



6-1 COLUMN ANALYSIS CONSIDERATIONS

Introduction

The general configuration and geometric details of a bridge are determined when a General Plan (GP) is developed. During GP development, the Design Engineer should assess the impact of the general configuration and geometric parameters on final design to minimize eventual reinforcement congestion and construction difficulties. These parameters include:

- Bridge layout – particularly bent locations
- Column size, end conditions and architectural features
- Number of columns per bent

Columns designed in accordance with AASHTO LRFD Bridge Design Specifications (LRFD-BDS), Caltrans Amendments to LRFD-BDS and the Caltrans Seismic Design Criteria (SDC) may result in dense reinforcement arrangements. Also, Strength and Service Limit States criteria for column design may sometimes conflict with those of Extreme Event I Limit State (Earthquake). To minimize the impact of such conflicting requirements, and to avoid construction-related difficulties while still conforming to design codes, the Design Engineer may be required to adjust several major design parameters to achieve adequate column design and bridge performance.

Preliminary Column Design Considerations

As a general guideline, all columns in a single column bent structure are analyzed, designed and detailed to be fixed at both column ends. Also, columns in a multi-column bent that is monolithic with the superstructure are pinned at the base (see Figure 1). In structures with drop bent caps, pinning the base of the columns is not advised unless the Design Engineer can ensure that there is adequate framing action between the bent cap and the superstructure to ensure longitudinal stability of the bridge. For additional considerations on bent geometry, see SDC 7.1.

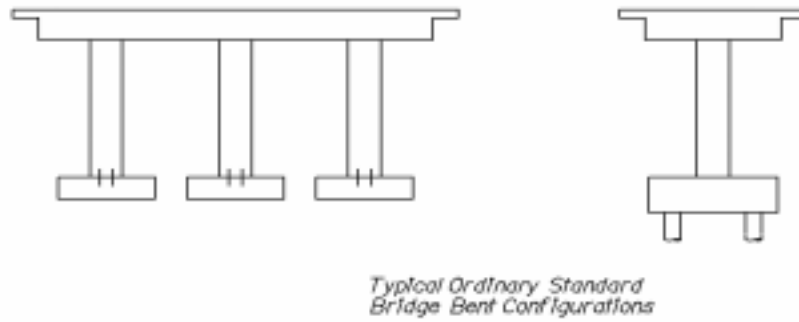


Figure 1

Pinning the base of columns leads to a reduction in the foundation size and foundation costs. In comparison to a fixed base column, a pinned base column results in a softer structure leading to larger drifts (lateral displacement) particularly under seismic demands. In addition, pinning the base may increase the moments at the top of the columns under strength and service load combinations compared to those in a fixed-fixed column. Consequently, these columns may be subjected to higher moment magnification factors. The combined effects of increased moments at the fixed end and the moment magnification may lead to an increase in a column's longitudinal reinforcement.

The Design Engineer must substantiate initial decisions concerning bent parameters by performing preliminary analyses. Preliminary linear analyses (using programs such as WIN-YIELD, RCPIER, VBENT) and nonlinear analyses (using programs such as using XSECTION and WFRAME, SECTION DESIGNER and SAP2000) will assist in evaluating the adequacy of a structure under Strength and Service Limit States as well as the Extreme Event Limit State. As a result of such analyses, if the longitudinal and transverse reinforcement in columns is found to be within code specified and constructible limits, then the geometric and structural frame arrangements can be assumed satisfactory.

More advanced analyses (using computer programs such as CTBridge and SAP2000) may sometimes be required particularly in the case of complex structures that involve connecting ramps, unusual external loads and atypical seismic conditions. In addition, when a structure is comprised of multiple frames, dynamic analysis is typically performed by dividing this structure into groups of overlapping frames. Special attention must be given to modeling the supports and the boundary conditions with springs as necessary.

Column Design Alternatives

If detailed analyses show that the column reinforcement exceeds acceptable limits, then the following alternatives should be considered:

1. **Modifying column end conditions in single column bents:** In single column bents, the bottom of columns is typically analyzed and designed as a fixed support. However, under extremely rare conditions, certain single columns may be pinned at the base if the structure can still retain its stability and the abutment or the adjacent bent with a fixed base can accommodate increased demands. Pinned columns must be supported throughout construction. This option is considered as a design exception (see MTD 20-11) and should be adopted as a last resort after appropriate review.

End columns in frames can also be designed to slide on the footing during prestressing and be externally keyed to the footing.

2. **Increase the number of columns per bent.** When the number of columns in a bent is increased, it can lead to a reduced column size as well as a reduction in its demands under Strength and Service Limit States. This step also affects the longitudinal and transverse frame stiffness and consequently impacting the seismic demands. When adding columns to single column bents, care should be taken to examine any resulting uplift from overturning, as this leads to a reduced shear capacity.

Adding more columns to a bent may not be aesthetically pleasing and may also result in increased foundation costs. While aesthetics is important, it should not take precedence over structural integrity.

3. **Use broader (oblong) columns.** This is often a viable option, especially in single column bents. Such columns typically have interlocking reinforcement cages. In rare cases, the oblong column may be pinned with reference to the longitudinal direction of the bridge to reduce foundation costs.
4. **Utilize torsional rigidity of the superstructure and more realistic load distribution to reduce P-load effects on single-column bents.** 3-D analyses show that superstructure rigidity reduces transverse moments significantly in many single column bent structures under dead and live loads as compared to a typical cantilever bent analysis. This reduction is also due to the loads getting distributed to adjacent bents. Therefore, the designer may take advantage of 3-D analyses if conventional cantilever analysis shows that the selected column size/shape is inadequate for the applied Strength Limit States, but is otherwise adequate.
5. **In multi-column bents, use larger columns.** A larger column section will allow more room to place main reinforcement and provide greater shear resistance for

Strength and Service Limit States. However, increasing the column size would also draw more moment and shear into the column due to increased stiffness.

From a seismic design perspective, an increase in column size may increase the column plastic moment. This may lead to an increase in footing and superstructure thickness. The resulting increase in the size of members will have an impact on horizontal and vertical roadway clearances when existing bridges are being widened.

- 6. Use higher strength concrete for columns.** This option may be used as a means to reduce main reinforcement without significantly increasing stiffness. This will also increase the shear capacity (unless tensile axial loads exist). However, the resulting increase in plastic moment capacity may lead to increased footing and superstructure size and costs.

The designer should consider the economics of specifying multiple high strength concrete regions in the design of bridge components.

- 7. Shorten spans lengths and add bents.** This option should be considered primarily for viaducts. Long structures, such as connector ramps, generally have bent locations dictated by facilities that are crossed such as roadways and railroads. Shorter spans can reduce structure depth that lowers dead load and proportionately reduces seismic demands on the bents. However, it will also lead to increased foundation work.

Where spans permit, the applicability of both conventionally reinforced as well as prestressed concrete sections should be considered. While prestressed concrete sections typically result in less dead load, they cause secondary prestress moments in columns and may require more expensive joint seals due to increased movement ratings at the joints. Short prestressed spans reduce dead load, but the superstructure depth must allow for the development length of column bars.

- 8. Add hinges in the superstructure.** This option should be considered primarily for long, prestressed structures. In general, it is preferable to avoid the use of hinges for maintenance reasons and to maintain structure continuity under seismic demands. However, adding a superstructure hinge effectively reduces a structures frame length and can be desirable where column heights change abruptly. The end bents of such frames, especially short bents near abutments, will draw less prestress moment.

Superstructure hinges make the structure more flexible and increase seismic displacements, but there may also be some benefits due to increase in a structure's fundamental period of vibration. Intermediate hinges that are strategically placed within long prestressed structures also allow for creep forces to stabilize.

9. **Increase the elastic length of shorter columns.** Significant moment reductions can be achieved, especially in prestressed concrete structures, by increasing the column elastic length through isolation casings. One disadvantage of this concept is that plastic hinging of such columns may occur below ground line making post earthquake inspection more difficult.
10. **Incorporate foundation flexibility in modeling and analysis.** This can be accomplished by taking advantage of footing flexibility due to elastic and plastic soil deformation. Detailed modeling and analysis will be required.
11. **Use pile shafts in lieu of footings.** The benefits of this option are similar to increasing the column lengths (see item 9 above). Generally, the resulting increase in footing flexibility will lead to reduced seismic forces but may increase displacements. Type I or II shafts are likely to be less expensive than fixed pile footings when there is a potential for significant sour, liquefaction or environmental constraints. However, shaft construction may become more challenging in the presence of shallow groundwater, loose sand, or boulders.
12. **Reduce prestress and thermal force coefficients.** Several theories describe the effects of prestress and thermal forces on structures. Some theories suggest that initial moments in columns due to prestress shortening eventually creep to nearly zero. It has also been suggested that the elasto-plastic characteristics of the soil surrounding the foundations permit some moment relief for the columns and lead to a further reduction in creep related moments. In addition, thermal stresses develop gradually and provide some plastic relief in thermal moments. Recognizing these issues, the AASHTO LRFD Specifications have accommodated some reduction in demands due to thermal and prestress shortening effects through modified load factors.

Column demands due to prestress and thermal effects can be obtained by using either a column's gross moment of inertia (I_g) or its effective moment of inertia (I_e) in analyses.

To determine the demands due to prestress effects in columns having fixed ends, when I_g is used, a load factor of 0.5 should be used (Table 3.4.1-3, CA Amendments to AASHTO LRFD). In such columns, if I_e is used in analysis, then the higher load factor of 1.0 should be used.

To determine the demands due to prestress effects in columns with a pinned base, I_e in conjunction a load factor of 1.0 should be used until the performance of such columns is better understood.

When refined analyses techniques are used to simulate foundation flexibility (example: modeling a shaft, using foundation springs etc), column demands due to prestress at

strength limit states should be obtained using I_e in conjunction with the load factor of 1.0.

13. **Use lightweight concrete.** Use of lightweight or sand lightweight concrete in the superstructure can significantly reduce dead load and corresponding seismic demands on columns. The designer should carefully consider the impact of changes in concrete properties, including modulus changes as well as increase in construction costs before incorporating lightweight concrete.
14. **Examine reinforcement configuration.** Double or triple bundles of main column reinforcement can often resolve some reinforcement clearance issues. Revising column hoops to as much as bundled #8 at five inch spacing can also enhance confinement while accommodating construction. However, other construction, and design issues should be considered before making such choices.

The designer may adopt any one or a combination of the above-mentioned options to reduce column demands. Some of the options may not appear to be cost effective, but could result in savings in other bridge elements leading to an overall efficient design. While cost should be a primary consideration, it should not be the only criterion. The designer should be aware that solving one problem may create another, and should consider the best combination(s) that apply to a specific project.

Miscellaneous Column Design Considerations

Additional factors that may influence column analysis and design are:

1. **Reinforcement Arrangement:** In columns with square and circular cross-sections, the longitudinal rebars should be arranged in a circular array. In rectangular and oblong columns, the rebars should be arranged in an interlocking circular array. The transverse reinforcement should conform to the requirements of ultimate splice (see MTD 20-9 and SDC). These requirements have been developed since a large number of tests have shown that columns with circular cores perform the best under seismic forces. Any deviation from this requirement should have the approval of Chief, Office of Structure Design.
2. **Aesthetic Features.** Column aesthetics often incorporate non-structural concrete features such as flares. Column flares should be isolated from the superstructure with a horizontal gap as shown in Attachment 1 unless structural considerations require that the flares be monolithic with the superstructure. The concrete in the flare region outside the column core shall be adequately reinforced locally to minimize

shrinkage and temperature related cracks and to prevent the separation between flares and the column core at design displacement ductility levels of approximately four. Flare reinforcement is the additional longitudinal and transverse steel provided in the flare region outside the confined column core.

When a gap is provided between the top of flare and soffit, only the dead load contribution from flares should be included for analysis. Tests on 40% scaled column models with top fixity and isolated flares have shown large displacement ductility capacities (see University of California, San Diego, Report # SSRP-97/06). These tests reveal that column plastic hinging forms in the concentrated region of the flare gap. The confining effects of the bent cap and the column flare reduce the plastic hinge length, but still provide the column with adequate displacement ductility capacity.

Monolithic (structural) flares should be avoided where possible for the following reasons:

- a) In columns where the flare is improperly designed and detailed, it is likely that the plastic hinge may form at the base of the column flare instead of at the top of the column. This not only increases the shear demand on the column, but may also result in a significant loss of bridge deck profile if plastic hinge failure were to occur. While proper design and detailing assures that the probability of failure of a plastic hinge is extremely low, it is possible that plastic hinges may fail due to unforeseen overloads.
- b) Monolithic flares lead to an increase in force demands on adjacent superstructure and substructure elements, and may result in reduced displacement ductility of bents. However, with proper justification, and with the approval of the Chief, Office of Structure Design, the Design Engineer may adopt monolithic flares.

When monolithic flares are approved for adoption, these flares shall be designed and detailed so that they are unlikely to separate from the column even at design displacement ductility levels. In such structural flares, the longitudinal and transverse flare reinforcement shall be determined in accordance with the column performance requirements specified in the Caltrans Seismic Design Criteria. The contribution to column strength and stiffness from the structural flares shall be modeled and incorporated in the seismic analysis to identify plastic hinge locations. The Design Engineer shall ensure that the plastic hinge forms at the top of column and not at the base of flare or in the superstructure. Proper attention to detailing is required.

3. **Outrigger Bents.** Outriggers are usually more vulnerable under seismic forces because they do not have the superstructure concrete enclosure at the column-cap



joint. To ensure adequate performance of such bents, it is desirable to pin the top of the column at the bent cap and fix the column base. Adequate confinement must be provided to ensure the integrity of the pinned connection.

Alternatively, if the top of the column is fixed to the bent cap, then the joint must be adequately confined using closed ties with seismic hooks to prevent joint degradation during plastic hinging. The details should ensure that a plastic hinge forms in the column and not in the cap. The exposed portion of the cap must also be properly designed for torsion and reinforced with closed seismic ties as required. The corner joint must be capable of resisting all torsion, moment, and shears occurring at the joint.

Conclusion

Proper column design can be a challenging and an iterative process. Numerous options exist to allow the designer to find an efficient design that is both cost effective and constructible. It is possible to design columns that not only meet code requirements but also are aesthetically pleasing.

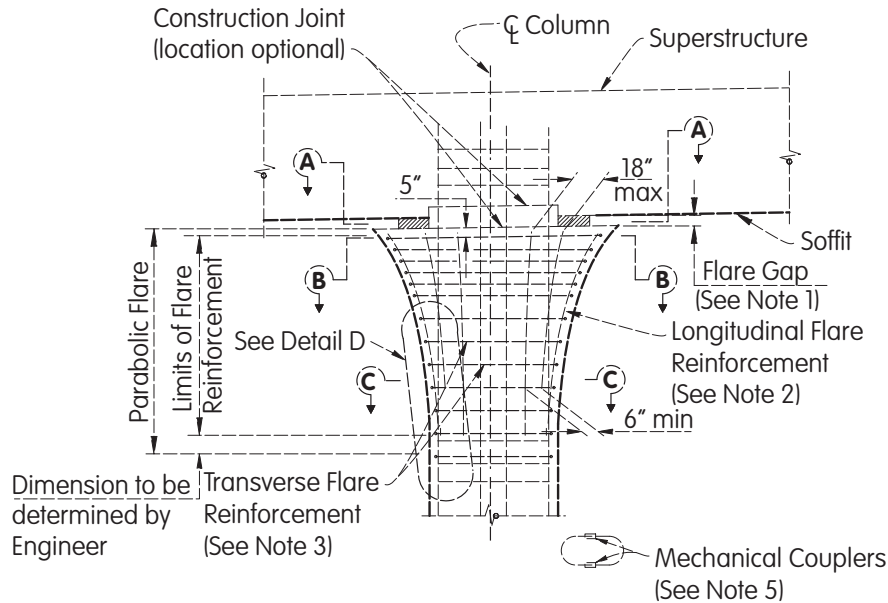
Additional References

1. California Department of Transportation, *Seismic Design Criteria 7.1*
2. California Department of Transportation, *Memos to Designers 20-4 and 20-9*

(original signed by Kevin Thompson)

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ATTACHMENT 1



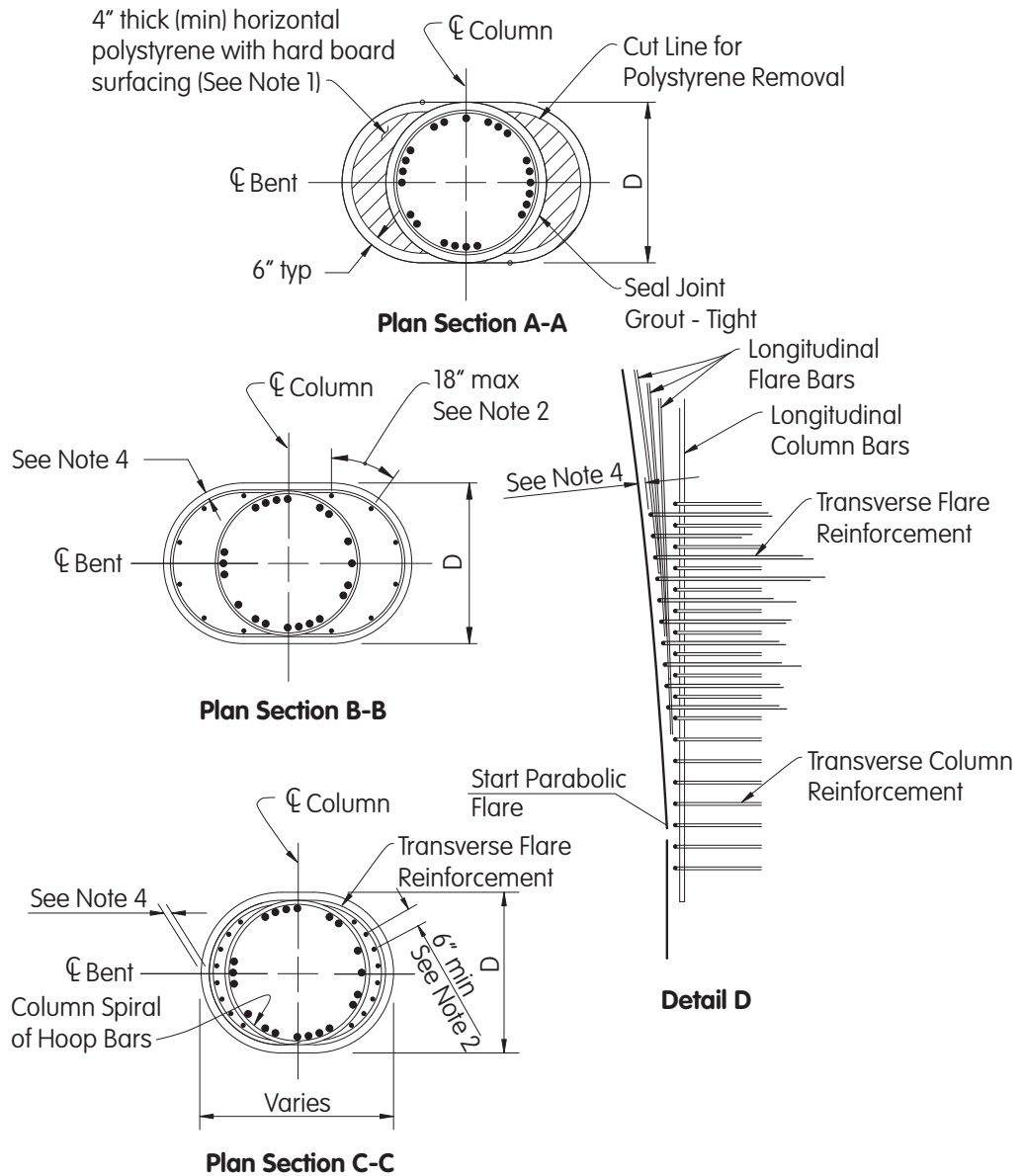
Flare Column Details-1

Table 1		
Column Dia or "D" (ft)	Transverse Flare Reinforcement	
	Upper Flare Region (Top 1/3 Flare Height)	Lower Flare Region (Lower 2/3 Flare Height)
4	#6 @ 3.5"	#4 @ 8"
5.5	#7 @ 3.5"	#5 @ 8"
7	#8 @ 3.5"	#5 @ 8"

Notes to Designer:

1. Typically, the minimum thickness of the flare gap should be 4". However, if analysis shows that the 4-inch flare gap is inadequate due to significant relative rotation between the column and the bent gap, then the required gap thickness per analysis should be provided.
2. The longitudinal flare reinforcement provided is nominal. The maximum spacing between longitudinal flare reinforcement should not exceed 18"; and the spacing should not be less than 6". (Eg. #6 at a maximum of 18"; minimum 6")
3. The minimum recommended transverse flare reinforcement ratio in the upper 1/3 of the flare height is $0.40\% \pm 0.05\%$, while that ratio for the lower 2/3 of the flare height is $0.075\% \pm 0.025\%$. See Table 1 for typical transverse reinforcement in the flare region of a circular columns with a standard one-way flare (BDD 7-31). This reinforcement is in addition to the required column core confinement/shear reinforcement. These column flare details have been developed after reviewing the results of laboratory tests.
4. Minimum clear cover shall conform to requirements of Section 5.12.3 of AASHTO LRFD Specifications & Caltrans Amendment to LRFD Specifications.
5. While laboratory tests were conducted with the transverse flare reinforcement having a lap of approximately 40 times bar diameter, the use of mechanical couplers (service splice) is recommended. When a column is subjected to multi-directional excitation, lap splices in transverse flare reinforcement may not be reliable if flare concrete spalls. To minimize reinforcement congestion, the location of mechanical couplers should be staggered.

ATTACHMENT 1



Flare Column Details-2