loads with a satisfactory ductility and the same stiffness as cast-in-situ joints.

Under specific design conditions, Peikko's Column Connection for seismic applications can be considered as energy dissipative, thus avoiding oversized joints. 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 now make the HPKM®–HPM®-EQ connection a safe, reliable and convenient solution for precast concrete structures in seismic areas.

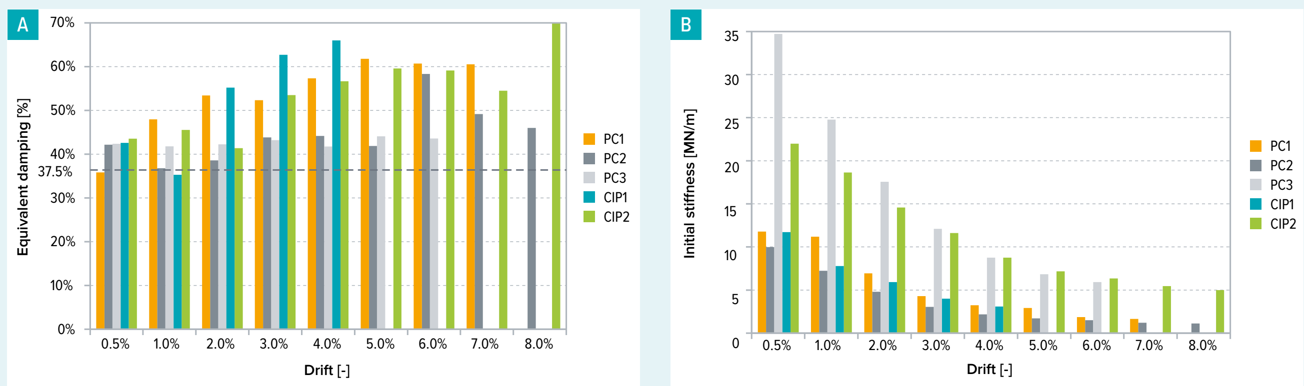

FIGURE 7. COMPARISON OF (A) THE DAMPING FACTOR AND (B) THE INITIAL STIFFNESS.

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