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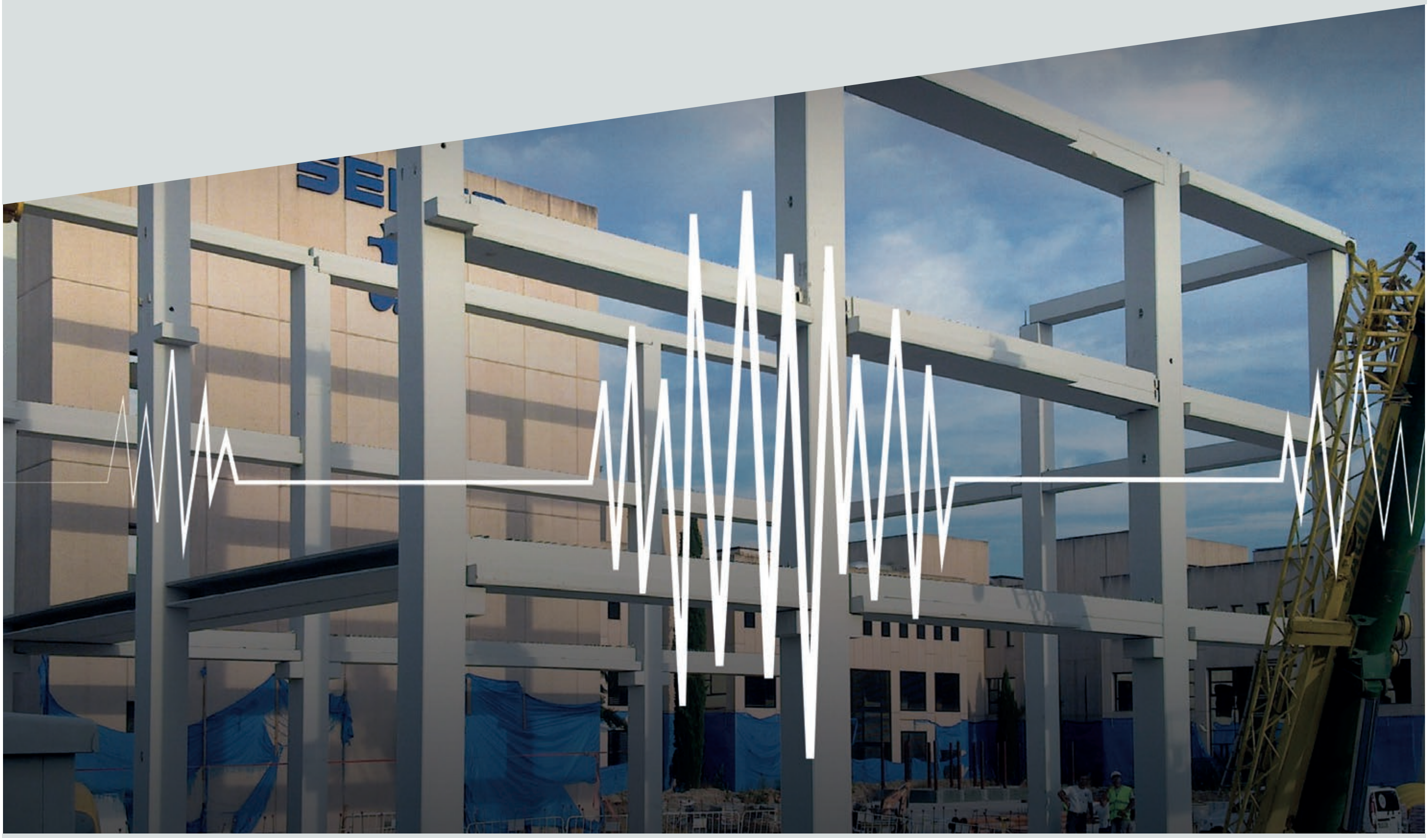

BOLTED CONNECTIONS FOR PRECAST STRUCTURES IN SEISMIC AREAS

PEIKKO SOLUTIONS AND DESIGN EXAMPLES

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A precast structure is an assembly of several finite members, such as beams, columns and walls, which are connected to one another, usually at their ends, and form a structural ensemble that behaves as a whole. Connections between different members of the precast systems ensure the flow of internal forces from one to another and enable the load path from the above-ground structure to the foundation level. The basic goal of connection design is not only to produce a joint that is simple and fast for the manufacturing and assembly purposes, but which also targets to provide effective and safe means of load transfer under all possible load conditions, including seismic effects.

Peikko bolted connections are an excellent solution for this purpose, as they combine the ease of installation of bolted joints with the latest technologies investigated by our product development team and the project related experience of our customer engineers. In fact, the traditional construction techniques of bolted joints can be updated and designed in order to fulfill even the most demanding requirements of the current seismic codes. And designers can do it **the Peikko way.**

INTRODUCTION

The advantages of precast concrete structures include speed of construction, higher performance of materials, controlled and safe construction environment, and more. Continuous advancements in precast construction technology provide innovative production techniques and make the lack of aesthetic and flexibility of excessively repetitious former precast products a thing of the past. In fact, over the last thirty years, precast concrete buildings have shown high-quality finishes and unique shapes in many prestigious architectural examples (Figure 1). Modern prefabrication does not include only industrial facilities, car parks or warehouses, but also residential houses, retail and office buildings, structures for education and culture, public services, and others.

Nevertheless, the fast and easy installation process is still the main reason why precast systems are usually preferred. This is even more true when bolted connections are selected, which allows to save time and money both during the design process and on site compared to welded or cast-in-situ joints.

BENEFITS OF BOLTED CONNECTIONS

Components of bolted connections are generally standardized so as to be economical from manufacturing point of view and detailed in such a way that they can accommodate any lack of fit or minor discrepancies in dimensions. Bolted joints basically need simple tools for installation and do not require specialized labor, which makes the progress in work fast. The crane time is shortened, and need for bracings or auxiliary elements is eliminated, since the connection supports the loads as soon as the bolts are tightened (Figure 2). This ensures a clear and less crowded working space and, as a result, a safer construction process. Such benefits are crucial especially in large scale projects that require many operations at the same time and need to fulfill a tight schedule.

Connections are among the most essential parts in prefabrication (Figure 3). Their role is to make the structure not just a sum of elements, but a coherent and robust whole that is able to take up all acting forces from erection to the final stage of construction. In fact, the way how different units or parts are connected to each other is what determines the overall behavior of the structure. Therefore, the design of structural connections must go beyond a mere question of choosing appropriate connecting devices and consider the resulting behavior of the joint, which comes from detailing of the joint faces and the end zones of the precast units as well. Otherwise, connections can be at the same time the distinguishing feature and the weak link of a precast system. This is especially true when seismic applications are considered.

FIGURE 1 EXAMPLES OF MODERN PRECAST STRUCTURES: (A)THE DUTCH VAULT, HOUTEN, NETHERLANDS; (B) WATER TANK, VALENCE, FRANCE; (C) OMNITURMN, FRANKFURT, GERMANY; (D) SCHOOL IN LES CABANYES, BARCELONA, SPAIN

FIGURE 2 SELF-SUPPORTING COLUMN BOLTED CONNECTION

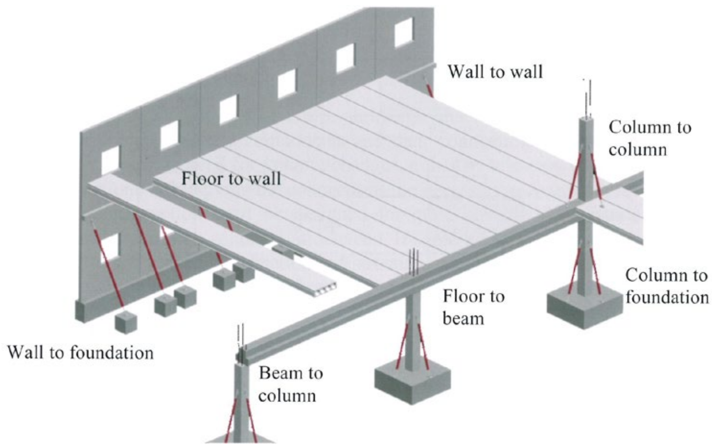


FIGURE 3 CONNECTIONS IN PRECAST STRUCTURES [9]

SEISMIC PERFORMANCE OF PRECAST STRUCTURES

Historically, seismic design provisions were added to the codes in response to the lessons learned from earthquake damage. As far as precast structures, failures that occurred in the past were due to scarce knowledge, lack of continuity or redundancy and poor detailing of precast members and their connections. This traditionally resulted in favoring cast-in-situ constructions in seismic areas. However, in the last decades the research has performed remarkable progress to ensure development of modern design codes and to guarantee satisfactory seismic performance of precast structures.

The main goal of the current code provisions is the mitigation of the seismic risk through a performance-based design. Four performance levels, namely fully operational, operational, life-safety and near collapse, are then set as limit states (Figure 4). Although the primary intent is to save human lives and prevent structural collapse, damage is accepted to occur during an earthquake event to an extent that depends on both the seismic intensity and the importance of the structure (Figure 5). For example, ordinary structures of civil engineering are usually designed to fulfill the life safety requirement in case of a rare earthquake event, while full operation is needed for strategic structures for the general public, such as hospitals, and essential facilities with inherent hazard, such as nuclear power plants.

In order to meet the fundamental requirements of collapse prevention and damage limitation, precast structures, as well as other structures, should be designed by using certain basic principles, such as structural simplicity, regularity and uniformity in plan and in elevation, plus continuity and redundancy. Given the peculiarity of prefabrication, where various members are cast elsewhere and then connected on site, the seismic design of precast structures should also account for establishing a suitable interaction between the bearing elements, such as beams, columns and walls, the floor systems and non-structural parts, such as cladding panels (Figure 6). This is usually obtained by providing a three-dimensional grid of ties and adequate connections.

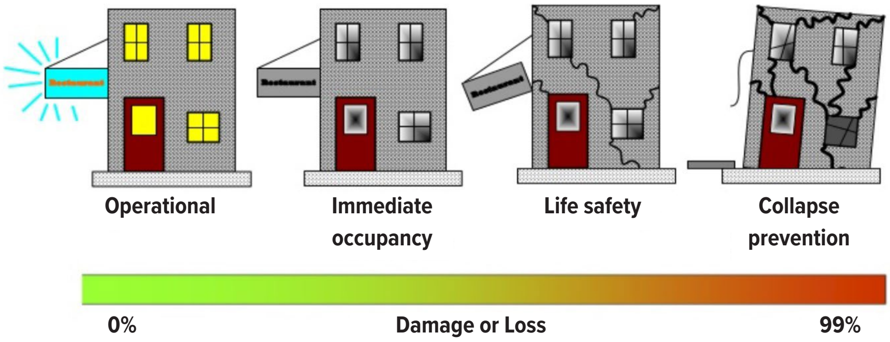


FIGURE 4 SEISMIC PERFORMANCE LEVELS AND CORRESPONDENT EXPECTED DAMAGE [8]

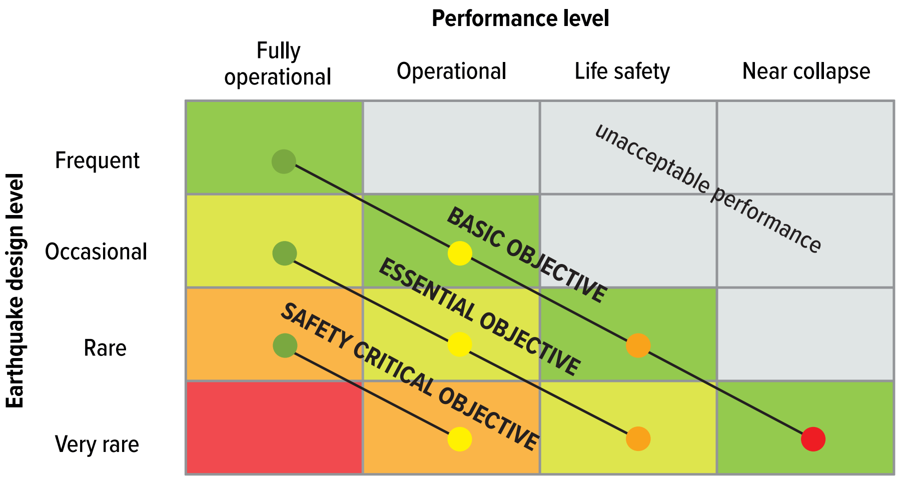


FIGURE 5 SEISMIC PERFORMANCE DESIGN OBJECTIVE MATRIX (ADAPTED FROM [16])

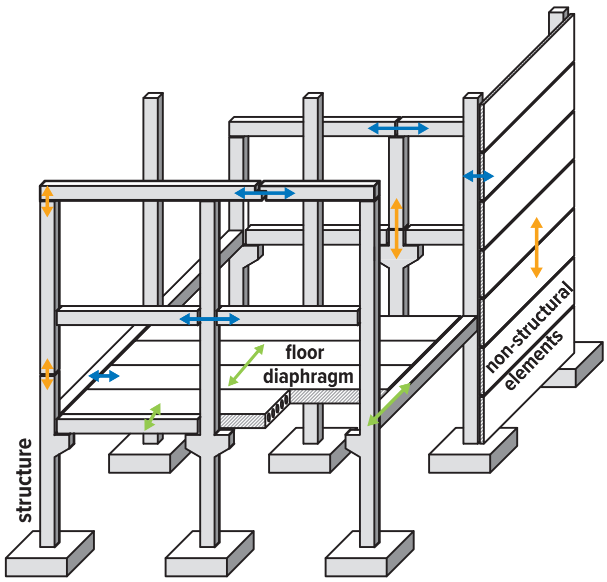


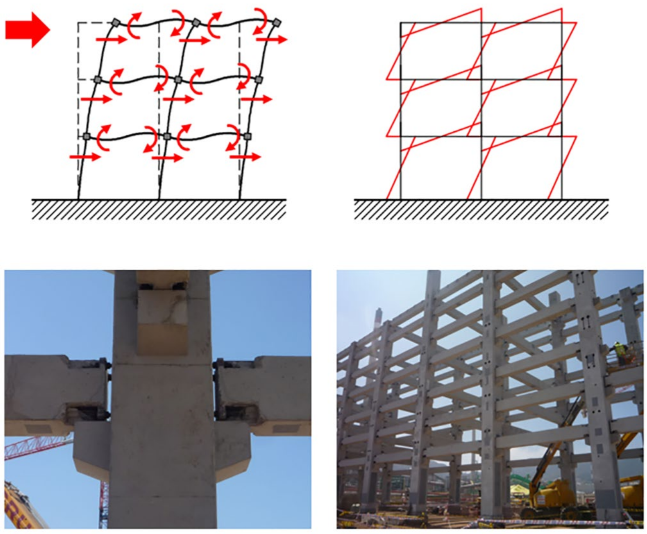
FIGURE 6 SCHEMATIC PRESENTATION OF THE TIE SYSTEM IN PRECAST STRUCTURES

FIGURE 7 PERFORMANCE REQUIREMENTS FOR CONNECTIONS OF PRECAST STRUCTURES

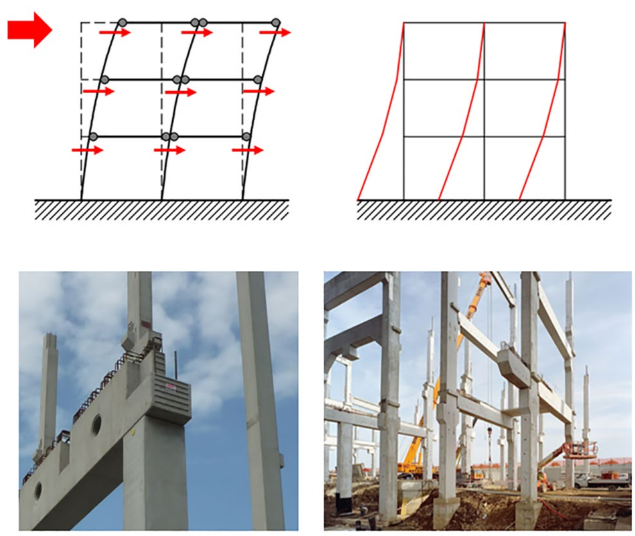
Current seismic design codes define specific performance targets for the connections of precast structures in terms of strength, stiffness, ductility and deformability (Figure 7). Adequate structural strength and stiffness are needed to ensure the load transfer between the members and achieve a seismic response similar to monolithic systems. On the other hand, connections should also possess sufficient deformability and ductility capacity to absorb seismic energy input by means of plastic deformations, i.e. damage, nonetheless without failing and ensuring overall structural integrity. In fact, the ability of a precast structure to suffer a controlled damage and to sustain the load-carrying capacity under seismic loading is much affected by the deformation compatibility of the joints between the members.

ALTERNATIVES FOR SEISMIC DESIGN OF BOLTED CONNECTIONS

Generally, moment-resisting connections are preferred in seismic applications. In fact, they are essential to develop the frame action in precast buildings by carrying the bending moments. Moment-resisting connections are used to stabilize and increase the stiffness of frame structures, in order to limit the sidesway and second order effects under seismic loading. Moreover, moment resisting connections redistribute the bending moment in beams, thus reducing column bending moments, and restore the structural continuity, thus improving the overall resistance of precast systems (Figure 8a). In some cases, simple, i.e. pinned, connections that transfer only axial and shear actions can be designed as well, for example for beam-column connections (Figure 8b). The advantage of having a pinned connection is generally the ease of production and installation. However, in seismic applications, beam connections must be all checked for both axial resistance and displacement compatibility, to ensure the transfer of horizontal loads and to avoid collapse due to short support lengths or lack of deformability.



a)



b)

FIGURE 8 EXAMPLE OF BOLTED (A) MOMENT-RESISTING AND (B) SIMPLE BEAM CONNECTION

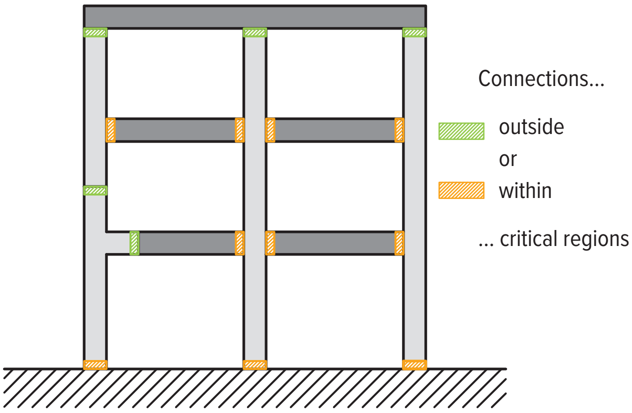


FIGURE 9 CLASSIFICATION OF CONNECTIONS FOR SEISMIC APPLICATIONS

FIGURE 10 BOLTED CONNECTIONS LOCATED OUTSIDE OF THE CRITICAL REGIONS

In seismic design, connections are usually classified depending on type and position (Figure 9). Connections can be located well outside the so-called critical regions, where the most adverse load combinations, and therefore damage, are expected to occur under seismic loads. Therefore, such connections play a minor role in the overall seismic performance. Examples of bolted connections of this type are column splices at mid-story height or beam-column connections that are placed at sufficient distance from column face (Figure 10).

However, in several cases connections are necessarily located within critical regions. This is generally the case of foundation connections, whose performance greatly affects the response of vertical load bearing elements and hence the overall stability of the structure. Two different approaches can be then adopted. In one approach, connections can be adequately overdesigned to remain elastic under design level seismic actions so that the plastic hinge, i.e. the possibly damaged zone, shifts to the adjacent element. Alternatively, connections can provide substantial ductility so that the connection itself offers the required deformation capacity of the joint. This is the essence of the capacity design method, in which distinct parts of the structure are selected and detailed to act whether as over strengthened or ductile, so that undesirable brittle mechanisms are protected by developing an appropriate hierarchy of resistances (Figure 11).

The selection of either connection design approach depends on various factors, such as the type of the structure and the seismic load condition, besides compliance with the current code provisions. Bolted connections can actually suit both design alternatives (Figure 12). In the overdesigned approach, the components of the connections, i.e. the bolts, are designed so that the connection has a greater resistance than the adjacent member. As if the connection were the strong link of a chain, under seismic loading, the connection experiences limited deformation, thus remaining elastic and suffering no damage. On the contrary, when the connection is meant as the deformable link of the chain, the cross-section with bolts is designed to match the capacity of the connected element, which generally results in a more convenient reinforcement of the joint compared to over strengthened bolted connections. On the other hand, the connection itself should possess a sufficient ductility capacity to satisfy global ductility demand, meaning that major deformation and damage might occur in the joint.

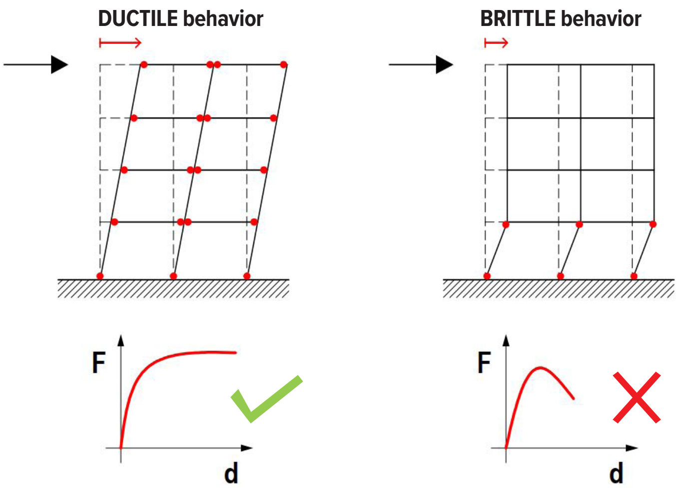


FIGURE 11 CAPACITY DESIGN METHOD CONCEPT: (A) SIDESWAY DUCTILE MECHANISM AND (B) BRITTLE SOFT-STORY FAILURE

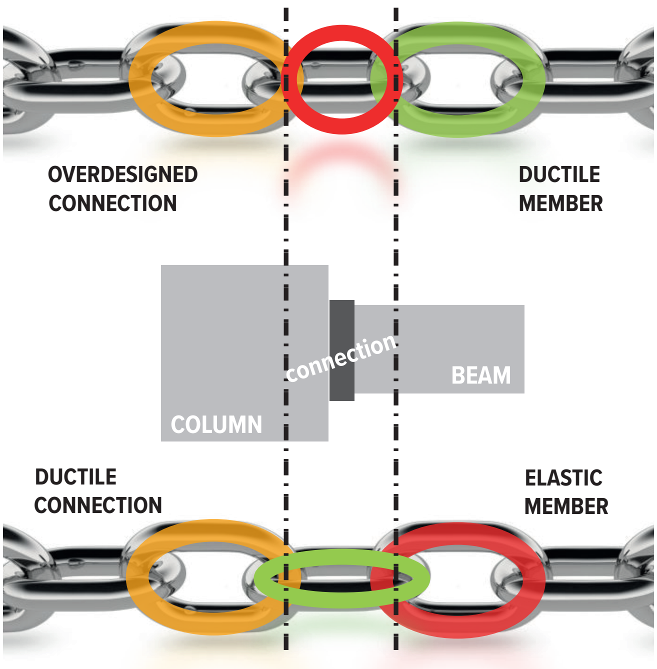


FIGURE 12 THE CHAIN ANALOGY FOR OVERDESIGNED AND DUCTILE BEAM-COLUMN CONNECTIONS

PEIKKO BOLTED SOLUTIONS FOR PRECAST SYSTEMS

Precast structures can be classified with respect to the primary seismic load resisting system. In fact, in the design process it is important to identify which elements are supposed to carry the horizontal loads so that the connections between those can be adequately designed. Most common structural types include frame systems, wall systems and wall-frame systems (Figure 13). In such structures, the lateral resistance is provided by moment-resisting frames, shear walls or cores, or a combination of both. Hybrid systems are also possible, where only part of the structure is designed for seismic loads and the rest for gravity load, while still contributing to the global stability.

For the above-mentioned structural types, Peikko offers a wide portfolio of bolted connections, which are briefly presented in the following part.

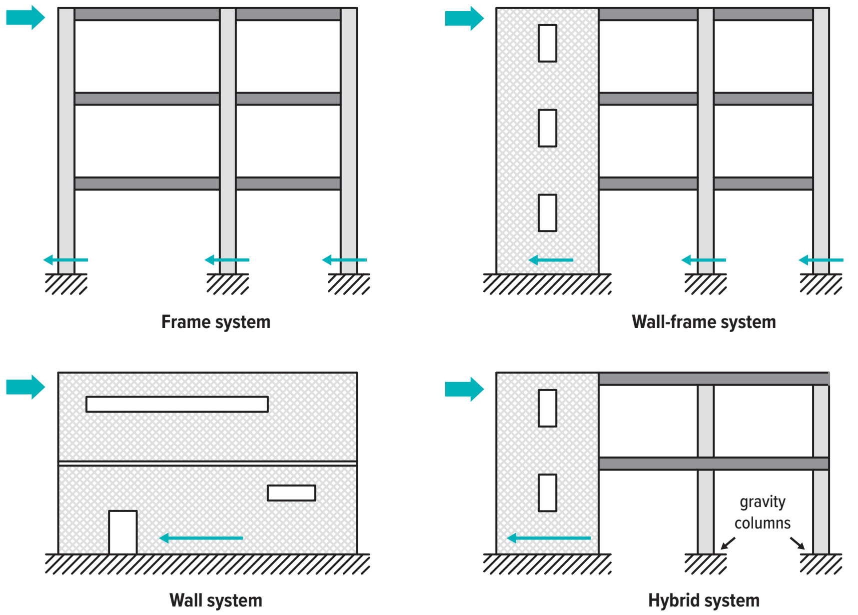


FIGURE 13 PRECAST SEISMIC LOAD RESISTING SYSTEMS

COLUMN CONNECTION

A typical precast bolted connection is made of column shoes and anchor bolts. Column shoes are placed in the formwork in precast factory during element production, while anchor bolts are cast on site into the foundation. The external threaded part of the bolt allows column shoe base plate to be tightened using a couple of washers and nuts. The open joint between the column and base structure is filled with non-shrink, cementitious grout. Depending on the loading conditions, the connection can use HPM® Rebar Anchor Bolts and HPKM® Column Shoes for moderate actions, while PPM® Rebar Anchor Bolts and BOLDA® Column Shoes for demanding anchoring applications.

When a ductile column connection is required, HPM®-EQ Rebar Anchor Bolts are the optimal choice. The debonding of the embedded thread and the use of the most ductile steel type keep the deformation capacity of the bolt at its maximum. The tightening of the joint under seismic loading is also secured by high strength and anti-lock washers. Finally, further special detailing compared to the standard connection is adopted to improve the cyclic performance of the joint while maintaining the simple basic concept and easy installation of bolted connections.

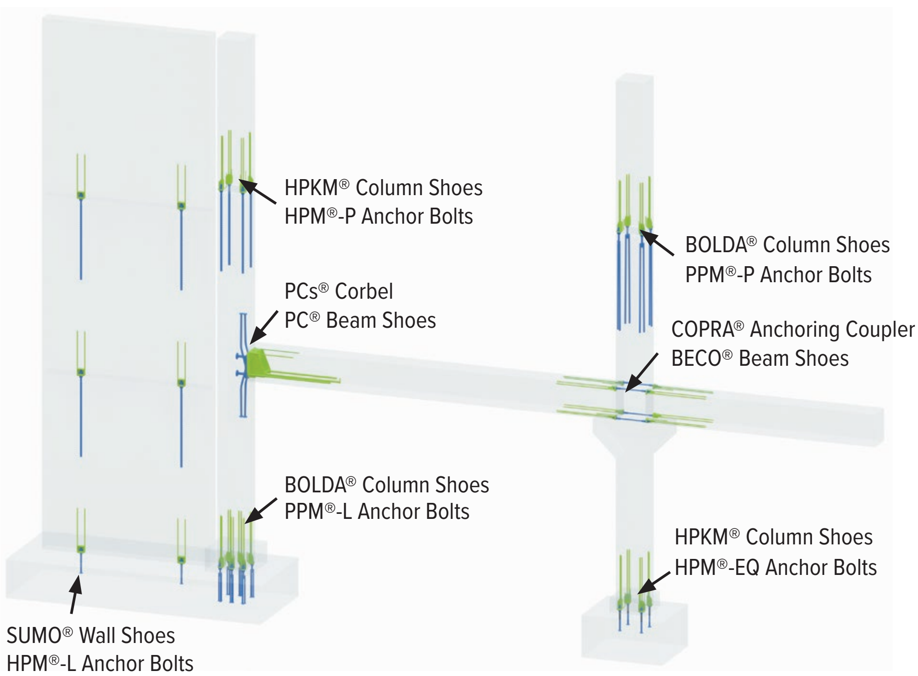


FIGURE 14 PEIKKO BOLTED CONNECTIONS IN PRECAST STRUCTURES

BEAM-COLUMN CONNECTION

The design of beam-column connection greatly depends on whether the joint is supposed to be hinged or moment-resisting. In case of a simple connection, PCs® Corbel and PC® Beam Shoe can be used. PCs® Corbel is a modular corbel where the cast-in part enables straight mold walls, and the bolted bracket offers superior adjustability and high resistances. As its counterpart, PC® Beam Shoes are used for easy installation of both reinforced and pre-stressed precast beams to columns. When bending moment resistance is required, COPRA® Anchoring Coupler and BECO® Beam Shoes can be designed accordingly. The wide product range is suitable for most loading conditions from light to heavy.

WALL CONNECTIONS

Walls are often used in precast as they can provide resistance and stiffness to the system. SUMO® Wall Shoes are used to create cost-effective tensile connections between precast concrete walls and foundations or between precast concrete walls. SUMO® Wall Shoe are used together with HPM® and PPM® Anchor Bolt types with specially designed AL washers.

CASE STUDIES

OVERDESIGNED VS ENERGY-DISSIPATIVE CONNECTION DESIGN

In order to understand the effect of the choice of different design approaches for precast column connections, the design of a 60x60 column shown in Figure 15 is studied in detail. The column is loaded at a 10% axial ratio and has a 2% reinforcement ratio.

In the energy dissipative design approach, the connection is verified by using 8-HPKM®39 and 8-HPM®-EQ39, as the joint capacity matches that of the column. In fact, the mutual resistances of the elements, i.e. the joint and the connection, must be considered besides the design actions, according to the capacity design principle. The resistance of the joint has then to be as great as that of the column to avoid brittle failures or plastic hinging at undesired locations. In simple words, as far as the flexural behavior, the resistance domain of the joint must include the green dot M_{Rd} representing the resistance of the column.

On the contrary, in the overdesigned approach, the joint would need to have even greater resistance than that of the column. According to the European seismic design (EN 1998-1), the value of overstrength factor depends on the ductility class which the structure is designed for. For the medium ductility class as considered herein, precast connections should be 20% more resistant than the connected column. Slightly different coefficients or ways to over strengthen the connection can be found in other codes, but the concept is the same and it leads to an equivalent level of safety. This requirement would not be satisfied as no more HPKM® Column Shoes would fit in the cross section to reach the needed resistance (red dot in the picture). Nevertheless, the overdesign case can still be solved by using BOLDA® Column Shoes and PPM® Rebar Anchor Bolts. The high resistances of such connection items and the improved shape of the column shoes suit well with the overdesigned approach even when the column cross-section space is limited. In this particular case, the connection is verified by using 8-BOLDA®45.

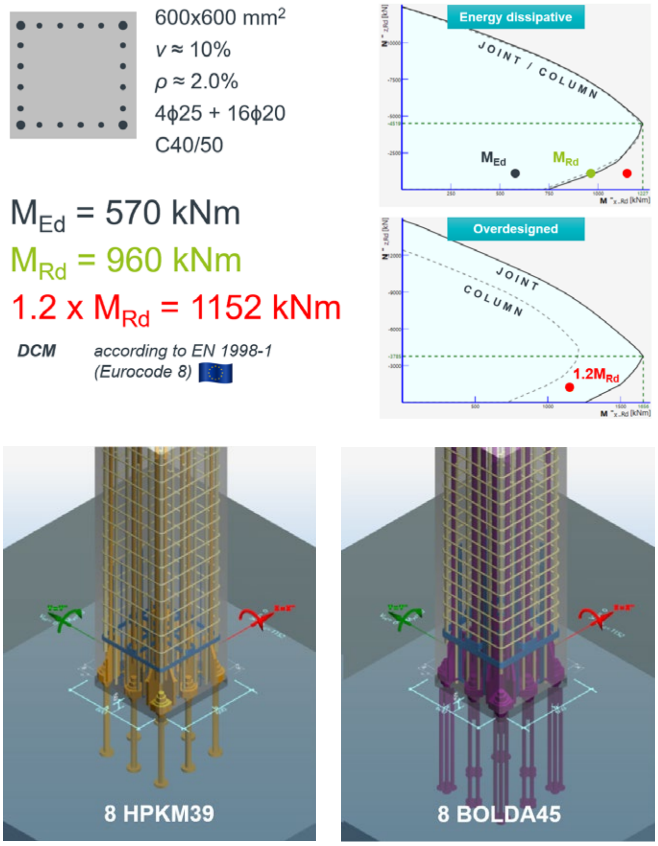


FIGURE 15 OVERDESIGNED VS ENERGY-DISSIPATIVE DESIGN EXAMPLE (M_{Ed} ACTING BENDING MOMENT; M_{Rd} COLUMN RESISTING MOMENT)

FIGURE 16 GENERAL RENDERED VIEW OF PROJECT SITE ON TINIAN ISLAND

FIGURE 17 ARCHITECTURAL FAÇADE ELEVATION

A COMPLETE SEISMICALLY RESISTANT PRECAST STRUCTURE WITH PEIKKO BOLTED CONNECTIONS: TIANNING HOTEL (NORTHERN MARIANA ISLANDS, COMMONWEALTH OF USA)

This unique project, which was initiated in 2019 and executed in 2020, has become a reference point for state-of-the-art design and a construction approach to precast buildings located in high seismic zones. The Tianning Hotel Project is located on Tinian Island of the Northern Mariana Islands, which are a Commonwealth of the United States of America located in the Pacific Ocean.

The design and construction of this interesting and challenging project has been a very international effort from start to finish. Northern Mariana Islands are located in the middle of the Pacific Ocean, where the local resources for construction materials as well as manpower are extremely limited. On the other hand, the high demand from the tourists visiting the island from China, Japan, and Korea is putting a pressure on the developing touristic industry on the island and this calls for construction of new hotels, resorts and residences. Considering all the conditions in the field, the investors have searched for alternative methods to conventional construction techniques to build their investments fast, safely and efficiently. This is where the precast construction idea coupled with the use of bolted connections came into the picture.

Chinese investors and their consultants decided to build a completely precast concrete super structure with the precast elements manufactured in mainland China and shipped over to the island. The precast system needed to be designed in such a way that it leaves very little work to the construction site on the island. Therefore, the structure was designed with bolted connections while utilizing means and methods to minimize the amount of cast-in-place activities. Furthermore, the structural design would have to be developed while considering extremely high seismic demands on the remote island.

The Commonwealth of the Northern Mariana Islands is an archipelago stretching over 500 miles and comprising of 14 islands which are of volcanic origin. The main Mariana Island arc was formed due to the subduction of the Pacific plate beneath the Philippine Sea plate. The continuous convergence between the two tectonic plates is the cause of the seismic activity in the Mariana Islands still nowadays. The maximum magnitude for an earthquake to occur in the region is in the range of 8.8 to 9.0 in the Richter scale. The design base earthquake, which has a 10% probability of exceedance in 50 years, has a Peak Ground Acceleration of 0.3g.

In addition to the logistics and seismologically unfavorable conditions, the challenging design process was conducted on a global scale. Architectural design was performed in China, while earthquake resistant structural design developed in Turkey. The multi-disciplinary coordination was carried out through several face-to-face meetings as well as online meetings. The precaster was also involved in the design and coordination process starting at a very early stage.

The project consists of three identical building blocks (Figure 16). Lateral load resisting structural system is a special moment resisting frame system comprised of complete precast reinforced concrete frame elements and precast slab units. All structural design is conducted according to U.S. codes, such as ACI 318 [1] and ASCE 7 [2]. All rigid moment resisting frame connections are enabled by Peikko bolted connection systems. Connection design is conducted as a “strong connection” design approach per ACI 318 code provisions.

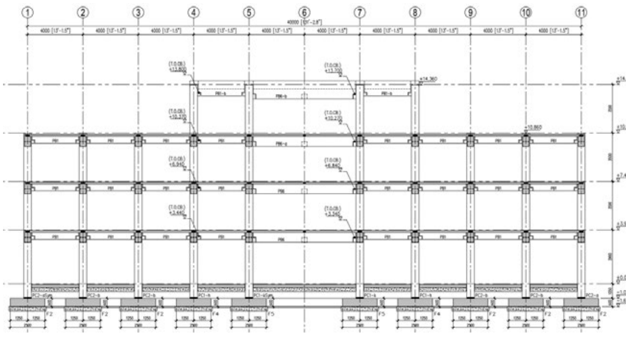


FIGURE 18 LONGITUDINAL ELEVATION OF STRUCTURAL PRECAST CONCRETE FRAME SYSTEM

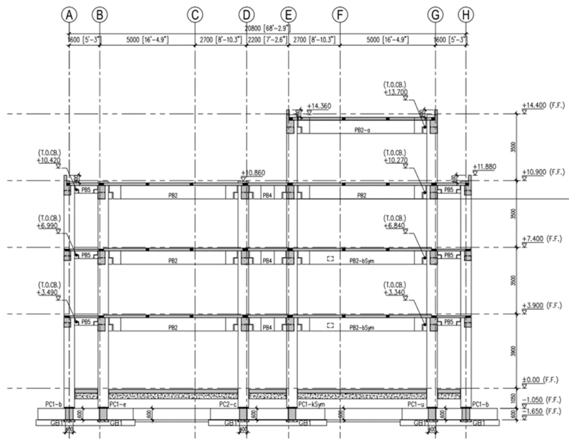


FIGURE 19 TRANSVERSE ELEVATION OF STRUCTURAL PRECAST CONCRETE FRAME SYSTEM

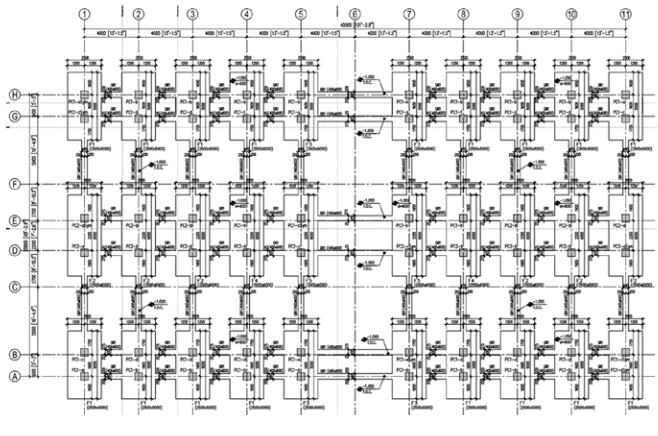


FIGURE 20 PLAN OF CAST-IN-PLACE FOUNDATION SYSTEM

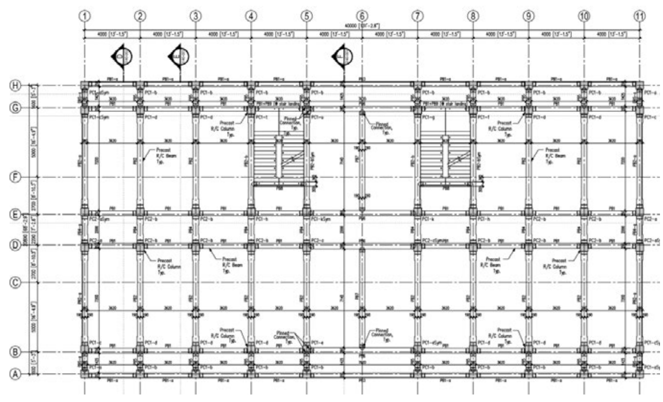


FIGURE 21 PLAN VIEW OF FRAMING SYSTEM FOR A TYPICAL FLOOR LEVEL

Architectural design of the building blocks is quite regular and suitable for precast construction technique. There are no basement levels. Buildings have three floors above the ground level and a partial roof over the stairwell (Figure 17).

Frame elevation also reveals that the structural system is quite regular and with relatively short spans, which are due to the architectural layout of hotel rooms (Figure 18 and Figure 19). Floor-to-floor heights vary between 3.5 meters to 3.9 meters as the minimum clear floor height becomes 2.6 meters considering a maximum 70 cm beam depth and 14 cm precast slab thickness.

The only cast-in-place part of the construction is the foundation (Figure 20). Feasibility was investigated by comparing a potential precast foundation system to a cast-in-place option. However, the benefits of precast foundations did not offset the cost of overseas transportation of precast foundation elements for this case. Spread foundations are interconnected with a grid of grade beams to safely transfer base shears due to lateral loads. A backfill on top of the spread foundations and a cast-in-place slab on ground provides the flooring for the ground level and the lobby of the hotel.

In providing moment resisting connections of frame beams to columns in both orthogonal directions, designers needed to coordinate the bolted connections to avoid any clashes and ensure safe and efficient installation (Figure 21).

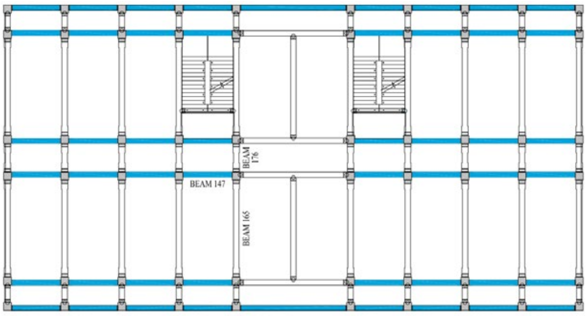


FIGURE 22 FRAME BEAMS DESIGNATED AS SECONDARY BEAMS

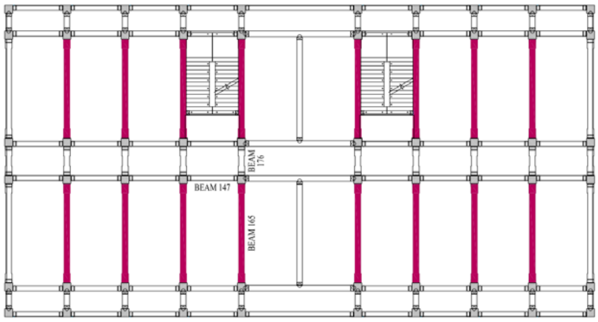


FIGURE 23 FRAME BEAMS DESIGNATED AS MAIN BEAMS

To achieve this, the blue beams shown in Figure 22 are designed as secondary beams – as the spans are short and the one-way load distribution from the precast slab units put less demand on these elements as far as gravity and seismic loads. On the other hand, the red beams (Figure 23) become the main beam elements as they receive most of the gravity loads from the floor slab, as well as seismic loads due to mass distribution and frame layout. The short beams over the corridors are also rigidly connected to the columns, acting as link beams for the transverse frames.

The plan view of the column-to-beam connections (Figure 24) points out the prioritization need as four bolts and four shoes need to come together around each internal column (Figure 25). Therefore, the congestion of all these elements within the precast formwork must be considered along with the regular column and beam element reinforcement. It should be noted that while using the strong connection approach per ACI 318, i.e. while the connection elements are designed with an overstrength factor, the designers are still required to adhere to regular ductile detailing and design requirements.

Column beam junction in Figure 25 illustrates the connection of secondary and primary beams and how the bolts of the main girder are located such that the largest moment arm is provided while adjusting the location of the bolts for the secondary beams to avoid clashes of embedded bolts for the transverse elements.

Connection of the column to the foundation (Figure 26) is a bit more straightforward and similar to common practice of strong connection approach of bolted column base connections. Additional stirrups are provided to ensure confinement and ductile behavior at the base of the column and within the foundation. In an attempt to optimize the connection capacity, larger size bolts and shoes are located at the four corners of the section considering the relatively high demands resulting from the seismic effects and over-strength design approach.

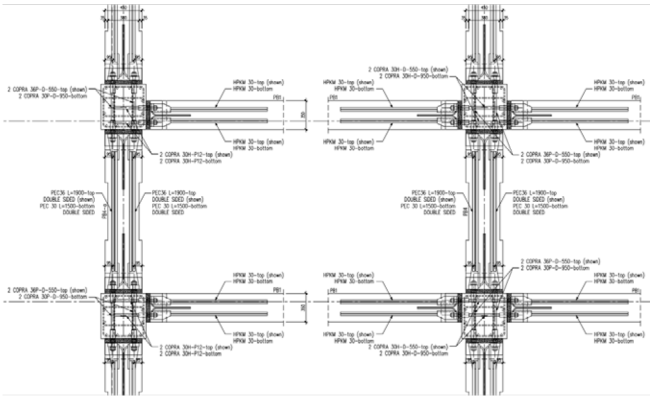


FIGURE 24 CLOSE-UP PLAN VIEW OF TYPICAL CONNECTION JUNCTIONS AT COLUMN-BEAM INTERFACES (ONLY BOLTED CONNECTION ELEMENTS SHOWN FOR CLARITY)

Another unique design element of this project is the precast slab system that is built with solid precast units. The precast slab system that provides the floor diaphragms, which is a crucial piece of the lateral load resisting system, is designed per ASCE 7-16 provisions without the use of a topping slab. The precast panels that distribute the in-plane diaphragm actions are connected to each other by use of strips of joints along their edges. These strips are reinforced with rebars and flexible wire loop elements and grouted after the installation. The edges of all the slab units are intentionally roughened to a quarter inch amplitude (Figure 27).

Design development and multi-disciplinary coordination was concluded and fabrication of precast elements, both structural and non-structural (interior partition walls, façade elements, stairs, etc.) were completed in the precast elements facilities in China. The precast elements were later shipped to the island and the construction works started. Although interrupted by the pandemic lockdowns, the installation and overall

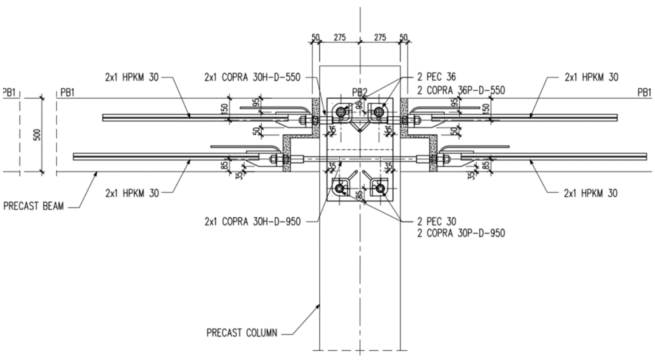


FIGURE 25 CLOSE-UP SECTION VIEW OF A TYPICAL CONNECTION JUNCTION AT COLUMN-BEAM INTERFACE (ONLY BOLTED CONNECTION ELEMENTS SHOWN FOR CLARITY)

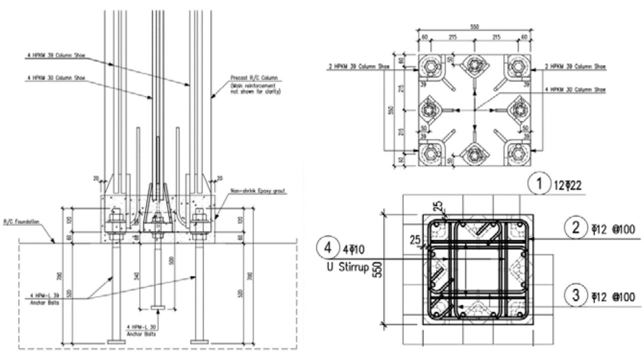


FIGURE 26 TYPICAL DETAILS OF COLUMN TO FOUNDATION CONNECTION WITH COLUMN SHOES AND ANCHOR BOLTS

FIGURE 27 PHOTO OF JOINT ALONG PRECAST SLAB UNITS

FIGURE 28 PHOTO OF CONSTRUCTION SITE WITH PRECAST STRUCTURAL ELEMENTS INSTALLATION IN PROGRESS

construction of the precast structure was completed in an extremely fast and efficient construction phase on the island (Figure 28 and Figure 29). Such successful reference project has quickly attracted the attention of other investors looking for an efficient and reliable construction method on the remote island.

CONCLUSIONS

In conclusion, the overall seismic behavior of precast concrete structures is much affected by the type and position of the connections in the structural system. What obviously applies to any other structure, is even emphasized for the precast systems: the entire assembly of finite elements must be adequately constructed and securely connected to perform well under seismic forces. In fact, lateral loadings are especially demanding because they actively attempt to the building equilibrium, whereas vertical loads usually sit still within the materials of the building.

Adequate precast connection design implies a clear understanding of how the load path will be established between the elements and where the major deformation is expected to take place in case of seismic loading. Strength, stiffness and deformation capacities are then needed to achieve the desired structural performance. In such regard, connections that are strong enough to transfer the earthquake forces maintain the integrity of the precast structure, and connections that allow for deformation within and/or close to the joints ensure a ductile overall response.

This shows that precast connections are particularly important. As a leading global supplier of bolted connections for precast structures, Peikko can offer tested and reliable products and solutions that are suitable also for seismic applications. The reference projects provide evidence that even challenging design situations can be handled well, and Peikko is able to provide technical support, which is based on the latest seismic engineering knowledge, so to guarantee safe and reliable design and construction of bolted connections in precast structures.

FIGURE 29 PHOTO OF CONSTRUCTION SITE WITH COMPLETED STRUCTURAL ELEMENTS INSTALLATION

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