SUPERSEDES BRIDGE DESIGN AIDS SECTION 14 DATED OCTOBER 1989

14-4 JOINT SHEAR MODELING GUIDELINES FOR EXISTING STRUCTURES

Introduction

Since the early 1990's, greater emphasis has been placed on joint shear considerations in the seismic design of bridges. While damage associated with joint shear may not necessarily create a collapse mechanism, a large number of adjacent joints that form pins could lead to instability of the structure. In these situations, the engineer is referred to Memo to Designers (MTD) 20-4 for policy guidance.

As a joint is cycled during a seismic event it may degrade and lose its ability to carry moment. The procedure shown below provides an approximate method for determining if such degradation could occur during the design event, and guidance for developing the analytical model accordingly. Generally, this procedure applies to structures designed between 1971 and 1994. Bridges designed prior to 1971 typically have minimal steel in the joints, and will likely degrade to the point where it loses its moment resisting capacity at small deformations. Bridges designed after 1994 have joints that should be detailed to resist joint shear under design loads resulting in full fixity in the joints.

Research has shown that the minimum displacement capacity of a poorly detailed shear capacity protected element is approximately 2.0 times its yield displacement (Δ_Y^{col}). In those cases where the displacement demand is less than 2 x Δ_Y^{col}, the column/cap joint may be assumed to remain essentially elastic, and a joint shear analysis is not required.

Joint Classification

The following procedure may be used to estimate joint shear capacity and its effects on the column/joint displacement capacity.

The joints are classified using the following criteria:

• **Weak joint** – nominal joint shear strength $w_n = 3.5\sqrt{f''_{ce}}$ (psi). This classification typically applies to joints that were designed prior to 1971. Typically, these joints have no or minimal amounts of transverse reinforcement in the joint. Once the cracking strength is reached the joint has minimal reserve capacity.

• **Moderate joint** – nominal joint shear strength $v_n = 5.0\sqrt{f'_{ce}}$ (psi). Joints falling into this classification have a nominal amount of transverse reinforcement (satisfying minimum requirements of the time, but not satisfying current design requirements), and are able to provide some moment resistance after cracking occurs. This joint shear reinforcement may be provided in the form of column transverse steel or exterior transverse reinforcement located in the effective joint region of the bent cap shown in Figure 7.7 of the Seismic Design Criteria (SDC). The example problem included in this Bridge Design Aid (BDA) shows the calculation for joint shear reinforcement. The column transverse reinforcement may be in the form of tied column reinforcement, spirals, hoops, or intersecting spirals or hoops. The joint shear reinforcement ratio ρ_{sj} may not be less than 0.25% and is calculated as:

$\dfrac{\rho_{sj1} + \rho_{sj2} + \rho_{sj3}}{3}$, where

1) ρ_{sj1} is the volumetric lateral reinforcement ratio provided for confinement of the column longitudinal reinforcement inside the cap region as defined in SDC Section 3.8.1. This ratio is taken as zero in the case where column transverse confinement is discontinued in the cap region.

2) ρ_{sj2} is the ratio of rebar area crossing (or penetrating) the effective joint horizontal plane in Figure 7.7 of the SDC over the area of the plane A_{jh}.

3) ρ_{sj3} is the ratio of rebar area crossing (or penetrating) the effective joint vertical plane with a length of 2 times the column depth in direction of bending and height equal to the height of the bent cap over the area of the plane A_{jv} (see SDC Section 7.4.4.1).

• **Intermediate joint** – nominal joint shear strength $v_n = 7.5\sqrt{f'_{ce}}$ (psi). This classification applies to joints that have a nominal amount of transverse reinforcement (satisfying minimum requirements of the time, but not necessarily satisfying current design requirements). It is sufficient to maintain integrity of the joint past cracking, but not sufficient to sustain large deformations near yielding of the framing members. Beam-column joints where bars are unable to develop their yield strength are in this category.

Bar development may be precluded by the lack of standard hooks, or by insufficient anchorage length for column bars passing through the joint. The minimum joint shear reinforcement may be provided in the form of column transverse steel or exterior transverse reinforcement continued into the bent cap. The column transverse reinforcement may be in the form of tied column reinforcement, spirals, hoops, or intersecting spirals or hoops. The joint shear reinforcement ratio ρ_{sj} may not be less than 0.4% and is defined the same as for a moderate joint.

• **Strong joint** — nominal joint shear strength to be calculated from the Caltrans Seismic Design Criteria limits on tensile (v_n = 12.0 $\sqrt{f'_{ce}}$ psi) and compressive (v_n = .25 f'_{ce} psi) principal stresses. This classification typically applies to beam-column joints designed after the early 1990's. These joints typically contain significant amounts of horizontal and vertical reinforcement in the joint to provide adequate confinement of the joint core and the necessary mechanisms for force transfer and bar anchorage. These joints are expected to be able to sustain large inelastic deformations of the framing members without significant loss in joint panel strength or stiffness. Joints classified as "Strong" are typically associated with new design and are not included in the procedure given below.

Joint Shear Modeling Procedure

Given a classification for a joint, the engineer should evaluate the joint shear stress demand compared to the capacity using capacity design principles per SDC.

After the joint classification is determined, the engineer should perform the following steps:

1) Calculate the tensile force T_c in the column section, and the joint vertical shear stress demand v_{jv}

$$v_{jv} = T_c / A_{jv}$$ (See SDC Figure 7.6)

where

$$A_{jv} = l_{ac} \times B_{cap}$$

$A_{jh} =$ The effective vertical joint area

$B_{cap} =$ Bent cap width

$H =$ Height of column

$l_{ac} =$ Length of column reinforcement embedded into the bent cap

$T_c =$ The column tensile force defined as M_o^{col}/h, where h is the distance from c.g. of tensile force to c.g. of compressive force on the section, or alternatively, T_c may be obtained from the moment-curvature analysis of the cross section

$M_0^{col} =$ The overstrength column moment capacity (SDC Section 4.3.1)

$$M_{pr} = \frac{v_n}{v_{jv}} \cdot M_0^{col} =$$ Reduced moment capacity of hinge model

2) Using the joint classifications as defined above, compare the joint vertical shear stress demand v_{jv} to the nominal joint shear strength v_n and select one of the following:

   a) If $v_{jv} \le v_n$ then consider the superstructure joints to be essentially elastic and may be modeled as "rigid". The joint is capable of developing a plastic hinge in the column.

   b) If $v_{jv} > v_n$ then the rigid joint superstructure in the demand model needs to be modified to account for the joint degradation. This may be accomplished by using a modified effective column stiffness[1] $(E_c I_{eff})_{\text{mod}}$ for the demand model[2] to determine the revised displacement demand.

$$(E_c I_{eff})_{\text{mod}} = 0.85\,(E_c I_{eff})(v_n / v_{jv})$$

The engineer then determines the displacement capacity of the combined column/joint element as follows:

The displacement capacity of the column/joint element of the bridge is considered to be the sum of the elastic displacement capacity and the plastic displacement capacity[3]. The elastic displacement capacity (using $E_c I_{eff}$ and M_{pr} instead of M_0^{col}) is calculated by the procedure specified in SDC Section 3.1.3. It includes the column elastic displacement in addition to any elastic displacement attributed to superstructure or foundation flexibility. The plastic displacement capacity is determined based on a plastic hinge rotation model θ_{pj} that is a function of the joint classification and is calculated as follows:

1) For a weak joint:

   $$\theta_{pj} = \theta_{yc} + 0.007$$

2) Moderate joint:

   $$\theta_{pj} = \theta_{yc} + 0.015$$

3) Intermediate joint:

   $$\theta_{pj} = \theta_{yc} + 0.020$$

   where θ_{yc} is the column yield rotation calculated based on a rigid joint model using $(E_c I_{eff})$.

   $$\theta_{yc} = \Delta_Y^{\text{col}} / \text{H}$$

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[1] $(E_c I_{eff})_{mod}$ approximates with a single element the combined stiffness of the various components of the column-joint system. It is used to simplify the secant stiffness demand analysis and is applied to the entire column. However, it should not be considered an actual structural characteristic. A more refined demand analysis may be performed when necessary. Guidance from the Office of Earthquake Engineering is available.

[2] In the demand analysis a linearized effective secant stiffness method is used, not an equal displacement method as described in MTD 20-1.

[3] The example calculation shown at the end of this BDA provides an illustration of the demand and capacity models for a three-column bent (See Figures 3 and 4).

In the case of rotational demand exceeding capacity, full degradation of the hinge model's moment resisting capacity may be assumed. The joint is not a seismic resisting element and the Engineer should adjust the global demand model accordingly.

Example Calculation:

The example calculation shown below illustrates the joint shear modeling procedure for a transverse bent column frame. The column-cap joint is moment-connected while the column-footing joint is pinned. The frame's details are shown in Figures 1 and 2.

The goal of this procedure is to determine whether a beam-column joint is capable of sustaining the rotational demands obtained from an elastic analysis. The rotational capacity of a joint is calculated based on its classification. If the rotational demand is greater than the capacity, then the expected degradation in the joint should be placed in the model by assuming the joint is pinned.

Given:

Expected concrete compressive strength, f'_{ce} = 5,000 *psi*

Superstructure depth, $D_s = 54\ in$

Column diameter, $D_c = 48\ in$

Column height = $20\ ft$

Column nominal moment = 6258 *k-ft*

Column axial force including the effects of overturning = 1440 *k*

Effective flexural stiffness $E_c I_{eff}$ 6.73 x 10^8 *k-in*^{2}

Column overstrength plastic moment, M_o =1.2 x 6258 = *7510 k-ft*

Column axial force (including the effect of overturning) equal to 1440 *k*

Longitudinal column reinforcement: #11 bars, total 32

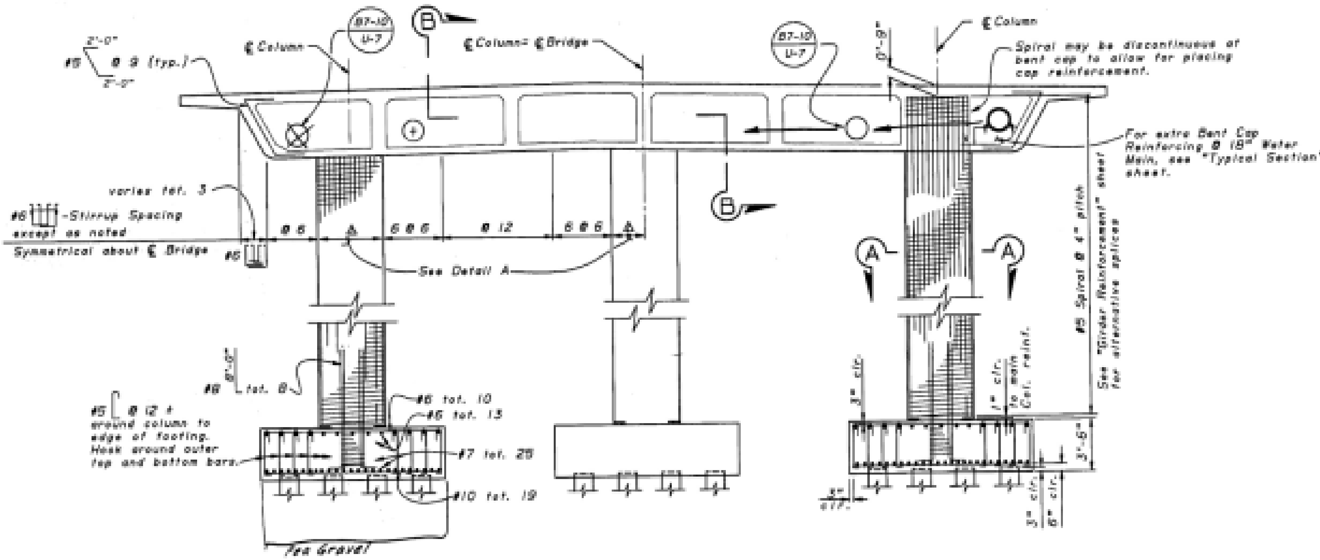
Transverse column reinforcement: # 5 spiral @ 4 in pitch

Effective flexural stiffness $E_c I_{eff}$ = 6.73 X 10^8 *k-in*^{2}

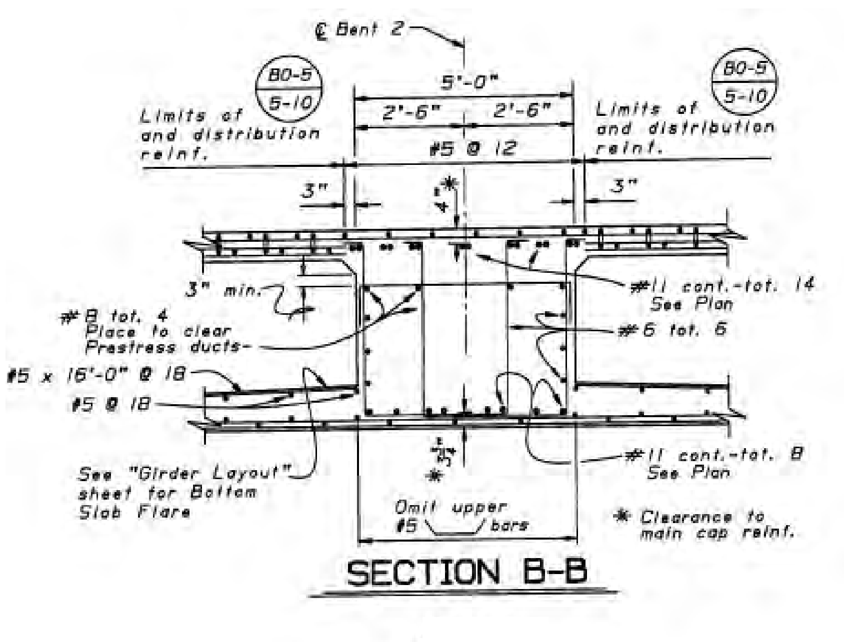
Concrete cover = $2\ in$

Column main reinforcement embedment length into the bent cap, $l_{ac} = 45\ in$

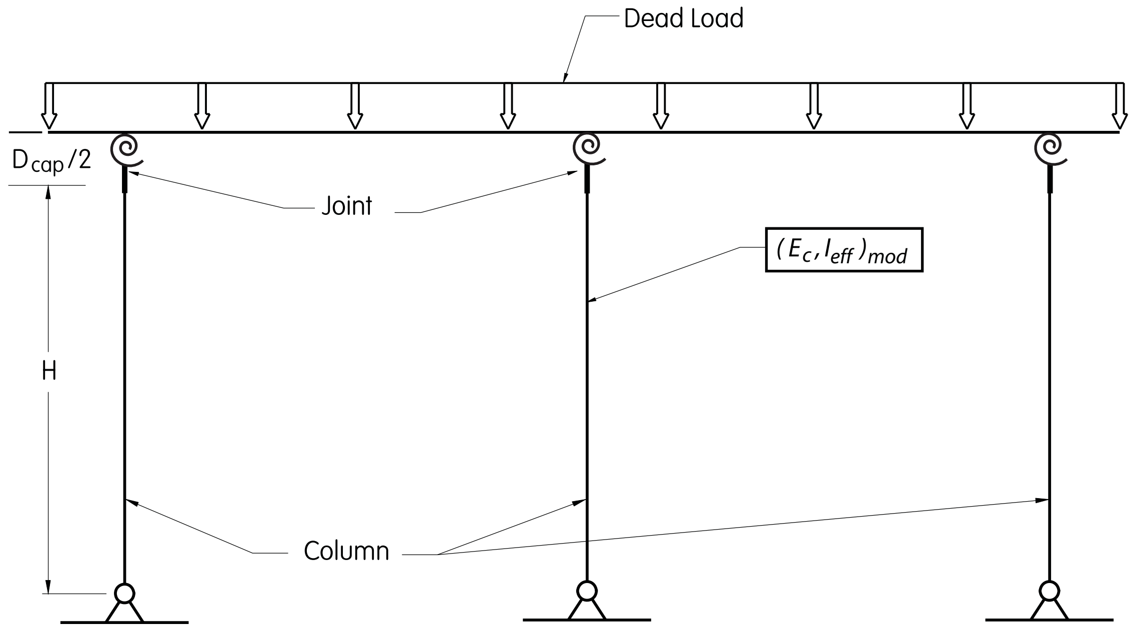
Bent cap width, $B_{cap} = 60\ in$



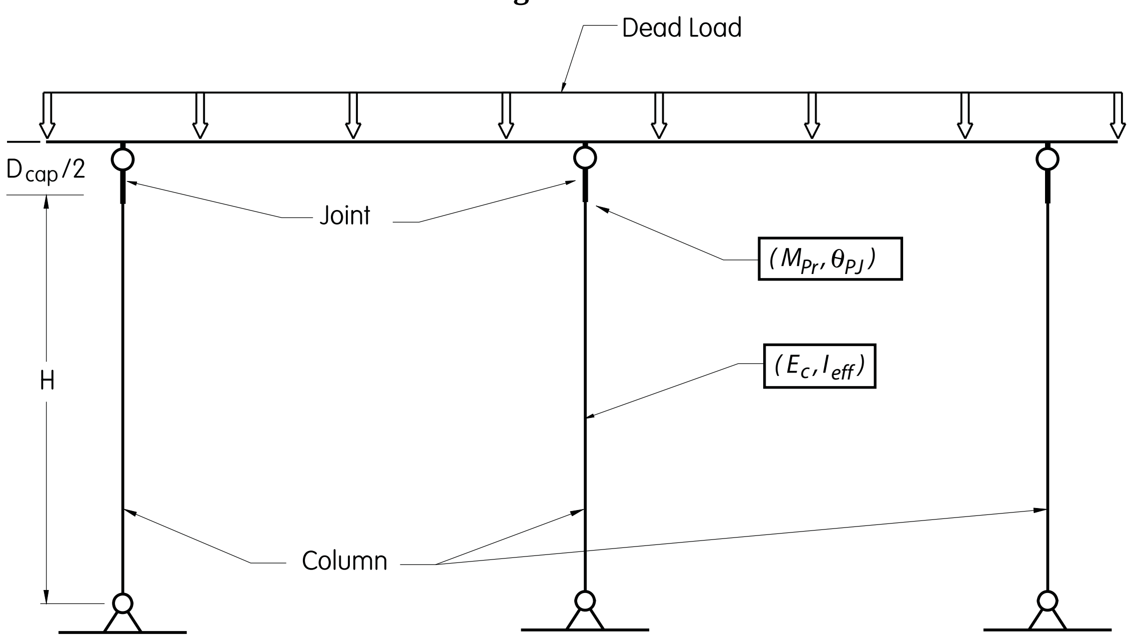
Three Column Bent
Figure 1



Bent Cap Section
Figure 2



Three Column Bent Demand Model
Figure 3



Three Column Bent Capacity Model
Figure 4

Determine the Joint Classification

1) Calculate lateral reinforcement ratio in the joint provided for confinement of the column longitudinal reinforcement

$$\rho_{sj1} = \frac{4A_b}{D_c s_h} = \frac{4(0.31)}{(48'')(4'')}\ 0.006458 = \text{or } 0.65\%$$

2) Calculate ρ_{sj2} for area of rebar crossing horizontal plane A_{ph} defined by Fig 7.7 of the SDC:

$$A_s = \left(\frac{4\ legs}{set}\right)\left(\frac{0.44\ in^2}{leg}\right)(13\ sets) = 22.88\ in^2$$

$$\rho_{sj2} = \frac{A_s}{A_{ph}} = \frac{22.88\ \text{in}^2}{(96\ \text{in})(60\ \text{in})} = 0.003972 \text{ or } 0.4\%$$

3) Calculate ρ_{sj3} for area of rebar crossing vertical plane A_{pv} with length of $2D_C$ and height equal to the height of the bent cap:

$$A_{s1} = \left(\frac{2\ legs}{set}\right)\left(\frac{0.44\ in^2}{leg}\right)(13\ sets) = 11.44\ in^2$$

$$A_{s2} = \left(\frac{1\ leg}{set}\right)\left(\frac{0.44\ in^2}{leg}\right)(9\ sets) = 3.96\ in^2 \quad \text{Assume \#6@12 } in$$

Total $A_{scol} = A_{s1} + A_{s2} = 15.4 in^2$

$$\rho_{sj3} = \frac{A_{scol}}{A_{pv}} = \frac{15.40\ \text{in}^2}{(96\ \text{in})(54\ \text{in})} = 0.002674 \text{ or } 0.27\%$$

Calculate joint shear reinforcement ratio ρ_{sj}:

$$\rho_{sj} = (\rho_{sj1} + \rho_{sj2} + \rho_{sj3})/3 = (0.65 + 0.4 + 0.27)/3 = 0.44\%$$

Based on ρ_{sj} equal to 0.44%, the joint is classified as "Intermediate". Therefore, the nominal joint shear strength is equal to $7.5\sqrt{f'_{ce}}$ = 530 *psi*.

After the joint classification is determined, the engineer should perform the following steps to determine the displacement capacity of the column joint element:

1) Calculate the over-strength moment capacity of the column in the transverse direction, the tensile force T_c in the column section, and the joint vertical shear stress demand v_{jv}

   $T_c =$ The column tensile force defined as M_o^{col}/h, where h is the distance from c.g. of tensile force to c.g. of compressive force on the section. Alternatively, T_c may be obtained from the moment-curvature analysis of the cross section

   $$A_{jv} = l_{ac} \times B_{cap} = 45 \times 60 = 2700 in^2$$

   $$v_{jv} = T_c / A_{jv} = \frac{2544000}{2700} = 942\ psi$$

   $A_v =$ The effective vertical joint area

   $B_{cap} =$ Bent cap width

   $l_{ac} =$ Length of column reinforcement embedded into the bent cap

   Effective flexural stiffness $E_c I_{eff}$ = 6.73 x 10^8 *k-in*^{2}.

2) Given a joint classification as defined above, compare the joint vertical shear stress demand v_{jv} to the nominal joint shear strength v_n.

   Since $v_{jv} > v_n$, the rigid joint superstructure model should be modified as follows:

   use a modified effective stiffness ($E_c I_{eff}$)$_{\text{mod}}$ in the demand model shown in Figure 3.

   where $(E_c I_{eff})_{\text{mod}} = 0.85(E_c I_{eff})(v_n / v_{jv}) = 0.85(E_c I_{ff})(530/942) = 0.48 E_c I_{eff}$

3) Determine the displacement capacity of the column/joint element as follows:

   The displacement capacity of the column/joint element of the bridge is considered to be the sum of the elastic displacement capacity and the plastic displacement capacity. The elastic displacement capacity includes the column elastic displacement in addition to any elastic displacement attributed to superstructure or foundation flexibility. The column's plastic displacement capacity is based on a plastic hinge rotation model θ_{pj} that is a function of the joint classification and is calculated as follows:

   $\theta_{pj} = \theta_{yc} + 0.015$

   where

   θ_{yc} is the column yield rotation calculated based on a rigid joint model using effective section properties.

$$K \quad \frac{3E_c I_{eff}}{L^3} \quad \frac{3 \quad 6.73 \quad 10^8}{20 \quad 12 \;\; ^3} \quad 146 \ kip / in$$

$$F_y = \frac{7510 \ k\text{-}ft}{20 \ ft} = 376 \ kips$$

$$\Delta_Y^{col} = \frac{F_y}{K} = \frac{376}{146} = 2.6 \ in$$

$$\theta_{yc} = \frac{2.6 \ in}{20 \times 12 \ in} = 0.011 \ rad$$

Therefore, $\theta_{pj} = \theta_{yc} + 0.015 = 0.011 + 0.015 = 0.026$ *radians*

Calculate the reduced moment capacity of hinge model, M_{pr},

$$M_{pr} = 7510 \ k\text{-}ft \ x \ \frac{530 \ psi}{942 \ psi} = 4225 \ k\text{-}ft$$

The plastic rotation capacity of the joint, θ_{pj} and the flexural plastic strength of the as-built joint M_{pr}, are incorporated in the "push over" capacity model in order to determine the overall displacement capacity Δ_c (See Figure 4).

The revised displacement demand Δ_D is then compared to Δ_c and the revised joint properties are applied to the global demand model.

References:

1. California Department of Transportation, Seismic Design Criteria

2. California Department of Transportation, Bridge Memo to Designers 20-1 and 20-4