



## 20-7 SEISMIC DESIGN OF SLAB BRIDGES

### Introduction

Slab bridges must meet the performance requirements in the Seismic Design Criteria (SDC). The designer is responsible for providing a suitable Earthquake Resisting System (ERS) whether the top of the columns are fixed, pinned, or have a reduced section. The superstructure must be capacity-protected using ductile pile/shaft extensions and reliable connections to ensure the superstructure remains elastic for the design seismic hazards. Standard Plans (Caltrans, 2010) pile details do not have sufficient ductility and must not be used as pile/shaft extensions for new slab bridges (SDC 7.7.4).

Pile/shaft extensions used as columns supporting slab bridges must be a minimum of 18 inches in diameter (precast) or 24 inches in diameter (cast-in-place) and have #4 or larger hoops/spiral reinforcement. Engineers must ensure that the superstructure slab is capacity-protected against the expected plastic moment and joint shear of columns whether they use the standard design charts in Bridge Design Aids 4-10 (Caltrans, 2009) or are providing a unique design. All top and bottom longitudinal slab reinforcement must be made continuous over the bents. There are four methods that can be used to meet the seismic design requirements for slab bridges.

- A. Increase slab depth until its capacity overcomes top of column capacity.
- B. Reduce section between the top of column and the slab (see SDC 7.6.2.2 Case (B)).
- C. Provide a pin detail to reduce top of column moments.
- D. Augment slab reinforcement and/or incorporate a drop cap.

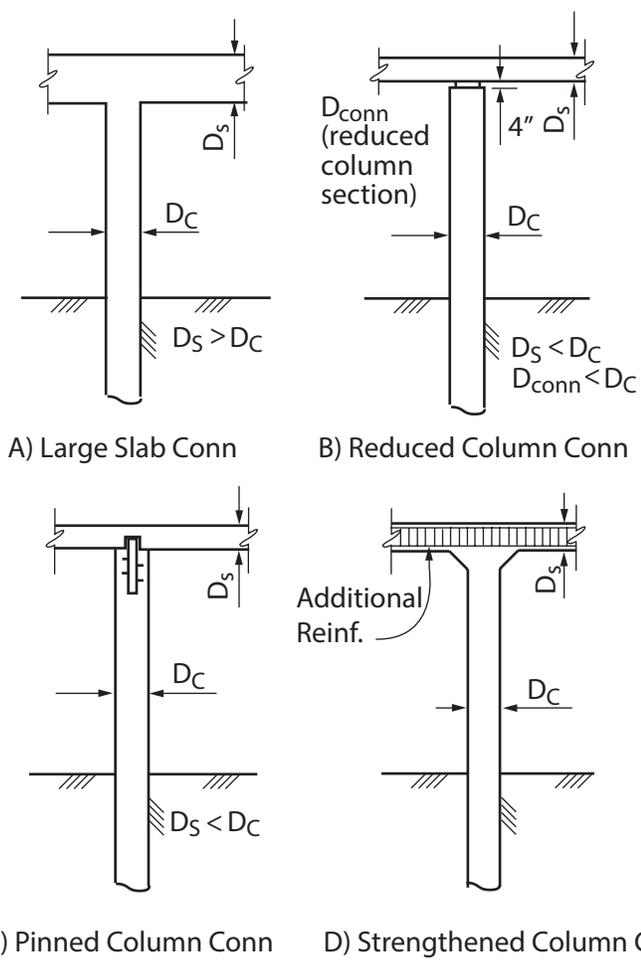


Figure 1. Slab Bridge Joint Design Alternatives to meet SDC Requirements

## Definition

- Piles—bridge support member driven into the ground.
- Shafts—bridge support members cast in a drilled hole in the ground.
- Pile Extension—the portion of the pile above the ground.
- Shaft Extension—the portion of the shaft above the ground.
- Pile and shaft extensions above the ground are considered and referred to as columns in this document.

## Pile Shaft Extension

Slab bridges supported on pile/shaft extensions must be designed as SDC-compliant columns per SDC 7.7.4. The pile/shaft extension's seismic performance depends on well detailed connections between the column and superstructure, sufficient confinement to form reliable plastic hinges where expected, and adequate displacement capacity.

Cross sections with spiral wire reinforcement, including Standard Plan piles and those from other older bridge references must not be used as pile/shaft extensions for new construction. The wire has poor ductility and does not meet the minimum diameter for compression member design (LRFD 5.10.6). Research has shown that wire-confined cross sections have a lower ductility capacity than conventionally reinforced columns (Moehle, 2001).

Pile/Shaft extensions for new slab bridges must comply with SDC Section 2.2.4. Pile/Shaft extensions for slab bridge widenings must be based on Memo to Designers (MTD) 20-12. Designers may use the limited ductility of wire-reinforced existing pile/shaft extensions in retrofit analysis of existing bridges per procedures specified in MTD 20-4.

## Column Superstructure Joint

A slab bridge's shallow cross section makes it difficult to satisfy SDC 7.6.1, which strongly recommends that the superstructure depth exceed the column diameter. Figure 1 and the more detailed drawings in Appendix A provide alternatives for designers to facilitate meeting SDC requirements. Appendix B provides pile/shaft extensions that qualify to be used as columns that meet SDC requirements.

Providing sufficient development length ( $l_d$ ) for column longitudinal reinforcement into a slab can be difficult since the slab is often too thin to provide adequate development for large diameter bars. The use of a drop cap provides the designer with as much as twice the

development length for anchorage of the column reinforcement. Until further testing is completed the following values must be used for the anchorage length ( $l_{ac}$ ) of the longitudinal reinforcement into a slab (where  $d_b$  is the diameter of the bar):

- Straight bars must have an anchorage length,  $l_{ac} \geq 24d_b$
- Hooked bars must have an anchorage length,  $l_{ac} \geq 19d_b$
- Full size ( $9_{Ab}$ ) 'T' headed bars<sup>1</sup> (where  $A_b$  is equal to the area of the bar) must have an anchorage length,  $l_{ac} \geq 11d_b$  (plus the 'T' head). Smaller sized ( $4A_b$ ) 'T' heads must not be used for column anchorage.

Slab bridge pile/shaft extension to superstructure joints must also conform to the SDC recommendations for T-joints and knee joints (SDC 7.4). Testing and modeling of pile/shaft-to-slab T-joint and knee-joint connections (Sanders, 2010) demonstrated that appropriately reinforced joint regions will limit damage and force plastic hinging into the column. The following equations and details are used for full moment connection joint reinforcement (see Table 1, and Figures 2 and 3). Figure 2 is a sketch for identifying the different joint shear reinforcement regions. The regions shown in Figure 2 are defined as follows:

**Effective width ( $B_{eff}$ )** = column diameter + 2 × slab thickness (see Figures 2 and 5)

- The effective width is the slab width around the column that is considered effective at resisting the column's plastic moment (see Figure 2).
- The effective width ( $B_{eff}$ ) is for both the longitudinal and transverse directions.
- Slab bridges with less than 16 inch thickness must use drop caps to resist the transverse column plastic moment. The drop cap should be no larger than the effective width and must be designed to resist the column plastic moment.
- If the columns are too closely spaced to provide an effective width between them, then the entire bridge width should be considered effective at resisting the plastic moment of all the columns.

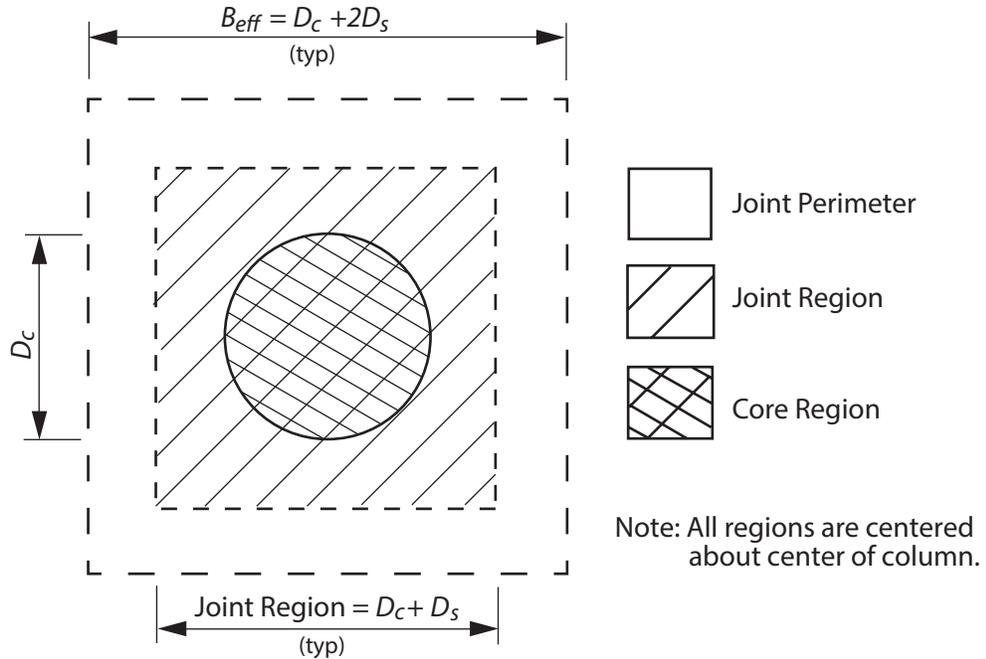
**Core Region** = Region of slab within the column cage above the column (see Figure 2).

**Joint Region** = Region of slab above the column with plan dimensions of (column diameter + slab thickness) in both the longitudinal and transverse directions. For a joint with a drop cap, the joint dimensions in both directions shall be the width of the drop cap (see Figure 2).

**Joint Perimeter** = Slab region outside the Joint Region (see Figure 2).

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<sup>1</sup>. Headed Bar Reinforcement is commonly referred to as 'T' headed bars.



**Figure 2. Reinforcement Regions for ‘T’ and Knee-Joints**

Note that the j-bars are to be placed in the Core Region while the vertical stirrups are positioned in both the Joint Region and Joint Perimeter (see Figures 2 and 3).

The Designer must also check two-way shear, following the requirements of LRFD 5.13.3.6.

When a reduced column section (such as in Figure 1B and Figure A-5a) is used to decrease the column demand moment going into the slab, the plastic moment of the reduced section must be used for determining the required joint reinforcement. The value of  $A_{st}$  for determining the joint shear reinforcement in Table 1 is the area of the reinforcement through the reduced region connecting the top of the column to the slab. The pattern for distribution of the stirrups and cap region reinforcement must be the same as for a full section analysis except that the reinforcement cannot be smaller than #4 rebar.

**Table 1: Reinforcement for Fixed Column to Superstructure Joints**

Requirement	Slab T-Joints (see Definitions and Figure 3)	Slab Knee-Joints (see Definitions and Figure 3)
Area of flexural reinforcement in the longitudinal and also in the transverse direction within effective width	$A_{cap}^{top}, A_{cap}^{bot} = [\text{Flexural reinf. required}^1 + \text{Add. reinf.}]$ Add. reinf. = $0.25 \times A_{st}$ (drop cap) Add. reinf. = $0.35 \times A_{st}$ (flat slab)	$A_{cap}^{top}, A_{cap}^{bot} = [\text{Flexural reinf. required}^1 + \text{Add. reinf.}]$ Add. reinf. = $0.35 \times A_{st}$ (long. dir.) $A_s^{u-bar} = 0.35 \times A_{st}$ (trans. dir.)
J-bars in the core zone of joint region	$A_s^{j-bar} = 0.35 \times A_{st}$	$A_s^{j-bar} = 0.35 \times A_{st}$
Total area of vertical stirrups in each of Joint region and Joint Perimeter	$A_s^{jv} = 1.15 \times A_{st}$	$A_s^{jv} = 0.85 \times A_{st}$
Horizontal ties	$A_s^{jh} = 0.1 \times A_{st}$	$A_s^{jh} = 0.01 \times A_{st}$
Horizontal side reinforcement	$A_s^{sf} \geq \begin{cases} 0.1 \times A_{cap}^{top} \\ \text{or} \\ 0.1 \times A_{cap}^{bot} \end{cases}$	$A_s^{sf} \geq \begin{cases} 0.1 \times A_{cap}^{top} \\ \text{or} \\ 0.1 \times A_{cap}^{bot} \end{cases}$
Horizontal cap end ties	-	$A_s^{jhc} = 0.33 \times A_s^{u-bar} \text{ min}$
Transverse column reinf. extended into slab <sup>2</sup>	$A_{v,joint} \geq 0.18 \times A_{st}$	$A_{v,joint} \geq 0.18 \times A_{st}$

## Definitions

<sup>1</sup>Flexural reinforcement required to force plastic hinge into column ( $M_{n,slab} \geq 1.2 M_{p,col}$ )

$${}^2\text{Number of hoops} = \left\lceil \frac{0.18 \times A_{st}}{\frac{\pi}{2} \times A_b} \right\rceil$$

where  $A_b$  = Area of individual reinforcing steel bar

$A_{cap}^{top}, A_{cap}^{bot}$  = area of top and bottom flexural reinforcement in each of the longitudinal and transverse directions within the effective width ( $B_{eff}$ ); a vertical stirrup shall be provided at each intersection point of these bars, which can be  $A_s^{jv}$  in the Joint Region or ;  $A_s^{j-bar}$  in the Core Region. The stirrups shall have hooks around the top and bottom longitudinal flexural reinforcement

$A_{st}$  = Area of main column reinforcement anchored in the joint. For reduced sections,  $A_{st}$  is the area of longitudinal steel connecting the top of column to the slab

$A_s^{j-bar}$  = Area of j-bars inside the Core Region above the column; the bars shall extend down to the top of the column

$A_s^{jv}$  = Total area of vertical stirrups in each of the Joint Region and Joint Perimeter; the stirrups shall be uniformly distributed

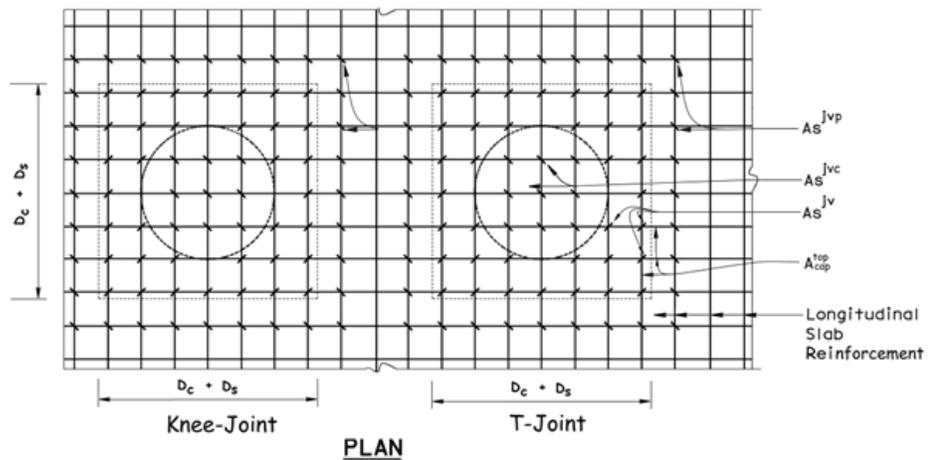
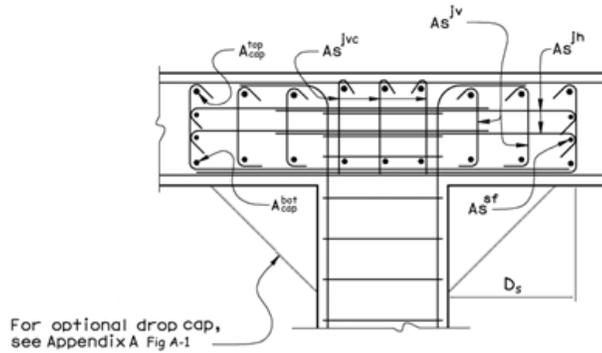
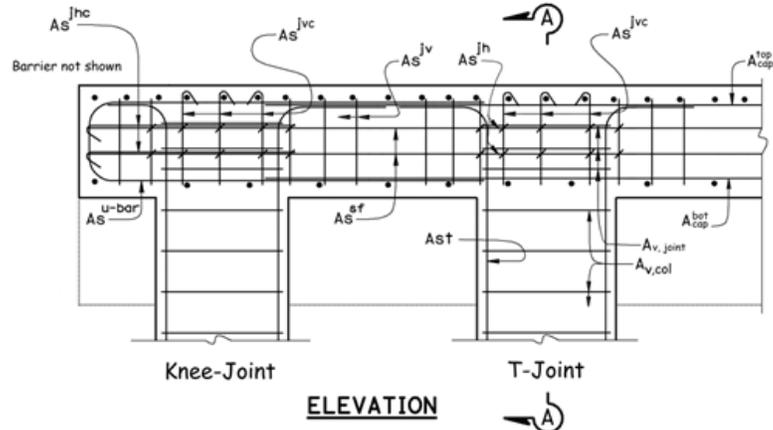
$A_s^{jh}$  = Total area of horizontal ties in the joint region along the longitudinal direction; two sets of at least two vertically distributed ties shall be placed within the Core Width, and one set of at least two vertically distributed ties shall be placed at each edge of the Joint Region

$A_s^{jhc}$  = Total area of horizontal ties along the transverse direction

$A_s^{jf}$  = Total area of bent cap side face reinforcement; one set of at least two bars distributed vertically must be placed at each side of the joint effective width

$A_s^{u-bar}$  = Area of additional bent cap reinforcement (u-shaped) for knee joints in the transverse direction

$A_{v,joint}$  = Transverse column reinforcement in the joint region



Slab Joint Shear Reinforcement (not all reinforcement shown)

Figure 3. Joint Shear Reinforcement

## Slab Reinforcement

Slab bridges must satisfy MTD 20-6 in order to obtain essentially elastic behavior of the superstructure in both the longitudinal and transverse directions. However, it is not necessary to apply the minimum reinforcement provision (#8 at 12" on center) from MTD 20-6 to conventional slabs. It is also not necessary to apply SDC 7.2.2 for vertical acceleration to the design of reinforced concrete slab bridges. However, lap splices in the top and bottom longitudinal slab reinforcement within the effective width of the slab (see LRFD 4.6.2.6) are only permitted at a distance between  $0.2L$  and  $0.3L$  from the centerline of the bents, where  $L$ =length from center of bent to center of bent (see Figure 4). Please note: stagger requirements per Standard Specification 52-6.03A must be met. As an alternative, when a service coupler is used to join longitudinal slab reinforcement, it can be located anywhere within the span.

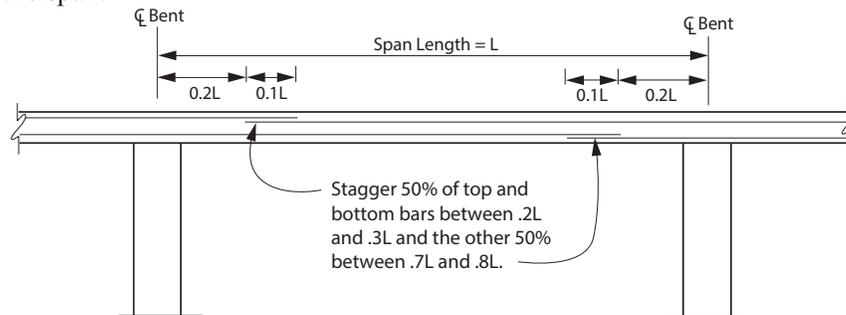


Figure 4. Allowable locations for reinforcement lap splices

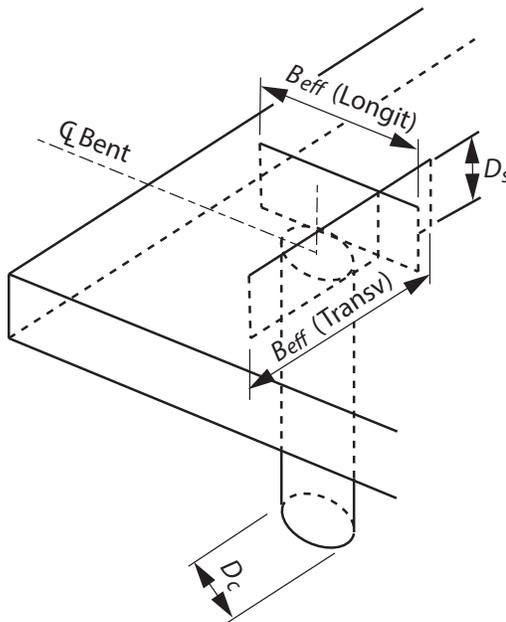
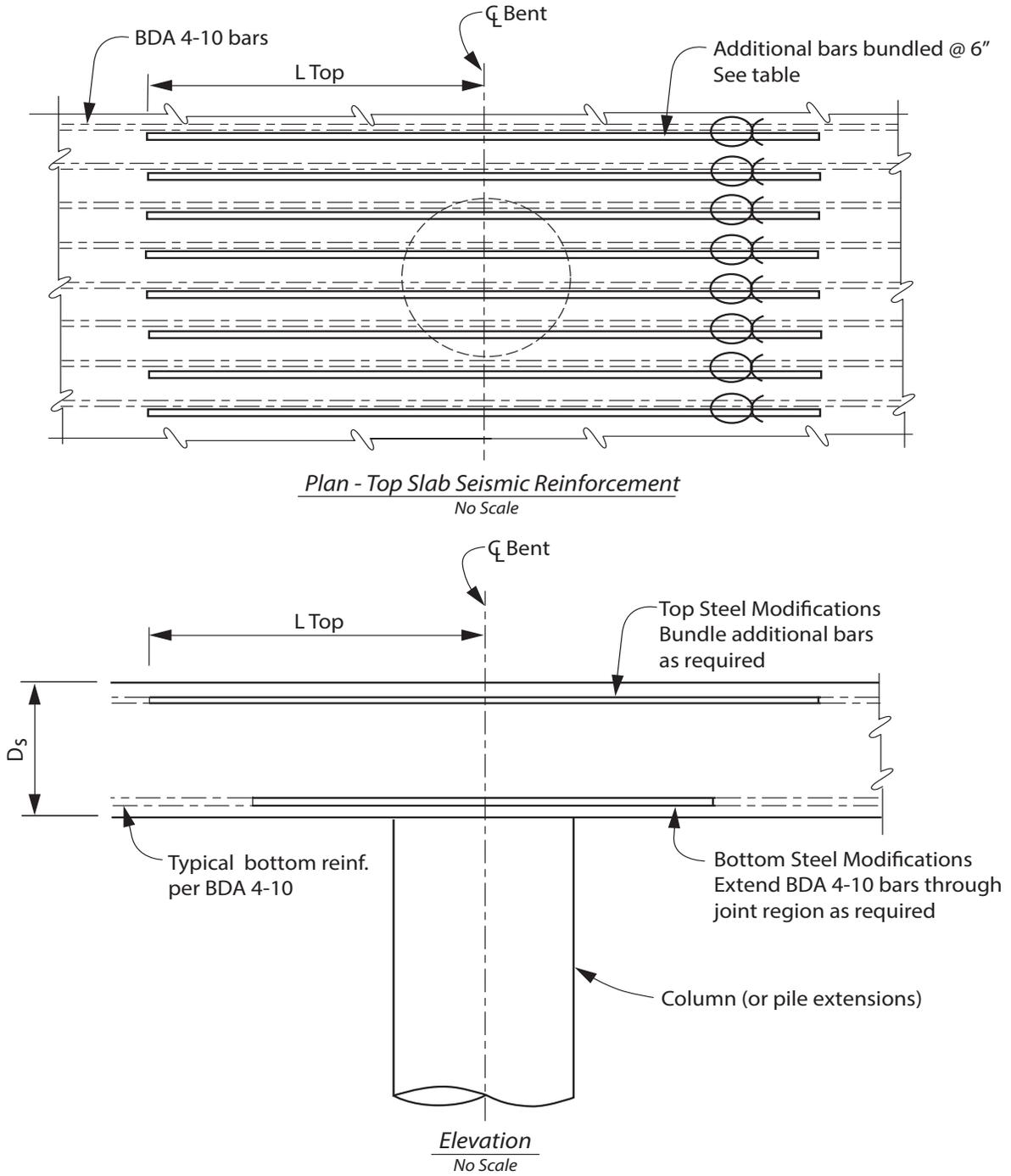


Figure 5. Slab Effective Width ( $B_{eff}$ )

If designers find that column seismic demand moments exceed superstructure nominal capacity, additional mild reinforcement shall be placed locally in the slab (Figures 1D & 6). This reinforcement can be placed adjacent to the service level reinforcement but it should be in the effective width as shown in Figure 5. The limits of additional reinforcement shall be shown on the plans.

The effective width ( $B_{eff}$ ) for each direction of concern shall be as defined previously (see Figures 2 and 5).

The reduced column section shown in Figure 1B shall have a moment capacity less than the capacity in the effective width of the slab based on the improved reinforcement details previously mentioned such as having all top and bottom longitudinal slab reinforcement made continuous over the bents. Only bars in the effective width are counted for resisting the column seismic moment and shear.



**Figure 6. Additional Mild Reinforcement required per SDC**

## Slab Hinges

Old slab hinge details such as those shown in the archived Bridge Standard Details XS1-210 must no longer be used as the details are not compliant with either AASHTO LRFD or SDC. Alternative hinge details in Figures 7(a) & (b) shall have a minimum seat width of 18 inches. Larger longitudinal displacement capacity and greater stiffness may be achieved with Figure 6(c) where independent frames eliminate the risk of unseating altogether.

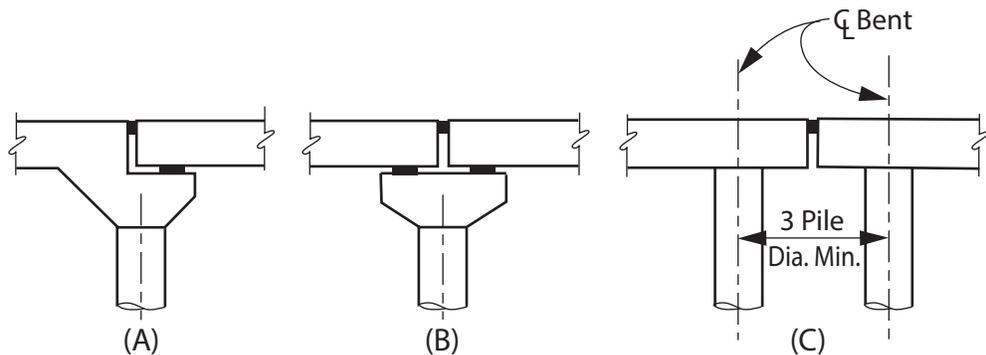


Figure 7. Slab Bridge Hinge Options

## Slab Abutment

Since the slab superstructure is to be capacity protected, the abutment must be designed to limit forces and moments being carried into the superstructure. Appendix A; Figures 7a, 7b, and 7c show ways to accomplish this either by reducing the abutment section below the slab, by providing a pinned connection between the slab and the abutment, or by providing a seat. Note that although SDC requires a minimum seat length for hinges and abutments of box girders, for slab bridges the required minimum seat length is 18 inches for in-span hinges and 24 inches for abutments. For seat-type abutments external or internal shear keys are required. However, the engineer shall ensure that  $\Delta_c \geq \Delta_d$  at all times.



## References

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