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Novel use of buckling-restrained braces in precast concrete frames

- An industrial facility using precast concrete beams and columns with buckling-restrained braces to resist lateral loads was recently constructed in the New Madrid seismic zone.
- The lateral-load-resisting system was designed using well-established design procedures for buckling-restrained braces in steel frames.
- Careful consideration of fabrication and erection tolerances and communication among members of the design team, brace supplier, and contractor were vital to the successful erection of the braced frames.

Buckling-restrained braced frames are an innovative and relatively new solution for lateral-load resistance in steel-framed buildings in high seismic zones. Buckling-restrained braces consist of a steel core surrounded by a grout-filled tube to restrict buckling of the brace. These braces gained acceptance in the United States in the early 2000s and since that time have been used extensively for new construction and retrofitting existing buildings.[1,2] The design of buckling-restrained braces in steel frames is well established and has been codified by the American Institute of Steel Construction's AISC 341.[3] Buckling-restrained braces have also been successfully used in projects with cast-in-place concrete elements, such as the John Wayne Airport parking structure in Santa Ana, Calif.,[4] and the State Bar of California Building in San Francisco, Calif.[5] The subject of this article is a new building in northeast Arkansas that was recently constructed using steel buckling-restrained braces in precast concrete frames to resist lateral earthquake loads. While the use of buckling-restrained braces in precast concrete buildings is somewhat limited, buckling-restrained braces were chosen for this project due to their high response modification coefficient *R* and were deemed to be the most effective means of fulfilling all of the project requirements.

The braced frames used in this structure were designed using sound engineering principles, including the requirements outlined in AISC 341 for steel buckling-restrained braced frames. The design and manufacture of the buckling-restrained braces themselves and the load transferred by the braces to the supporting beams and columns is based on AISC 341 requirements. In addition to AISC 341 requirements, the engineer of record stipulated specific detailing requirements for the precast concrete members so that they may remain elastic in a seismic event. The provisions in AISC 341 do not explicitly apply to buckling-restrained braces in precast concrete frames; however, the authors were able to use sound engineering principles to ensure that this lateral-load resisting system is adequate for this application.

This structure is a food-processing facility located less than 100 mi (160 km) from the New Madrid seismic zone. This region is home to the infamous 1811 and 1812 earthquakes and several other earlier seismic events with a magnitude of 7.0 or higher.[6] The local building code requirements reflect this history of seismic activity and the high potential for large future earthquakes.

Mapped spectral response acceleration parameters at a short period S_s and a period of one second S_1 for the project site are equal to 0.807*g* and 0.284*g*, respectively, where *g* is acceleration due to gravity.[7] The geotechnical evaluation of the building site determined that the subsurface conditions are characteristic of Site Class C, which requires the structure to be designed and detailed to comply with the requirements of Seismic Design Category D.

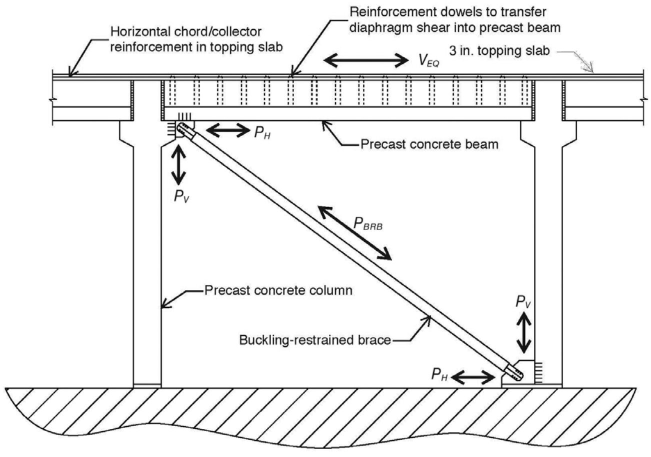
The 235,000 ft^2 (21,800 m^2) facility consists of several one- and two-story independent structures with seismic separation joints between areas with different structural systems. Some areas of the facility are framed with steel beams and columns with steel-braced frames or moment frames. Others are framed with precast concrete double tees and precast concrete shear walls.

Two areas of the facility require large open spaces and high ceilings to accommodate specialty equipment. One such area is a 190 × 230 ft (58 × 70 m) single-story structure with 30 to 50 ft (9 to 15 m) spacings between columns and a height of 25 ft (7.6 m). The other area is two stories framed with precast concrete on the lower level and structural steel on the upper level. This area is 90 × 290 ft (27 × 88 m) in plan, with 30 to 40 ft (12 m) spacings between columns.

During the initial design phase of the project, many lateral-load-resisting systems were studied for the two large open areas described previously, including cantilever concrete columns, precast concrete moment frames, and interior concrete shear walls. However, buckling-restrained braced frames with precast concrete beams and columns were deemed the best to meet the project requirements.

The use of moment frames or cantilever columns would have resulted in large columns and large seismic separation joints, both of which were considered unacceptable by the facility owner. Interior shear walls could not be used in these spaces because large openings are required for mechanical equipment to pass between building bays. Buckling-restrained braced frames were ultimately chosen due to their reduced impact on facility operations and superior seismic performance.

During the design development phase, preliminary pricing exercises substantiated that the cost of the buckling-restrained braces was competitive with the other options considered. There were also discussions regarding the differences in tolerances between precast concrete construction and structural steel construction, and it was decided that allowances would be necessary during construction to mitigate these differences.



Load path for seismic loads in the lateral-load-resisting system. Note: P_{BRB} = seismic load in buckling-restrained brace; P_H = horizontal load in brace connection; P_V = vertical load in brace connection; V_{EQ} = seismic load in roof diaphragm.

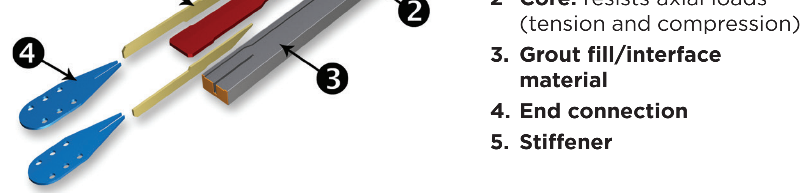
The use of buckling-restrained braced frames at the two building areas described resulted in a base shear of 605 kip (2690 kN) in the one-story area and 425 kip (1890 kN) in the two-story portion using a response modification coefficient *R* of 8.0.[7] The structural system in these areas consists of precast, prestressed concrete double tees with a 3 in. (75 mm) thick, normalweight, cast-in-place concrete topping slab supported by precast, prestressed concrete beams, and columns. The concrete topping slab functions as the roof/floor diaphragm, transferring lateral loads into the precast concrete beams using steel reinforcement dowels and shear friction. The load in the beams is then transferred into the buckling-restrained braces and columns via embedded steel plates and steel gusset plates.

The steel cores of the buckling-restrained braces resist axial compression and tension forces, and the grout-filled encasement prevents the steel from buckling. The core of the brace is decoupled from the grout fill, allowing the steel element to axially deform and yield without engaging the grout-filled encasement. There is a steel lug at the ends of the buckling-restrained brace core that connects the brace to a gusset plate either by bolts, by welds, or with a single pin. Fabrication of buckling-restrained braces requires stringent testing, and the buckling-restrained brace supplier must provide test data showing that the braces will perform as intended when subjected to earthquake loads.

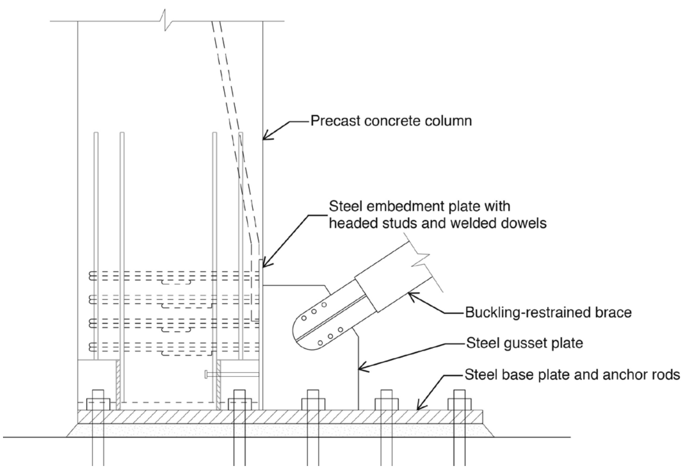
During the final design stages of the project, the engineer of record worked closely with the buckling-restrained brace supplier to size the braces. The structure was analyzed in accordance with the local building code using the equivalent-lateral-force procedure, and the engineer of record determined the braced frame layout and preliminary steel core area. The required core area was determined by dividing the load demand by the yield strength of the steel in the brace. The engineer of record provided the buckling-restrained brace supplier with the frame layouts and brace sizes in addition to a finite element model. Using this information, the buckling-restrained brace supplier verified the engineer of record's analysis and provided brace stiffness values and overstrength factors. The stiffness values were used to check seismic drifts to confirm compliance with the allowable limits listed in *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-10.[7] These drifts were also used to size the seismic separation joints.

For this type of lateral system, the overstrength factors are important in determining the load demands on gusset plates, embed plates, and precast concrete beams and columns. The overstrength factor β is defined by AISC 341 as the compression adjustment factor and ω is defined as the strain hardening adjustment factor, both of which are determined from testing performed by the buckling-restrained brace supplier. An additional adjustment factor R_y is also used in buckling-restrained braced frame design to account for the expected yield strength of the steel material. AISC 341[3] defines R_y as the ratio of the expected yield stress to the specified minimum yield stress. To reduce uncertainty and reduce the design loads on the precast concrete connections, the engineer of record required that coupon tests be performed on all the steel used in the braces, essentially eliminating R_y by making it equal to 1.0. Knowing the yield stress of the brace steel, the buckling-restrained brace supplier was able to fabricate the braces with the exact steel area required.

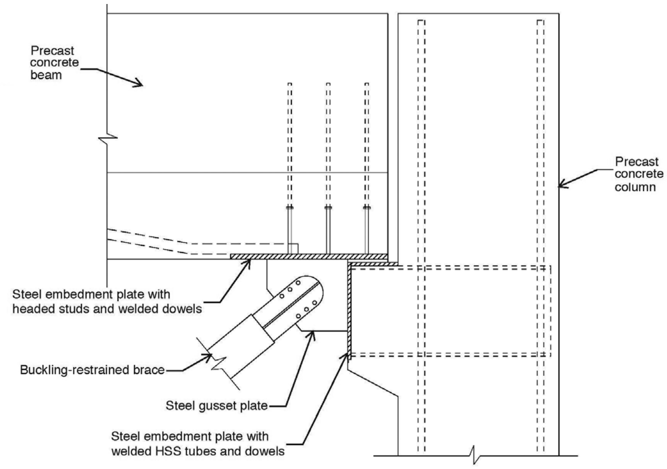
Structural drawings and specifications prepared by the engineer of record included all pertinent information for both the buckling-restrained brace supplier and the specialty precast concrete engineer, including the required



A typical buckling-restrained brace, including an exploded view illustrating each component of the brace. Courtesy of CoreBrace.



Connection detail of buckling-restrained brace to base plate and precast concrete column.



Connection detail of buckling-restrained brace to precast concrete beam and column. Note: HSS = high-strength steel.

area of steel for each brace. The construction documents stipulated that the buckling-restrained brace supplier provide the loads, including all relevant overstrength factors, required at the connection of the braces to the other components of the frame. Loads in the buckling-restrained braces for this building, including all overstrength factors, ranged from approximately 120 to 270 kip (530 to 1200 kN).

The design of the gusset plates connecting the buckling-restrained braces to the precast concrete embedment plates was the responsibility of the steel fabricator, and the design of the embedment plates, including the attachment of the embedment plates to the precast concrete members, was the responsibility of the precast concrete specialty engineer. The precast concrete corbel had to be designed to resist a combination of gravity loads and earthquake loads in accordance with load combinations listed in the local building code, and the design of the corbel was the responsibility of the precast concrete specialty engineer. At the top brace connections, the design of the gusset plates and determination of the loads transferred from the gusset plate to the precast concrete members assumed that the entire horizontal component of the brace force goes directly into the embedment plate attached to the precast concrete beam and the entire vertical component of the brace force goes directly into the embedment plate attached to the precast concrete column and corbel.

Prior to fabrication of the buckling-restrained braces, the engineer of record organized a meeting of all appropriate parties to discuss the design criteria and thoroughly reviewed the buckling-restrained brace, precast concrete, and structural steel submittals to ensure that all parties understood the design intent. The buckling-restrained brace supplier also coordinated with the precast concrete supplier to precisely locate embedment plate locations for attaching the braces to the precast concrete members. The buckling-restrained braces and gusset plates were detailed as fully bolted connections; however, the connection design allowed for the lugs to be either bolted or welded, providing some flexibility in the field. Because of the differences in construction tolerances between steel and precast concrete, it was possible that the bolt holes might not align during erection.

Due to the relatively long lead time for the buckling-restrained braces, which was compounded by a requirement that the braces be hot-dip galvanized, they were put into production prior to the precast concrete being erected. Precast concrete columns and beams were erected with special attention paid to tolerances, and all elements were erected within PCI recommendations.[8] While fabrication tolerances between steel and concrete structures are different, erection tolerances, such as acceptable out-of-plumbness of columns, are similar in steel and concrete construction. The table shows the tolerance requirements for both steel and precast concrete construction, which demonstrates the differences between the two types of construction.[8–10]

Erection/fabrication tolerances

Criterion	Precast concrete	Structural steel
Beam/column depth, in.	±1/4	±1/8
Column length, in.	±1/2	±1/32
Beam length, in.	±3/4	±1/16 for ≤ 30 ft ±1/8 for > 30 ft
Column variation from plumb	1/4 in. per 10 ft = 1/480	1/500

Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Typical buckling-restrained braced frame.

After precast concrete erection, the general contractor verified all precast concrete column and beam locations using laser measurements, allowing the gusset plates to be fabricated taking into the account the as-built conditions. The braced frames were erected by first welding the upper gusset plate to the embedments in the precast concrete beam and column. The buckling-restrained brace was then connected with a single erection bolt, swung into place, and aligned with the lower connection. Any fit-up problems discovered between the lower gusset plate and the buckling-restrained brace were rectified by field trimming the gusset. The gussets were fabricated slightly oversized to allow for this trimming. After all fit-up issues were resolved, the lower gusset plate was welded to the lower embedment plate and column base plate. Finally, the buckling-restrained brace was attached to the upper and lower plates with the required number of bolts. Thanks to careful coordination between the design team and the contractor, this diligence and precision prior to gusset plate fabrication allowed for problem-free installation of the braces and none of the buckling-restrained brace lugs needed to be welded to the gusset plates.

As buckling-restrained braces continue to gain acceptance in steel-framed buildings and in new and retrofit applications for cast-in-place concrete structures, the use of buckling-restrained braces in precast concrete

Typical lower connection of buckling-restrained brace to base plate and precast concrete column.

Typical upper connection of buckling-restrained brace to precast concrete beam and column.

frames has the potential to play a significant role in precast concrete structures located in high seismic zones. Using sound engineering principles and well-established design procedures for buckling-restrained braces in steel frames, this structure has been successfully designed, permitted, and constructed in the New Madrid seismic zone. With an *R* of 8.0 and relatively small connection forces, the use of buckling-restrained braces with precast concrete frames was determined to be the best option for lateral-load resistance in this structure. Although careful consideration of fabrication and erection tolerances was critical, communication between members of the design team allowed for successful completion of the project.

Acknowledgments

The authors served as the engineer of record for this project and would like to thank other members of the design team, including Charles N. Clark and Associates. The authors would also like to thank the buckling-restrained brace supplier, CoreBrace; the precast concrete specialty engineer, Salmons PC; the precast concrete supplier, Prestressed Casting Co.; and the general contractor, Jesco Construction Inc.

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Notation

g = acceleration due to gravity

P_{BRB} = seismic load in buckling-restrained brace

P_H = horizontal load in brace connection

P_V = vertical load in brace connection

R = response modification coefficient

R_y = ratio of the expected yield stress to the specified minimum yield stress

S_1 = mapped spectral response acceleration parameter at a period of 1 second

S_s = mapped spectral response acceleration parameter at short periods

V_{EQ} = seismic load in roof diaphragm

β = compression strength adjustment factor

ω = strain hardening adjustment factor

About the authors

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Abstract

An industrial facility using precast concrete beams and columns with buckling-restrained braces to resist lateral loads was constructed recently in the New Madrid seismic zone. The lateral-load-resisting system was designed using established design procedures for buckling-restrained braces in steel and cast-in-place concrete frames. Careful consideration of fabrication and erection tolerances and communication among members of the design team, brace supplier, and contractor were vital to the successful erection of the braced frames.

Keywords

Buckling-restrained brace, design, seismic, tolerance.

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