ACCELERATED BRIDGE CONSTRUCTION IN WASHINGTON STATE – FROM RESEARCH TO PRACTICE

by
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ABSTRACT

The Federal Highway Administration is actively promoting Accelerated Bridge Construction (ABC) as part of the "Every Day Counts" initiative, in an effort to reduce bridge construction time while improving work-zone safety and minimizing environmental impacts. The "Every Day Counts" initiative promotes Highways for LIFE (HfL) projects, allowing states to implement new and innovative technologies for better performance of prefabricated bridge elements in seismic zones. Prefabricated bridge components are in increasing demand for accelerated bridge construction. Precasting eliminates the need for forming, casting, and curing of concrete on site, making bridge construction safer while improving quality and durability. This paper describes the development and implementation of a precast concrete bridge bent system suitable for ABC in high seismic zones, such as western Washington State. At the base of the bent, the column is connected to a spread footing using a socket connection, while at the top the column is joined to the cap beam using bars grouted in ducts. In both cases the connection was verified by testing before the system was implemented on site by the Washington State Department of Transportation (WSDOT). WSDOT has been aggressively pursuing ABC, and this bridge bent system forms part of that effort.

Keywords: Bridge, ABC, LRFD, HFL, Precast, Seismic, Connections, Rapid Construction

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INTRODUCTION

Bridge construction frequently leads to traffic delays, which incur costs that can be measured in terms of time, wasted fuel and emotional distress. Transportation agencies are therefore seeking methods for accelerating bridge construction, commonly referred to as Accelerated Bridge Construction (ABC). Use of precast concrete for bridge substructures offers potential time savings on site and represents promising technology for ABC. Furthermore, limiting the amount of on-site work improves safety for both the motoring public and highway workers, and reduces environmental impacts. For these reasons, transportation agencies are gradually embracing the ABC philosophy for many of their urban construction projects.

Connections in precast substructures are typically made at the beam-column and column-foundation interfaces to facilitate fabrication and transportation. However, for structures in seismic regions, those interfaces represent locations of high moments and shears, and large inelastic cyclic strain reversals. Devising connections that are not only sufficiently robust to accommodate those inelastic cyclic deformations, but are also readily constructible, is the primary challenge for ABC in seismic regions. This paper describes the development, experimental validation and implementation on site of a precast concrete bridge bent system that is intended to meet those challenges. The development was possible only by close cooperation among members of the team, which included the disciplines of design, research, precast fabrication and construction.

POTENTIAL BENEFITS OF ABC AND CRITERIA FOR SELECTION

The primary benefits of ABC accrue from the savings of time on site. Conventional bridge construction typically induces traffic congestion and delays for an extended time period. The induced traffic congestion adversely affects individual travelers' budgets and the region's economy, impacts air quality due to increased vehicle emissions, and reduces quality of life due to personal time delays. Also, untimely service due to delays for workforce, supplier, and customers can incur significant costs to the traveling public and region businesses.

Prefabrication of structural elements is the essence of accelerated construction. Although prefabrication can decrease total contract time, reduction of the time spent on site is the critical component. The details of ABC usage in Washington State and WSDOT's strategic plan for ABC are given in Reference 1.

Precast units are often constructed in specialized plants. There, repetitive construction permits investment in high-quality steel forms, which more easily allow for high-quality finishes and accurate dimensional control. Plant precasting also allow tight quality control of materials, rapid production, good schedule control, and the possibility of prestressing. Site precasting offers other advantages, such as allowing workers to work at ground level, and removing the need for, and limitations of, long-distance transportation to the site. While precasting the substructure may impose a construction cost premium, it can often be offset by the economic benefits of the time saved through ABC.

USE OF PRECAST SUBSTRUCTURES IN SEISMIC REGIONS

For many years the State of Washington has designed and constructed precast, prestressed concrete girder superstructures because they have proven durable and cost-effective. Girder technology has been continually improved so that spans in excess of 200 ft are now possible[2].
However, precast substructures have seldom been used in high seismic regions. Western Washington is such a region. The transverse seismic forces cause the largest moments to occur at the connections, as

shown in Fig. 1. Those connections must be moment-resisting and robust under cyclic loading in order to maintain the integrity of the structure, but if the members are precast, the connections must also be easy to assemble on site. Achieving both characteristics simultaneously represents a significant design challenge.

In Washington State, the cap beam is typically poured in two stages. In a cast-in-place bridge bent, the lower stage is first cast on the columns, then the girders are set on it, and finally the upper stage is cast with the deck slab.

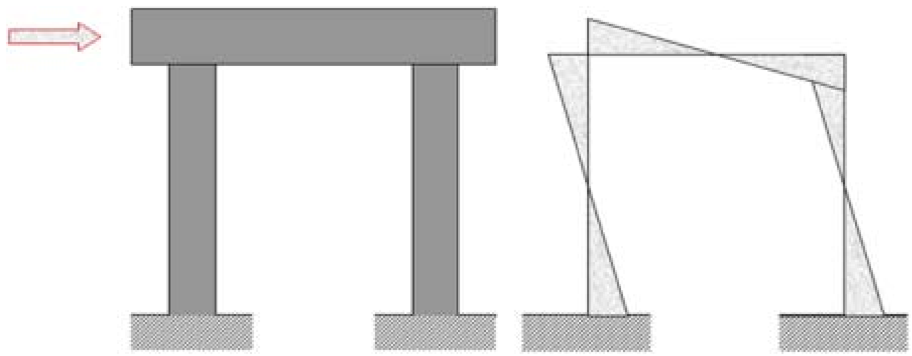

Fig. 1: Moment Diagram of a Bridge Pier with Fixed Connections

Under longitudinal seismic loading, it is highly desirable that a moment connection exist between the girders and cap-beam. Such a system is referred to as an integral bent cap and is commonly achieved by casting the upper-stage cap beam around bars and strands that project from the girder ends, thereby connecting them rigidly to the completed cap beam. In the absence of such a moment connection the columns must act as cantilevers, and such a system is not as efficient as one in which plastic hinging occurs at both the top and bottom of the columns.

DESIGN SPECIFICATIONS AND GUIDELINES

Currently there are two methods for seismic design of bridges: 1) Force-based design by the AASHTO LRFD Bridge Design Specifications (AASHTO LRFD)[3] and, 2) Displacement-based design by the AASHTO Guide Specification for LRFD Seismic Bridge Design (LRFD Seismic Guide Specification)[4].

WSDOT's seismic design is based on the LRFD Seismic Guide Specification as modified by the WSDOT Bridge Design Manual (WSDOT BDM)[5]. The displacement-based design is intended to achieve a "No Collapse" condition for bridges using one level of Seismic Safety Evaluation, and the fundamental design principle is "capacity protection", where selected elements are identified for plastic hinging while others are protected against potential damage by providing them with sufficient strength. The displacement-based analysis is an inelastic static analysis using expected material properties of modeled members. This methodology, commonly referred to as "push over" analysis, is used to determine the reliable displacement capacity of a structure or frame as it reaches its limit of structural stability.

The procedure outlined below is for displacement-based analysis and applicable to bridges made of precast components. The basic assumption is that the displacement demand obtained from linear-elastic response spectrum analysis can be used to estimate the displacement demand even if there is considerable nonlinear plastic hinging.

1. Develop an analytical model with appropriate foundation stiffness and yielding member stiffness based on moment-curvature relationships. For capacity protected members consider cracked section properties, including cracking of precast girder-to-diaphragm connection.
2. Perform linear elastic response spectrum analysis of the bridge based on design acceleration spectra specified by national or local specifications.
3. Determine the lateral and longitudinal displacement demands at each pier, including appropriate directional combinations.
4. Perform pushover analysis of each pier in the local transverse direction and in the longitudinal direction. For this purpose, the plastic hinging behavior for each column must be included, and this will generally be based on the moment-curvature relationships used in Step 1. Use foundation stiffnesses that are consistent with those used in the displacement demand model.
5. Compare the total displacement capacity of the pier, based on concrete and steel strain limits, to the displacement demand. Also compare the displacement ductility demand to the permissible capacity. If either the displacement or ductility capacity is insufficient, then revision is required.
6. Capacity protect the superstructure and foundation for the overstrength forces (typically, 20% higher capacity than the plastic capacity of the columns) to make sure that plastic hinges occur within the column. Also capacity protect the column in shear for these same overstrength forces.

CONFIGURATION SELECTED

Fig. 2 shows the configuration of the system that was developed. It consists of a cast-in-place spread footing, a precast column and a precast first-stage cap-beam. The second-stage cap beam is cast in place, just as it would be in a fully cast-in-place system. The footing-to-column and column-to-cap beam connections are the critical elements that lead to the system's viability, and the genesis of each is reviewed here.

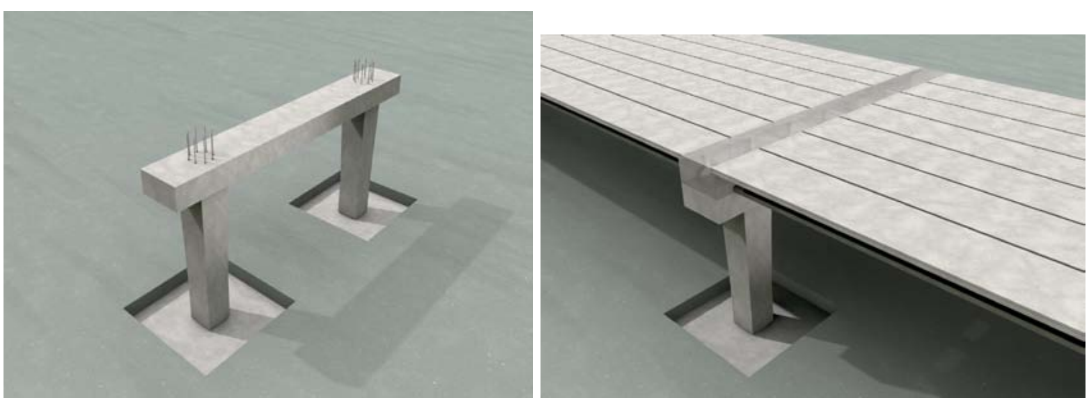

Fig 2: HfL System Configuration

The footing-to-column connection is referred to as a socket connection. It is made by placing the precast column in the excavation, placing the footing steel, then casting the footing concrete. Alternatively, the footing steel may be placed before the column is set. The precast column-to-footing connection's primary advantage is construction speed, because it allows a footing and a column to be cast in little more time than that needed to cast a footing alone. Furthermore, because the connection strength is much greater than the weight of the cap beam, the footing needs to gain only a fraction of its full strength before the cap beam can be placed. The time to the start of setting girders on the cap beam is a critical measure of the savings provided by the bent system.

The socket concept was used previously in Washington State in a modified form. In that case, the contract called for cast-in-place columns, but the contractor elected to precast them on site, and to use a socket connection in order to save time. The footing was 6 ft (1.8 m) thick, the columns were 4 ft (1.2 m) square, and the connection between them was made by both roughening the column surface locally and by adding horizontal form-saver bars. Those bars screwed into threaded couplers embedded in the face of the column within the depth of the footing to provide shear friction across the interface, and were inserted after the column had been placed.

Fig. 3: Socket Connection Concept

The column-to-cap beam connection was made with vertical bars projecting from the column that were grouted into ducts in the cap-beam. The concept was also used once previously in the high seismic zone of western Washington State. Figure 4 shows fabrication and subsequent placement of that precast bent cap. The bridge site is in an extremely congested urban area with high visibility from the traveling public and high scrutiny from associated municipalities. To open the bridge as quickly as possible, the contractor proposed precasting the cap beams for the intermediate piers instead of casting them in place as shown on the contract plans. This change saved the owner and the contractor several weeks on the contract duration. The columns were reinforced with the same 14 #14 column bars as on the original plans. They were grouted into 4” (100 mm) galvanized steel ducts that were placed in the precast bent cap using a template. The cap beams weighed approximately 100 tons (890 kN) each and were precast on the ground adjacent to the columns.

Fig. 4: Precast Bent Cap under Construction in Washington State

For the system described in this paper, the grouted bar-beam connection was modified by using the largest bars possible, up to and including #18 (D57) bars. That choice allows the ducts to be large in diameter and few in number; both features facilitate fit-up on site and reduce the probability of accidental misalignment. However, anchorage of such large bars within the depth of the cap beam is not possible if the development length equations of AASHTO LRFD must be satisfied. Previous studies had indicated that bars grouted into ducts resulted in significantly shorter development lengths than predicted by the standard equations due to the confinement provided by the duct, but those studies examined smaller bars and tighter ducts than proposed here. Research was therefore undertaken to determine the development properties of large bars grouted into large-diameter ducts[6], and the response of such connections to cyclic lateral loading[9]. That research is described in detail below.

The cap beam-to-column connection for the proposed system is shown in Fig. 5. A precast concrete column, with six #18 (D57) vertical column bars projecting from the top, is placed in the excavation, braced, and then the footing is cast around it. Later, the precast cap beam, which contains 8 in. (200 mm) diameter corrugated metal ducts, is fitted over the column bars and grouted in place, completing the bent. The selection of 6 #18 vertical column bars reduces the congestion at the column-to-cap beam connection while providing generous assembly tolerances.

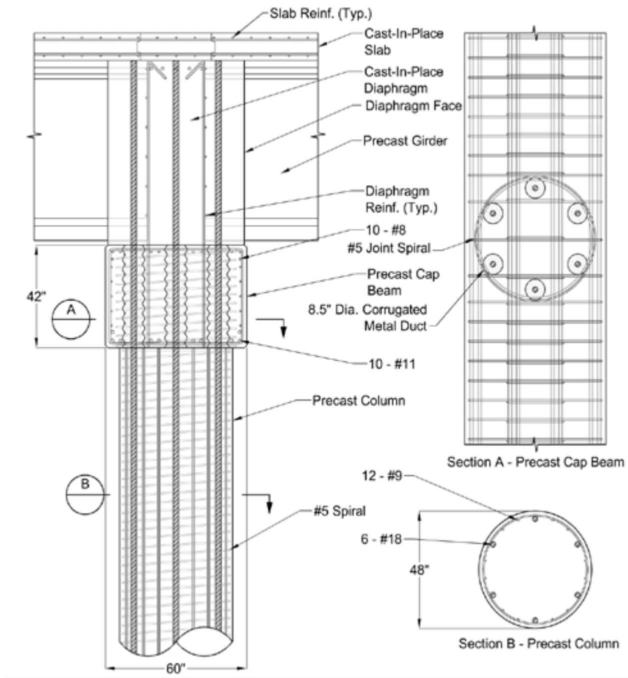

Fig. 5: Column to Cap Beam Connection

The top and bottom connections are different because, even though the seismic performance requirements are similar in both locations, the construction needs are not. A spread footing for a typical overpass is generally too heavy for precasting to be viable, so it is likely to be cast in place. Then, the socket connection provides generous tolerances and fast construction. However, using the socket concept at the top would mean casting the cap beam in place, and that would eliminate much of the time advantage of prefabrication. Thus a socket connection at the base and a grouted-duct connection at the top were selected as practical solutions to this problem.

The connections may be compared with other alternatives, such as those given in ref. 10. For example, grouted sleeves have been adopted for the base connection by a number of agencies, such as the State of Utah. The sleeves are typically cast into the column and fit over bars projecting upwards from the footing. The socket system proposed here has the advantages that the placement tolerances for the column are significantly greater than those available with a sleeve system, and the connection requires no special or proprietary hardware.

SUPPORTING RESEARCH – CAP BEAM CONNECTION

The major questions about the system that required investigation concerned the connections. At the cap beam, the dominant issues were anchorage of large bars in ducts and the inelastic cyclic performance of a moment connection made with large bars.

The bar anchorage demands can be divided into two categories. For the first-stage precast cap beam, the length available for bar development is limited by the depth of the cap beam, and the loads consist of the weight of the girders and slab. (The second-stage cap beam is typically cast with the last section of slab, so most of the slab weight will be in place before the second stage is cast). Because all the girders on one side of the cap beam may be placed before any are set on the other side, the cap beam may experience torsional loading. It is this torsional loading that leads to the potential for tension stress in the bars, which controls the development demand in the first-stage precast cap beam. In the great majority of cases, anchorage sufficient to develop the yield strength of the bar would be sufficient to resist the construction loads.

To investigate the development of bars grouted in steel ducts, the University of Washington[6] performed fourteen monotonic pullout tests with bars as large as No. 18. They supplemented a previous test series at smaller scale[7].

The material characteristics in the tests included: ASTM A706 Grade 60 deformed reinforcing bars, corrugated galvanized pipes, and cementitious grout with compressive strength of 8.0 ksi (56 MPa). The corrugated pipes are available in diameters from 6 in. (152 mm) to 12 ft (3.7 m). The pipes have thicker walls, deeper corrugations and potentially better bond and confinement properties than those of standard post-tensioning duct.

The results of the pullout tests are summarized in Fig. 6, which shows the bar stress at failure plotted against embedment length. To permit comparison among different bar sizes, the embedment length is normalized with respect to bar diameter. In the nomenclature for the tests 18N06 means a #18 bar, with no fiber in the grout, embedded 6 bar diameters. The letter F signifies fiber in the grout, and S indicates a failure near the surface, which was controlled by a tension failure cone in the concrete surrounding the duct, rather than a shear failure in the grout. A nonlinear numerical model was calibrated against the test results, and the model's results are also shown.

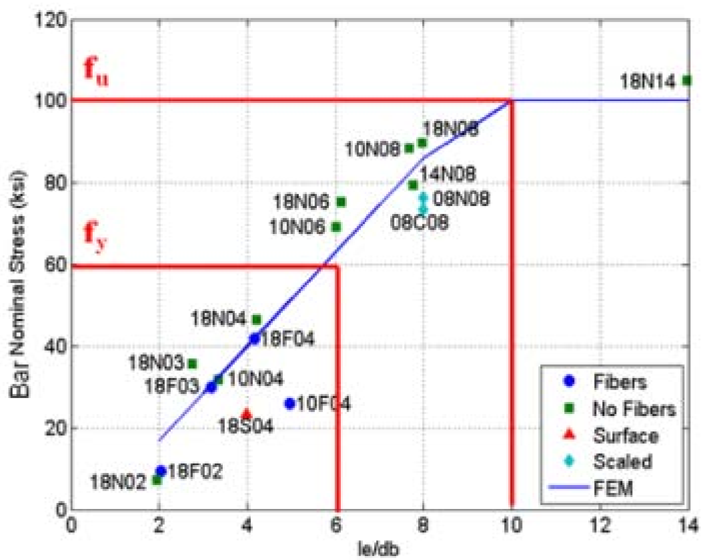

Fig. 6: UW Grouted Bar-Duct Pullout Test Results

Once the anchorage properties under monotonic tension loading had been established, column-to-cap beam connection tests were conducted under cyclic lateral loading[8]. A typical test is shown in Fig. 7. The specimens were tested upside down for convenience, so the cap beam could be bolted to the base of the test rig. The specimens were 42% scale, so the 20" (508 mm) test column represented a 48" (1220 mm) prototype. The goal was to investigate the behavior of complete grouted bar connections under cyclic lateral load.

Fig. 7: Test Setups of Large Bar-duct Pullout and Column-to-cap beam Connection

SUPPORTING RESEARCH – SPREAD FOOTING CONNECTION

FHWA awarded a Highways for LIFE (HfL) project to the team, with the goal of combining the upper connection and the socket footing connection into a complete bent, which would be taken to the point of implementation on site. To achieve that goal, three socket connections were tested in the laboratory[11], and a bridge was then constructed with the system over Interstate-5

The goal of the laboratory tests was to evaluate the connection’s response to combined cyclic lateral load and constant vertical load. The test specimens consisted of 20” (508 mm) diameter, precast concrete columns embedded in cast-in-place foundations. The columns were cantilevers, and were loaded at a location that corresponded to the inflection point in the prototype column. The cantilever height was 60” (1524 mm), or three column diameters. Fig. 8 illustrates the construction and testing.

In the first two spread footing specimens, SF-1 and SF-2, the footing depth was approximately equal to the column diameter. These proportions are typical of cast-in-place construction. Those two specimens failed in the column with no damage at all to the footing, so a third specimen was constructed with a footing depth that was only half the column diameter. The goal was to force failure into the connection region in order to gain a better understanding of the flow of forces there and the possible failure mechanisms.

Fig. 8: UW Test setups for precast column-to-footing connection

SITE IMPLEMENTATION

Following the testing of the foundation connection, and based on the success of the column-to-cap beam connection, a demonstration project that uses these connections was planned and executed by WSDOT as part of the Highways for LIFE project[11]. The objective of the project was to demonstrate the constructability of the bent system on a bridge project that would be competitively bid. The demonstration project is a replacement bridge that was built on an alignment parallel to an existing bridge and crosses a major north-south freeway in Washington State, I-5. The bridge has two spans, tall abutments at each end and a center bent that is located in the median strip of I-5. The bridge features are:

- Unique socket connection of precast column to footing
- Precast columns in segments, joined by bars grouted in ducts
- Precast cap beam, made in two segments
- Cast-in-place precast cap beam closure pour
- Precast superstructure with CIP closure at intermediate pier
- Precast end and intermediate diaphragms

The details of the new connections were essentially identical, apart from scale, to those tested in the laboratory.

The steps in the construction sequence for the column-to-footing connection are listed below and are shown in Fig. 9.

- Excavate for footing and install forms
- Place leveling pad and set first segment of column
- Place footing reinforcing and cast footing concrete
- Remove forms and backfill around the excavation

Fig. 9: Construction sequences for placement of precast column segment into footing

The columns used in this project were spliced to permit erection in segments. While the columns of the demonstration project were small enough to be handled as a single piece, the segmental concept was used to demonstrate the technology for use on other projects where the columns are longer and cannot be transported or lifted as a single piece.

The steps in the construction sequence for placement of precast column segments and bent cap are listed below and are shown in Fig. 10.

- Place and shim middle column segments
- Place and shim top column segments
- Install column bracing
- Place and shim precast bent cap segments

Fig. 10: Column Segment Placement

The precast bent system used in the HfL project relied on the standard Washington State practice of integrating the prestressed girders with the cast-in-place second-stage cap beam. This system provides longitudinal moment transfer from the bent columns, through the cap beam, to the girders. The precast first-stage cap beam for the demonstration bridge was built in two pieces that were integrated with a closure pour near mid-width of the bridge. This was required because the bridge is 84 ft (25.6 m) wide, including sidewalks. Ideally, the precast first-stage cap would be built as a single piece to avoid the time required for splicing segments, but lifting and shipping weight restrictions led to the two-piece solution in this case. This decision could, of course, vary by project.

The joints between column segments and the column to bent cap were all grouted at one time. The process included the following steps and is illustrated in Fig. 11.

1. Install grout forms and seal
2. Pump grout and close grout tubes
3. Remove grout forms and inspect grout in joint and grout tubes
4. Repair unfilled grout tubes and patch back grout tubes

Fig. 11: Grouting the Joints between Column Segments and between Column and Bent Cap

CONCLUSIONS

A precast concrete bridge bent system is presented that is simple, rapid to construct and offers excellent seismic performance. The following conclusions are drawn:

1. The system described here addresses the demands of both seismic performance and constructability. It provides an example of a successful transfer of research to practice, but was possible only through the close cooperation between team members representing research, design, fabrication and construction.
2. Precast prestressed concrete bridge systems are an economical and effective means for rapid bridge construction. Precasting eliminates traffic disruptions during bridge construction while maintaining quality and long-term performance.
3. The use of precast cap beams results in time and cost savings by eliminating the need for elevated false work and shoring. It also improves worker safety because reinforcement and concrete can be placed at the ground level.
4. The column-to-cap beam connection is made with a small number of large bars grouted into ducts in the cap beam. Their small number, and the correspondingly large ducts sizes that are possible, lead to a connection that can be assembled easily on site.
5. The development length of a reinforcing bar grouted into a corrugated steel pipe is much shorter than implied by current code equations.
6. The socket connection between the cast-in-place spread footing and the precast column provides excellent performance under combined constant vertical and cyclic lateral loading, and is quick and easy to construct.

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