A P P E N D I C E S

NCHRP 12-105

App. A – Survey of State Departments of Transportation

App. B – Proposed AASHTO/ASTM Standard Test Method for Bar Couplers

App. C – Proposed AASHTO Specifications for ABC Columns

App. D – Detailed Design Examples

APPENDIX C: COLUMN CONNECTIONS FOR ACCELERATED BRIDGE CONSTRUCTION

TABLE OF CONTENTS

APPENDIX C:

COLUMN CONNECTIONS FOR ACCELERATED BRIDGE CONSTRUCTION

C1.0—INTRODUCTION

C1.1—PURPOSE

The use of Accelerated Bridge Construction (ABC) methods and technology provides owners with a less invasive method of constructing bridges by minimizing the impact to users. The purpose of this appendix is to provide the needed guidance to implement ABC connections in seismic regions to achieve similar seismic performance as cast-in-place construction. The use of the connection types discussed in this document is at the discretion of the bridge owner.

CC1.1

The development of this appendix was the result of NCHRP Project 12-105. More detailed information can be found in the NCHRP Report ??? (NCHRP 2019). While the technology for ABC has matured, little guidance has been available on how to implement these techniques in seismically active regions. The connection details often utilized in ABC construction introduce uncertainty regarding the ability to sustain significant inelastic deformations as are required by Type 1 Seismic Design Strategy outlined in Section 3.

C1.2—APPLICABILITY

This appendix applies to precast columns utilizing mechanically spliced reinforcing steel in the plastic hinge regions, as well as those using pocket and grouted duct connections. In addition, this appendix shall only apply to components designed in accordance with these Guide Specifications. This appendix may also be applied to wall piers in the weak direction.

Unless specifically superseded by provisions of this Appendix, all of the requirements of these Guide Specifications shall apply.

C2.0—NOTATION

A_{sp} = *area of one hoop or spiral used as transverse reinforcing steel bar (in.^{2})*
B_{cap} = *bent cap width (in.)*
D_{cl} = *column cross-sectional dimension in the longitudinal direction (in.)*
D_{cm} = *column largest cross-sectional dimension (in.)*
D_{ct} = *column cross-sectional dimension in the transverse direction (in.)*
D_h = *hole diameter above pocket (in.)*
D_p = *pocket diameter (in.)*
d_{bl} = *nominal diameter of largest column longitudinal reinforcing steel bar being coupled (in.)*
d_d = *actual inner diameter of a duct (in.)*
f'_c = *compressive strength of concrete (ksi)*
f'_g = *compressive strength of grout (ksi)*
f_{ye} = *expected yield stress for longitudinal reinforcing steel bar (ksi)*
f_{yh} = *nominal yield stress for transverse reinforcing steel bar (ksi)*
f_{yp} = *steel pipe yield stress (ksi)*
H_{cap} = *depth of cap beam (in.)*
H_p = *depth of pocket in column adjoining member (in.)*
H_{sp} = *distance from the connection interface to the coupler end closest to the interface (in.)*
L_{ag} = *embedment length (in.)*
L_{cr} = *length of coupler region (in.)*

L_p = *analytical plastic hinge length (in.)*

L_p^{sp} = *analytical plastic hinge length with spliced bars (in.)*

L_{sp} = *physical length of mechanical coupler (in)*

s = *spacing of transverse hoops or spirals (in.)*

t_p = *pipe thickness (in.)*

α_{sp} = *capacity reduction factor*

β = *coupler rigid length ratio*

ε_s = *strain in steel (in./in.)*

ε_{sp} = *reduced strain in coupler region (in./in.)*

θ = *angle between the horizontal axis of the bent cap and the pipe helical corrugation or lock seam (deg)*

C3.0—MECHANICALLY SPLICED CONNECTIONS IN PLASTIC HINGE ZONES

C3.1—GENERAL

For some types of ABC connections, in particular those with mechanically spliced reinforcement in the plastic hinge region, there is a reduction in deformation capacity that shall be accounted for.

CC3.1

For bridge columns, this reduction usually results in a decrease in displacement capacity when these connection types are used; however, when properly designed and constructed, seismic performance of columns with these connections will be satisfactory provided seismic couplers are used.

C3.2—SPLICED REINFORCEMENT BAR

The length of the coupler region of a mechanically spliced connection shall be defined as:

$$L_{cr} = L_{sp} + 2d_{bl} \qquad \text{(C3.2-1)}$$

where:

L_{sp} = physical length of mechanical coupler (in.)

d_{bl} = diameter of the larger bar being spliced (in.)

Only seismic couplers that have demonstrated through testing per AASHTO M xxx-yy Standard Method of Testing for Mechanically Spliced Steel Reinforcing Bars to consistently fail outside of the coupler region shall be used in plastic hinge zones of columns.

The length of the coupler, L_{sp}, shall not exceed 15 times the diameter of the smaller bar spliced.

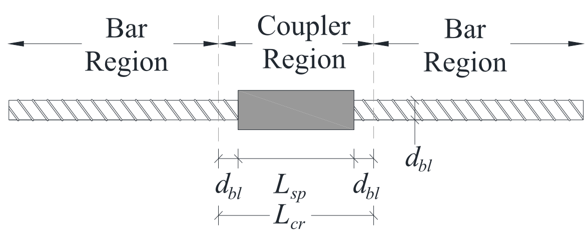

Figure C3.2-1—Coupler Region Definition

CC3.2

The limitation on the length of the coupler is needed to minimize adverse effects on the rotation capacity of the member due to a reduction in plastic hinge length, as well as the fact that test data for longer couplers is not available.

C3.3—SPLICED BAR DISPLACEMENT DUCTILITY

To account for the effect of splices in the plastic hinge the displacement capacities calculated using the equations of Article 4.8.1 shall be reduced by the factor α_{sp}:

$$\alpha_{sp} = (1-0.18\beta)\left(\frac{H_{sp}}{L_{sp}}\right)^{0.1\beta} \quad \text{(C3.3-1)}$$

where:

β = coupler rigid length ratio

H_{sp} = distance from the connection interface to the coupler end closest to the interface (in.)

Figure CC3.3-1 shows some of the terms from Eq. C3.3-1. When the coupler is flush with the end of the column, a minimum value of 0.1 in. shall be used for H_{sp}.

CC3.3

The presence of a coupler reduces the length over which a reinforcing bar can yield, which reduces the resulting displacement ductility capacity of a plastic hinge that includes couplers. Eq. C3.3-1 is applicable to bars with more than one coupler along the length, as long as the clear spacing between couplers is greater than L_{sp}.

Values for β can vary depending on a variety of factors including the specific details of the coupler being tested, and the bar sizes. The β values listed in Table CC3.3-1 are intended to facilitate the preliminary design of some of the more widely available coupler types. Values of β may be found for any coupler type according to AASHTO M xxx-yy.

In lieu of test data for a specific mechanical bar splice, the values given in Table CC3.3-1 may be used for preliminary design only. Final design values shall come from testing according to AASHTO M xxx-yy.

Table CC3.3-1— Values for β

Splice Type	β
Grouted Sleeve	0.55
Headed Bar	0.5
Swaged	0.9

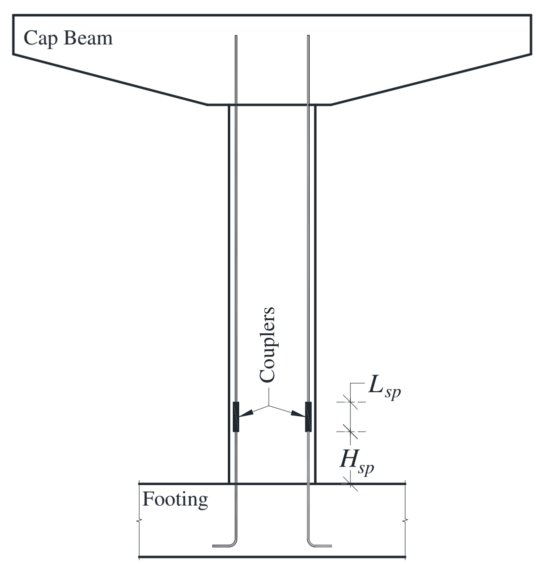

Figure CC3.3-1—Coupler Location

C3.4—ANALYTICAL PLASTIC HINGE LENGTH

The analytical plastic hinge length, L_p, given in Article 4.11.6, shall be replaced with the spliced hinge length, L_p^{sp}, when using mechanically coupled bars in the plastic hinge

CC3.4

Eq. C3.4-1 is applicable to bars in plastic hinges with more than one coupler along the length of the bar, as long as the clear spacing between couplers is greater than L_{sp}.

region. The plastic hinge length for spliced bars shall be taken as:

$$L_p^{sp} = L_p - \left(1 - \frac{H_{sp}}{L_p}\right)\beta L_{sp} \leq L_p \qquad \text{(C3.4-1)}$$

where:

L_p = plastic hinge length for unspliced bars, given in Article 4.11.6 (in.)

L_{sp} = physical length of mechanical coupler (in.)

When using splices within connecting elements such as footings or cap beams, the column plastic hinge length adjacent to the connection shall be taken as 0.75 L_p but no less than L_p^{sp}.

The possibility of a plastic hinge forming outside of the coupler region shall be considered.

When splices are embedded in connecting elements rather than the column, reduction in the plastic hinge length is less significant than that in Eq. C3.4-1. However, the plastic hinge length is shortened because strain penetration is restrained to some extent. In the absence of additional research data, a 25 percent reduction in L_p is used.

C3.5—COUPLER REGION STRAINS

For use in spliced section analyses, the strain in the coupler region shall be reduced by the following relationship:

$$\frac{\varepsilon_{sp}}{\varepsilon_s} = \frac{L_{cr} - \beta L_{sp}}{L_{cr}} \qquad \text{(C3.5-1)}$$

where:

ε_{sp} = reduced strain in the coupler region (in./in.)

ε_s = strain in the steel had no coupler been present (in./in.)

CC3.5

When utilizing a pushover analysis, in which the plastic hinge is modeled with fiber section distributed plasticity, the effects of the presence of couplers need to be accounted for. Eq. C3.5-1 is used to adjust the steel stress-strain relationship in the coupler region.

C4.0—CONNECTION DETAILS

C4.1—DETAILS OF POCKET/SOCKET CONNECTIONS

Design of pocket/socket connections shall conform to the provisions of this section.

CC4.1

One of the viable precast bridge column connection types for accelerated bridge construction (ABC) is the pocket/socket connection. Design and detailing guidelines for columns connecting to bent caps (seat-type or integral type), footings, and pile shaft with pocket connections based on experimental and analytical studies are presented herein. Little experimental data exists on knee type connections, and therefore they are not covered in this section.

C4.1.1—Minimum Depth of Pocket

The depth of a pocket, H_p, as shown in Figure C4.1.1-1, shall satisfy the following criteria:

CC4.1.1

Experimental studies have shown that the full column plastic moment can be transferred to the cap beams when the embedment length of column or column longitudinal

$$H_p \geq D_{cm} \quad \text{(C4.1.1-1)}$$

$$H_p \geq 0.79 d_{bl} \frac{f_{ye}}{\sqrt{f'_c}} \quad \text{(C4.1.1-2)}$$

$$H_p \geq 24 d_{bl} \quad \text{(C4.1.1-3)}$$

in which:

D_{cm} equals the larger of D_{cl} and D_{ct}

where:

D_{cl} = column cross-sectional dimension in the longitudinal direction (in.)

D_{ct} = column cross-sectional dimension in the transverse direction (in.)

d_{bl} = diameter of largest column longitudinal bar in the pocket region (in.)

f_{ye} = expected yield strength of the column longitudinal reinforcing steel (ksi)

f'_c = nominal compressive strength of the column concrete (ksi)

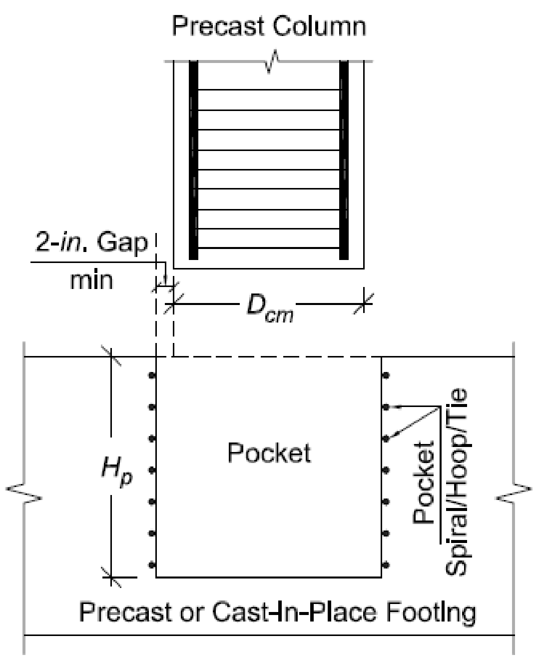

Figure C4.1.1-1—General Pocket Notation

reinforcement into the pocket is $1.0D_{cm}$. Eq. C4.1.1-1 was developed based on these findings. Matsumoto et al. (2001) proposed an equation similar to Eq. C4.1.1-2 for embedment length of column longitudinal bars into precast bent caps based on monotonic testing. Because it was only slightly different than Eq. 8.8.4-1, that form is adopted here. The minimum development length of straight bars in cap beams according to the Caltrans SDC (2013) is calculated by Eq. C4.1.1-3 which is based on CIP tests. When headed longitudinal bars are used in the column, Eq. C4.1.1-3 may be adjusted to account for the reduced embedment length requirement of the bars in the pocket.

C4.1.2—Pocket Material

Pockets for circular columns shall be constructed with helical, lock-seam, corrugated steel pipes conforming to ASTM A760 (AASHTO M36). The pipe thickness (t_p)

CC4.1.2

According to ASTM A760, 31 sizes are allowed for corrugated steel pipes with inner diameter of 4.0 in. to 144 in. Furthermore, seven thicknesses are specified from 0.04

shall be at least:

$$t_p = \frac{A_{sp} f_{yh}}{\left(s f_{yp} \cos\theta \right)} \geq 0.06\ in. \qquad \text{(C4.1.2-1)}$$

where:

A_{sp} = area of one column hoop or spiral (in.^{2})

f_{yh} = nominal yield stress of column reinforcing (ksi)

s = spacing of column hoop or spiral (in.)

f_{yp} = steel pipe yield stress (ksi)

θ = angle of the pipe helical corrugation or lock scan, measured from axis of bent cap or footing (deg.)

in. to 0.168 in. Table CC4.1.2-1 presents diameter and thickness of steel pipes for common bridge column diameters. Eq. C4.1.2-1, a modification to that proposed by Restrepo et al. (2011), compensates for the lack of column transverse reinforcement inside the pocket, when column dowels are extended into the pocket, and ensures sufficient confinement by the corrugated steel pipe. It does not account for vertical shear reinforcement within or outside the joint. Nevertheless, extension of column hoops or spirals into the pocket is highly recommended as illustrated for Alt-2, Alt-4, and Alt-5 in Figure C4.2.1-1. Alt-5 is the simplest alternative and expedites construction by a factor of four compared to cast-in-place bents (Tazarv and Saiidi, 2015). The angle between the horizontal axis of the bent cap and the pipe helical corrugation (θ) is always less than 30° for pipes presented in the table according to the ASTM A760 limitations. $\theta = 30°$ is recommended to simplify the pipe design. With $\theta = 30°$, the pipe thickness is overestimated by no more than 13 percent, which is insignificant.

Table CC4.1.2-1—Galvanized Steel Pipe Dimension for Pocket Connections

Inside Diameter, in.	Specified Thickness, in. [2 2/3” x 1/2” Corrugation]	Specified Thickness, in. [3” x 1” or 5” x 1” Corrugation]
36	0.064 0.079 0.109 0.138	N/A
42	0.064 0.079 0.109 0.138 0.168	N/A
48	0.064 0.079 0.109 0.138 0.168	N/A
54	0.079 0.109 0.138 0.168	0.064 0.079 0.109 0.138 0.168
60	0.109 0.138 0.168	0.064 0.079 0.109 0.138 0.168
66	0.109 0.138 0.168	0.064 0.079 0.109 0.138 0.168
72	0.138 0.168	0.064 0.079 0.109 0.138 0.168
78	0.168	0.064 0.079 0.109 0.138 0.168
84	0.168	0.064 0.079 0.109 0.138 0.168
90	N/A	0.064 0.079 0.109 0.138 0.168

C4.1.3—Pocket Filler Material

The pocket shall be filled with concrete, self-consolidating concrete, or grout when columns are partially precast. In fully precast columns, and for footing pockets, the pockets shall be filled with non-shrink, high-flow grout. The grout shall be fluid when the column is placed. The compressive strength of the filler material sampled and tested according to an appropriate ASTM standard shall not be less than the bent cap or footing concrete compressive strength. When grout is used, the grout compressive strength shall be at least 15 percent higher than the cap-beam concrete compressive strength.

CC4.1.3

For partially precast columns (Alt-1 to Alt-4 in Figure C4.2.1-1), concrete, self-consolidating concrete (SCC), or grout may be used to fill the pocket, but SCC is preferred. Pockets with smaller void spaces, typical of fully precast column connections and footing connections, require grout. Aggregate-based grout should not be used in Alt-5 since this type of grout is not sufficiently workable. The strength of the filler material should be at least equal to the adjoining member strength to avoid a weak link in the connection. A 15 percent overstrength is required when grout is used because the grout compressive strength is often based on testing of 2.0-in. cubic samples, which is higher than the strength determined from cylindrical samples.

C4.1.4—Pocket Gaps

For precast column connections, the gap between the precast column and the pocket walls, including the top wall, shall be no less than 2.0 in., but shall not exceed 4.0 in. Spacers shall be installed to maintain this gap in the vertical direction.

CC4.1.4

The specified gap between the surfaces of the fully precast column and the pocket ensures that the grout will flow through the entire pocket.

C4.1.5—Precast Column Surface Preparation

The surface of the sides of a precast column within the limits of the pocket shall be roughened to an amplitude of 0.25 in. or greater.

C4.1.6—Bent Cap to Column Top Gaps

When a gap, often referred to as a bedding layer, greater than 1 in. is present between the top of the precast column and the underside of the bent cap, lateral confinement reinforcement equal to that provided in the column shall be provided in the bedding layer.

CC4.1.6

No bedding layers were used between the column and cap beam in several previous laboratory tests of large-scale models (Mehrsoroush and Saiidi, 2016; Mohebbi, et al. 2018; Mehraein and Saiidi, 2016). However, depending on the geometry of the connection and the superelevation in the bent cap, provision for a bedding layer may be needed. Refer to Restrepo, et al. 2011 for design of bedding layer.

C4.2—DETAILS FOR BENT CAP POCKET CONNECTIONS

C4.2.1—Minimum Depth of Bent Cap

The depth of bent cap (H_{cap}) shall be equal to or greater than the pocket depth (H_p) when column longitudinal reinforcement is extended outside the precast column and is anchored into the full-depth pocket (Alt-3 and Alt-4 in Figure C4.2.1-1). For fully precast columns (Alt-5) or cap beams with partial-depth pockets (Alt-1 and Alt-2), the depth of bent cap (H_{cap}) shall not be less than $1.25H_p$ as shown in Figure C4.2.1-2. These limits supersede the more restrictive dimensional limits of 8.13.5. Bent caps with a depth of $1.6D_c$ or greater shall be designed based on the strut and tie provisions of *AASHTO LRFD Bridge Design Specifications* or as approved by the

CC4.2.1

Alternatives 1 through 4 of Figure C4.2.1.-1 have a cast-in-place portion of the column within the pocket depth, while Alternatives 5 utilizes a full height precast column in the pocket. Alternatives 1 and 2 have a top to the pocket with an access hole, while Alternatives 3 and 4 use an open pocket. Alternatives 1 and 3 pass the column longitudinal steel through the cap bottom steel, while Alternatives 2, 4, and 5 bundle the cap bottom steel at the sides.

When connecting fully precast columns to cap beams with pocket (Alt-5 in Figure C4.2.1-1), the depth of bent cap above the pocket should be sufficiently large to avoid cracking above the pocket during lifting, and to avoid

Owner.

Consideration shall be given to the resistance to punching shear at the top of the pocket/socket.

punching shear failure above the pocket due to the weight of the cap beam. Bent cap depth of $1.25H_p$ can be used as initial design height when columns are either fully or partially precast. Mehrsoroush and Saiidi (2014) showed that bent caps incorporating pocket connections with a total depth of $1.6D_c$ can be designed using conventional design methods. In the absence of test data, deeper cap beams should be designed with the strut and tie method.

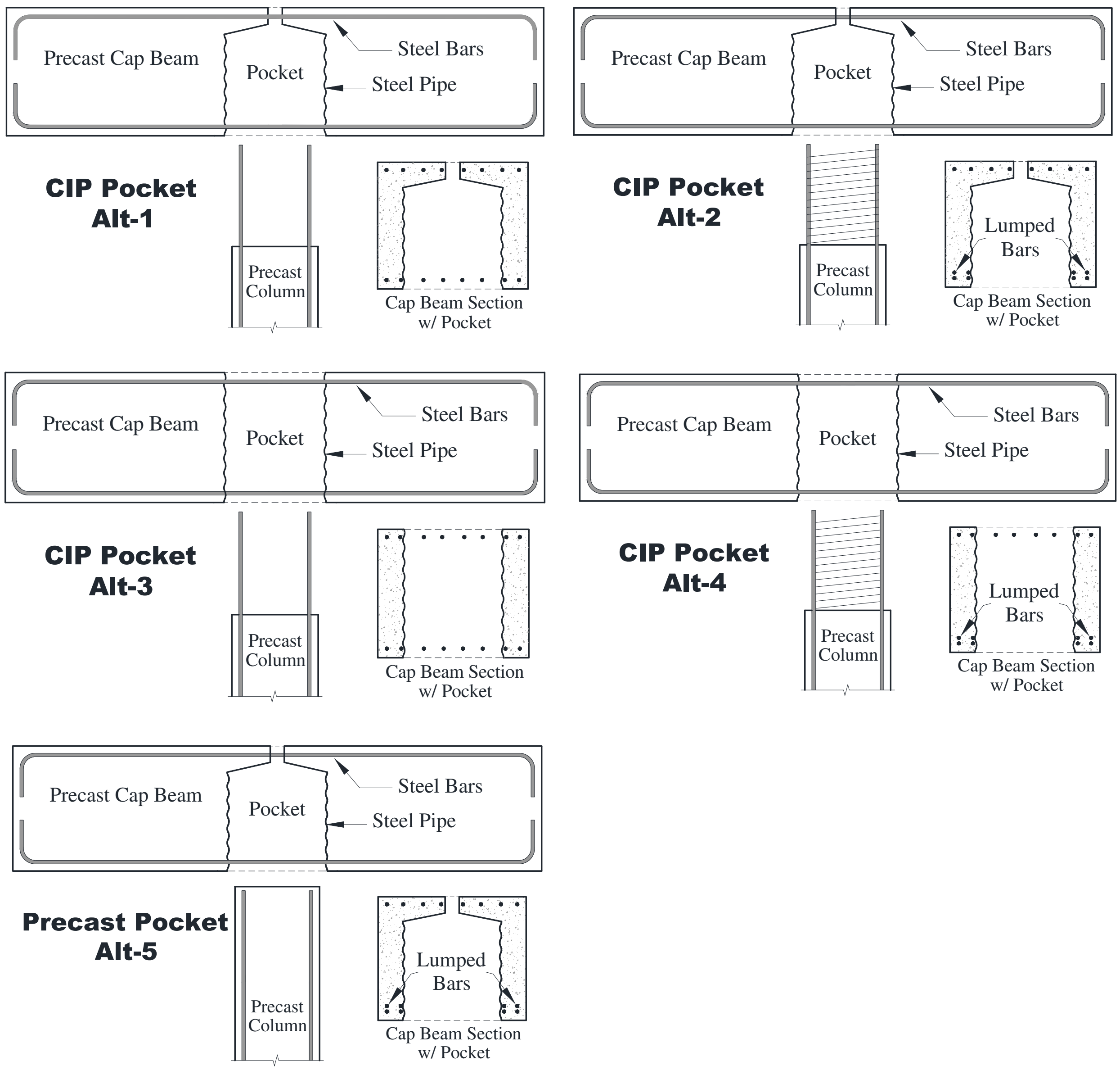

Figure C4.2.1-1—Detailing Alternatives for Pocket Connections

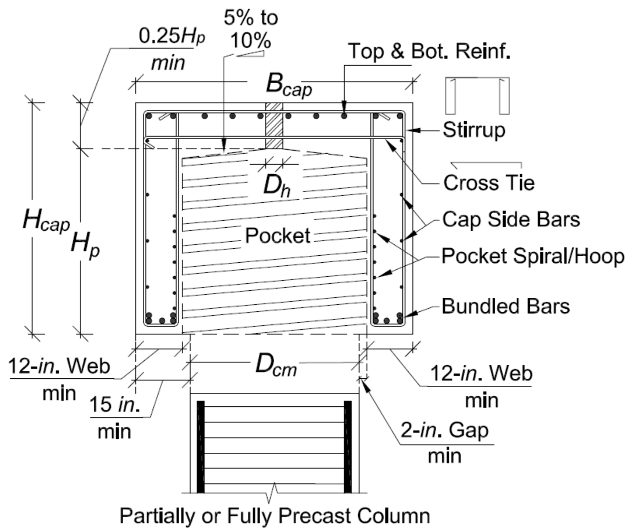

Figure C4.2.1-2—Detail of Bent Cap Pocket Connection

C4.2.2—Minimum Width of Bent Cap

The width of bent cap with pocket (B_{cap}) shall extend at least 15.0 in. on each side of the column when bent cap longitudinal bars are clustered beside the pocket as shown in Figure C4.2.1-2. The width of bent cap needs only satisfy the clear cover requirements when bent cap longitudinal bars are distributed across the width of the beam (Alt-1 and Alt-3). The gap between the column and the pocket face shall not be less than 2.0 in. but shall not exceed 4.0 in. when the column is fully precast. In this case, the bent cap web at the pocket shall be at least 12.0 in. wide.

CC4.2.2

The minimum width of an integral cap beam according to Article 8.13.4.1.1 is the column diameter (or side dimension) plus 24.0 in. This limitation was used as a baseline for this Article with a 6.0-in. increase to accommodate the pocket. In this instance it is applicable to non-integral cap beams as well. The minimum proposed bent cap width (D_c+2.5 ft) provides sufficient space to lump the bottom longitudinal reinforcement of the cap beam in the web. This requirement is waived when bars are distributed across the width of the cap beam (e.g. Alt-1 and Alt-3). The specified gap between the column and the pocket provides sufficient construction tolerance for multi-column bents while ensuring adequate grout thickness.

C4.2.3—Vent for Pumping Grout

The diameter of the opening above the cap beam pocket (D_h) shall be less than 0.1 D_{cm}, but in no case less than 4.0 in. to allow for placement of concrete or grout. The top face of the pocket shall be sloped between 5 to 10 percent as shown in Figure C4.2.1-2.

CC4.2.3

The American Concrete Pumping Association (2011) recommends limiting the maximum size of the coarse aggregate to one-third of the smallest inside diameter of the pump or placing line. A 4.0-in. opening provides sufficient access to cast concrete and grout from top of the bent cap. The recommended slope in the top face of the pocket is to avoid entrapment of air during casting of the filler material.

C4.2.4—Pocket Transverse Reinforcement

The cap beam transverse reinforcement (spiral or hoops) around the pocket (Figure C4.2.1-2) shall be placed in the lower half of the bent cap. The transverse reinforcement volumetric ratio shall not be less than that of the column transverse reinforcement.

CC4.2.4

The required transverse reinforcement around the pocket ensures the integrity of the cap beam in the pocket region. Research has shown that transverse reinforcement is necessary only in the lower half of the pocket (Mehrsoroush and Saiidi, 2014).

C4.2.5—Bent Cap Longitudinal Reinforcement

Bundling of bent cap longitudinal bars shall be allowed subject to AASHTO LRFD limitations for bundled bars. The bent cap longitudinal bars shall be continuous over the columns. Bent cap longitudinal bar splices in any form shall not be allowed within $1.0D_{ct}$ from the column center line. Clear cover requirements do not apply to bars that are adjacent to the filler material in the pocket.

CC4.2.5

AASHTO LRFD (2013) specifies the reinforcement detailing (e.g. spacing and bundling) in Article 5.10. Minimum clear cover is not necessary for the reinforcement inside the pocket because sufficient protection against corrosion is provided by the pocket filler material.

C4.3—DETAILS FOR FOOTING POCKET CONNECTIONS

A minimum of eight reinforcing steel bars diagonal to the footing reinforcement, as shown in Figure C4.3-1, shall be placed immediately below the footing top reinforcement around the pocket. The diagonal reinforcement size shall be the same as the footing top reinforcement size spaced diagonally no more than six times the bar diameter ($6d_b$) apart. Bar lengths shall be equal to or greater than twice the development length, but in any case equal to or greater than the dimensions of the pocket.

Transverse reinforcement in the form of spirals, hoops, or ties, shall be placed around the pocket for the full depth of the pocket. Spirals shall be closed at their ends. The transverse reinforcement volumetric ratio shall not be less than 50 percent of the column transverse reinforcement.

CC4.3

Diagonal or radial reinforcement close to the pocket was used in all previous studies, which investigated the performance of footing pocket connections. These bars are used to minimize footing damage under seismic loading.

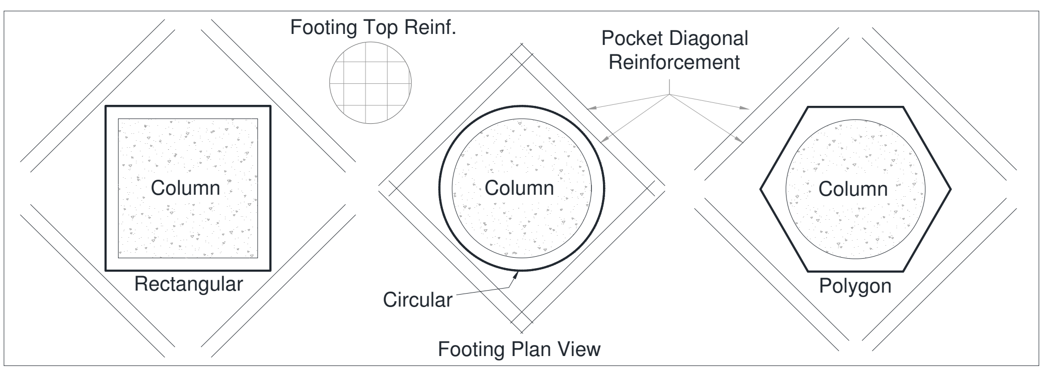

Figure C4.3-1—Diagonal Reinforcing Around Footing Pockets

C4.4—DETAILS FOR DRILLED SHAFT POCKETS

The diameter of a drilled shaft with pocket shall be at least 28.0 in. larger than the column diameter as shown in Figure C4.4-1. This minimum does not account for shaft placement tolerances or minimum covers. In this figure, the typical drilled shaft reinforcement has not been shown for clarity.

Transverse reinforcement in the form of spirals or hoops shall be placed over the full height of the pocket, and the volumetric ratio of the transverse reinforcement shall not be less than that provided in the column.

CC4.4

AASHTO SGS (2014) does not specify a minimum size for cast-in-place enlarged drilled shafts. Caltrans SDC (2013) requires cast-in-place oversized shafts to be at least 24.0 in. larger than the column diameter with a moment capacity of 1.25 times the column moment capacity. Finite element parametric studies performed as part of NCHRP 12-105 on drilled shaft pocket connections have confirmed the adequacy of the Caltrans requirements.

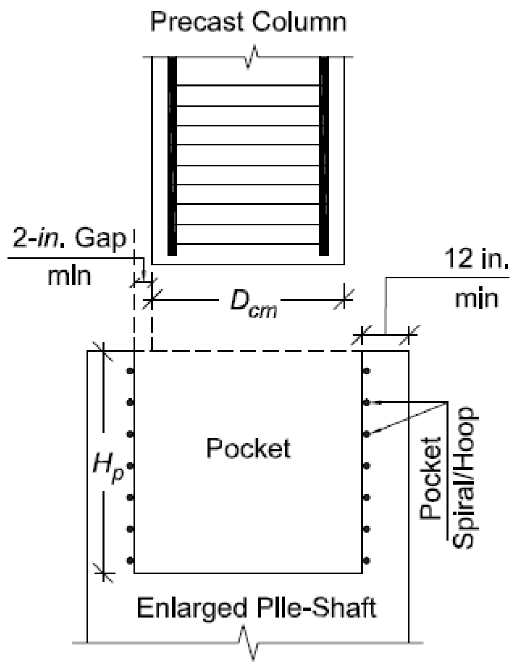

Figure C4.4-1—Drilled Shaft Pocket Details

C4.5—GROUTED DUCTS

Ducts used in grouted duct connections shall be corrugated galvanized steel strip ducts in conformance with ASTM A653, and shall have a minimum wall thickness of 0.018 in. Figure C4.5-1 shows the general arrangement of a grouted duct and the relevant terminology, with L_{ag} representing the embedment length. Plastic and other materials shall not be used. The actual inner duct diameter shall be no less than 2.75 times the bar diameter anchored in the duct. For bundled bars, a minimum inner duct diameter of 2.5 times the equivalent bar diameter may be used. The grout used shall be the non-shrink type.

When anchoring column reinforcement into grouted ducts, the minimum length of the embedment into the duct shall be taken as the larger of:

$$l_{ab} = \frac{0.68 d_{bl} f_{ye}}{\sqrt{f'_g}} \qquad \text{(C4.5-1)}$$

$$l_{ad} = \frac{2.25 d^2{}_{bl} f_{ye}}{d_d \sqrt{f'_c}} \qquad \text{(C4.5-2)}$$

where:

l_{ab} = limiting embedment length based on bond strength between the bar and grout (in.)

l_{ad} = limiting embedment length based on bond strength between the duct and concrete (in.)

d_{bl} = diameter of the column bar, or equivalent

CC4.5

AASHTO SGS (2014) does not specify a minimum size for cast-in-place enlarged drilled shafts. Caltrans SDC (2013) requires cast-in-place oversized shafts to be at least 24 in. larger than the column diameter with a moment capacity of 1.25 times the column moment capacity. Finite element parametric studies performed as part of NCHRP 12-105 on drilled shaft grouted duct connections have confirmed the adequacy of the Caltrans requirements.

diameter of bundled bars (in.)

d_d = actual inner diameter of the duct (in.)

f_{ye} = expected yield stress of the column bar (ksi)

f'_c = nominal compressive strength of the concrete (ksi)

f'_g = nominal compressive strength of the grout (ksi)

The coating factor, λ_{cf} , defined in Article 5.10.8.2.1a of the *AASHTO LRFD Bridge Design Specifications* shall be used to modify the calculated value of l_{ab}, when appropriate.

Reinforcing bars may be bundled into a single duct, provided no more than three bars are bundled together. An equivalent diameter of the bundled bars shall be used in Eqs. C4.5-1 and C4.5-2, based on the total area of the bundled bars.

The ducts shall be located within an area of transverse reinforcement no less than that contained in the plastic hinge region of the column anchoring into the ducts.

Ducts shall be spaced no less than the larger of:

- 2.0 in.
- 1.3 times the largest aggregate size.

Any gaps between a column and a bent cap, footing, or drilled shaft shall be reinforced as required in C4.1.6.

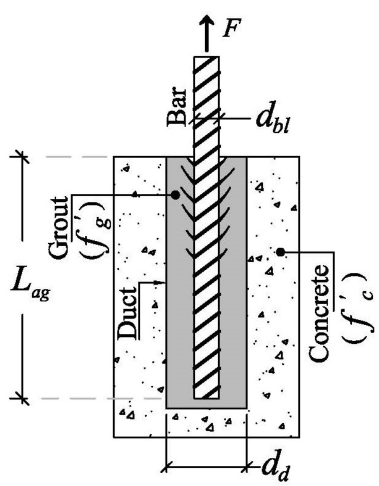

Figure C4.5-1—Grouted Duct Nomenclature

The diameter of enlarged drilled shafts with grouted duct column connections shall be at least 24 in. larger than the column diameter.

REFERENCES

AASHTO. 2013. "AASHTO LRFD Bridge Design Specifications," Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. 2014. "AASHTO Guide Specifications for LRFD Seismic Bridge Design," Washington, DC: American Association of State Highway and Transportation Officials.

American Concrete Pumping Association. 2011. "Guidelines for the Safe Operation of Concrete Pumps," Ver. 03.11, Lewis Center, OH, 40 pp.

ASTM A653. 2015. "Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process," West Conshohocken, PA, 13 pp.

ASTM A760. 2015. "Standard Specification for Corrugated Steel Pipe, Metallic-Coated for Sewers and Drains," West Conshohocken, PA, 15 pp.

Caltrans. 2013. "Seismic Design Criteria Version 1.7". Caltrans, Sacramento, CA.

Matsumoto, E.E., Waggoner, M.C., Sumen, G. and Kreger, M.E. 2001. "Development of a Precast Bent Cap System," Center for Transportation Research, The University of Texas at Austin, FHWA Report No. FHWA/TX-0-1748-2, 402 pp.

Mehraein, M and Saiidi, M.S. 2016. "Seismic Performance of Bridge Column-Pile-Shaft Pin Connections for Application in Accelerated Bridge Construction," Center For Civil Engineering Earthquake Research, Department of Civil and Environmental Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-16-01.

Mehrsoroush, A., and Saiidi, M.S. 2014. "Experimental and Analytical Seismic Studies of Bridge Piers with Innovative Pipe Pin Column-Footing Connections and Precast Cap Beams," University of Nevada, Reno.

Mehrsoroush, A., and Saiidi, M. 2016. "Cyclic Response of Precast Bridge Piers with Novel Column Base Pipe Pins and Pocket Connections," Journal of Bridge Engineering, ASCE, Vol 21, No. 4.

Mohebbi, A., Saiidi, M.S., and Itani, A. 2018. "Shake Table Studies and Analysis of a Precast Two-Column Bent with Advanced Materials and Pocket Connections," Journal of Bridge Engineering, ASCE, Vol. 23, No. 7.

Restrepo, J.I., Tobolski, M.J. and Matsumoto, E.E. 2011. "Development of a Precast Bent Cap System for Seismic Regions," NCHRP Report 681, Washington, D.C.

Tazarv, M. and Saiidi, M.S. 2015. "Design and Construction of Precast Bent Caps with Pocket Connections for High Seismic Regions," Center For Civil Engineering Earthquake Research, Department of Civil and Environmental Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-15-06, 101 pp.