RAPID CONSTRUCTION DETAILS FOR BRIDGES IN SEISMIC ZONES.

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ABSTRACT

Rapid construction of bridges is desirable to counteract the costs caused by traffic congestion, exposure of workers to risk of accidents, and environmental damage. Use of precast concrete components offers an opportunity to reduce the duration of site operations, but poses potential problems when used in seismic regions because of the difficulty in designing connections that can accommodate the forces and inelastic deformations induced by earthquake ground motions. This paper presents options for selecting precast concrete bridge bent systems and associated connections that are suitable for use in seismic regions. Some use technology that is already proven and may be implemented now, while others are based on rational principles but may require proof testing prior to construction. The paper outlines the testing program that is being undertaken for one of those systems.

Introduction

Construction activities have always had negative impacts on the operation of transportation systems. Examples are traffic congestion, worker safety and environmental damage. In recent years, those effects have become increasingly critical, so various agencies have worked to develop systems that reduce those impacts, and in particular they have sought ways to achieve rapid construction. For example, FHWA (2004) provides general information on the development and implementation of accelerated construction methods.

Precast concrete bridge components offer an alternative to conventional reinforced, cast-in-place concrete components that has the potential to address some of the problems. Precasting can facilitate rapid construction, minimize traffic disruption, improve work zone safety, reduce environmental impacts, improve constructability, and lower life-cycle costs. Precast, prestressed, concrete bridge girders are widely used throughout the United States, and precast components are sometimes used in slab systems. This paper addresses the use of precast concrete component as a means of accelerating construction of bridge bents that are suitable for use in seismic regions. It does not address deck systems.

Precast components have been used for rapid construction in non-seismic regions (e.g., Jones and Vogel 2001; Wolf and Hyzak 2004; LoBuono, Armstrong and Associates 1996). In contrast, they have seldom been used in seismic regions (e.g., Josten *et al.* 1995; Cruz Lesbos *et al.* 2003), mainly because of the need to provide sufficient strength and ductility in the connections. In addition, the high amount of reinforcement required in beam-column joints in seismic regions can lead to constructability problems in cast-in-place concrete, and can become even more challenging in precast structures, in which additional space may be needed for ducts.

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Precast concrete is sometimes perceived as unsuitable for use in seismic regions, largely because of difficulties in designing suitable connections. Optimizing the members from the precaster's viewpoint often means using line members, connected at their ends. However, in a frame structure, this is where the largest seismic forces, and the inelastic deformations, typically occur. The connections, including any anchorage of embedded components, must therefore be designed to accommodate these forces and deformations, and this process is indeed challenging. The poor performance of some precast structures during the 1994 Northridge earthquake is testament to those difficulties. However, recent research, such as the PRESSS program, (Nakaki et a. 1999) has demonstrated that precast structures can provide seismic response that is at least as good as, and in some regards better than, cast-in-place concrete structures. Achieving that good performance requires that the designer account for the unique characteristics of precast construction rather than treating it exactly as if it were cast-in-place.

Constructability Criteria

Good seismic performance may be measured using objective characteristics such as displacements and damage. By contrast, no universal standard for constructability exists, because ease and speed of construction depend on the local availability of equipment and expertise, and these vary widely among regions and even among companies within a region. While optimizing constructability within a state may be feasible, because each state Department of Transportation has its own standards and concomitant building culture, generating constructible systems with broader appeal requires development of a range of modular solutions, from which an owner or contractor may choose elements to suit his or her needs.

Constructability criteria also depend on the stage of construction under consideration, including plant fabrication, transportation and handling, and field conditions. In some cases, choices made to improve constructability in the plant may adversely affect it in the field. For example, several states are now producing "super-girders" (e.g. Seguirant 2003). These very large precast, prestressed girders have the benefit of spanning long distances and avoiding the need for columns in waterways (good for field constructability) but they are too large to be handled in the plant and transported in one piece. Furthermore, constructability requirements often appear to oppose structural needs. For example, a joint may require a large number of ties to resist high joint shear stresses, but the bar congestion caused by them may impede construction. Tolerances are a major issue in constructability that may affect plant and site constructability and structural performance. The contractor generally prefers the greatest possible allowance for adjustment, but this may lead to large ducts that promote cracking or crowding of adjacent reinforcement (bad for plant constructability) and eccentric load paths (bad for structural behavior). It is therefore apparent that constructability is not a single issue that can be addressed in isolation, but rather a balance between a large number of costs and benefits that accrue to different parties in the building team.

Categorization of systems

The structural and constructability characteristics of a precast concrete bridge bent are determined largely by the way that it is broken into elements down for precasting, and the consequent locations of the connections. The possible approaches may therefore be broken down according to bent systems that are distinguished by their precast element configurations. These are described in this section of the paper. Within each bent system, many different approaches to making the individual connections are possible, and some of them may be applied to several different systems. Connection types are discussed in the next section. Finally, certain broad-based implementation considerations must be addressed when selecting a rapid construction methodology, and these are discussed last.

Bridge Bent Systems

Bent systems are divided here into four broad systems. In each case, the perceived advantages and challenges of the system are listed, and an evaluation is offered.

Post-and Beam (PB) Systems

In post-and-beam systems, the columns are erected, and a precast cap beam is placed on them. Many variants on the basic concept exist, but in all cases, a moment connection is needed between the column and cap beam. For these purposes, the term "post-and-beam system" includes multiple-column bents, single-column bents and pile bents. The column may in fact be a concrete or steel pile, it may be cast-in-place, it may be precast and erected by placing it first and then casting the foundation around it, or it may be constructed by other means. The cap beam-to-column connection may be made in many ways (see later section on Connection Types).

Advantages: Linear pieces simplify fabrication and transportation. However, for land transportation, weight may anyway restrict the loads to one cap beam per truck.

Challenges: The connection is made at the point of maximum moment, shear and joint shear demand. Even if inelastic action is forced out of the connection region and into the column, as is desirable, the column plastic hinge occurs adjacent to the connection.

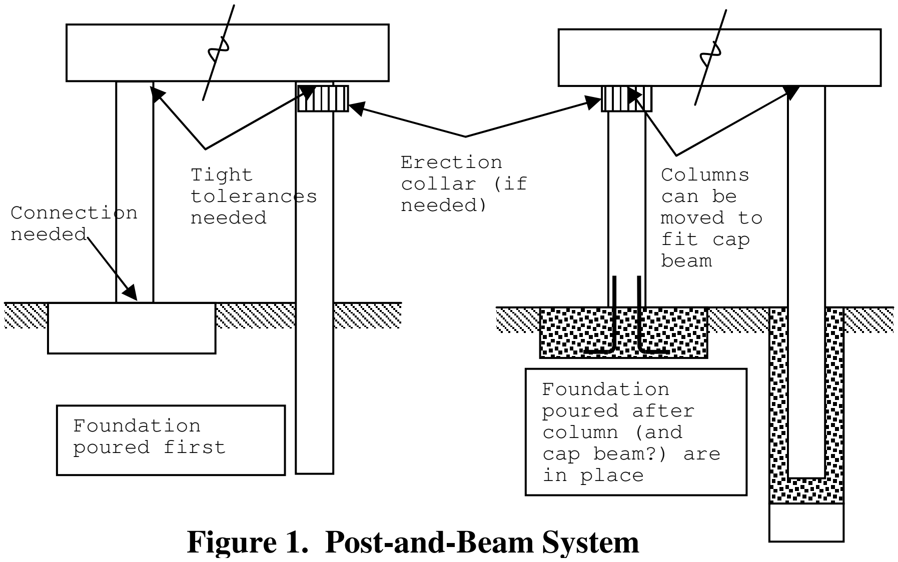


Figure 1. Post-and-Beam System

Evaluation: The post-and-beam system is versatile in that it allows the smallest pieces, and they are line elements. Ensuring good seismic behavior with it is challenging because the connection is at a critical location.

Mid-Column (MC) Connection Systems

Precast half-height columns are erected on the foundations, using any one of several different methods. A precast bent cap is fabricated integrally with half columns and is then lifted on as a single unit. The connection is made at mid-height of the column, where the moment demand is low. This may be achieved by several methods. The examples shown consist of a steel sleeve and a bar-in-duct system. The partial column attached to the cap beam must be made short enough to allow the piece to be transported. If a bar-in-duct connection is used, the ducts should be in the upper column piece to facilitate transportation by minimizing the length of the partial column attached to the cap beam.

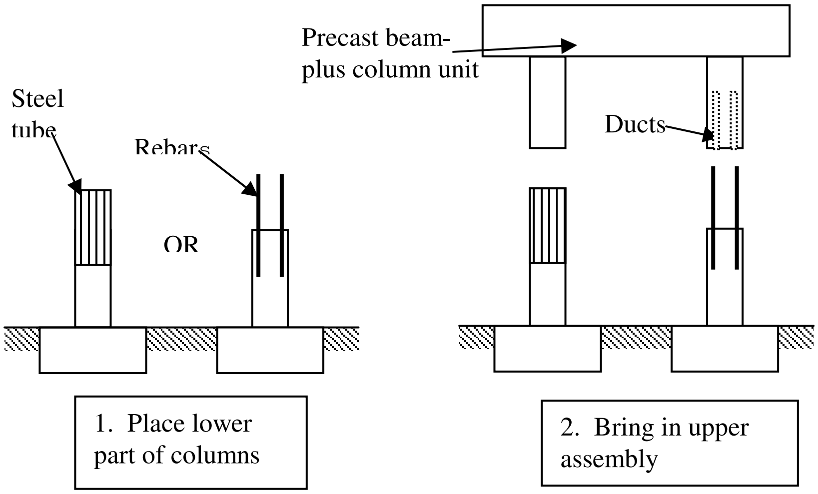


Figure 2. Mid-column Connection System

Advantages: Making the connection at an inflection point allows conventional design and detailing to be used for the potential plastic hinge site at the column-cap beam intersection. The force demands at the connection are low, so the connection can be designed to be simple and to remain elastic.

Challenges: Fabrication of the upper element probably requires two separate pours in the precasting plant. Accurate alignment of the column pieces may require templates. The upper element must be stabilized after placement while the connection is completed.

Evaluation: Can use existing, well-documented detailing in critical plastic hinge region.

Hammerhead (HH) System.

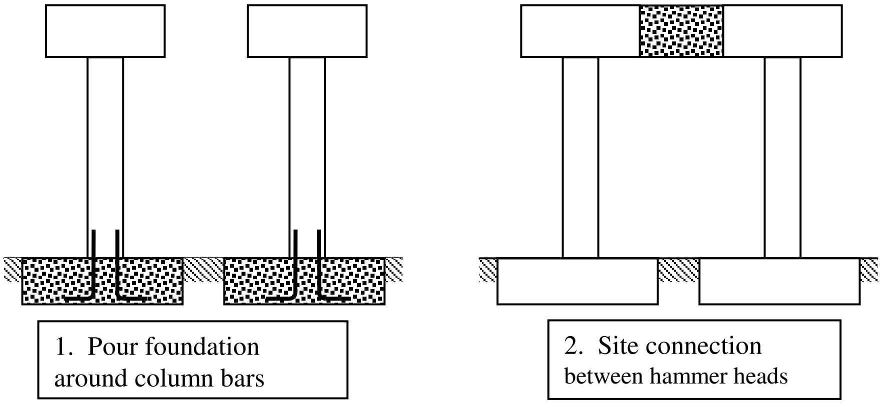


Figure 3. Hammerhead System

Each column is cast integrally with the part of the cap that is tributary to it to form a hammerhead. The Ayuntamiento Bridge in Cuernavaca, Mexico used this approach (Cruz Lesbros *et al. 2003).* Each hammerhead piece is then erected by holding the column in place while the foundation is poured around it. To alleviate alignment problems, the hammerhead pieces could all be erected, aligned and connected temporarily prior to pouring the foundations. The cap beam pieces are then connected permanently. To decrease site construction time further, the hammerheads could also be designed so that girders could be placed on them before the cap beam connection is completed. The cap beam could then be poured with the diaphragm.

Advantages: Making the beam connection at a point of low moment is much simpler than making it at a plastic hinge, with the heavy confinement needed there.

Challenges: Fabrication and transportation of the cap beams. Fabrication may require two operations in the plant. Column and partial cap beam dimensions must be chosen to allow transportation, especially if by road.

Evaluation: The connection is made away from the plastic hinge zone, where conventional detailing can consequently be used. Use depends on the dimensions and weights of the pieces and the ability to transport them.

Complete Precast Bent (CP) System (no illustration).

The whole bent, including columns and cap beam is cast as a single unit. It is then erected and the foundation is cast around the column feet.

Advantages: Smallest possible number of site picks (one). All site tolerances easily addressed at the cast-in-place footing.

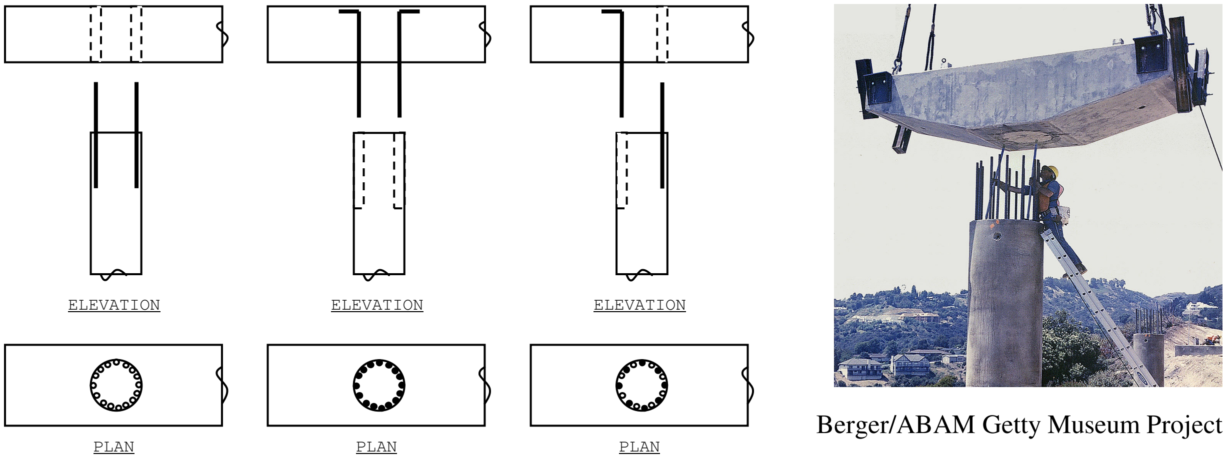
Challenges: Heavy, awkward pieces if precast in a yard and then transported. Success of the system depends on being able to cast the footings around the columns.

Evaluation: Not suitable for all applications, but could minimize erection time in some cases.

Connection Types

Each system contains connections, each of which may be achieved in several ways. Some possible methods of making the various connections are described here.

Grouted Ducts. (Applicable to PB and MC systems).



Berger/ABAM Getty Museum Project

Figure 4. Bars Grouted in Ducts

Bars are grouted into ducts to achieve tension and moment continuity. Note that bars grouted in ducts provide bond that is significantly better than that available in cast-in-place construction (Raynor et al. 2002), so anchorage lengths may be shorter than conventional development lengths. If used for the PB system (as shown in Figure 4), ducts may be in the column, in the cap beam, or both. Placing the ducts in the cap beam means that the cap beam can be cast right side up, which simplifies casting the girder seats. Placing them in the column means that the congestion is eased in the cap beam, because bars are smaller than ducts, but made worse in the column. Placing some in each may offer an acceptable compromise by providing more erection tolerance, but it makes congestion problems worse. Moment redistribution (see the section on Implementation Considerations) may offer some congestion relief. If grouted ducts are used in the MC system, the moment demand is low, so the number of bars needed for strength may be determined based primarily on shear requirements.

Advantages: Eliminates the need for fresh concrete on site. Bars grouted in ducts have very high bond capacity.

Challenges: Steel congestion, because ducts must be large enough to allow for erection tolerances. Alignment of bars with ducts, especially if making two or more connections to a single piece (e.g. two columns to one cap beam).

Evaluation: Versatile. Widely used in building practice (also with proprietary grouted splice sleeves). Used now in bridges. (e.g. Josten *et al.* 1995). System has been used in non-seismic regions with several bars in slots rather than individual bars in ducts. e.g. Redfish Bay and Morris and Cummings Cut Bridges in Texas (Wolf and Hyzak 2004).

Tenon and Mortice. (Applicable to PB and MC systems).

Similar to the grouted duct connection, except that a single, large, tension/bending element is used. This may be the column itself (e.g. Berger/ABAM's use of a steel pile in Alaska, Fig 6.), shown schematically in Fig. 5, a large steel element (e.g. Bayshore Concrete's steel pipe secured by c.i.p. concrete), also shown schematically in Fig. 5, or some other component. If used with the MC system, a large bar or steel section may be grouted into a central duct in the two column pieces.

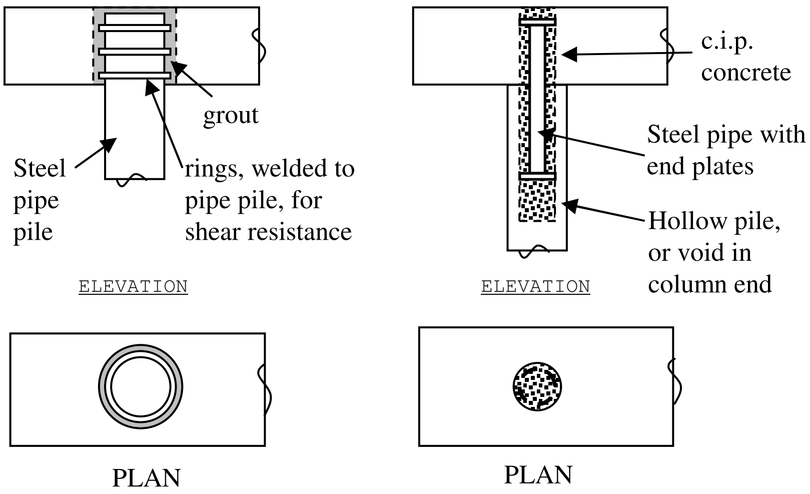


Figure 5. Tenon and Mortice System

Figure 6. Berger/ABAM Project in Keyport, WA

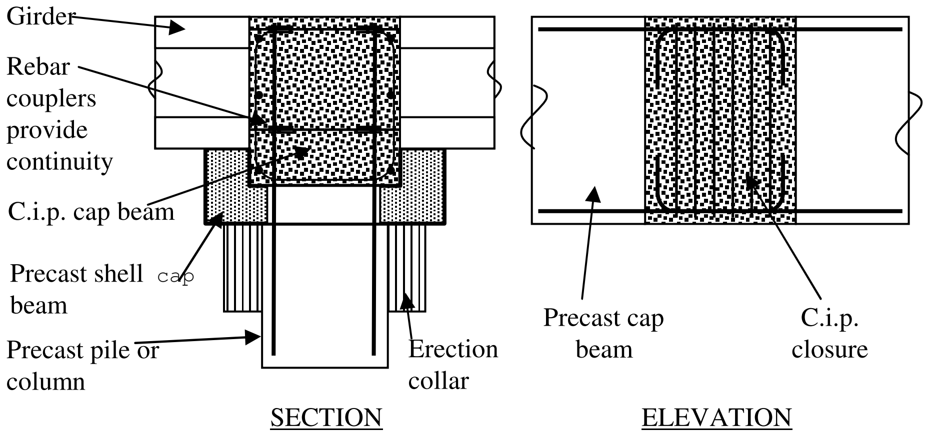
Advantages: Simple to implement. Few elements to align.

Challenges: Joint shear may control the size of the cap beam.

Evaluation: Simplicity leads to fast erection. Lateral load proof testing may be necessary.

Cast- in-Place Closure Pour. (Applicable to PB and HH systems).

Bars projecting from adjacent precast elements are tied together by c.i.p. concrete, which provides continuity between elements. A shell beam may be used to reduce the amount of temporary formwork needed.



CLOSURE POUR USING PRECAST SHELL CAP BEAM

CLOSURE POUR IN SOLID CAP BEAM

Figure 7. Cast-in-Place Closure Pour

Advantages: Achieves continuity. Shell design, if used, minimizes the weight of the precast cap beam.

Challenges: Shear stress transfer between precast and c.i.p. concrete (especially for shell). Shell cap beam needs to carry girder weight during erection. Alignment of precast elements and congestion of rebar in c.i.p. region may cause difficulties.

Evaluation: C.i.p. connections have been widely used by the precast industry for many years. (ACI Committee 550). A shell cap beam connection was used in the San Mateo Bridge.

External Steel Sleeve. (Applicable to MC system).

One precast column piece has a short length of steel tube cast around the end, which projects beyond the end. The mating column piece fits inside the projecting part of the tube. Grout is pumped into the space between tube and column.

Advantages: Simple connection between column pieces. Sleeve thickness can be selected to satisfy shear and moment demands.

Challenges: Alignment of precast elements if more than one column segment is cast with the cap beam. A template may be necessary. Not suitable if the column is subject to net tension.

Evaluation: The connection has been used successfully for many years to splice precast piles.

Welded Steel Embeds. (Applicable to PB and MC systems)

These connections are likely to be suitable for low seismic zones only. For the PB system, a plate could be embedded in the bottom of the cap beam at the column location, and the precast column is fabricated with a steel tube around its top end. The two components are site welded together after the cap beam is placed. Rotational ductility of the connection may be obtained, at the expense of moment strength, by placing the studs that anchor the plate at some distance from the steel tube. For the MC system, a steel element can be embedded in the end of each column piece, and the two can be welded after the column is erected.

Advantages: Simple to implement. Tolerances on location of elements do not need to be tight.

Challenges: Need for, and quality of, site welding. Appearance. Low moment strength (for PB systems). Need for corrosion protection after welding.

Evaluation: Limited to low seismic zones.

Implementation Considerations

The following section discusses some key implementation considerations.

Seismicity level.

The seismicity level is critical in determining the location and types of connection. In a region of high seismicity, placing connections at locations of maximum moment and joint shear stress creates real difficulties, especially when the contractor also seeks the most generous dimensional tolerances possible. Therefore, for those applications, solutions in which the connection is moved away from the highly stressed region may be more appropriate. However moving the connection location may impose other penalties, such as more awkward-shaped components that are harder to build and transport. In regions of lower seismicity a connection at the joint may be feasible and these penalties may not be worth paying.

Steel vs. concrete girder bridges.

Steel and concrete girder bridges have different characteristics that affect the design of the bent system. For example, steel bridges are typically lighter, which may permit a smaller bent cap cross-section that would facilitate transportation. Steel girders are also often continuous over the bent cap, resting on a single bearing at the centerline of the cap, thereby minimizing both the required width of the bent cap and any temporary torsion loading on it during construction. In concrete bridges a diaphragm is usually cast integrally with the bent cap and the two act compositely to carry the in-service loads. By contrast in a steel bridge, the diaphragms are usually steel, so the bent cap alone must carry all the girder loads both during construction and in service.

Use of site-cast concrete in environmentally sensitive areas.

Site-cast concrete provides a versatile way of connecting precast components and leads to an "emulative system" in which the seismic performance of the finished structure emulates that of a comparable monolithic one (ACI Committee 550). However, the presence of fresh concrete on site carries with it the possibility of a spill, and that may be unacceptable in areas of particular environmental sensitivity. In that sense, solutions that minimize the use of site-cast concrete offer advantages.

Need for integral connections between the girders and bent cap.

Making the girders act integrally with the bent cap may be desirable in order to provide some resistance to longitudinal seismic loads. (The need for longitudinal seismic resistance depends on whether the abutments can be used for the purpose). This is commonly done for precast, prestressed girder bridges by embedding into the diaphragm strand extensions or reinforcing bars from the girders. Durability is also generally improved, by reducing the number of components that move relative to one another.

Durability.

Durability of a system can be jeopardized by ingress into the concrete of moisture and corrosive liquids, such as deicing salts. Their effects can be counteracted by use of epoxy-coated reinforcement and exterior coatings, but any steel embeds must also be protected similarly. Threats to durability are also posed by thermal or shrinkage cracking, including at cold joints between cast-in-place and precast concrete, and cracking caused by minor earthquakes. The intensity of the earthquake that might lead to the cracking can be judged by comparing the design life of the bridge and the return periods of ground motions of various intensities.

Use of post-tensioning.

Unbonded post-tensioned precast concrete systems have recently been developed (e.g., Stone et al 1995, Stanton et al. 1997) to provide superior seismic resistance in concrete structures. The concept has been used in practice in a number of buildings in California (e.g., Englekirk 2002) and is also being studied for use in steel structures (Christopoulos et al. 2002). The primary benefits are the low level of damage after the earthquake and the fact that the structure re-centers, leading to negligible residual drift. Its use for cast-in-place bridge columns has been studied by Sakai and Mahin (2004). For precast bent caps, it may also offer some useful alternatives for connecting the components. Against these advantages must be weighed the need for corrosion protection, particularly of the anchorages. Many of the systems and connection types suggested here could be modified to incorporate the benefits of post-tensioning.

Moment redistribution.

In a reinforced concrete structure, the completed cap beam-diaphragm combination is usually much stiffer and stronger than the columns that support it. Therefore, under seismic loading, columns in multi-column bents tend to behave as fixed against rotation at top and bottom, thus inducing equal moments there if the reinforcement is prismatic. However, the same lateral force capacity could be achieved by decreasing the flexural strength at one end (say, the top), and increasing it at the other. This offers the practical advantage of designing for a smaller moment at a location where steel congestion may be significant (e.g. the top). Of course, such moment distribution is not available in single column bents.

Experimental Verification

The following section discusses an experimental program that is being conducted to investigate a post-and-beam connection system.

Selection of System

The systems discussed above were reviewed with the Washington State DOT and a representative group of contractors. The group's preference was for a post-and-beam system. Different ways of making the individual connections were then considered and evaluated for ease of construction and seismic resistance. The evaluations are given in Table 1. Most of the connection systems use bars embedded in openings of some size and shape. The primary differences lie in the number of bars connected in each opening. For the "large opening" connection, all the bars extend from the column into a single circular opening in the cap beam, and are secured there by pouring cast-in-place concrete. At the other end of the scale, the "ducts" connection consists of bars each grouted into its own individual duct. The primary disadvantages of using many ducts are the difficulty of simultaneously aligning many bars in many ducts and the difficulty of locating the ducts between the main reinforcement of the cap beam when the latter is cast. However, bars grouted in ducts typically have much shorter development lengths than bars cast directly into concrete (Raynor et al. 2002), and this characteristic proves valuable when using large bars. Use of grout also reduces the need for fresh concrete on site.

The system selected for detailed study represented a compromise between these two extremes. It consists of six 57 mm (No. 18) bars, each grouted into a large duct. This grouping was chosen because the small number of ducts allows their diameter to be large (approx 200 mm), which provides ample allowance for slightly misplaced bars. The steel area represents approximately 1% reinforcement in a 5 ft diameter column.

Proposed tests

The system must function under two different circumstances. The first is during construction. Then, the diaphragm has not been cast, so the cap beam connection must resist any loads using the development length available within the cap beam alone, which is typically 1.070m (3'-6"). However, the primary source of moment applied to the cap beam at the time arises from eccentric load that causes torsion in the cap beam, such as placing girders only in the span on one side of the cap beam. The tension demand may be less than full yield, which helps to compensate for the short available development length. The second design condition is for seismic loading after the bridge is complete. Then, the diaphragm has been cast over the cap beam, and the available development length is much longer, approximately 3 m (10 ft). For the system to function as desired, successful anchorage of the bars is essential. Raynor's (2002) work covered 19, 25, 32 mm bars (No. 6, 8 and 10). The first task in the present experimental study is to extend Raynor's results to 44 and 57 mm. bars (No. 14 and 18). Some 32 mm. (No. 10) bars will be included as well, to permit comparison with Raynor's results after accounting for the inevitable slight differences in material properties. Although Raynor applied cyclic loading to some of his bars, it required construction of a special rig. The present tests will be carried out only in tension, using a simpler apparatus. On completion of the pull-out tests, seismic tests of the cap-beam to column connection will be undertaken.

Table 1 Constructibility Evaluation of Systems

System	Fabrication		Construction				
	Forming	Steel and Duct Placement	Speed of Construction	Temporary Erection Devices	Extra Materials	Site Tolerance	Size of Crossbeam
1 Ducts	(1)	(3) Maintain tolerances, 1/2 in. bars and ducts	(3) Alignment of ducts and bars	(3) Template & Collar or shims	(2) Ducts	(3) Col.: +/- 1.5 in. Orientation of Column.	(2) (6x3.5)
2 Large Opening	(2) Circular opening. Corrugated surfaces.	(1)	(4) Need fresh concrete on site	(2) Collar	(1) None	(1) Col.: +/- 1.5 in.	(2) (6x3.5)
3 6 #18	(1)	(2) Ducts	(1)	(1) Collar or shims	(3) #18 bars & ducts	(2) Col.: +/- 1.5 in. Orientation of Column.	(1) (5x3.5)
4 Solid Column (RC)	(2) Circular opening. Corrugated surfaces.	(1)	(1)	(2) Collar	(1) None	(1) Col.: +/- 1.5 in.	(3) (6.5x3.5)
5 Solid Column (PSC)	(2) Circular opening. Corrugated surfaces.	(1)	(1)	(2) Collar	(1) None	(1) Col.: +/- 1.5 in.	(3) (6.5x3.5)
6 CFT	(2) Tube projecting from column	(1)	(1)	(1) Collar or shims	(3) Tube	(1) Col.: +/- 1.5 in.	(1) (5x3.5)
7 Slotted	(4) Odd shapes / Block outs	(2) Congestion in column top	(2) Alignment of slots and bars	(1) Collar or shims	(3) Bars in top of column	(2) Col.: +/- 1.5 in. Orientation of Column.	(1) (5x3.5)

Table 2 Seismic Evaluation of Systems

	Structural Performance				TOTAL
	Transfer of Vertical Load	Bar Location in Cross Beam	Ductility	Outstanding Structural Issues	Negative points
1 Ducts	(1) Bearing	(2) Sides (some in-between ducts)	(1) Similar to current bridges	(1)	(22)
2 Large Opening	(2) Friction, use corrugated surfaces	(2) Sides	(1) Similar to current bridges	(1)	(19)
3 6 #18	(1) Bearing	(1) Evenly distributed	(2) Splicing in inelastic region	(2) Bond of #18 bars (and ducts)	(17)
4 Solid Column (RC)	(2) Friction, use corrugated surfaces	(2) Sides	(1) Similar to current bridges	(3) Transfer of Crossbeam Torsion	(19)
5 Solid Column (PSC)	(2) Friction, use corrugated surfaces	(2) Sides	(1) Similar or better than current Bridges	(3) Transfer of Crossbeam Torsion	(19)
6 CFT	(1) Bearing	(1) Sides (but closer to middle)	(3) Difficult splicing in inelastic region	(3) Moment transfer / size of tube	(18)
7 Slotted	(1) Bearing	(1) Evenly distributed	(2) Splicing in inelastic region	(3) Group Pull Out Bond Failure	(22)

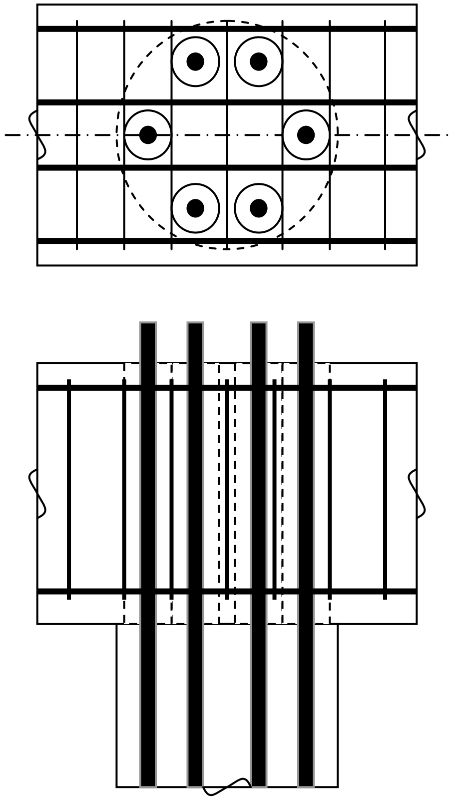


Figure 8. 6#18 System - Configuration

Conclusions

Precasting offers benefits for constructing bridge bents. It can lead to reductions in traffic congestion and lower aggregate risk to worker safety through shorter site operation times, and lower risk of environmental damage through reductions in the quantity of cast-in-place concrete needed on site. However, it requires coordination with an additional party (the precaster) and may require additional equipment (e.g. heavy cranes). If it is used in seismic regions, it also creates challenges for the designer in that the connections must resists seismic forces and may be required to accommodate inelastic deformations.

Bridge bent systems and associated connection technologies can be developed to satisfy these needs. This paper categorizes possible systems, provides concepts for connections details and an evaluation of the strengths and weaknesses of major classes of systems.

Acknowledgments

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