ACCELERATED BRIDGE CONSTRUCTION IN WASHINGTON STATE

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ABSTRACT

The need for accelerated bridge construction (ABC) arises from inevitable increases in traffic congestion that have occurred in the past few decades, and the corresponding costs and safety manifested in many forms, including exposure of workers to traffic hazards, and most importantly, waste of time due to delays. Precast bridges consisting of pre-tensioned girders, post-tensioned spliced girders, trapezoidal open box girders, and other types of superstructure members are often used for accelerated bridge construction; however, bridge engineers are concerned with durability and performance of bridges made of precast members in areas of moderate or high seismicity.

INTRODUCTION

Bridge construction frequently leads to traffic delays, which incur costs that can be measured in time, money and wasted fuel. Agencies are therefore seeking methods for accelerating bridge construction, referred to as ABC. Use of precast concrete for bridge substructures in seismic regions represents promising technology for ABC.

Safety enhancements benefiting the motoring public and highway workers, as well as lessened environmental impacts are directly attributable to limiting in-situ work requirements. For these reasons, transportation agencies are gradually embracing the ABC philosophy for many of their urban construction projects.

Precast concrete bridge systems provide effective and economical design solutions for new bridge construction as well as for rehabilitation of existing bridges. Proper seismic design entails a detailed evaluation of the connections between precast components as well as connections between superstructure and the supporting substructure. In seismic regions, provisions must be made to transfer greater forces through connections, and to ensure ductile behavior in both longitudinal and transverse directions.

Precast connections are typically made at the beam-column and column-foundation interface to facilitate fabrication and transportation. However, for structures in seismic regions, these interfaces represent locations of high moments and large inelastic cyclic strain reversals. Designing connections that are not only sufficiently robust to accommodate those cyclic loads, but are also readily constructible, are the primary challenges for ABC in seismic regions. The precast concrete bridge bent system described in this paper is intended to meet these challenges. Different connection systems

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are used at the column-to-foundation and the cap beam-to-column interfaces, because the conditions at each location offer unique opportunities.

SEISMIC DESIGN CRITERIA AND ANALYSIS METHODS

The current AASHTO LRFD Bridge Design Specifications 5th edition 2010[1] is a probability-based limit state code. Earthquake is categorized under the load combination referred to as “Extreme Event I”.

The new AASHTO Guide Specification for LRFD Seismic Bridge Design[2] is a displacement based design applicable to conventional superstructure construction with spans not exceeding 500 ft. WSDOT seismic design is based on the AASHTO Guide Specification for LRFD Seismic Bridge Design and modifications per the Bridge Design Manual. The displacement based design is intended to achieve a “No Collapse” condition for bridges using one level of Seismic Safety Evaluation.

The displacement-based analysis is an inelastic static analysis using expected material properties of modeled members. Inelastic static analysis, commonly referred to as “pushover” analysis, is used to determine reliable displacement capacities 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 is an upper bound of the displacement demand even if there is considerable nonlinear plastic hinging.

1. Perform linear elastic response spectrum analysis of the bridge based on design acceleration spectra specified by national or local specifications.
2. Determine lateral and longitudinal displacement demands.
3. Calculate the moment-curvature diagram for each column and from that, the elastic and plastic and ultimate curvatures. Moment-curvature diagram of cracked concrete may be considered if cracking of precast girder to diaphragm connection is evident.
4. Using the above information and pier geometry (single or multi-column configuration), compute the displacement ductility of each column, and ultimate displacement capacity.
5. Perform pushover analysis of each pier in transverse direction. Also, perform pushover analysis of the bridge in longitudinal direction. For this purpose, the plastic hinging moment for each column must be computed and it might be necessary to incorporate foundation flexibility as well.
6. Compare the total displacement capacity of the pier to the displacement demand. If the capacity is insufficient, then higher ductility is required.
7. Design the superstructure and foundation for 20% higher capacity than the plastic capacity of the columns to make sure that plastic hinges occur within the column.

SEISMIC RESPONSE OF BRIDGES WITH PRECAST COMPONENTS

The provisions contained in the AASHTO LRFD Bridge Design Specifications[1], are largely based on the conventional force method, where bridge analysis is performed and the forces on its various components are determined. Plastic hinging is the basis of the ductile design for bridge structures. Plastic hinges may be formed at one or both ends of a reinforced concrete column. After a plastic hinge is formed, the load path will change until the second plastic hinge is formed. The philosophy of ductility and the concept of plastic hinging are applicable to precast bridges if connections are monolithic.

The lack of monolithic action between the superstructure and bent cap in precast, prestressed concrete beam systems causes either the girder seats or the column tops to act as pinned connections. Consequently, while the transverse stability of multi-column bents is ensured by frame action in that direction, stability in the longitudinal direction requires the column bases to be fixed to the foundation supports. This requirement places substantial force demands on the foundations of multi-column bents, particularly in areas of moderate to high seismic zones. Developing a moment connection between the superstructure and substructure makes it possible to introduce a pinned connection at the column bases. This results in less expensive foundations. Integral bent caps are beneficial in precast, prestressed concrete beam systems by introducing moment continuity at the connection between the superstructure and the cap, the columns are forced into double-curvature bending, which substantially reduces their moment demands. As a result, the sizes and overall cost of the adjoining foundations are also reduced.

PRECAST SUPERSTRUCTURE

The majority of bridges in Washington State are prestressed girder bridges. In Washington State, the use of prestressed I-girders started in the 1950's. Since then the Washington State Department of Transportation (WSDOT) has developed standard girders for composite and non-composite sections to facilitate economical design and construction.

CONNECTION OF PRECAST GIRDERS AT INTERMEDIATE PIERS

The most common types of connections for precast prestressed girder bridges are fixed connection for high seismic zones (western Washington), and hinge connection for low seismic zones (eastern Washington). Precast columns may be used if monolithic moment resistant connections meeting seismic design and detailing requirements are provided.

Monolithic action between the superstructure and substructure components is the key to seismic resistant precast concrete bridge systems. Lack of monolithic action causes the column tops to behave as pin connections resulting in substantial force demands on the foundations of multi-column bents, particularly in areas of moderate to high seismicity. Developing a moment connection between the superstructure and substructure reduces the moment in the footing.

The connection shown in Fig. 1 is for continuous spans with fixed moment resistant connection between super and substructure at intermediate piers. Cast-in-place diaphragm is completed in two stages to ensure precast girder stability after erection, and completion of diaphragm after slab casting and initial creep occurs. Extended strands and reinforcing bars are provided to ensure performance of the connection during a major seismic event. The design assumptions for fixed diaphragms are:

1. All girders of adjoining spans are the same type, depth and spacing.
2. Design girders as simple span for both dead and live loads.
3. Provide reinforcement for negative moments at intermediate piers in the deck due to live loads and superimposed dead loads from traffic barrier, pedestrian walkway, utilities, etc.
4. Determine resultant plastic hinging forces at centroid of superstructure.
5. Determine the number of extended strands to resist seismic positive moment.
6. Design diaphragm reinforcement to resist the resultant seismic forces at centroid of diaphragm.
7. Design longitudinal reinforcement at girder ends for interface shear friction.

The design procedure to calculate the required number of extended strands is described herein. This calculation is based on developing tensile strength of the strands at ultimate loads. Since the distance across the connection is too short to develop the strands by concrete bond alone, mechanical anchors are provided to develop the yield strength of the strands. Extended bottom prestressed strands are used to carry positive earthquake load, creep, and other restrained moments from one span to another. Strands used for this purpose must be developed in the short distance between the two girder ends.

PRECAST GIRDER CONNECTION AT END PIERS

Precast girders are often supported on elastomeric bearing pads at end piers. Semi integral cantilever abutments are used for precast bridges less than 450 ft (137 m) and L abutments for longer bridges are typically used for precast girder bridges. Bridge ends are free for longitudinal movement, but restrained for transverse seismic movement by girder stops. The bearings are designed to be accessible so that the superstructure can be jacked up to replace the bearings after a major seismic event.

WSDOT STRATEGIC PLAN FOR ACCELERATED BRIDGE CONSTRUCTION

Consisting of subject matter experts the task force outlined a strategic plan to develop, implement, and promote ABC practice in Washington. The WSDOT ABC team has formulated a strategy and work plans with the specific tasks outlined below. It is important, to understand that the success of ABC implementation rests largely on widespread acceptance of the associated techniques by project development staff (both internal and external), funding partners, and the contracting industry.

The Department’s larger goal, as stated in its Mission/Vision statement, is to enhance mobility. Therefore, ABC should be viewed as a subset of a larger “accelerated project delivery" effort encompassing all aspects of project development through contract acceptance for construction. Consideration related to lane rental rates should also be considered to address funding issues. This latter requirement stems from the fact that quite often new techniques involve unassigned risk that must be borne by the Contractor at a premium until the comfort level garnered from successes has been realized.

ABC DECISION CRITERIA AND TYPE SELECTION

ABC requires special construction practices that typically demand a premium in construction costs as nighttime work may be involved. ABC project delivery costs could yield a 30-100% increase in conventional construction costs, but user costs are reduced.

ABC can result in substantial economic benefits that can offset most construction cost premiums. Conventional bridge construction typically induces traffic delays and congestion for an extended time period. The induced traffic congestion adversely affects individual traveler's budgets and the region's economy; impacts air quality due to increased vehicle emissions, and reduces the quality of life due to personal time delays. Also, untimely service for workforce, supplier, and customers can incur significant costs to the traveling public and region businesses. In some instances, the associated costs to the public from traffic delays can reach into the tens of thousands of dollars per weekday. ABC can reduce traffic delays and hazards, and thus yield economic savings to the traveling public and the regional economy. While the State may pay a construction premium in advance, the cost savings from reductions in delays, fuel and travel time would apply directly to the traveling public.

DECISION-MAKING MATRIX

The decision-making matrix checklist should be accompanied with all bridge preliminary plans. This matrix allows identifying ABC candidates at early stage of bridge design. The same process could be used at the project development stage for some expedited projects. Typical questions for decision-making matrix are:

- High traffic volume
- Emergency replacement
- Worker safety concerns
- High daily traffic control costs
- Evacuation route or over railroad or navigable channel
- Lane closures or detours
- Critical path of project
- Close during off-peak traffic
- Rapid recovery/repair required
- Adverse economic impact
- Weather constraints
- Environmentally sensitive site
- Natural or endangered species

- Feasibility if historic bridge
- Multiple similar spans (segments)
- Problem for ready-mix concrete
- Delay-related user cost concern
- Innovative contracting strategies
- Group with other bridges
- Future use

RESEARCH PROJECT- PRECAST CONCRETE PIERS IN SEISMIC REGIONS

An experimental research program at the University of Washington has developed and evaluated details for a precast concrete bridge bent substructure system having satisfactory seismic performance and suitability for rapid construction. The objective of this research is to examine two design procedures for precast concrete piers:

1- An equivalent lateral force design procedure.

2- Direct displacement-based design procedure.

Details of the cap beam-column connection consist of 6 #18 vertical column steel bars grouted into 8 in. (200 mm) diameter corrugated metal ducts embedded in the cap beam as shown in Fig. 3. Precast concrete columns with six bars protruding are brought onto site, braced, and then cast integrally with their footing. Later, the precast cap beam is fitted over the column bars through the corrugated ducts and grouted in place, completing the bent substructure. The small number of bars and the generous tolerances in the connection lead to good constructability, but the structural integrity of the connection depends on the anchorage of the bars in the ducts. The selection of 6 #18 vertical column bars was to reduce the congestion at column to cap connection while providing adequate tolerances for precast construction.

Full scale monotonic pull-out tests, with different embedment lengths, were first conducted to investigate the bond characteristics of large bars grouted into corrugated ducts. These tests confirmed that the #18 bars could be developed in the typical 4 ft (1.22 m) depth of the cap beam. The specifics of the connection test such as column hysteresis graphs and plastic hinging formation are presented in the University of Washington report.

Two one-third scaled connections, one with fully bonded vertical bars in ducts and another de-bonded eight bar diameters in the cap beam, were tested under 10% axial load and were subject to cyclic lateral displacements to study their performance. Both specimens performed well to 7% drift, failing as a result of bar buckling and fracture in the hinge region. Less damage to the cap beam was observed in the de-bonded specimen than the bonded, which saw moderate spalling around the underside of the beam as a result of duct slip. However, both demonstrated satisfactory strength and ductility, while allowing easy and rapid erection and generous construction tolerances.

The above laboratory experiment was applied to a three span prestressed precast concrete bridge in high seismic zone of western Washington. The project increases mobility and safety within the growing metropolis. This project is the first application by the highway owner that uses precast concrete for bridge girder support crossbeams. Based on the project success, the owner anticipates incorporating this method as an available practice for future designs. The bridge site is 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 pre-casting intermediate pier bent caps crossbeams in lieu of the cast-in-place requirements in the contract plans. This change would save the owner and the contractor several weeks in the contract duration.

The bridge uses wide flange WF74G girders to span a wetland, a railroad right of way, and an urban arterial. Precast concrete girders were the best choice for the superstructure. They are durable and have low maintenance and lifecycle costs. Precasting the girders increases the public's safety and convenience during construction by minimizing road closures and eliminating false-work over traveled lanes. The substructure cross beam was precast in order to save construction time. The use of precast concrete made duplicating the cast-in-place design feasible. As shown in Fig. 4, the 14 #14 column bars went through the 4" (100 mm) galvanized steel ducts placed in the precast bent cap using a template.

The constructability advantages of the system are that it is quick and simple to build, the column is easy to transport because no hooked bars project from the bottom, it avoids any potential problems of fit-up of bars in ducts, the column detailing can be almost identical to that of a cast in place column, and no grouting is needed.

The longitudinal reinforcement in the column is developed at the base by mechanical anchors, rather than the traditional method of bending the bars outwards. Doing so offers the construction advantage that the precast column becomes a large concrete cylinder with no protruding reinforcement, and is therefore simpler and safer to cast and transport.

DEMONSTRATION PROJECT

The connections described above are designed to be used with a precast bent system that includes precast columns and a precast cap beam. 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 tested by the Washington State Department of Transportation. The objective of the project was to demonstrate constructability of the bent system on an actual bridge project that will be competitively bid. The demonstration project is a replacement bridge on Interstate 5 that will be built on an alignment parallel to an existing bridge. It is two-span bridge with tall abutments and a center bent that is located in the median strip. An elevation of the center bent is shown in Fig. 5.

The superstructure of the bridge is comprised of 35-inch (890 mm) deep decked-bulb tee prestressed girders that span 88 feet (26.8 m). These are supported by the center bent comprised of spread footings, precast column segments, a precast dropped cap beam and a cast-in-place diaphragm with a 5-inch (125mm) cast-in-place topping over the decked bulb tees, whose flanges act as stay-in-place forms. The columns used in this project are spliced to permit erection in segments. While the columns of the demonstration project are small enough to be handled in a single pick with a crane, the segmental concept will demonstrate the technology for use on projects where the columns are longer and cannot be lifted with a single pick. Additionally, the laboratory specimens for the foundation connection include the same segmental connection, so that the capacity protection aspect of the system will be verified in the laboratory tests.

The precast bent system to be used in the demonstration project uses the common Washington State practice of integrating the prestressed girders with the integral full-depth diaphragm over a first-stage cap beam. This system provides longitudinal moment transfer from the bent columns to the superstructure. The precast first-stage cap beam for the demonstration bridge will be built in two pieces that are integrated with a closure pour near its mid-span. This is required because the bridge is 84 feet (25.6 m) wide, including sidewalks. Ideally, the precast first-stage cap would be built as a single piece element to avoid the time required for splicing segments, but pick and shipping weight restrictions led to the two-piece solution. This decision could, of course, vary by project.

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 use of precast bent caps results in cost savings by eliminating the need for elevated false work. It also improves worker safety as rebars and concrete can be placed at the ground level.
2. The column-to-cap beam connection is made with a small number of large column bars grouted into ducts in the cap beam. Their small number, and the correspondingly large ducts sizes lead to a connection that can be assembled easily on site.
3. The column-to-cap-beam connection has been tested under cyclic loading in three variations. All three behaved essentially identically to a cast-in-place column with similar properties. All four specimens reached a drift of approximately 6 percent before bar buckling in the column precipitated failure.
4. Precast prestressed concrete bridge systems are economical and effective for rapid bridge construction. Precasting eliminates traffic disruptions during bridge construction while maintaining quality and long-term performance.

REFERENCES

1. AASHTO-LRFD Bridge Design Specifications, 5th Edition, 2010.
2. AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2009.

3. Bridge Design Manual, Publication No. M23-50, Washington State Department of Transportation, Bridge and Structures Office, Olympia, Washington, 2007.

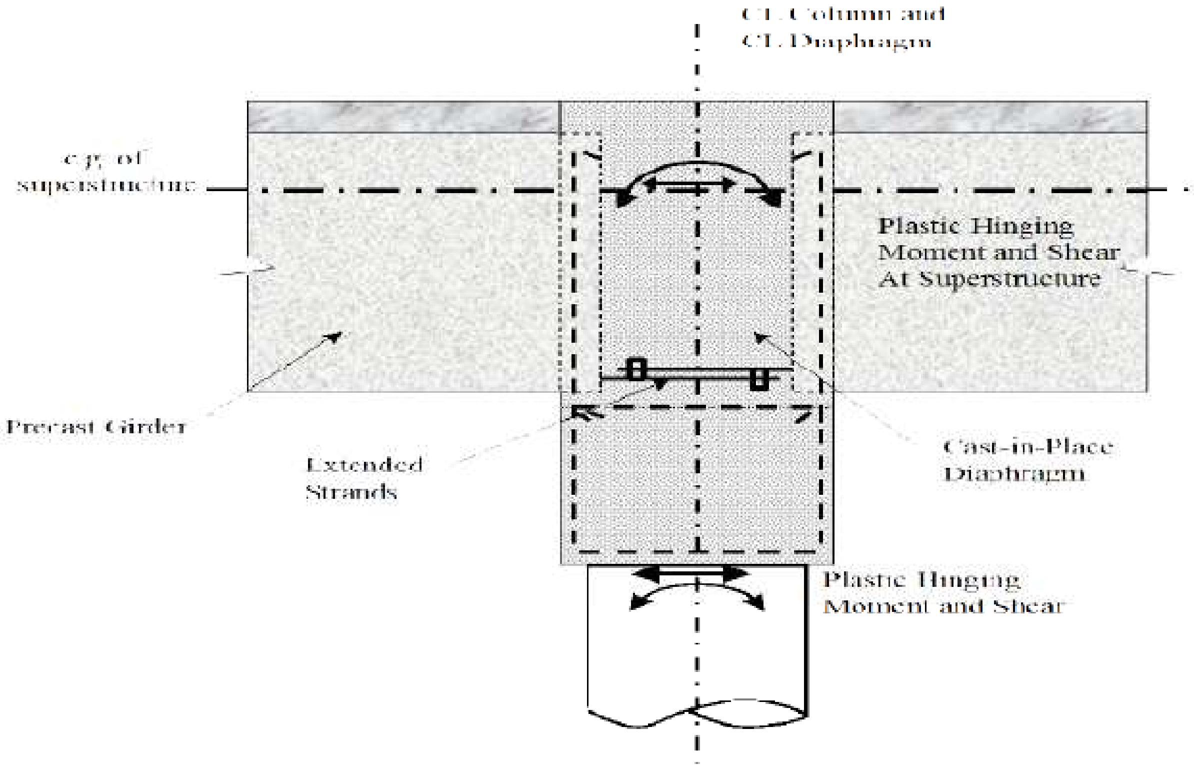

Fig. 2 Typical Monolithic Moment Resistant Connection

Fig. 3 Experimental Research Program at the University of Washington

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

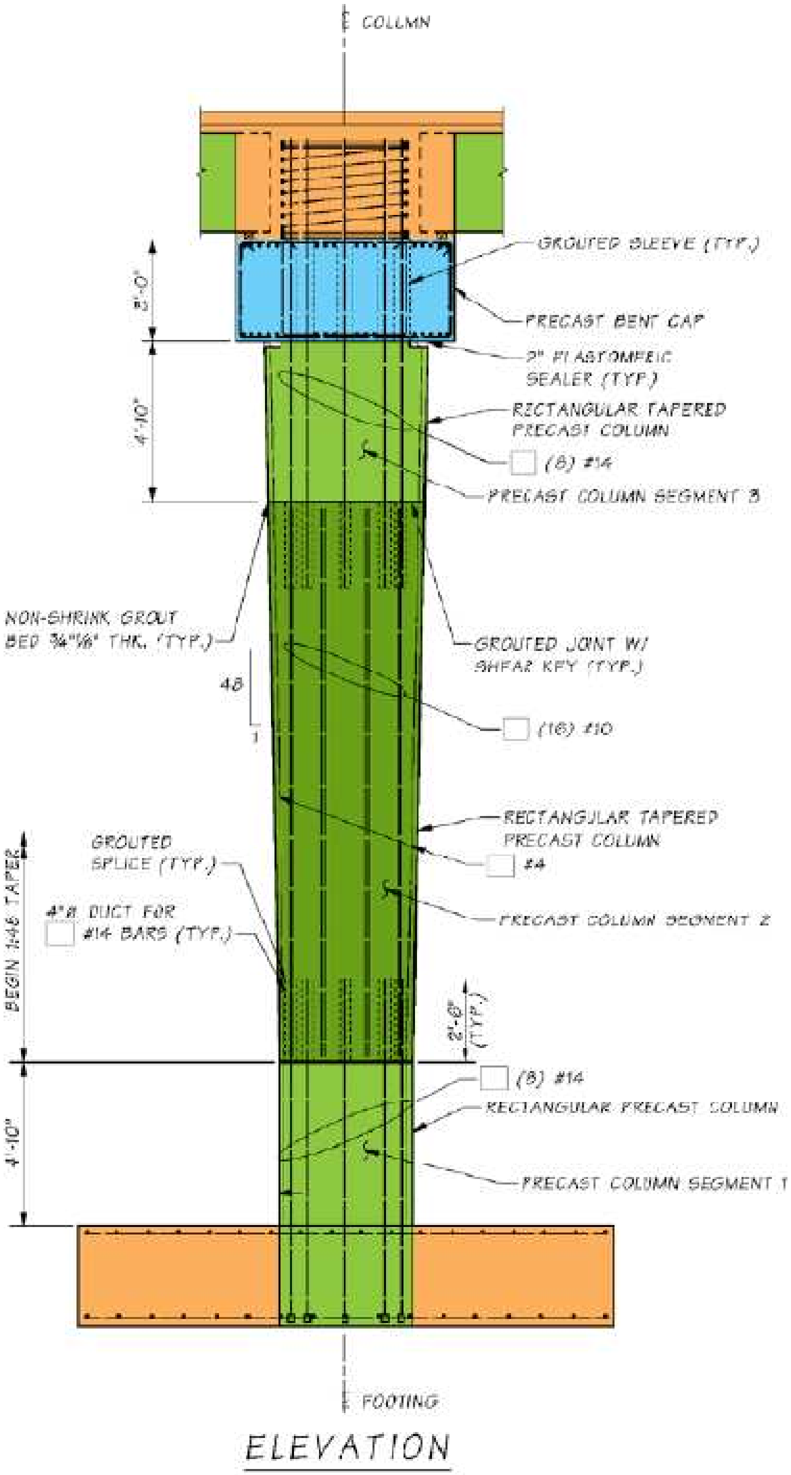

Fig 5. Demonstration Project Bent Configuration