Precast concrete, steel-braced, hybrid pipe rack structures

Sebastián F. Vaquero, Damián R. Correa, and Sergio F. Wolkomirski

T he construction of a precast, reinforced concrete pipe rack supporting process pipelines has many boundary conditions to be considered in design and construction. The most important ones are the following:

- The strict safety guidelines of petrochemical facilities discourage the use of cast-in-place concrete. Normally all maintenance, repair, and construction work must be conducted with a proper work permit, which can be difficult to get. The permit is a detailed document that authorizes certain people to conduct specific work at a specific site at a specific time and sets out the main precautions needed to complete the job safely. Precast concrete systems help minimize such problems.

- In the petrochemical industry, delays are costly.

- Flare gas pipelines are gravity fed because their condensate is extremely corrosive. Unlike other process lines, they cannot be placed on the ground with slider bearings.

In the operation of an oil refinery, flare stacks are primarily used for burning off flammable gas released by pressure relief valves during unplanned overpressurizing of plant equipment. Gas-gathering pipelines are required to transport flammable gases to the flare stack to provide a means

■ This paper presents a case study of the design and construction of a pipe rack in an operating petroleum refinery located in a high seismic zone in Argentina.

■ The pipe rack comprises precast, reinforced concrete moment frames with a single cast-in-place connection as the transverse load-resisting system, longitudinal precast, reinforced concrete beams as shear keys, and steel bracing as the longitudinal load-resisting system.

■ The connections comply with the requirements of the Argentine seismic code, taking into account the erection tolerances and minimizing on-site concrete work as well as working at heights.

Figure 1. Project characteristics. Note: 1 m = 3.28 ft, 1 mm = 0.0394 in.

of safe disposal of the vapor streams from the facility by burning them under controlled conditions so that adjacent equipment or personnel are not exposed to hazards while at the same time obeying environmental regulations. Thermal variations due to the content of the pipes or ambient temperature differentials result in significant anchor forces. The pipe rack is intended to resist, or limit, the movement of the piping because equipment connections, such as the ones available in vessels or tanks, are not generally designed to handle the resultant thermal forces. The specific project characteristics were as follows:

- The process pipelines are supported on precast concrete cantilever columns along a 300 m (1000 ft) path.

- The piping is anchored to the frame at the end of the path, resulting in significant horizontal thermal loads (about 60 kN [13.5 kip]).

- The structure's height is 11 m (37 ft) due to process requirements.

- The main pipes have external diameters of 10, 20, and 60 in. (250, 510, and 1520 mm).

- Gate valves are required for each pipe according to the applicable security regulations. The 60 in. valve, plus accessories, weighs about 140 kN (31.5 kip), and the 20 in. valve, plus accessories, weighs about 15 kN (3.4 kip).

- Platforms are required for access valves, instruments, and maintenance.

These requirements generate significant seismic demands on the structure (**Fig. 1**).

In this particular case the client requested that the structure be precast concrete to minimize cast-in-place concrete work and to accelerate construction. These circumstances, added to the fact that the facility is located in a high seismic zone in Mendoza, Argentina, required the designer to use connection details with good seismic performance, which should simplify the erection. **Table 1** summarizes the main seismic parameters, and **Fig. 2** shows the elastic design spectrum.

In addition, the final structure should facilitate the maintenance of the pipelines and their accessories, which are essential for the processes taking place at the petrochemical facility.

To comply with the boundary conditions, the use of precast, reinforced concrete moment frames in the transverse direction was proposed with just one cast-in-place concrete connection as the transverse load-resisting system; simply supported longitudinal precast, reinforced concrete beams as shear keys; and steel V-bracing as the longitudinal load-resisting system. Only precast, reinforced concrete members were used, rather than pretensioned or posttensioned precast concrete members.

Table 1. Seismic main parameters

Direction	System	$R^†$	Displacement ductility†	Overstrength factor$^^$	Period, seconds
Transverse	Precast concrete frame	5.0	5.0	3.0	0.268
Longitudinal	Special steel concentrically braced frame	4.5	4.5	2.5	0.502

* Response modification coefficient in accordance with ASCE 7-10 chapter 11

† In accordance with INPRES-CIRSOC 103 (applicable design code)

$^^$ In accordance with ASCE 7-05 chapter 12

This paper shares the experience in developing this kind of pipe rack.

Foundation system

Because underground interference is common in operating petrochemical facilities, the following guidelines were created:

• Minimize spread foundation size.

• Accomplish a high degree of flexibility, allowing for last-minute changes.

The applicable regulatory structural code[1] requires the use of tie beams between isolated footings for redistribution of lateral forces between them. To avoid differential settlements, comply with the applicable regulations, and reduce the superstructure sections, cast-in-place concrete footings with stiff tie beams were used. In retrospect, it might have been feasible to construct any of those components using precast concrete instead of a full cast-in-place concrete system, but at the time the lack of information about underground interference discouraged this approach.

Due to the excellent geotechnical conditions of the site, the footings were designed to carry vertical loads only and the tie beams to resist all of the column flexural moment. Tie beam bars were anchored outside the foundation socket core to avoid interference between bars. **Fig. 3** shows the resulting structural design.

In addition, the footings were designed to safely absorb the tension from the columns due to the reduced vertical loads and full lateral loads. To allow for large erection tolerances, absorb errors in the foundation's concrete works, adopt a local widely used solution, and achieve good seismic performance,[2–4] the footings were designed with a socket foundation with smooth interfaces. This detail provides significant resistance to uplift. According to a series of tests conducted,[5] a static shear strength of 620 kPa (90 psi) can be assumed in design for smooth contact surfaces. The values of shear strength given before should be reduced by a factor of 0.5 to take into account the possibility of unsupervised construction.

The horizontal force acting on the front transverse wall was obtained using the Leonhardt and Mönning equations[6] (**Fig. 4**) using the seismic load effect with an overstrength
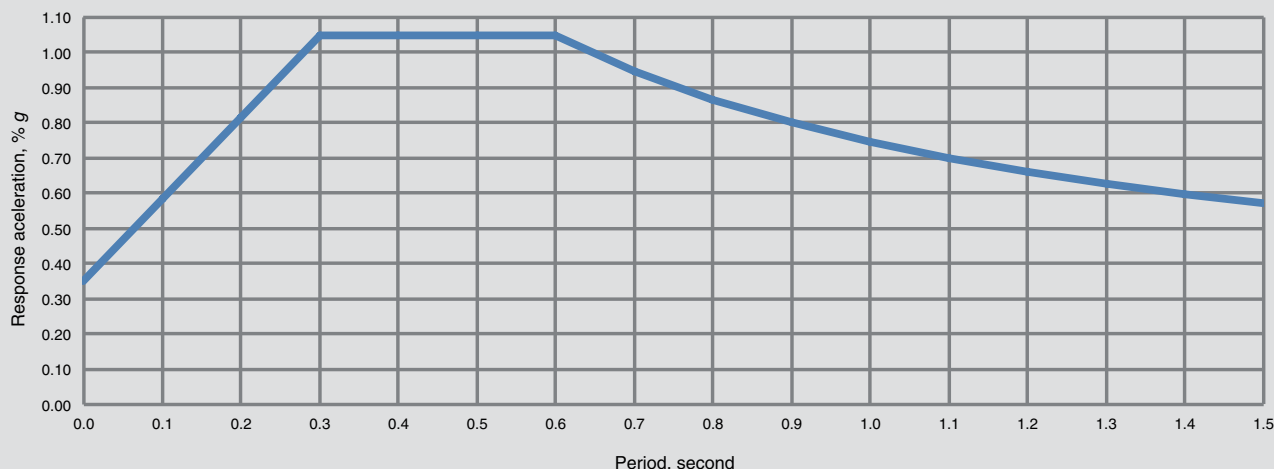
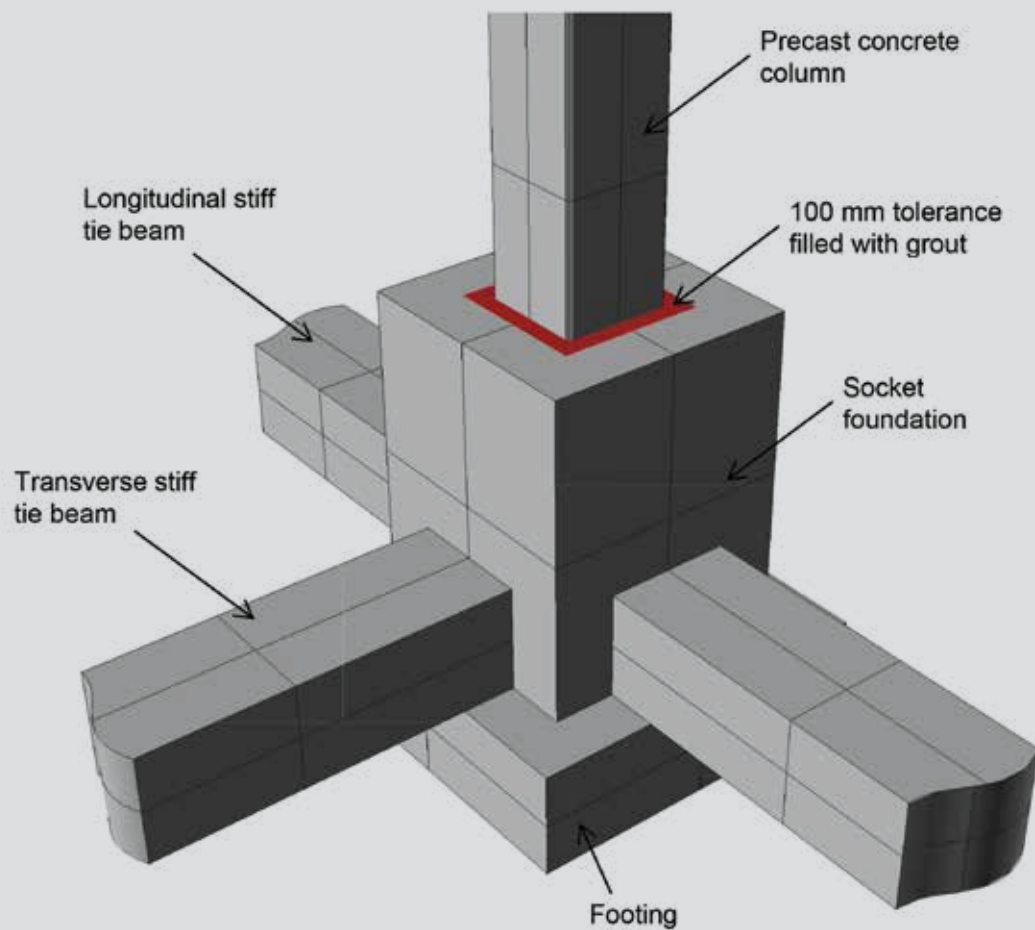**Figure 2.** Elastic design spectrum. Note: g = acceleration due to gravity.

Figure 3. Foundation system. Note: 1 mm = 0.0394 in.

$$H_o = \tfrac{3}{2} M/t + \tfrac{5}{4} H$$

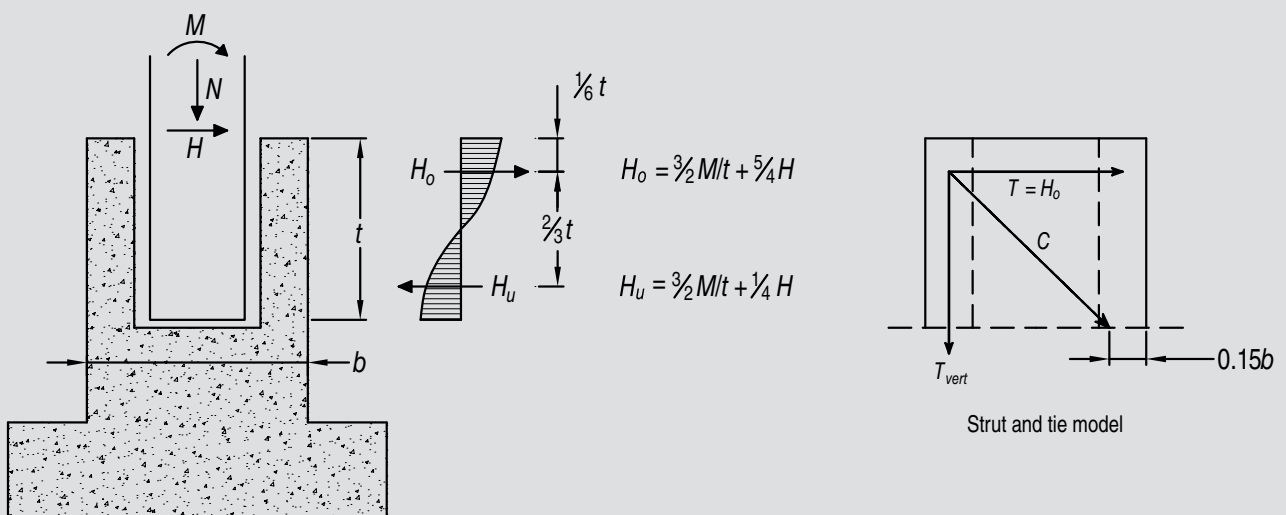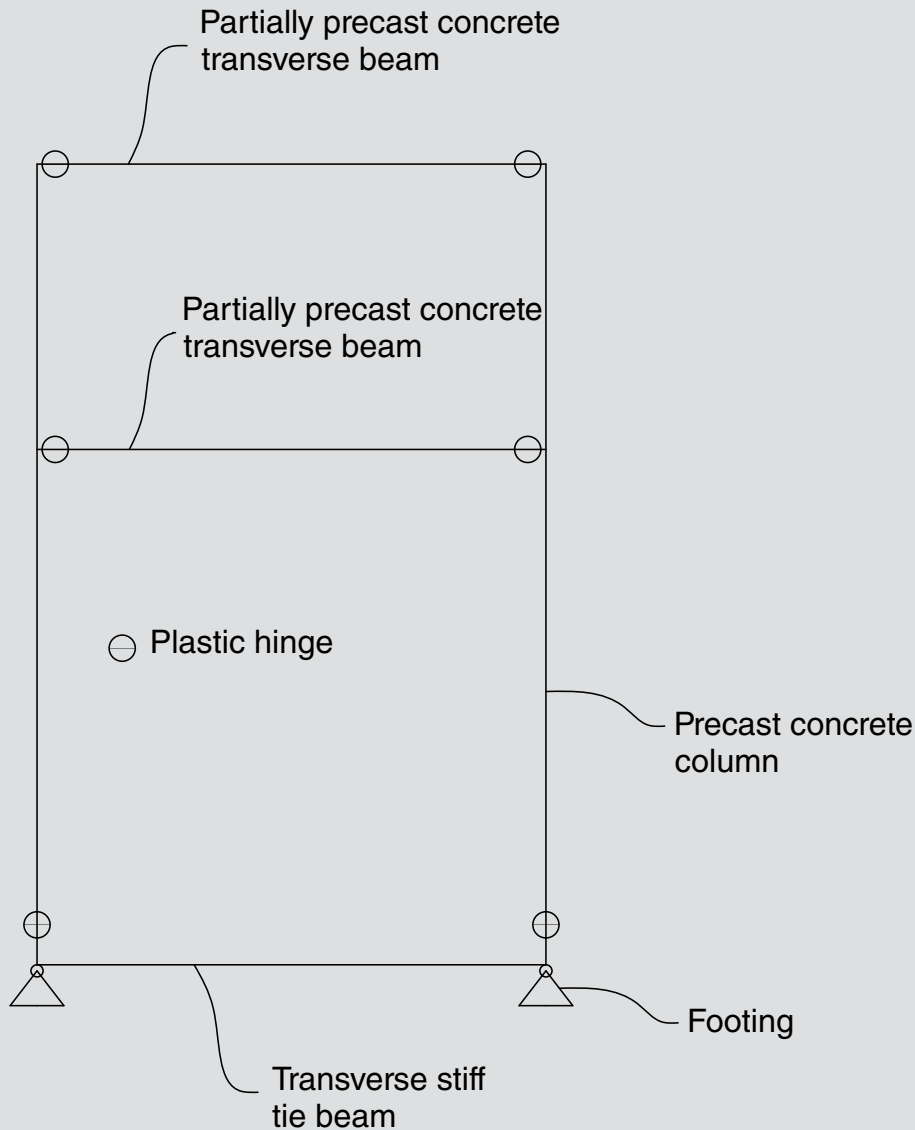$$H_u = \tfrac{3}{2} M/t + \tfrac{1}{4} H$$

Figure 4. Leonhardt and Mönning equations. Note: b = external width of the socket; C = compressive force of concrete; H = shear force; H_o = upper reaction force; H_u = lower reaction force; M = overturning moment; N = axial force; t = height of the socket; T = tensile force of horizontal reinforcement; T_{vert} = tensile force of vertical reinforcement.

Figure 5. Kinematic plastic mechanism.

factor Ωo to permit inelastic yielding in the columns only. Subsequently, the column was carefully detailed to ensure that estimated ductility demands could be reliably accommodated.

Transverse load-resisting system

The following features summarize the capacity design philosophy:[7]

- A kinematic admissible plastic mechanism was chosen to maximize overall ductility and minimize inelastic rotation demands in the plastic hinges.

- The plastic hinge regions were clearly defined.

- Parts of a structure intended to remain elastic were designed so that the maximum actions corresponding to overstrength in the plastic hinge did not result in inelastic deformation in those regions.

- A clear distinction was made with respect to the nature and quality of detailing for potential plastic hinge regions, and those that were to remain elastic in all events.

The frame structure was designed in accordance with the weak beam/strong column philosophy[8] (**Fig. 5**). Potentially brittle regions or those not suited for stable energy dissipation were protected by ensuring that their strength exceeded the demands originating from the overstrength of the plastic hinges.
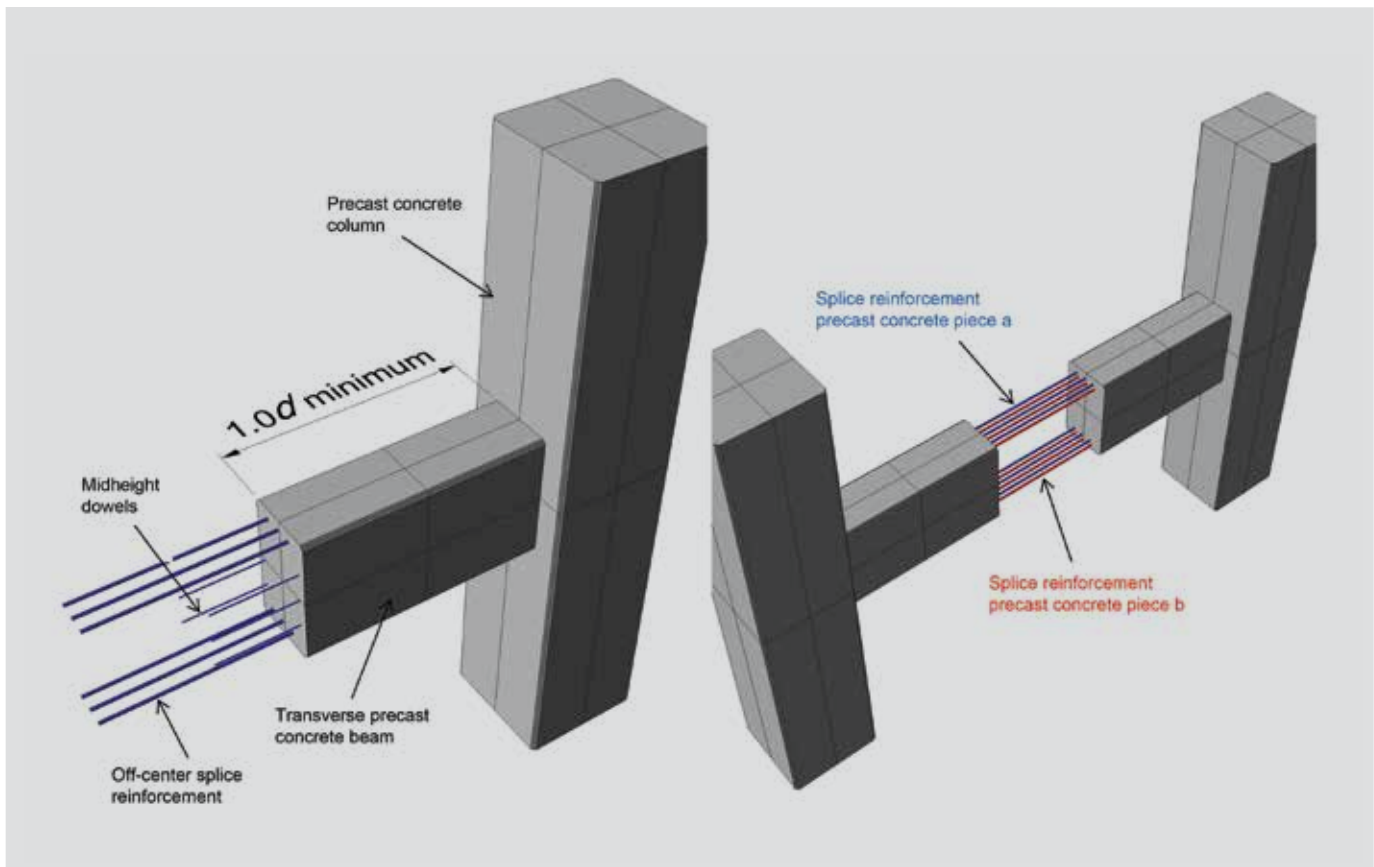
Figure 6. Off-center splice reinforcement. Note d = effective depth of the beam.

The fact that within the region of a potential plastic hinge, yielding of the reinforcement (in both compression and tension) must be expected (with possible strain hardening) invalidates the standard connection, in which the reinforcement splice is located at the beam-column joint. Both local and international structural codes prohibit bar splices at a distance closer than one effective depth of the beam. With this in mind, the splice was located at the midspan of the beam, away from the plastic hinge region, where the flexural moments due to lateral forces are smaller. This connection is widely used in several regions with high seismic demands, such as Hawaii and New Zealand.[9,10] Its seismic performance is well documented by tests conducted by Park, Restrepo, and Buchanan.[11] They found the following:

• The system can be analyzed and designed to emulate cast-in-place, reinforced concrete frames.

• Connections between precast concrete beams involving bar splices can commence as close as one effective depth of the beam from the critical regions where plastic hinges are expected without compromising strength, ductility, or energy dissipation.

• There is no need to specify a roughened surface or application of a bonding agent at the vertical construction joints.

• The splice length can be obtained considering the direction of casting of the concrete or top bar effect and the beneficial effect of the transverse reinforcement surrounding the lapped bars.

Based on these results, an F-shaped precast concrete element comprising the column, beam-column joint, and ends of the beams was designed. The splice reinforcement was located away from the centerline (**Fig. 6**) to avoid bar interference during erection and to minimize formwork cost. The design allowed the contractor to save on oversized hauling costs.

Once the precast concrete elements were erected, they were connected with cast-in-place concrete at midspan. The compressive strength of the joint concrete was specified to be at least as great as that of the precast concrete elements.

Longitudinal load-resisting system

Constructing longitudinal frames was quickly discarded because of the problems arising from fabrication, shipping, and erection of such a precast concrete element. In addition, concrete bracing was also discarded due to difficulties associated with its connections. In the longitudinal direction, a special steel, concentrically braced frame
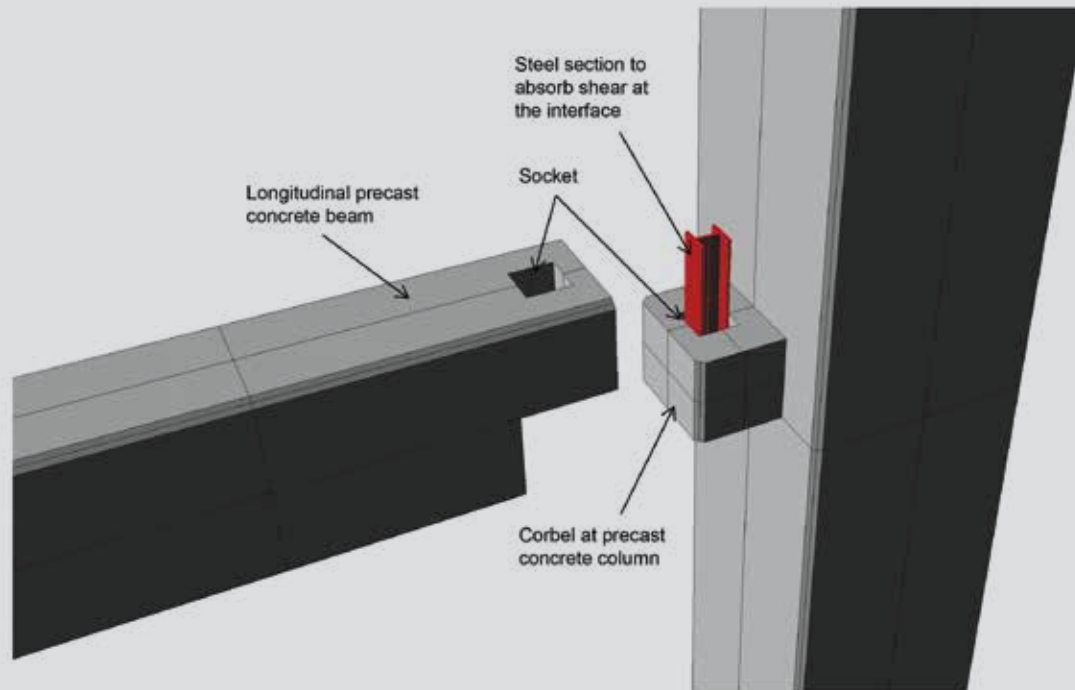
Figure 7. Beam-corbel connection.

was provided in accordance with the recommendations of American National Standards Institute (ANSI)/American Institute of Steel Construction (AISC) 341-05.[12] For all other items (including beam corbel, column corbel, and bolted connections), where reliable inelastic response or energy dissipation could not be provided, an overstrength factor Ωo was used to amplify the prescribed forces for use in design of such components or limit states.

Steel V-bracing with bolted connections was found to be the best solution for this particular case because of the following:

• The connection between the steel brace and the frame is located away from the plastic hinge region.

• All tolerances were able to be met between the different systems by leaving sockets on the pier.

• The ANSI/AISC 341-05 provisions require that a special concentrically braced frame system balance the compression and tension braces.

This kind of structure was studied and tested with satisfactory results by various authors.[13–15]

The longitudinal simply supported reinforced concrete beams, the dapped-end beam, and the corbels at the columns were designed to remain elastic by using the seismic load effect with an overstrength factor Ωo analogous to that for collector elements in the American Society of Civil

Engineers' *Minimum Design Loads for Buildings and Other Structures*.[16] With this concept in mind, this connection was designed by leaving sockets in the dapped-end beam and the corbel at the column (**Fig. 7**). The force transmission can be developed through proper embedment of a steel section into the socket. Strut-and-tie action was assumed in the design of the reinforcing. **Figure 8** shows the assumed internal truss system. Dry-pack grout was placed directly into the socket to ensure force transmission and connection durability. All calculations were made in accordance with PCI[17–18] and ANSI/AISC 341-05 recommendations.

The biggest challenge was to meet all tolerances among the different systems: cast-in-place concrete, precast concrete, and steel bracing. For the brace diagonals, a bolted joint connection with perpendicular, oversized holes in both plies was designed meeting the requirements for slip-critical connections using the seismic load effect with an overstrength factor. The oversized holes were sized according to the tolerances given in PCI's *Tolerance Manual for Precast and Prestressed Concrete Construction*.[19] In addition, an embedded steel plate was placed below the corbel for welding the connection plate (**Fig. 9**). The entire connection was also designed using the seismic load effect with an overstrength factor.

The connection between the steel brace and the longitudinal concrete tie beam was designed to allow large tolerances among the different systems. A concrete pier resting on the tie beam was introduced with three sockets
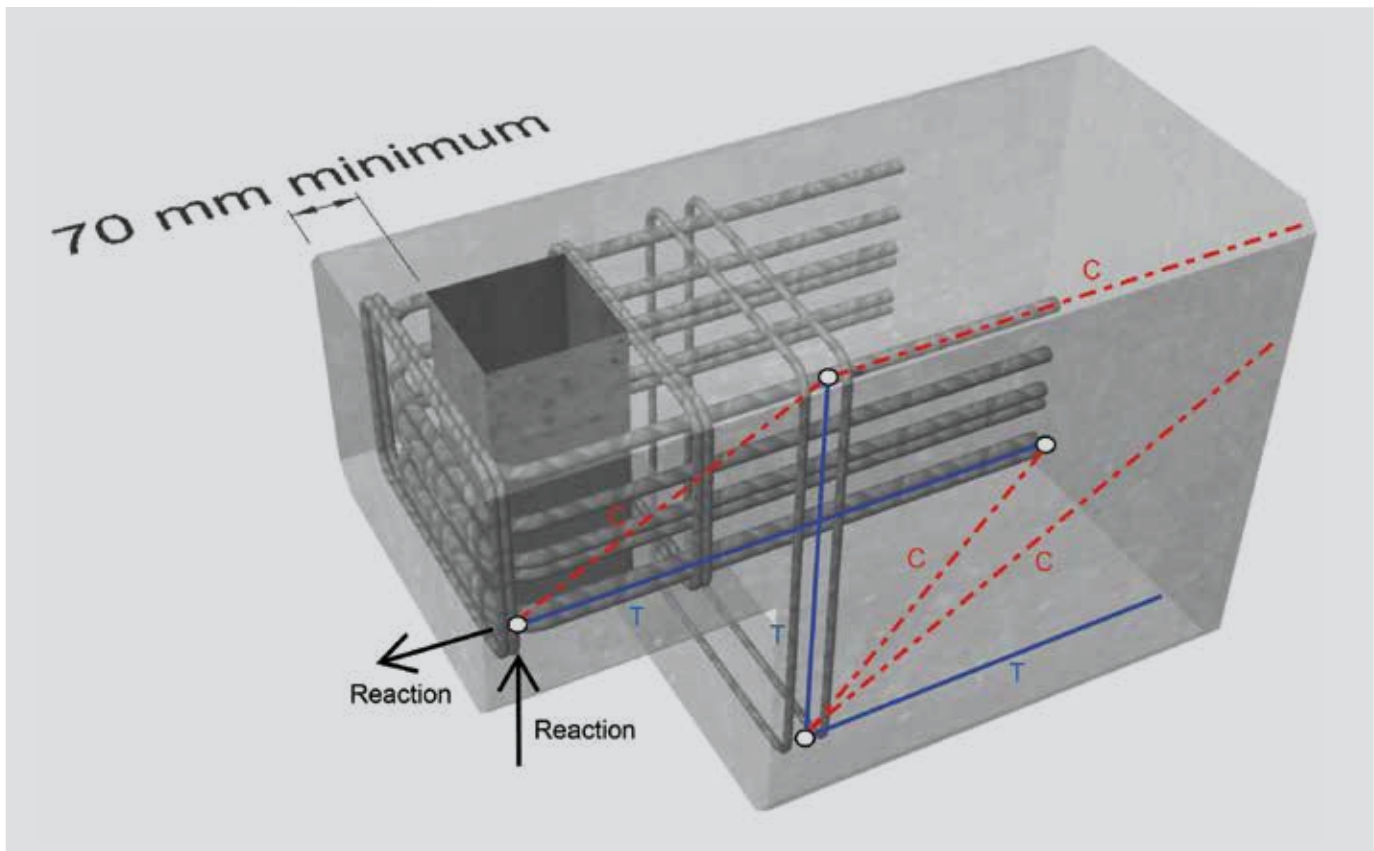
Figure 8. Beam-corbel internal truss system. Note: 1 mm = 0.0394 in.

intended to provide anchorage to the steel brace (Fig. 9). Once the steel brace was in its correct position, the sockets were filled with a dry-pack grout. With the implementation of this feature, the contractor was able to absorb possible construction and erection errors.

V-braced frames exhibit a special characteristic that sets them apart from braced frames comprising beam-column connections. As one of the braces buckles, an unbalanced vertical force must be resisted by the connection and supporting members.[12] To take this effect into account, the longitudinal beams, corbels, and pier were designed with an overstrength factor. In Argentina, the steel provision is more expensive than labor costs. For this reason, members with lattice ties are commonly used.

For longer pipe racks, contraction and expansion joints every five to six bays are required to reduce the forces on the steel bracing induced by temperature changes and concrete creep.

Casting, construction, and erection

Casting, shipping, alignment, and erection resulted as expected without any setbacks. Certain minimal changes were necessary to allow placement of the lifting devices. **Figures 10 through 12** show the construction and erection of the pipe rack.

Conclusion

This paper presents an innovative design philosophy developed for precast, reinforced concrete pipe racks in high seismic zones. From design and construction, the following conclusions were made:

- This case study in handling seismic conditions using precast concrete structural components shows that the use of the capacity design philosophy is fundamental for good seismic performance. Potentially brittle regions, or those not suited for stable energy dissipation, should be designed using the seismic load effect with an overstrength factor.

- By splicing the reinforcement at midspan, the connection is located away from the plastic hinge region.

- The use of a steel brace allowed compliance with the project requirements and shortened the construction time.

- A braced reinforced concrete frame designed using the same force reduction factor as that of a conventional moment frame with moderate ductility would behave adequately during an earthquake.

- The design of reinforced concrete sections in a braced reinforced concrete frame can be conducted using
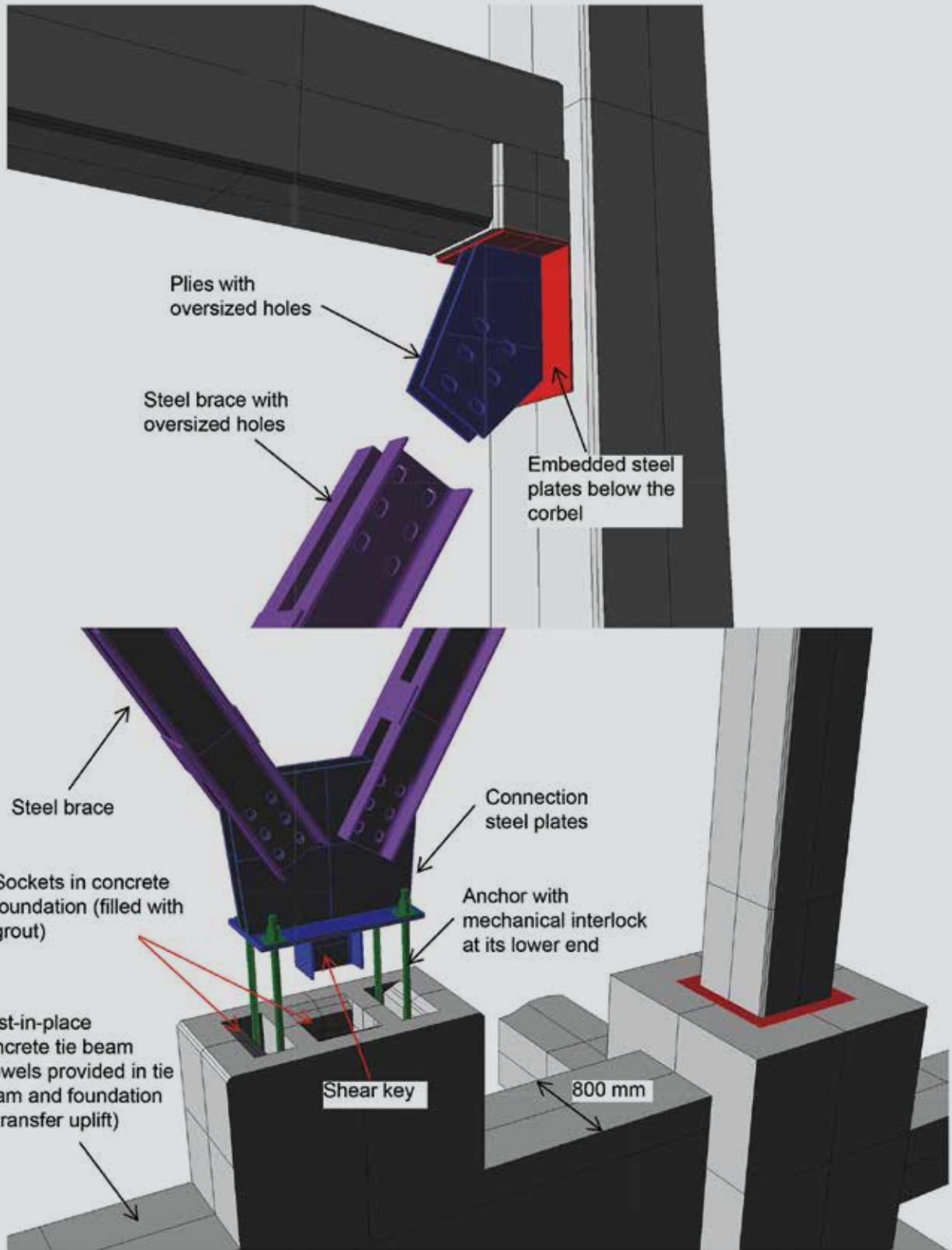
Figure 9. Steel brace connection/anchorage. Note: 1 mm = 0.0394 in.

Figure 10. Foundation construction.

Figure 11. F-shaped precast concrete elements.

conventional design methods. General reinforcement detailing requirements are adequate, and there is no need to use special seismic detailing.

• The brace members and their connections can be designed using a similar procedure to that for braces in steel structures.

References

1. Instituto Nacional de Prevención Sísmica Centro de Investigación de los Reglamentos Nacionales de Seguridad para las Obras Civiles. 1996. *Normas Argentinas Para Construcciones Sismoresistentes*. INPRES-CIRSOC 103. Buenos Aires, Argentina: Instituto Nacional de Tecnología Industrial.

2. Sezen, H., and A. Whittaker. 2006. "Seismic Performance of Industrial Facilities Affected by the 1999 Turkey Earthquake." *Journal of Performance of Constructed Facilities* 20 (1): 28–36.

3. Blandón, J., and M. Rodríguez. 2005. "Behavior of Connections and Floor Diaphragms in Seismic-Resisting Precast Concrete Buildings." *PCI Journal* 50 (2): 56–75.

4. Belotti, D., D. Bolognini, and R. Nascimbene. 2008. "Seismic Behavior of Reinforced Concrete Precast Traditional Italian Frames and Subassemblies." Paper presented at the 14th World Conference on Earthquake Engineering, Beijing, China, October 2008.

5. Concrete Technology Associates. 1976. "Composite Systems without Ties." Technical bulletin 76B4. Tacoma, WA: Concrete Technology Associates.

6. Leonhardt, F., and E. Mönning. 1977. *Vorlessungen über Massivbau*. Berlin, Germany: Springer Verlag.

7. Paulay, T., and N. Priestley. 1992. *Seismic Design of Reinforced Concrete and Masonry Buildings.* New Jersey: John Wiley & Sons.

8. Park, R. 1980. "Ductile Design Approach for Reinforced Concrete Frames." *Earthquake Spectra* 2 (3): 560–620.

9. Yee, A. 1973. "New Precast Prestressed System Saves Money in Hawaii Hotel." *PCI Journal* 18 (3): 10–13.

10. Park, R. 2002. "Seismic Design and Construction of Precast Concrete Buildings in New Zealand." *PCI Journal* 47 (5): 10–13.

11. Park, R., J. Restrepo, and A. Buchanan. 1995. "Test

Figure 12. Precast concrete frame.

on Connections of Earthquake Resisting Precast RC Frames." *PCI Journal* 50 (4): 44–52.

12. AISC (American Institute of Steel Construction). 2005. *Seismic Provisions for Structural Steel Buildings*. ANSI/AISC 341-05. Chicago, Illinois: AISC.

13. Maheri, M., and R. Akbari. 2003. "Seismic Behavior Factor, R, for Steel X-braced and Knee-Braced RC Buildings." *Engineering Structures* 25 (12): 1505–1513.

14. Youssef, M., H. Ghaffarzadeh, and M. Nehdi. 2006. "Seismic Performance of RC Frames with Concentric Internal Steel Bracing." *Engineering Structures* 29 (7): 1561–1568.

15. Viswanath, K., K. Prakash, and A. Desai. 2010. "Seismic Analysis of Steel Braced Reinforced Concrete Frames." *International Journal of Civil and Structural Engineering* 1 (1): 114–122.

16. ASCE (American Society of Civil Engineers). 2006. *Minimum Design Loads for Buildings and Other Structures*. ASCE/SEI 7-05. Reston, VA: ASCE.

17. PCI Industry Handbook Committee. 2010. *PCI Design Handbook: Precast and Prestressed Concrete*. 7th ed. Chicago, IL: PCI.

18. PCI. 2008. *PCI Connection Manual for Precast and Prestressed Concrete Construction.* 1st ed. Chicago, IL: PCI.

19. PCI. 2000. *Tolerance Manual for Precast and Prestressed Concrete Construction*. MNL 135-00. 1st ed. Chicago, IL: PCI.

Notation

b = external width of socket

C = compressive force of concrete

d = effective depth of the beam

g = acceleration due to gravity

H = shear force

H_o = upper reaction force

H_u = lower reaction force

M = overturning moment

N = axial force

R = response modification coefficient

t = height of socket

T = tensile force of horizontal reinforcement

T_{vert} = tensile force of vertical reinforcement

Ω_O = overstrength factor

About the authors

Sebastián Felipe Vaquero is a research engineer and an assistant professor in the Structural Engineering Department at the University of Buenos Aires in Argentina. He has been in engineering practice since 2006.

Damián Raúl Correa is a professor in the Structural Engineering Department of the University of Buenos Aires. He has been in engineering practice since 1998.

Sergio Fabián Wolkomirski is co-owner of Fontan Balestra & Associates, Buenos Aires, Argentina. He has been in engineering practice since 1995.

Abstract

The construction of a pipe rack in an operating petroleum refinery located in a high seismic zone in Argentina presents singular issues related to its construction and structural typology. In this particular case the structure was required to be made of precast reinforced concrete, as requested by the client to facilitate its construction, minimize on-site work, and comply with the applicable Argentinean regulatory requirements. In addition, the lack of bracing in the cross section was required to allow for maintenance of the pipes.

To comply with the boundary conditions, it was proposed to use precast reinforced concrete moment frames with a single cast-in-place concrete connection as the transverse load-resisting system, longitudinal precast reinforced concrete beams as shear keys, and steel bracing as the longitudinal load-resisting system. The connections comply with the requirements of the seismic code, taking into account the erection tolerances and minimizing on-site concrete work as well as working at heights.

This paper explains the calculation methodology and presents the results of the erection of the precast concrete frames.

Keywords

Connection, frame, pipe rack, reinforced concrete, seismic.

Review policy

Reader comments