Practical Design and Detailing of Steel Column Base Plates

by

William C. Honeck
Derek Westphal

Forell Elsesser Engineers, Inc.
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# PRACTICAL DESIGN AND DETAILING OF STEEL COLUMN BASE PLATES

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PRACTICAL DESIGN AND DETAILING OF STEEL COLUMN BASE PLATES

1.0 INTRODUCTION

1.1 Preface

Steel column base plates are one of the most fundamental parts of a steel structure, yet the design of base plates is commonly not given the attention that it should by engineers. This results in base plate details that are expensive, difficult to fabricate and may even contribute to the hazards of the steel erection process by not providing stability for erection loads applied to the column.

Base plates serve two basic functions:

1. They transfer column loads to the supporting member or foundation. These loads include axial due to gravity, moments, shears and sometimes axial due to uplift;
2. They allow the column to stand as a temporary vertical cantilever after the lifting line is released without having to guy off the column. The column and base plate must withstand temporary wind and erection loads safely.

Steel fabricators and erectors who are members of the Structural Steel Educational Council (SSEC) have commented that there are a variety of base plate designs and details from engineers. Some fabricators are critical of many of these designs because they are difficult to fabricate, or specify materials that are hard to obtain or that do not exist in the sizes specified. The designs often result in columns that are hard to erect or are unstable without guying the column. When anchor bolts are not properly set, expensive corrective work is required before the column can be erected, resulting in delays in the steel erection process. This publication of Steel Tips attempts to address these issues.

In order to understand better and respond to the fabrication and erection issues, a questionnaire was distributed to several SSEC member firms requesting their comments about problems experienced in their shops during fabrication and in the field during steel erection. Specific issues included overly expensive designs and problems with obtaining the materials specified. Suggestions on how these designs could have been more economical were solicited. The questionnaire asked about steel erection problems experienced and requested suggestions to mitigate those problems. The responses received were very informative and many of the suggestions in the responses have been incorporated into this publication.

1.2 Purpose

The purpose of this issue of Steel Tips is to provide practical guidelines for engineers, fabricators and contractors regarding the design and detailing of steel column base plates. Guidance is provided toward resolving common design, fabrication and erection problems. Many of the topics discussed are simple to implement, yet are often overlooked.

Unfortunately the behavior of base plates in moment frames and braced frames subjected to earthquake forces is not fully understood. Research and code guidance are limited. The engineer is forced to use judgement in order to achieve a desired level of performance and it is hoped that this publication will initiate more research and development in the areas of base plate behavior and design guidelines for base plate assemblies that are subjected to high moments where some sort of yielding is necessary to achieve the desired performance.

1.3 Organization

The focus of this issue of Steel Tips is directed toward the practical aspects of the design and detailing of base plates particularly as they relate to economical fabrication and steel erection. Section 2.0 discusses fabrication issues. Section 3.0 discusses erection and anchor bolt placement
issues. Section 4.0 discusses the “issues” involved in the design of base plates, rather than providing “how to” design methods or guidelines, and lists the names of other authoritative publications where the reader can find design formulas and definitive procedures for design of base plates. Section 4.0 also discusses fixed and partially fixed column bases, for instance, moment frames which resist wind or earthquake forces.

2.0 DESIGN GUIDELINES FOR MATERIALS AND FABRICATION

Engineers have numerous types of steel to choose from when designing anchor bolts and base plate assemblies. However, materials are often specified that are not readily available or are not suitable for specific applications. Base plate details often are hard to fabricate, overly complicated, call for expensive welds and/or specify impossible welds. The following sections provide design guidelines for specifying suitable materials and suggestions for details to make fabrication easier and more economical.

2.1 Materials

According to the AISC Specification for Structural Steel Buildings Allowable Stress Design and Plastic Design (ASD Specifications), there are 16 ASTM designations specified for structural applications. For specific material properties, suitable applications and complete dimensional information, the reader should refer to the ASTM Specifications.

2.1.1 Anchor Bolts and Nuts

The most common and readily available anchor bolt materials are ASTM A36 and A307. Smaller bolts generally are supplied in A307 and larger diameter in A36. The material properties for these relatively “low strength” bolts are very similar. These two grades are weldable and should be specified when possible. When high-strength bolts are required, the materials typically available are A499, A354 and A193 type B7 (often referred to as “B7”). B7 bolts are the same material as AISI 4140 and can be substituted for A499 because A499 and B7 bolts both have material properties that are almost identical. A325 bolts only come in “headed” form, are limited to 1 1/2 inch diameter maximum and are limited in the lengths available. The properties and chemistry for A325 bolts are similar to A449 and B7. Generally, it is better to specify A449, A354 or B7 bolts when high-strength bolts are necessary. High-strength bolts come as plain bar stock and threads must be cut into both ends. Headed bolts fabricated from A325, A490 or A588 should not be specified since these are not readily available. All of these high strength materials are heat treated alloy steels and are therefore not suitable for welding. Before specifying a bolt material, contact local fabricators for information regarding material availability and review the ASTM standards for the grades being considered to determine their suitability.

It is important to specify the correct grade of nut that corresponds to the specified anchor bolt material. ASTM A563 specifies the various nut grades that are typically used in building construction and nuts suitable for use with the various grades of bolts (see Reference 4). The “Heavy Hex” nut style should be specified regardless of the nut grade that is selected. Footnote A below table X1.1 makes reference to ASTM A194 grade 2H as a substitute for A563 when certain sizes conforming to A563 are not available. A194 is a specification for pressure vessel and non-building uses, but the grades referenced in footnote A are suitable for use for anchor bolts in buildings.

2.1.2 Plates

The most common base plate materials are A36, A572 and A588. Fabricators responding to the questionnaire recommended that A36 material be specified if possible because it is the most readily available material. The table on the following page
contains material availability guidelines based on plate thickness.

### Table 1 - Availability of Plate Material

<table>
<thead>
<tr>
<th>Thickness (t)</th>
<th>Plate Availability</th>
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<tbody>
<tr>
<td>t ≤ 4&quot;</td>
<td>A36</td>
</tr>
<tr>
<td></td>
<td>A572 Gr 42 or 50</td>
</tr>
<tr>
<td></td>
<td>A588 Gr 42 or 50</td>
</tr>
<tr>
<td>4&quot; &lt; t ≤ 6&quot;</td>
<td>A36</td>
</tr>
<tr>
<td></td>
<td>A572 Gr 42</td>
</tr>
<tr>
<td></td>
<td>A588 Gr 42</td>
</tr>
<tr>
<td>t &gt; 6&quot;</td>
<td>A36</td>
</tr>
</tbody>
</table>

#### 2.2 Base Plate Design for Fabrication

Typically, except for very large columns with very heavy base plates, such as for high rise buildings, base plates are shop welded to the column. Unless the weld is a complete penetration weld, the bottom end of the column needs to be cut square so that there will be full bearing where the column is in contact with the base plate. Some years ago, this was accomplished using milling machines in the shop. Today the cold sawing equipment used in most shops provides a column finished end with a maximum ANSI roughness height value of 500 which is satisfactory for contact bearing compression joints.

For very large columns, the base plate is erected first, using three leveling bolts around the perimeter of the base plate to level it, then the column is erected onto the base plate and connected using angles or other connection methods. The base plate is grouted before the column is erected. The mating surfaces should be prepared by milling or other means so that the column is in full contact with the base plate. Use of thick base plates can introduce welding problems due to difficulty of meeting preheat requirements.

#### 2.2.1 Material versus Labor

A common suggestion from steel fabricators for engineers to remember is that “material is cheap relative to labor.” If specifying thicker base plates will result in not having to add stiffener plates to the base plate, this will result in less labor to fabricate and will result in a more economic design. Adding stiffeners and other plates to a base plate assembly is labor intensive compared to using a thicker base plate that could eliminate the need for these additional stiffener plates.

#### 2.2.2 Welding

The engineer should attempt to at least match the thickness of the base plate with the column flange thickness in order to prevent warping during welding, particularly if heavy welding, such as partial or complete penetration welds, is required to connect the column to the base plate. Thicker base plates without stiffeners are often more economical than using a thinner base plate with stiffeners. Stiffeners, if used, will have an impact on column finish dimensions. See Section 4.7 “Architectural Issues” for further discussion.

Another common suggestion from fabricators is to reduce weld sizes as much as possible (but account for minimum AWS weld sizes based on material thicknesses) and specify fillet welds in lieu of complete penetration welds where possible. Complete penetration welds require more labor due to the need to bevel the end of the column and fit up, and require extensive inspection. It is more economical to detail larger fillet welds, even if more weld metal is required for the fillet welds, as a substitute for partial penetration welds.

Fabricators have also pointed out that “all around” welds should be avoided. Fillet welds that wrap around the flange toes (ends of column flanges) and the column web-to-flange fillets (the “k” region) can cause cracks due to high residual stresses in the welds. Such welds often require welding repair. Stop fillet welds 1/2 inch from these locations. See Figure 1 for clarification.

Welds should be detailed to account for clearances and access of welding equipment. Obviously the engineer should not show welds that are
impossible to access. For example, a common mistake is to specify “all around” welds at plate washers that are backed up against the column flange or web.

High strength bolts fabricated from high strength, heat treated steel (such as A354, A449 or B7) cannot be welded - not even tack welded - without adversely affecting the properties of these steels.

2.2.3 Base Plate Dimensions

Where possible, the plate dimensions and bolt pattern of base plates should be symmetrical about both axes. This will preclude welding the base plate rotated 90 degrees from the correct orientation. Having a doubly symmetrical bolt pattern will also help avoid potential field problems (See Section 3.1.2).

The engineer should try to specify the same bolt hole diameter whenever possible to eliminate the need for multiple drill bit sizes. This also applies to any vent holes required to vent out air from under the larger base plates during the grouting operation.

Obviously the base plate dimensions should be sufficient to accommodate the column dimensions plus anchor bolt holes with sufficient dimensions to the column flanges and to the edge of the base plate. Also account for any square plate washers, if used. Several fabricators have stated that engineers sometimes erroneously assume their “typical” base plate detail will cover all conditions. Columns that are in different size groups require different base plate sizes. It is generally more economical to design a “typical” larger base plate to cover more than one column size in a column group (such as W10, W12, W14 groupings), than to design specific base plates for each column size. The fewer variations of base plates required will generally result in economy in fabrication even if more material is required. This is true because of the labor savings in shop drawing preparation and the different shop setups required for each variation in base plate configuration. It is also true that having fewer “different” anchor bolt patterns will lead to less confusion during anchor bolt placement. See Figure 1 on the following page for suggested details.

3.0 DESIGN GUIDELINES RELATED TO ERECTION

Anchor bolts and base plates should be designed and detailed to accommodate steel erection loads. Some simple, yet effective, attention to details and dimensions can go a long way in helping to prevent some common problems encountered during steel column erection. A previous edition of Steel Tips (Reference 7) contains useful strategies for dealing with common field erection errors.

3.1 Anchor Bolts

Anchor bolt placement is obviously a difficult task but too often errors result due to poor quality control and quality assurance or lack of preparedness in the design. There are several ways to mislocate anchor bolts and typically one of the following will occur.

3.1.1 Anchor Bolt Position Mislocation

Position mislocation is unfortunately a common problem. The horizontal location of the anchor bolts is often incorrect by as much as 1 to 2 inches. In some cases one of the anchor bolts is not in the correct location with respect to the remaining bolts and in other cases the entire layout is in the wrong location. There are several ways to avoid this problem during the design phase.

1. The best method for preventing anchor bolt mislocation is for the contractor to properly set and hold anchor bolts in the correct position for plan location and elevation. It is the contractors responsibility to set anchor bolts correctly within the tolerance given in the AISC Code of Standard Practice (Refer to Reference 3). A check by an independent surveyor will help locate misplaced bolts before steel is erected so that corrections can be made by the contractor before steel erection
1. Use square plate and hole pattern dimensions where possible to avoid problems associated with mis-placed anchor bolts, rotated anchor bolt patterns or plates that are accidentally rotated 90 degrees during fabrication.

2. Try to reduce numerous base plate variations by sizing typical plate based on the largest column in a size group (e.g. W10's, W12's or W14's). Reducing the number of variations will reduce the chance for error during erection and fabrication, and allow for simpler verification in the field. Provide maximum edge distance to bolt to allow base plate slotting if bolts are mislocated.

3. When additional bolts are required, add additional holes to make double symmetric bolt patterns. This is useful even if not all holes and bolts are needed. Four bolts is the suggested minimum for any base plate.

4. Anchor bolts should be at least 1" diameter. This is beneficial for erection safety and the anchor bolts are harder to accidentally bend in the field. Specify A307 or A36 material when possible. Both are easier to obtain and weldable.

5. Oversize holes in base plates should be used whenever possible to accommodate anchor bolt placement tolerances.

6. Plate washers with field welds should be used in conjunction with oversize holes to resist nut pull-through and to transfer shear from the base plate to the anchor bolts. Special attention should be directed toward weld access. Plate washer should have hole 1/16" larger than bolt diameter. Welds may not be needed if the column is for "gravity only" and there are no shear forces at the base of the column.

7. Leveling nuts are recommended in lieu of leveling plates or shims for ease of construction, safety and efficiency.

8. The thickness of grout specified should accommodate the leveling nuts and be in proportion to the dimensions of the base plate (for example do not specify 3 inches of grout under a W6 column).

9. Specify an additional bolt extension above the top of the base plate to accommodate bolts that are set too low. Also specify extra threaded length to accommodate bolts set too high.

10. Specify fillet welds whenever possible. Partial penetration welds and complete penetration welds should only be specified when required.

11. Avoid specifying all-around welds. There should be no weld at the ends of the flanges and in the fillet (k region) of the column.

12. If a grout hole is needed, specify the same diameter as the anchor bolt holes to reduce the number of drill bit sizes required during fabrication.

FIGURE 1 - SUGGESTED BASE PLATE DETAILS
begins. This requirement should be included in the job specifications. In addition, the engineer should specify 1/8" sheet metal templates for every base plate. Typically contractors make one metal template and construct plywood copies of the template. This method of constructing templates and placing anchor bolts introduces several obvious opportunities for error.

Anchor bolts need to be rigidly held in position both top and bottom to prevent movement during concrete placement and to prevent the anchor bolts from tilting. Plates that connect the anchor bolts at the bottom should be considered, particularly for large anchor bolts.

2. Specify oversize bolt holes in the base plate with washer plates ("weld washers") that are field welded to the base plate (See Figure 1). The weld washer should have a standard hole (bolt diameter plus 1/16 inch). The AISC Code of Standard Practice allows the following oversize hole diameters,

<table>
<thead>
<tr>
<th>Bolt Diameter</th>
<th>Oversize Hole Dia.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4&quot; to 1&quot;</td>
<td>5/16&quot;</td>
</tr>
<tr>
<td>1&quot; to 2&quot;</td>
<td>1/2&quot;</td>
</tr>
<tr>
<td>over 2&quot;</td>
<td>1&quot;</td>
</tr>
</tbody>
</table>

For larger bolts this may not be enough oversize allowance; a larger oversize of up to 2 inches would be better. Weld washers are necessary when using oversize holes to prevent nut pull-through and for shear transfer to the anchor bolt. The extra cost of the weld washers is small compared to the cost of making field corrections and erection delays due to misplaced anchor bolts.

3.1.2 Rotated Anchor Bolt Patterns

Anchor bolts with a non symmetrical pattern are sometimes turned 90 degrees from correct orientation. Detailing anchor bolt patterns with doubly symmetric patterns will prevent this problem. See Section 2.2.3.

3.1.3 Anchor Bolts Set Too Low or Too High

Specifying anchor bolts with extra bolt projection will help for anchor bolts set too low. The extra projection will also prevent the problem of nuts that do not have full thread engagement. If a full nut cannot be obtained, there are methods to extend the bolt length. Specifying A36 bolt material allows welding a stub onto the low bolt. Sometimes, the nut cavity above a low anchor bolt can be "filled out" with weld metal if weldable nut and bolt materials were specified.

Engineers should specify more of the bolt shank to be threaded than is actually needed. If the bolt is set high, the extra threads will allow the nut to be run down the bolt without requiring additional washers.

3.1.4 Columns Next to Walls

Another problem that frequently occurs is inaccessible anchor bolts due to a column located next to a wall. This occurs when the anchor bolts are located between the column flanges or at a corner where two walls intersect (See Figure 2). For these conditions, special base plate/anchor bolt patterns are necessary so that all anchor bolts are accessible. Refer to the ASD Manual, Connection Section, for assembly clearance requirements at nuts.
3.2 Washers

If high strength anchor bolts are “tensioned”, hardened “cut” washers should be used in addition to any weld washer plates used. This will prevent the nuts from galling the weld washer or base plate. Normally, anchor bolts are not tensioned; nuts are usually tightened with a wrench using a “cheater”.

3.3 Base Plate Leveling

Some erectors favor the use of leveling nuts instead of shim packs or leveling plates (See Figure 1), other erectors favor shim packs. Leveling nuts are easier to level and provide a more stable base for resisting erection loads than shim packs. Generally, leveling plates are reserved for special cases and should not be specified for typical use.

4.0 ENGINEERING GUIDELINES FOR DESIGN OF BASE PLATES

This section covers the engineering design of base plates. The focus of this section is not so much “how to” calculate base plates, but what the engineer needs to consider when engineering and detailing base plates. The reader is referred to other publications with formulas, design aids and procedures. See References 1, 2, 3, 5, and 6.

The base plate assembly must be designed to transfer all forces from the column to the supporting member whether it is a girder or a foundation. These forces include axial forces, shears and moments from the column. The magnitude and combinations of these loads will determine the design and details of the base plate. The simplest and most common condition encountered in practice is a column supporting gravity loads only. When there are high shear forces and moments, such as in a moment frame, the design becomes more complicated and the base plate and anchor bolts become heavier. The following subsections discuss the issues related to the various loads and combinations of loads.

4.1 Design for Temporary Construction Loads

The first function of a base plate is to temporarily support the column from overturning due to temporary wind, earthquake, and erection loads, and from the column getting bumped during erection until the beams are attached to “tie in” the column. Therefore the base plates and anchor bolts need to be at least sufficient to resist the overturning moment and shear from these forces. Although erectors often check the column by assuming a one kip load applied horizontally at the top, this does not relieve the engineer from providing an adequate design.

If the anchor bolts and base plate are too small, for example, with only two anchor bolts or anchor bolts that are too close together, the base plate assembly may not be capable of resisting erection loading (See Figure 3).
anchor bolts should be detailed and spread apart as much as possible. See Figure 1 for suggested details.

4.2 Design for Gravity and Other Downward Loads

The most common base plate condition is a base plate that transfers gravity loads to the supporting member or foundation with relatively low shear forces and moments at the base of the column. These are “gravity only” columns that are not part of moment frames or braced frames. The base plate must be large enough so that the area of the concrete beneath it is sufficient to support the loads. Usually these columns will transfer nominal shear and moments to the supporting member or foundation. Such forces are normally caused by story drift due to wind or earthquake loads.

The AISC Manual of Steel Construction (Reference 3) provides a two step procedure for the design of axially loaded base plates. First, the area of the plate is calculated based on the allowable bearing stress defined by the following equations.

**ASD:**

\[ F_p = 0.35 \, f'c \, \sqrt{\frac{A_2}{A_1}} \leq 0.70 \, f'c \]

**LRFD:**

\[ \varphi_c \, P_p = 0.85 \, \varphi_c \, f'c \, A_1 \sqrt{\frac{A_2}{A_1}} \leq \varphi_c \, 1.7f'c \, A_1 \]

where,

- \( F_p \) = Allowable bearing stress (ksi)
- \( f'c \) = Concrete compressive strength (ksi)
- \( A_1 \) = Base plate area (in²)
- \( A_2 \) = Area supporting base plate that is geometrically similar (in²)
- \( \varphi_c \) = 0.85 for compression
- \( P_p \) = Ultimate capacity of the concrete in bearing

Based on this equation, the most efficient base plate area \( (A_1) \) is at most one-fourth of the concrete support area \( (A_2) \); or the concrete supporting area \( (A_2) \) is ideally four times the base plate area \( (A_1) \).
The final step in determining the required base plate thickness is defined by calculating the flexural demand for a critical section of plate acting as a cantilever. For Allowable Stress Design (ASD) the elastic section modulus (S) is used; whereas for Load and Resistance Factor Design (LRFD) the plastic section modulus (Z) is used. The dimensions of the critical section are based on 0.95d and 0.8b_f for wide flange sections, 0.80 times the outer diameter of pipes and 0.95 times the out-to-out dimension of tubes (See Figure 4). According to ASD, the allowable bending capacity is equal to 0.75F_y where F_y is the allowable yield strength of the steel. If LRFD is preferred, the design strength is equal to 0.90F_y. See References 1, 2, 3, 5 and 6 for useful design equations and design aids.

4.3 Design for Gravity Loads in Combination with Uplift Loads

When there are net uplift loads, such as can occur in the end columns of concentric or eccentric braced frames (CBF or EBF), the anchor bolts and base plates need to be checked and increased in size if necessary. When uplift loads are very high, it may be necessary to add stiffener plates welded to the column flanges and design longer anchor bolts above the base plate to accommodate the stiffeners. However, it still may be more economical to use a thicker base plate than to add the stiffeners because of the high labor cost involved with the stiffeners. Anchor bolts need to be well embedded in the supporting foundation concrete to develop the tensile capacity of the anchor bolts, and to preclude anchor bolt pullout due to shear cone failure in the concrete. This detail becomes even more critical for braced frames or moment frames subjected to wind or earthquake forces where failure of the base plate assembly would cause overturning due to uplift resulting in loss of lateral resistance in the braced frame or moment frame. For earthquake loads, since actual loads are much higher than code design forces (which have been reduced to account for “ductility” in the braced frame), yielding should occur in the brace for a CBF or in the “link” beam for an EBF. The base plate assembly needs to be strong enough to ensure that yielding will occur in these other elements.

4.4 Design for Gravity Loads in Combination with Shear Forces

Taking section 4.3 a step further, if a brace occurs at the base of a column, a high shear force is
introduced from the horizontal force component in the brace. This force must be resisted by the base plate assembly. There are various proposed methods to transfer this shear force:

1. **Anchor Bolts** (See Figure 5a);

2. **Shear Key** - A steel shear key is welded to the bottom of the base plate to interlock with the concrete (See Figure 5b);

3. **Embedded Shear Plate** - Shear plates are field welded to the sides of the base plate and to an embed plate that has welded shear studs or shear lugs to transfer shear forces to the concrete foundation (See Figure 5c);

4. **Embedded Shear Strut** - A strut member with welded shear studs or shear lugs is connected to the base plate or a column gusset plate. The shear studs or shear lugs transfer the shear force into the slab concrete and then to the foundation through rebar dowels (See Figure 5d). The following is a discussion of the design issues pertaining to these methods of transferring shear at the base of a column.

1. **Anchor Bolts**: When column shear forces are resisted by the anchor bolts, they must be checked for a combination of column shear, bending and tension. If oversize holes are used in the base plates for anchor bolt placement tolerance, welded washer plates must be added so that the base plate will not slip before engaging the anchor bolts. The washer plates are added to the top of the base plate and the additional bending in the anchor bolts must be accounted for due to the increased distance from the concrete to the washer plate. There is a practical limit to the amount of shear the anchor bolt/concrete interface can resist before the anchor bolts become very large. When shear forces are high, methods 2, 3 or 4 should be considered.

2. **Shear Keys**: Steel shear keys can be welded to the underside of the base plate to provide a shear interlock with the concrete foundation below. The bending and shear forces that the shear key imparts to the base plate must be accounted for. The use of such keys requires block-out voids to be formed in the top of the foundation to allow space for the keys and surrounding grout. Any rebars in the foundation under the base plate must be positioned vertically and/or horizontally to allow for the depression in the foundation concrete to accommodate the steel key. Shear keys are effective in transferring shear forces from a brace into the foundation, so that the anchor bolts only have to resist tension forces.

3. **Side Plates**: Another strategy would be to cast an embed plate into the top of the foundation. The embed plate would have shear studs or lugs welded to the bottom to transfer shear forces into the foundation. The embed plate would be larger than the base plate to accommodate setting tolerance and to accommodate side plates to transfer shear forces from the base plate to the embed plate and foundation. The column would be erected and leveled in the same manner as any conventional column. Loose plates would be added and field welded to the sides of the base plate and to the embed plate. Grouting between the base plate and embed plate would be the final step in the process. This detail is practical because it provides a template for the anchor bolts and allows for confinement of the grout.

4. **Struts**: When shear forces are high and shear keys or embedded plates are not practical for detailing reasons, steel struts can be added that are embedded into the slab concrete. The strut is welded or bolted to the base plate or to a stiffener or gusset plate welded to the base plate. The strut should have shear studs or lugs welded to it to transfer axial forces from the strut to the concrete slab. The slab adjacent to the strut should be doweled to the foundation to transfer forces from the slab to the foundation. Attention to construction details and sequencing is important so that the rebars around the strut do not interfere...
with being able to position and connect the strut to
the base plate.

4.5 Design for Gravity Loads in Combination
with Shear Forces and Moments

When a base plate assembly must transfer column
base moments to the foundation, the mechanism
for resisting the moments is typically taken by the
combination of the tensile capacity of the anchor
bolts and the bearing capacity of the concrete or
masonry. This forms a "couple" consisting of the
tension force in the anchor bolts and the equivalent
force at the centroid of the bearing area under the
base plate. This is analogous to the internal forces
to resist bending in a concrete "cracked" section.
The other gravity, shear, and uplift forces acting in
combination with the bending moment must also
be added and accounted for.

Two methods are presented for consideration
when designing base plates subject to bending
moment. See References 1, 2, 3, 5 and 6 for
additional information on how to calculate and
design for this combination of loads.

The first method is based on the assumption that
stresses caused by the moment are linear across
the base plate length. The tensile force in the
anchor bolt is dependent on the bearing area. An
equation is provided in Reference 1 to calculate
the effective length of bearing. (See Figure 6,
Method 1). This may not be consistent with actual
behavior since the assumption relies on linear
deformation of the base plate.

The second method is based on the assumption
that the resultant of the bearing length is directly
beneath the column flange. The basis of this
assumption is that the flange experiences a greater
axial load compared to the web because of the
higher combination of axial and flexural stresses,
and the relative width of the column flange to the
web (See Figure 6, Method 2). This method may
produce inaccurate results as well since the
bearing length may extend over to the anchor bolt
in tension. More testing and research is required
to confirm the validity of either method with actual
behavior. See References 1 and 5 for further explanation and useful equations.

When the column moments are known, the design is more straightforward than if the moments are more unpredictable, such as at the base of moment frame columns which resist earthquake forces where ductility becomes an important issue. See Section 4.6 for additional discussion of base plate assemblies that resist seismic forces.

4.6 Design for Moments due to Seismic Forces

Unfortunately, the behavior of base plates in moment frames and braced frames subjected to earthquake forces is not fully understood. Research and code guidance are limited. The engineer is forced to use judgment and the interpretation of the results from tests on assemblies with similar components in order to achieve a design that hopefully will have the desired level of performance.

Trying to fix, or partially fix, the base of moment frame or braced frame columns against rotation may be necessary to reduce the drift in the story above the base plate location. Consider the following scenarios:

1. Continue the column into the foundation or into a basement level below;

2. Design a heavy base plate assembly strong enough to force a plastic hinge in the column. This is difficult to accomplish even for relatively small columns. The base plate and anchor bolts become very large and anchor bolt anchorage becomes difficult. The foundation must be capable of resisting the high moments from the column base assembly (See Figure 7a). Currently, research is ongoing at the University of Michigan by Professor Subhash Goel on base plate assemblies of this type;

3. If the steel frame is supported on spread footings with moment resisting grade beams between the footings or supported on a grade beam grid system, partially fix the base of the column by designing the footing/grade beam system to form plastic hinges in the grade beams that behave in a ductile manner. Size the base plate assembly to develop the strength of the footing/grade beam considering the overstrength of the concrete sections. Any plastic hinges should occur in the grade beams;

4. Design a partially fixed base plate assembly. This will help limit drift, and the base plate and anchor bolt dimensions will be more manageable than with a fixed base solution. Drift can be reduced dramatically because the column will be forced to bend in double curvature. The challenge is to design the base plate assembly to behave in a ductile manner. If partial fixity is lost during an earthquake due to the failure of the base plate or stretching or breakage of the anchor bolts, the drift of the first story will increase dramatically resulting in more damage and possible failure of the column. A failure of the second floor beams could also occur if they were not designed for the extra bending or are not ductile enough to accommodate the extra rotation. (See Figures 7b, 7c, and 7d);

5. "Pin" the base of the column by designing a base plate assembly that will have relatively little moment resistance, but will be ductile enough to accommodate the first story seismic drift.

Some design issues relative to scenarios 4 and 5 will be discussed further. Scenarios 1, 2 and 3 are beyond the scope of this paper. For all column to base plate welded connections, the same issues relative to beam to column connections in ductile moment frames should be considered to preclude a failure in or near the weld, particularly if a full plastic hinge in the column above the base plate is the desired design goal. The reader should refer to the documents and research currently being done by the SAC Joint Venture on moment frames (See Reference 8).
For a partially fixed column base as described in scenario 4, there are two mechanisms to achieve the ductility in the base plate assembly:

a. Design the base plate to yield in bending by designing the anchor bolts to be strong enough to force plastic hinges in the base plate (See Figure 7b). The plate must be large enough, but not too thick so that a plastic hinge region can form between the column flanges and the anchor bolts without inducing a shear failure in the base plate. A leveling plate should be provided under the base plate to protect the grout while the base plate undergoes deformations during the cyclical bending excursions.

b. Design the base plate strong enough to force yielding in the anchor bolts (See Figures 7c and 7d). Nuts and washers must be used above and below the base plate (Figure 7c) or the top horizontal plate (Figure 7d) to force the anchor bolts to resist axial forces in both tension and compression so that there will be cyclic capacity and ductility in the assembly. There must be sufficient unbonded length in the bolts to allow for the required elongation without overstraining the bolts. The ultimate strength of the bolt must be high enough to preclude failure at the reduced section in the threaded portion of the bolt before the bolt yields. This can become a problem when the ultimate strength of the bolt ($F_u$) is too close to the yield strength ($F_y$). Some accommodation must be made so that the bolts will not buckle when they are in compression. De-bonding and buckling resistance can be provided by using pipe sleeves within the footing (Figure 7c). If the yielding portion of the anchor bolts is above the base plate, sleeves or "guides" can be provided to resist bolt buckling (Figure 7d).

Very few test results are available to validate the behavior of either mechanism described in a or b. More research and development into base plate behavior and design guidelines are needed for anchor bolt/base plate assemblies that are subjected to very high moments where yielding is necessary to achieve the desired performance.

4.7 Architectural Issues

Architectural issues should be considered when designing and detailing base plate assemblies. Anchor bolt assemblies need to fit within slab thicknesses. There needs to be sufficient distance between the top of foundation and the top of slab to accommodate grout, leveling nut and washer...
plate below the base plate, the base plate, the washer plate, nut and bolt projection plus concrete cover above the top of bolt. Usually, this dimension is at least 12 inches. For projects with large columns and thick base plates, 12 inches is not enough. This is an important dimension to establish early because it affects the foundation depth.

Any stiffener plates added above the base plate must fit within the architectural finish around the column. If stiffeners are needed, the dimensions should be co-ordinated with the architect early in the design since it may be necessary to increase the finish dimensions, since this dimension will affect useable floor space. Also, the dimensions of any vertical stiffener plates should be checked to insure that the stiffener plates will not protrude above the slab outside of the column finish dimensions.

5.0 CONCLUSIONS

Base plates serve a critical role in transferring column loads to the foundation. This Steel Tips discusses design, fabrication and erection issues related to base plates and anchor bolts. Suggested details are presented and details to be avoided are shown. The engineer needs to be aware of materials available and should recognize that special attention to base plate and anchor bolt details can result in reduced costs during fabrication and erection. Base plate assemblies must be designed to accommodate temporary erection loads until the column is tied in with other structural members. Special attention by contractors when placing anchor bolts can reduce field problems and delays due to mislocated anchor bolts.

More research and design guidelines are needed for base plate assemblies subjected to high bending moments, such as in moment frames subjected to earthquake forces. For partially fixed column base assemblies, mechanisms that must behave in a ductile manner are needed. Some alternative strategies and concepts are presented.

6.0 REFERENCES

8. SAC Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures, FEMA 267, August 1995
About the Authors

Bill Honeck, a Principal of Forell/Elsesser Engineers, Inc., has 34 years of experience in structural engineering, 9 of which were in structural steel design, fabrication and erection. This also included 2 years designing electric transmission towers and substation framing. In addition, several of his large-scale projects have been produced on fast-track.

From 1965 to 1974 Bill Honeck was project manager/engineer for Bethlehem Steel in the construction of numerous highrise and large scale structures. During these 9 years Bill Honeck had practical experience in structural steel highrise buildings and large bridges. His responsibilities included structural steel erection, cost estimating and erection engineering, coordinating jobs, scheduling, reviewing costs, and implementing savings where possible.

He worked in the field and office in connection with steel erection as a field engineer, and was in charge of erection engineering for the Western District from 1967 to 1974. He was also responsible for designing falsework and related structures, erection scheming, and checking structural integrity of steel framework for erection related loads.

Derek Westphal, a project engineer and analyst with Forell/Elsesser, began his career with the firm in early 1996. In his experience to date he has developed a strong background in the seismic retrofit of historic buildings as well as the new construction of office buildings, laboratory, and university facilities.
The local structural steel industry (above sponsors) stands ready to assist you in determining the most economical solution for your products. Our assistance can range from budget prices and estimated tonnage to cost comparisons, fabrication details and delivery schedules.

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