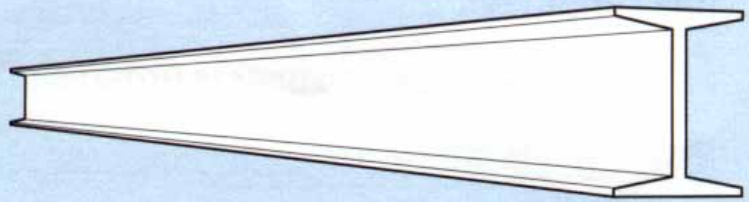


# Steel TIPS

STRUCTURAL STEEL EDUCATIONAL COUNCIL



TECHNICAL INFORMATION & PRODUCT SERVICE

June 2008

## ***Seismic Behavior and Design of Base Plates in Braced Frames***

By

**Abolhassan Astaneh-Asl, Ph.D., P.E.**

Professor

University of California, Berkeley

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# ***Seismic Behavior and Design of Base Plates in Braced Frames***

By Abolhassan Astaneh-Asl, Ph.D., P.E., Professor of Structural Engineering,  
University of California, Berkeley

**Abstract**—This Steel Technical Information and Product Services (Steel TIPS) report provides information and technologies on seismic behavior and design of base plates in concentrically braced frames. These base plates are primarily subjected to axial load of downward compression and uplift in combination with shear force. Normally, compared to axial load and shear force, bending moments in these base plates are small and ignored in design. Chapter 1 is an introduction to base plates in ordinary and special concentrically braced frames and outlines the seismic design and detailing issues. Chapter 2 provides information on the performance of base plates in concentrically braced frames during past earthquakes as well as the tests conducted in laboratories. Chapter 3 discusses provisions of the AISC Seismic Provisions (2005) that are applicable to base plates in ordinary (OCBF) and special concentrically (SCBF) braced frames. It also discusses seismic and gravity design issues in terms of strength, stiffness, and ductility under downward compression and uplift. Chapter 4 provides economical and efficient detailing suggestions for base plates in concentrically braced frames.

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Abolhassan Astaneh-Asl, Ph.D., P.E. Professor of Structural Engineering,  
University of California, Berkeley  
Phone and Fax: (925) 946-0903,  
Personal web site: <http://www.astaneh.net>  
University web site: <http://www.ce.berkeley.edu/~astaneh>

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*This Steel Technical Information and Product Services (TIPS) report is dedicated to the memory of the late Larry McLean , a leader in the steel construction for more than four decades and a longtime member of the Structural Steel Educational Council.*

*Abolhassan Astaneh-Asl*

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The author and his graduate and undergraduate research students at the University of California at Berkeley conducted the research projects reported in Chapter 2. In particular, the excellent work of former research collaborators and student Timothy E. Kelley in conducting the base plate tests is acknowledged and appreciated. The staff of the Structural Engineering Laboratory at the University of California at Berkeley fabricated the test specimens, and the tests were conducted in the Structural Laboratories of the Department of Civil and Environmental Engineering of the University of California at Berkeley. The efforts of William Mac Cracken, Chris Moy, Richard Parsons, Mark Troxler, and Douglas Zulaica, all laboratory staff at UC Berkeley, are sincerely appreciated. The research projects were supported, in part, by the University of California Berkeley.

Special thanks are due to Mary Finley, U.S. documents librarian, and Dr. Susan Curzon, dean of the university library, both at the California State University, Northridge, for providing valuable information on the damage, recovery, and reconstruction of the Oviatt Library. Thanks are also due to John Hammett for his efforts in editing and proofreading this document.

The chapter on suggested details is prepared to ensure that the suggested details satisfy the expectations of the structural engineers regarding seismic issues, strength, stiffness, and ductility while the connections are economical and easy to fabricate.

The input from Michael Cochran, Richard Denio, Mark Gilligan and Dr. Ahmad Rahimian on many aspects of material covered in this report are sincerely appreciated. If the reader finds any crown gems in this report, the credit is entirely due to these friends and if there are short-comings, errors or omissions, they are all due to my short comings. I hope that the reader in her/his generosity will forgive those short comings and will find the time to notify me of the errors and omissions so that I can post corrections.

The opinions expressed in this document are solely those of the author and do not necessarily reflect the views of the University of California, Berkeley, where he is a professor of structural engineering, or the Structural Steel Educational Council where he is a member of and other agencies and individuals whose names appear in this report.

# SEISMIC BEHAVIOR AND DESIGN OF BASE PLATES IN BRACED FRAMES

**By:**

**ABOLHASSAN ASTANEH-ASL, P.E., Ph.D.**

Professor

University of California, Berkeley

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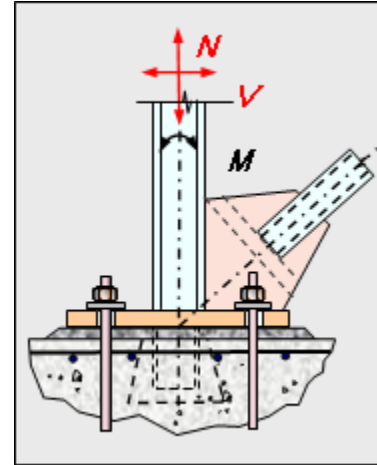
# Notations

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|              |  |
|--------------|--|
| $A_{ar}$     | Area of anchor rod based on nominal diameter   |
| $A_{BN}$     | Area of base plate equals $B$ times $N$ (see Figure 3.3)   |
| $A_f$        | Area of the foundation or pedestal supporting the base plate   |
| $A_{uar}$    | Cross sectional area of upset portion of upset rods  |
| $b_f$        | Width of flange  |
| $B$          | Length of base plate parallel to flange (Figure 3.3)   |
| $d_h$        | Diameter of the anchor rod hole  |
| $f'_c$       | Specified compressive stress of concrete   |
| $F_y$        | Specified minimum yield stress of the type of steel to be used   |
| $F_{yar}$    | Specified minimum yield stress of anchor rod material  |
| $F_u$        | Specified ultimate strength of anchor rod material   |
| $k$          | A factor representing the confinement effects of large foundations   |
| $L$          | Length of the base plate cantilever  |
| $M$          | Applied bending moment in the base plate   |
| $M_p$        | Plastic moment of a 1-inch strip of base plate   |
| $M_{pl}$     | Bending capacity of one line of the plastic hinge in the base plate  |
| $n$          | Number of anchor rods in one plastic hinge   |
| $N$          | Length of the base plate parallel to the web (Figure 3.3)  |
| $p$          | Pressure acting under the base plate assuming a uniform distribution of pressure   |
| $P_{nar}$    | Nominal tensile strength of the anchor rod   |
| $P_{nb}$     | Axial force that results in formation of a plastic hinge in the base plate   |
| $P_{nb-up}$  | Collapse capacity of the base plate in uplift given as:  |
| $P_{ns}$     | Nominal shear strength of the base plate concrete under the base plate   |
| $P_{sh-key}$ | Capacity of the shear key to transfer shear  |
| $P_u$        | Required strength of the base plate equal to the axial load that can be delivered to the top of the base plate by the brace and column connected to the base plate when both of them reach their respective expected yield strength. In calculating the expected yield strength of the brace and column connected to the base plate, instead of $F_y$ , the specified yield stress, $R_y F_y$ , the expected yield stress, should be used. |
| $P_{uc}$     | Required strength of the base plate in compression   |
| $P_{uni}$    | Nominal capacity of a brittle failure mode involving fracture of steel or failure modes of concrete  |
| $P_{yni}$    | Nominal capacity of a ductile failure mode involving yielding of steel   |
| $R_y$        | Ratio of the expected yield stress to the specified minimum yield stress, $F_y$  |
| $t$          | Thickness of the base plate  |
| $V$          | Applied shear acting on a 1-inch-wide strip of the base plate  |
| $V_p$        | Shear yield capacity of a 1-inch-wide strip of base plate  |

|          |   |
|----------|---|
| $W$      | Length of the plastic hinge, smaller of $B$ or $N$  |
| $Z$      | Plastic section modulus of the 1-inch-wide strip of base plate                                  |
| $\phi$   | Reduction factor for shear key = 0.90   |
| $\phi_b$ | Resistance reduction factor for yielding equal to 0.90  |
| $\phi_c$ | Resistance reduction factor for concrete supporting a base plate = 0.60                         |
| $\phi_s$ | Resistance reduction factor for shear failure modes   |
| $\phi_y$ | Reduction factor for ductile yield failure mode = 0.90  |
| $\phi_u$ | Reduction factor for brittle failure modes given by the AISC <i>Specifications</i> (AISC 2005a) |

# 1. Introduction



## 1.1. INTRODUCTION TO BASE PLATES IN BRACED FRAMES

In the United States, a typical steel column base connection consists of a steel base plate welded to the bottom of the column and in most cases resting on the foundation. In some cases the base plate, instead of foundations, rests on other supporting members such as steel transfer girder, reinforced concrete pedestal, walls or an elevated reinforced concrete flat plate. The connection is typically referred to as the column base plate connection. The steel column base plate connection is designed to support the column's gravity loads and when the column is part of the building's lateral load resisting system the base plate supports seismic/wind forces in the column as well.

Three types of base plate connections, shown in Figure 1.1, are (a) base plates for gravity columns in braced or moment frames where the base plate is primarily subjected to axial compression load due to gravity, (b) base plates for columns that are part of a braced frame where the applied load is primarily axial load ( $N$ ) and shear force ( $V$ ); and (c) base plates for columns of moment frames where the base plate connections act as rigid connections and transfer the axial load ( $N$ ), the shear force ( $V$ ), and the bending moment ( $M$ ).

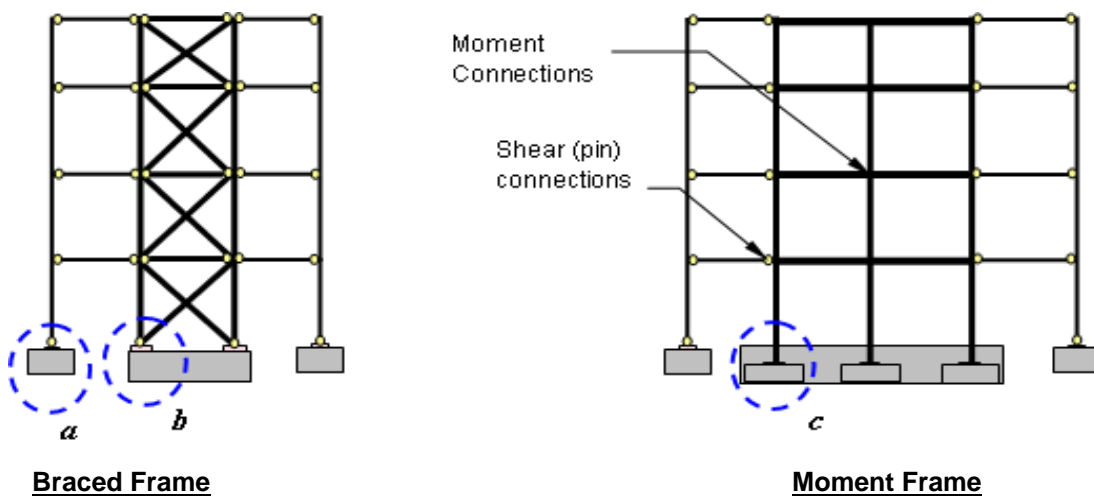


Figure 1.1. Three Types of Base Plates in Braced and Moment Frames

The discussion of column base plate design in this Steel Technical Information and Product Services (Steel TIPS) report is limited to base plates for the braced frames in building foundations only, base plates *a* and *b* in Figure 1.1, although much of the information may be applicable when the steel column base plate connection is supported by building framing members other than the foundation. In addition, the focus of this Steel TIPS is base plates for Special Concentrically Braced Frames.

The column base plate connection is typically surface mounted to the top of the foundation (that is concrete footings or concrete pile caps) after the foundation has been placed and allowed to cure for a period of time, Figure 1.2(a). The base plate is secured to the foundations by nuts threaded onto anchor rods that are set ahead of time and cast in the concrete foundation.

When the column base plate connection is part of the buildings lateral resisting system such as in braced frames or moment frames, there can be large compression and uplift axial forces to transfer to the foundation. When the column axial uplift forces become excessive, the steel column may need to be encased in the concrete foundation, Figure 1.2(b) to transfer the uplift forces to the foundation instead of depending upon the surface mounted base plate with anchor rods transferring the uplift to the foundation. Even in this case for large amounts of uplift forces, the concrete encasement may not be sufficient for uplift transfer. In these cases a solution, used successfully by some structural engineers, is to manage the uplift by anchor rods using ASTM F1554 Gr. 105 with up to 3" diameter. Obviously in this case the base plate needs to be designed most likely with stiffeners to avoid very thick base plates. In projects where composite solution is attractive for various reasons, including gaining additional stiffness and strength, the entire height of the column for multi-floors can be encased in concrete which also helps to address the uplift issue by engaging the concrete and rebars with the foundation and

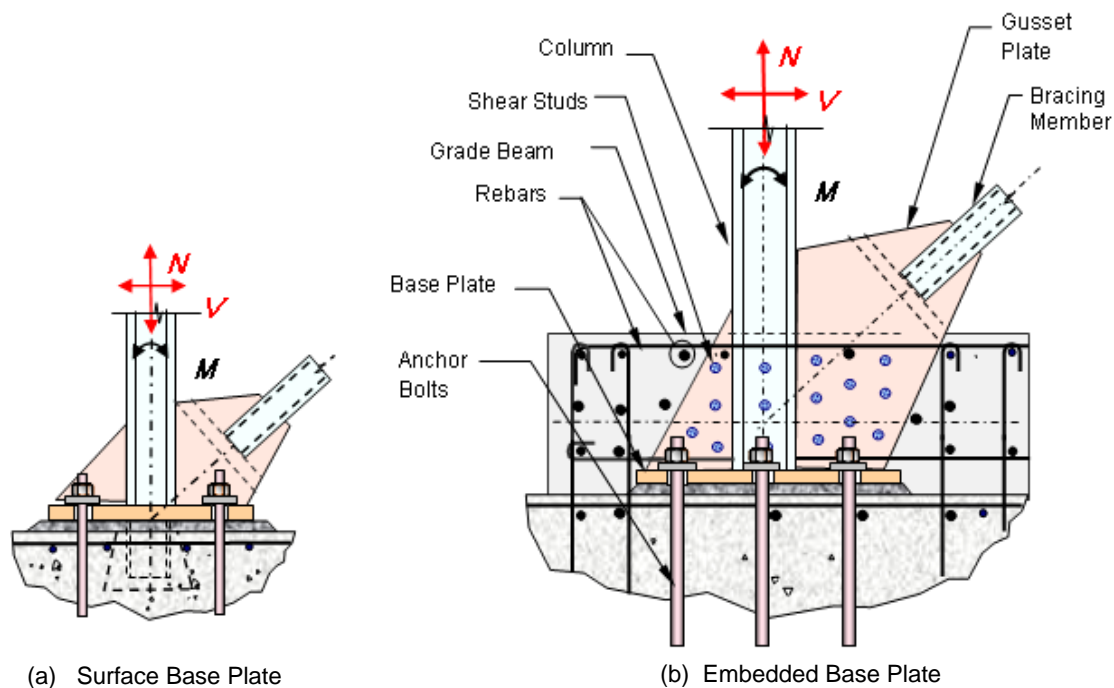


Figure 1.2. Examples of (a) Surface Mounted and (b) Embedded Base Plates



transferring some of the uplift of column directly to the foundation by rebars. This solution can also be used when the column is in the basement and reinforced concrete retaining walls are attached to the steel column. Chapter 4 provides suggested details for surface mounted as well as embedded column base plates in braced frames.

The principal function of an axially loaded base plate is to distribute the load of the steel column to a greater area on the concrete foundation and to prevent compression failure of the concrete under the steel column. Usually 4 to 12 anchor rods are used to connect the base plate to the foundation. The anchor rods have two roles. During construction and erection of the steel structure, the anchor rods prevent toppling of the columns. After completion of the structure, anchor rods resist uplift forces and, in some applications, transfer shear force from the base of the column to the foundation. Figure 1.3 shows typical base plates designed to carry axial load and shear force if present.

Depending on the number of anchor rods, their strength, stiffness, and location, axially loaded base plates carry some moment and act in a somewhat semi-rigid or partially restrained manner. In most of the current design practice and analysis, base plates in braced frames are assumed to be only axially loaded and they are modeled as pin connections. However, some structural engineers, especially in seismic applications where seismic Response Modification Factor,  $R$ , is greater than 3.0, design the base plates in a braced frame for the moment at the column to foundation interface as well. The magnitude of this moment can be established by modeling the base plate as semi-rigid in the analytical model. The amount of semi-rigidity to be assumed here depends primarily on the stiffness of the anchor rods in tension which can be used to establish rotational stiffness of the base plate. In some cases, there can be significant bending action in the columns given the stiffening of the frame by the gusset plates. In other words, when relatively large and thick gusset plates are attached to the column and base plates and the base plate is connected to the foundation with large number of anchor bolts, obviously such connection can no longer be assumed to be a pin connection in modeling with no moments developed at the base of the column. Design for these moments will likely become a larger part of design practice and in these cases the effects of bending moment should be included in the design.

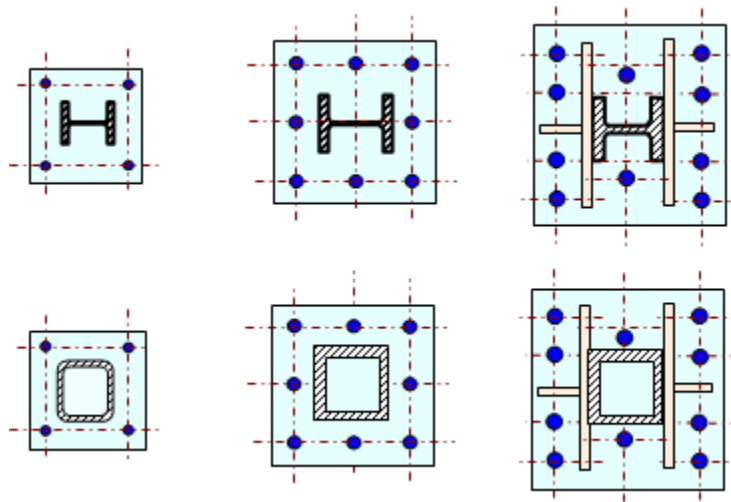
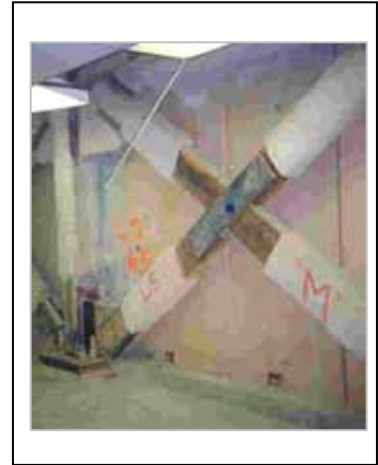


Figure 1.3. Typical Base Plates Designed to Carry Axial Load

The literature available on the behavior and design of base plates in braced frames under cyclic loading is quite limited. In particular, the behavior of anchor bolts in base plate connections where the bolts bending in grout is a common behavior, according to structural engineers consulted for this report, there is a lack of consistency and agreement in design offices in how to account for this. It seems that the current AISC Seismic Provisions (AISC, 2005c) prudently is formulated to decrease the potential for inelastic action in the base plate connection by requiring that the connections be designed to develop the yield capacity of the brace member. The next chapter is devoted to behavior of axially loaded base plates under cyclic loading typical of earthquakes. Small but more frequent cyclic loading of base plates due to wind are not of concern since they are not expected to cause inelasticity and under elastic conditions the number of cycles will not be enough to cause fatigue fracture.

## 2. Seismic Behavior of Base Plates in Braced Frames



### 2.1. INTRODUCTION TO CYCLIC BEHAVIOR OF BASE PLATES IN BRACED FRAMES

The information on cyclic behavior of base plates in braced frames, where base plate is primarily subjected to cyclic axial load, is very limited. Kelly and Astaneh-Asl (1988) subjected three base plate specimens to cyclic push-down and uplift axial loads. The main variable in these tests was base plate thickness. The following section gives a summary of the test results. We used the results and findings to develop design guidelines in Chapter 3 and the suggested details in Chapter 4. We could not find other cyclic test results of axially loaded base plates in a literature search. However, there were four reports on cyclic tests of base plates under combined effects of bending moment and axial load by Astaneh-Asl, Bergsma, and Shen (1992); Shen and Astaneh-Asl (1996); Burda and Itani (1999); and Yee and Goel (2001). Since bending moment was the dominant action in these tests, we have not summarized their results here, though we have used many of their valuable findings, especially the results on the behavior of individual components, in formulating the recommendations here and especially in developing the suggested ductile base plate details in Chapter 4.

Similar to the cyclic test results, damage reports of base plates during actual earthquakes are very limited. In the aftermath of earthquakes, it is very difficult for reconnaissance teams to investigate damage to unexposed areas of the structure, such as the base plates, which are usually buried under the lowest floor of the building. However, the lack of such reports does not necessarily indicate a lack of damage.

Generally some seismic damage is expected to occur in axially loaded base plates in the form of cracking of the grout immediately below the base plates, cracking of the concrete below the grout, tension yielding or fracture of the anchor rods, and bending yielding or, in extreme cases, fracture of the base plates. None of these damages, if they occur in limited extent, jeopardizes the capacity of the structure to resist gravity loads. Therefore it is possible that any damage to the base plates in some structures during actual earthquakes did not have visible consequences, such as settlement or large lateral displacements, for the rest of the structure, and the damage itself was not observed simply because of the hidden location of the base plates.

In the aftermath of the 1989 Loma Prieta and the 1994 Northridge earthquakes, the author observed damage in the axially loaded base plates of two important structures (Astaneh-Asl 1990 and Astaneh-Asl 1995). One of the structures was a major and modern library, and the other was a very important industrial facility. Section 2.7 summarizes the two base plate damage cases and the lessons learned.

## 2.2. BEHAVIOR OF BASE PLATES SUBJECTED TO AXIAL CYCLIC FORCE

### 2.2.a. Behavior of Base Plates Subjected to Axial Compression

When a base plate that has nuts only above the base plate is subjected to only axial compression, either with or without shear but with no moment, the distribution of compressive stresses under the base plate will be non-uniform, as shown in Figure 2.1(a). The larger compressive bearing stresses concentrate immediately under the column footprint. The distribution of bearing pressure under a base plate depends strongly on the bending stiffness of the base plates. If the base plate is relatively thick and stiff, the stress distribution will be more or less uniform. This is shown in Figure 2.1(b). As the compressive axial load in the column increases, the deformation of the grout and concrete under the base plate alters the compressive stresses' distribution to make it even more uniform due to redistribution to the outer areas of the base plate. In the current design, distribution of bearing stresses under the base plate is assumed to be uniform. In this case, since the anchor rod nuts are used above the base plate, they do not participate in carrying the compressive force.

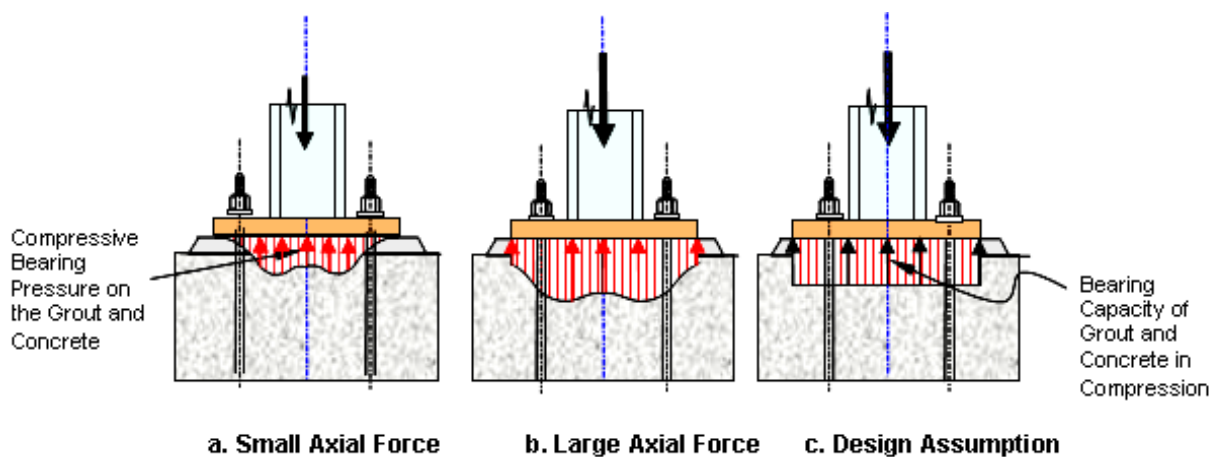


Figure 2.1. Distribution of Pressure under an Axially Loaded Base Plate

(Ref: Astaneh-Asl 2008)

If a base plate has double nuts in its anchor rods, one below and one above, its behavior in compression will be more complex than if the nuts are above the base plate. Our engineering literature search did not find any published document on tests or analysis of behavior of base plates with double nuts. In the absence of such information, considering the principals of mechanics of behavior of material and the equilibrium of forces, I expect that the compression

force applied to the base plate with double nuts is distributed to the anchor rods and the grout depending on their relative stiffness as well as the bending stiffness and strength of the base plate itself. The two parallel elements, grout and anchor rods, go through their own elastic and inelastic range of behavior as the applied load increases. For relatively thick and rigid base plates, the anchor rods, at least initially and while they are elastic, share the applied compression with the grout and concrete support. However, as the steel anchor rods yield in compression and shorten, the bulk of additional applied axial load will go to the grout and concrete under the base plate until the grout or confined concrete reaches its compressive bearing strength and fails in compression. Figure 2.2 shows expected bearing stresses under a base plate with double nuts.

In seismic applications, without the benefit of availability of research results, it appears that the use of double-nut anchor rods can provide additional redundancy and ductility to the base plate without causing any adverse effects. However, it is very important that, if double nuts are used before packing the grout under the base plate, the nuts below the base plate are turned as much as needed until all of them are supporting the base plate. Also, in this case, the base plates need to be checked for the bearing force distributions shown in Figure 2.2(c), which include bearing reactions due to the yielding of anchor rods under compression.

If the nuts below the base plates are used only for leveling purposes, after the base plate is leveled and is in its correct elevation, the base plate should be supported on wedges at its edge and the nuts below the base plate should be turned away from the base plate leaving a gap between the base plate and the nut below.

Due to the importance of base plate connections in the overall performance of steel structures and the lack of sufficient research results in this field, there is a need for research, especially experimental research, into the behavior of base plates subjected to combined cyclic axial load and shear as it occurs in the base plates of braced frames.

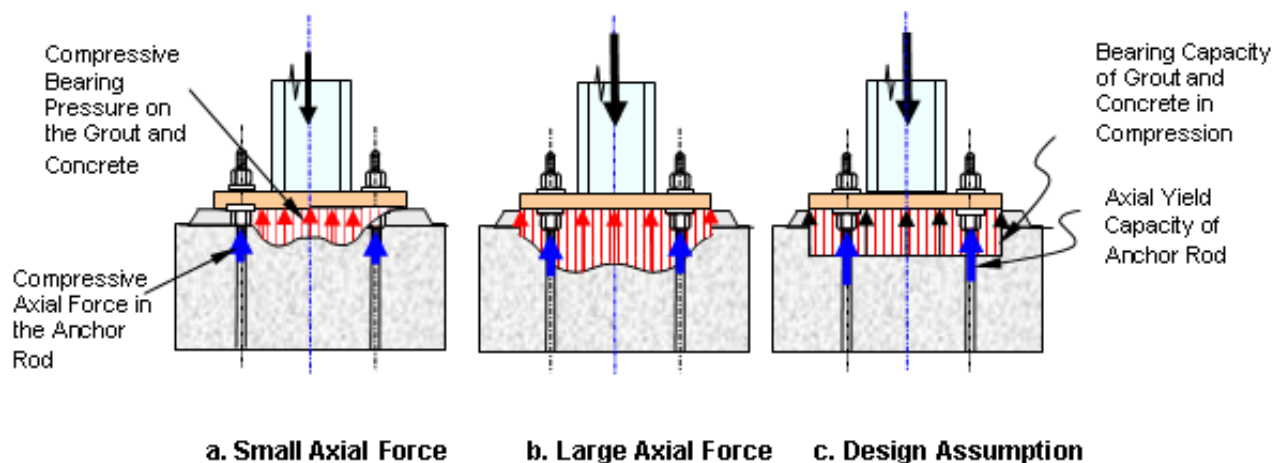


Figure 2.2. Distribution of Pressure under an Axially Loaded Base Plate with Double Nuts on the Anchor Rods

(Ref: Astaneh-Asl 2008)

Base plates, when under compression forces, press against the supporting grout and concrete and show elastic behavior with relatively high stiffness. As the loading continues, if the limit state of crushing of the supporting grout or concrete occurs, the behavior will be relatively brittle. Repairing such damage will be very difficult and costly since the column is under the gravity load of the floors above and any repair of grout or concrete under the base plate will require providing temporary supports for the column and the removal of its axial load. If the failure mode of bending yielding of the base plate occurs, the behavior will be relatively ductile. However, after formation of the plastic hinge in the base plate, the distributed pressure under the base plate will have very high values in the areas just under the column footprint, resulting in compressive crushing of the grout or concrete.

Generally grout has higher compressive stress than the concrete used in foundations. Some structural engineers basically follow a simple design check for grout which is as follows: bearing stresses are checked at the grout surface using ACI-318 considering that there is no confinement. Then they check the bearing stresses at the foundation surface considering the confinement effect where it exists which can increase the bearing capacity by a factor two. This is the main reason that the grout generally needs to have a higher strength than the supporting footing by up to a factor of two. As a result, in the design of base plates only the compressive failure mode of the concrete is considered. However, investigations of the performance of the axially loaded base plates during past earthquakes have indicated that the failure of grout with catastrophic consequences is quite possible when the grout is relatively thick and has no reinforcement inside, or external confinement such as concrete floor slab placed over the top of the footing.

One serious case of damage to grout under the base plate was the compressive failure of the grout under the base plates of the modern Oviatt Library at California State University, Northridge during the 1994 Northridge earthquake. More information on this case is provided in Section 2.7.b. The cause of the failure might have been the unusually thick grout layer under the relatively thick and rigid base plate. Such thick grouts can act as an un-reinforced pedestal and fail in a combination of compression crushing and tensile splitting failure modes. There is almost no published research on the performance of thick grouts. It would be prudent to limit the thickness of the grout to approximately two inches, and for grouts thicker than that to use reinforcing mesh or, preferably, fiber reinforcement in the grout. The use of fiber-reinforced grout can help make the packing of the grout under the base plate easy during construction, without interference from the bars in the reinforcing mesh.

The failure modes of a base plate subjected to axial compression are:

- a. Yielding failure of the base plate due to bending
- b. Compression yielding of anchor rods when double nuts are used, one above and one below the base plate
- c. Compressive failure of concrete under the base plate
- d. Failure of the grout under the base plate
- e. Shear failure of anchor rods if shear is also present
- f. When shear is present, shear failure of shear keys if used to transfer shear from the base plate to the foundation

In Chapter 3, we provide design information for these failure modes.

### 2.2.b. Behavior of Base Plates Subjected to Axial Uplift Force

The boundary columns of braced frames and their supporting base plates are usually subjected to uplift forces. When a base plate is subjected to axial uplift, depending on the bending stiffness and strength of the base plate, one of the three cases shown in Figure 2.3 occurs. If the bending stiffness and the strength of the base plate are relatively small, the base plate bends and undergoes the plastic collapse mechanism shown in Case I of Figure 2.3. If the base plate is very stiff and strong in bending, it acts as a rigid plate remaining almost elastic and the uplift force is directly transferred to the anchor rods as shown in Case III of Figure 2.3. In this case the base plate remains essentially elastic while eventually the anchor rods reach their capacity and remain elastic as well. Case II in Figure 2.3 shows an intermediate case in which the base plate is not sufficiently strong and stiff and both base plate bending and anchor rod elongation contribute to the strength and stiffness of the base plate assembly.

If double-nut anchor rods are used, as shown in Figure 2.2, the uplift behavior of the base plate will not be affected in a noticeable way by having a nut under the base plate. The benefit of having double nut is that at the end of uplift cycle, when the load is reversed and the column is coming down, the drop of base plate on the grout will not be a free fall generating impact but instead the drop of column will be smooth with no impact.

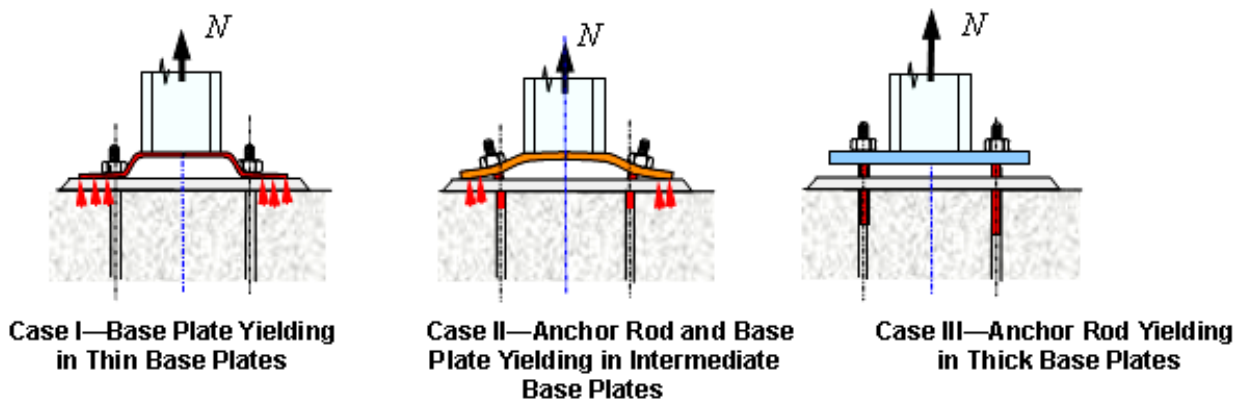


Figure 2.3. Three Cases of the Behavior of Base Plates Subjected to Uplift

The failure modes of a base plate subjected to axial uplift force are:

- a. Yielding failure of the base plate due to bending
- b. Yielding of anchor rods in tension
- c. Pull-out failure of anchor rods
- d. Failure of concrete under the base plate due to compression created by the prying action

- e. Failure of the grout under the base plate due to compression created by the prying action
- f. Cone failure of the concrete holding the anchor rod during the uplift phase
- g. Shear failure of anchor rods if shear force is also present
- h. Shear failure of shear keys if used to transfer shear from the base plate to the foundation

In Chapter 3, we provide information on design for these failure modes.

## 2.3. TESTS OF BASE PLATES UNDER AXIAL CYCLIC LOAD

To investigate the actual cyclic behavior of base plates subjected to cyclic axial load, we conducted three base plate column assembly tests (Kelly and Astaneh-Asl 1988; Astaneh-Asl, Kelly, and Trousdale 1990). The main parameter of study in these tests was the effect of base plate thickness on the uplift behavior of the axially loaded base plates. The thickness of the base plate as a single parameter of study was selected to represent the effects of bending strength and stiffness, both dependent on the thickness, on the cyclic behavior. The three test specimens had

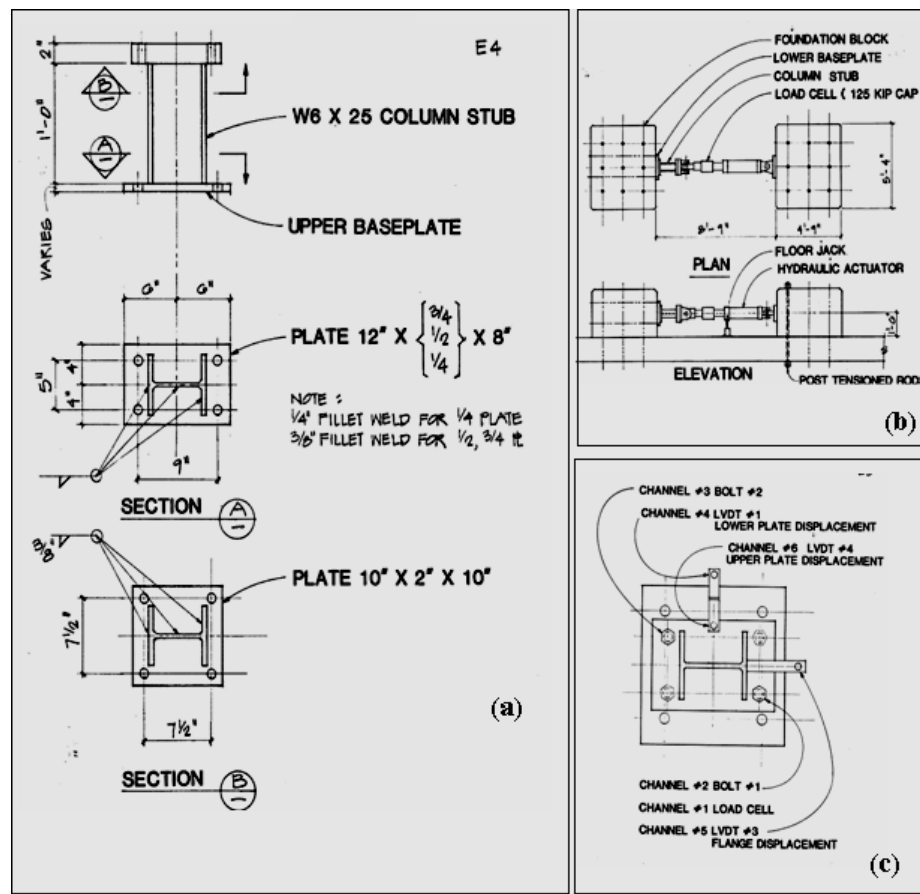


Figure 2.4. (a) Test Specimens, (b) Instrumentation of Specimens, and (c) Test Setup for Tests of Base Plates Subjected to Cyclic Axial Load  
(Ref: Kelly and Astaneh-Asl 1988)



the same size base plates and details except for the thicknesses of the base plate, which were  $\frac{1}{4}$  inch,  $\frac{1}{2}$  inch, and  $\frac{3}{4}$  inch for Specimens 1, 2, and 3, respectively. Figure 2.4 shows the details of the specimens, the instrumentation, and the test setup used to conduct the tests. The three specimens represented the three cases of behavior of flexible, semi-rigid, and rigid shown in Figure 2.3 and discussed earlier.

Figure 2.5 shows two specimens. The one on the left is Specimen 1 with a  $\frac{1}{4}$ -inch base plate which was a flexible base plate and the one on the right is Specimen 3, which had a  $\frac{3}{4}$ -inch-thick base plate and could be considered rigid. Specimen 2, not shown, had a  $\frac{1}{2}$ -inch-thick base plate and was representing semi-rigid base plates. As Figure 2.5 shows, in order to separate the behavior of the base plate from the behavior of the grout and foundation, a relatively thick support plate was placed under each base plate. So, the effects of grout behavior and its failure modes were excluded from these tests.

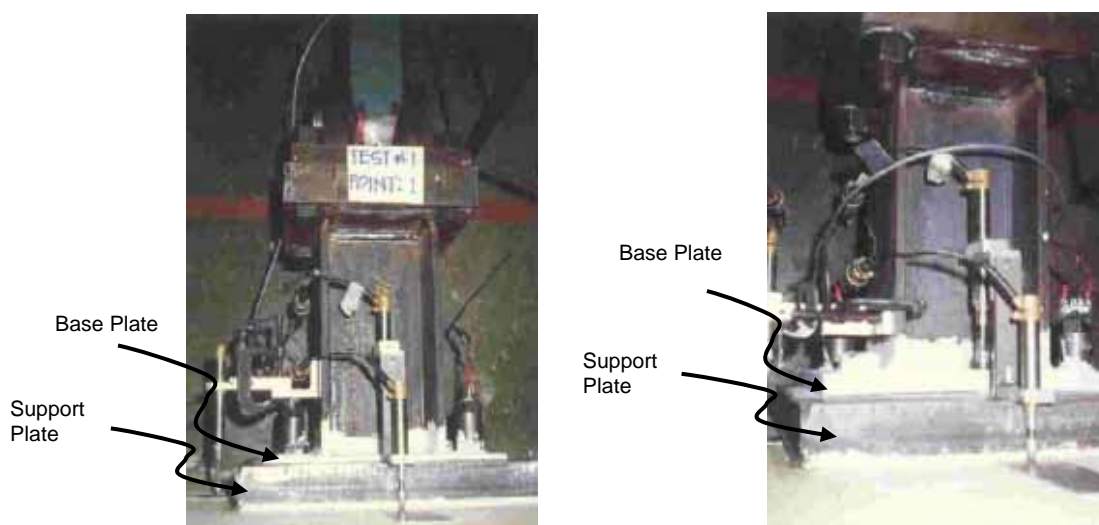


Figure 2.5. Thin ( flexible) and Thick (rigid) Base Plate Specimens

Figure 2.6 shows the variation of axial deformation versus the axial push-down and uplift forces. The specimen with the thin plate, Test 1, which resembled the Case I behavior in Figure 2.3, developed plastic hinges along the tips of the column flanges and along the bolt lines and showed a relatively small failure load compared to the two other specimens. This specimen showed the largest ductility of the three tests. The specimen with the thick plate, Test 3, which resembled the Case III behavior in Figure 2.3, developed a relatively larger force and smaller displacement compared to the two other tests. Test 2, resembling Case II behavior in Figure 2.3, developed almost the same load as the specimen with the thick plate but was more ductile due to bending of the base plate as well as elongation of the anchor bolts. In other words, the intermediate thickness of Specimen 2 resulted in developing high strength of the thick plate and high ductility of the thin plate. Based on only three tests, we should not make generalized conclusions. More tests have to be done to establish interaction of the grout and base plate and to use the test results to develop robust seismic design recommendations. All we can deduct from these limited tests is a better understanding of effects of base plate strength and stiffness on its cyclic behavior.

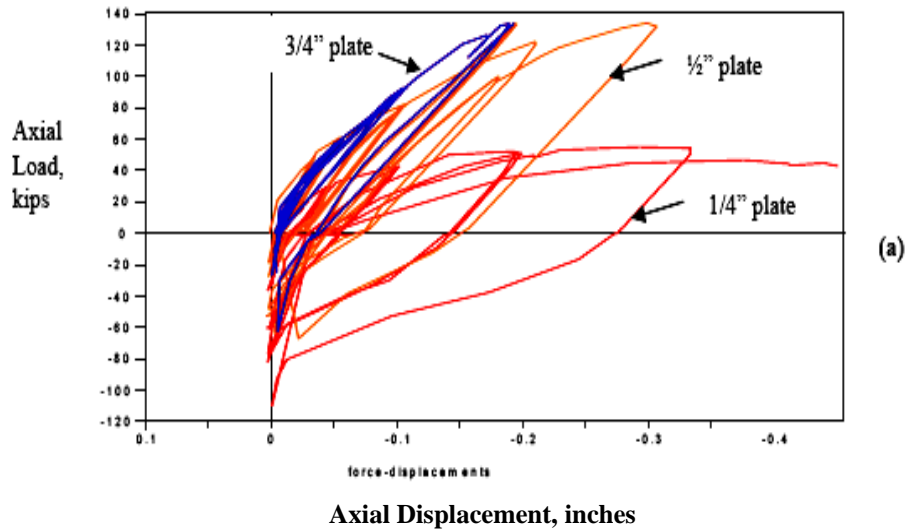


Figure 2.6. Variation of Axial Force in the Column versus Axial Displacement for the Base of the Column in Three Specimens (Astaneh-Asl, Kelly, and Trousdale 1990)

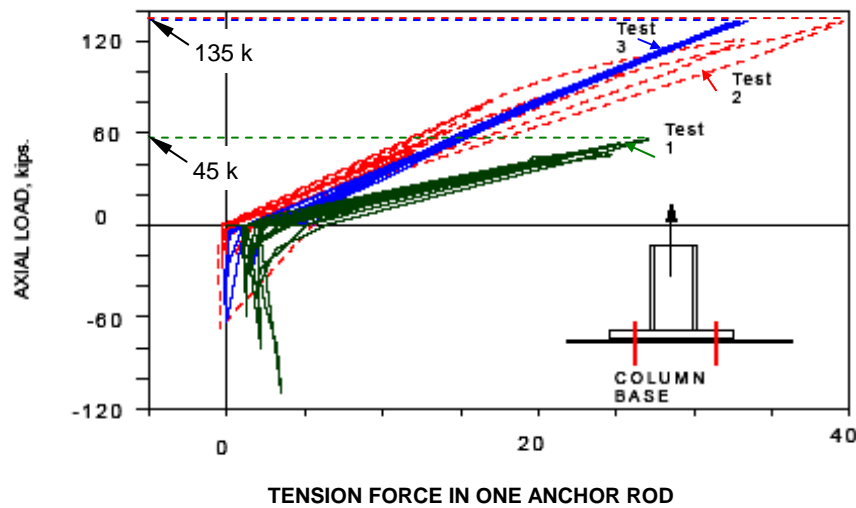


Figure 2.7. Variation of Axial Force in the Column versus Axial Force in One Anchor Rod in Three Specimens (Astaneh-Asl, Kelly, and Trousdale 1990)

Figure 2.7 shows the variation of axial force in one anchor rod versus the applied load. Notice that the specimens had four anchor rods with double nuts, one above and one under the base plate. It is interesting that, as expected, the bolt force in Test 3, with the thick plate specimen, was almost exactly one quarter of the applied uplift force, indicating no additional prying force. However, for Tests 2 and 1, where the plates were intermediate and thin, respectively, we measured prying forces of about 20% and 80% of the axial force in the anchor rod.

To establish the elastic uplift stiffness of the specimens, we can use the stiffness of the unloading branch of the curves in Figure 2.6. The stiffness of the thick plate and the stiffness of the intermediate thickness plate specimens were very close, but the stiffness of the thin plate specimen was almost half of the stiffness of the two other specimens.

## 2.4. MODELING OF BEHAVIOR OF BASE PLATES UNDER AXIAL LOAD

In analysis of braced frames, quite often in design offices, base plates in braced frames are modeled as pin connections free to rotate but restrained against horizontal and vertical movements. Based on limited test results available on the actual behavior of base plates in braced frames, such an assumption appear to be appropriate in the design of multistory buildings that use the current force-based code procedures. However, for predicting the actual behavior of base plates and modeling it in a performance-based design, we developed and used the model in Figure 2.8 (Shen and Astaneh-Asl 1996). In this model, the stiffness and strength of the base plate in uplift is represented more realistically.

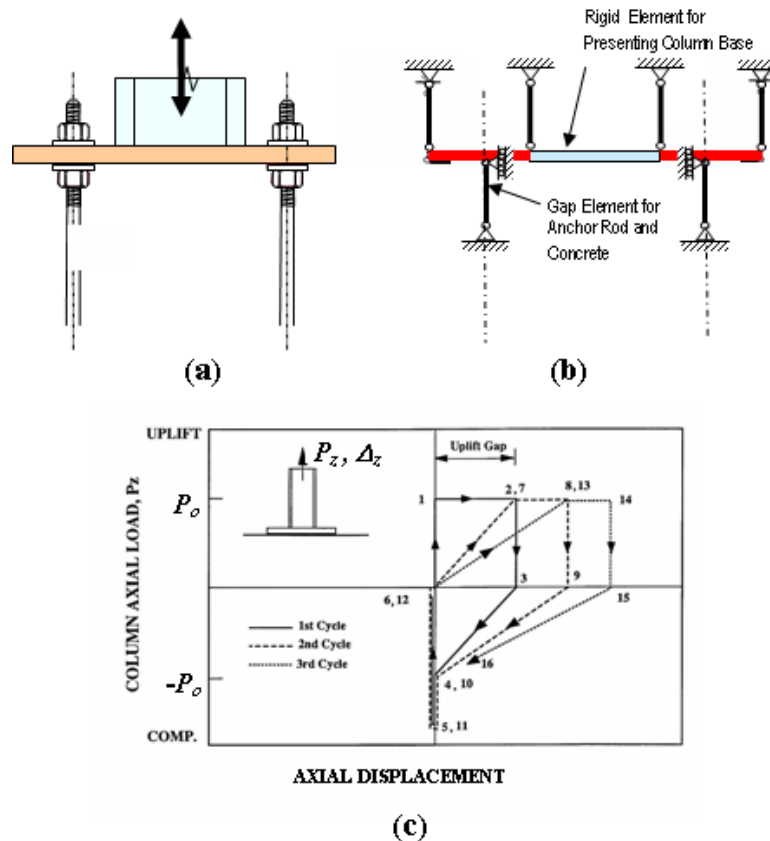


Figure 2.8. (a) Typical Base Plate, (b) Idealized Representation, and (c) Model of Axial Load–Axial Displacement Behavior of Base Plate  
(Ref: Astaneh-Asl, Kelly, and Trousdale 1990)

Using the mathematical models shown in Figure 2.8, we expected the model to predict the response of the base plate as was observed in the tests summarized above. Figure 2.9 shows the actual test results for Specimen 1 (the thin base plate) and the prediction of the model.

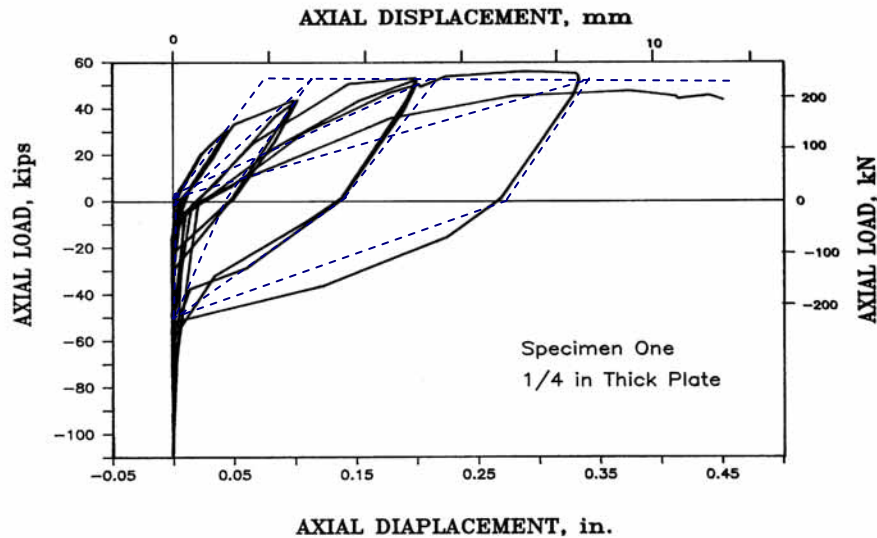


Figure 2.9. Actual Behavior of the Thin Base Plate Specimen and Prediction of the Model Shown in Figure 2.8  
(Ref.: Shen and Astaneh-Asl 1996)

## 2.5. EFFECT OF AXIAL STIFFNESS OF THE BASE PLATE ON THE DYNAMIC RESPONSE OF BRACED FRAMES

The uplift stiffness of a base plate can affect the response of a structure to an applied load. If the applied load is static or has a relatively low acceleration, such as steady wind, the larger the applied load, the more the uplift, which will result in bigger drifts. However, for cases in which the applied load is dynamic with relatively high acceleration, such as major earthquakes, the amount of the base plate uplift and the resulting drift is more complex and depends on many parameters. These parameters include the character of the ground motion, the stiffness of the superstructure above the base plate, the stiffness of the foundation system, and damping.

## 2.6. AN EFFECTIVE BASE PLATE

To accommodate the benefits of the thin and ductile base plates in uplift with the need for thick base plates to distribute the compression force, The author proposed a double base plate for seismic applications in 1988. For this variation, a base plate is designed to carry the compressive load of the column and another much thinner base plate is placed on top of it. Only the thin base plate is connected to the column. The proposed base plate is shown in Figure 2.10. When the column applies compression to the base plate, the top one is almost neutral and plays no role, while the bottom base plate distributes the compression onto the foundation. When the column is subjected to uplift, since only the top, thin base plate is attached to the column, it uplifts and performs in a ductile and very desirable manner, reducing the dynamic response. As soon as the

seismic event subsides, the gravity load of the column pushes the thin plate down, and the column once again rests on the thick base plate. Figure 2.11 shows a similar concept but using angles.

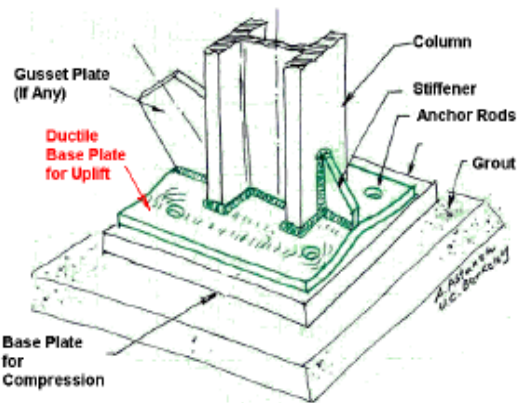


Figure 2.10. Double Base Plate  
(Ref.: Astaneh-Asl 2008)

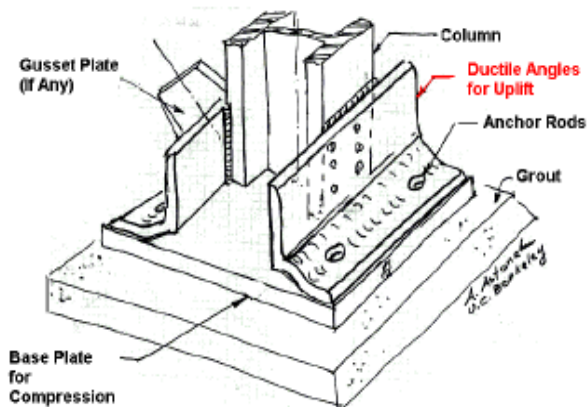


Figure 2.11. Angle Acting as Double Base Plate

In recent years the beneficial effects of the base plate uplift has been employed to control the seismic response of braced bridge towers such as the Carquinez Bridge in California, Figure 2.12. As a measure of seismic retrofit, the design team, of which the author was a member, decided to allow the braced tower legs in this bridge to uplift in a controlled manner, which would result in the braced tower having a long-period rocking motion during a major seismic event. The towers' rocking motion in turn would result in significant reduction of the bridge's seismic response in terms of the forces generated in the bridge as well as the displacements. In order to allow the tower legs to have controlled uplift, the nuts were removed to release the existing anchor rods, and a horizontal beam was added to the tower legs' base to bend and allow the legs to uplift and return to their original positions. The concept was similar to what is shown in Figure 2.11 but using angles.

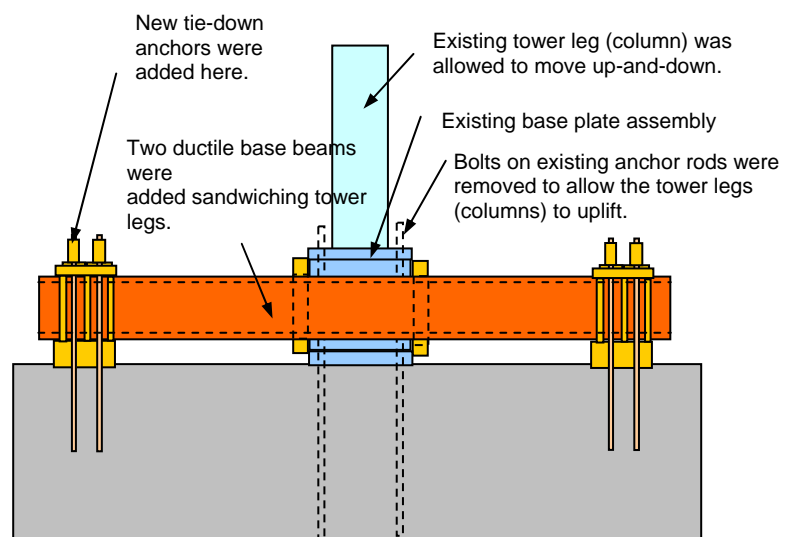


Figure 2.12. Carquinez Bridge and Schematic Detail of Tower Base to Allow Controlled Uplift



Another method to take advantage of column uplift motion in braced frames is to use vertical viscous dampers between the base plates and the columns instead of directly connecting the columns to the base plates.

Some structural engineers, to improve the performance at the base plates, are greasing the top 8-inches or so of the anchor rods, or covering this length with duct-tape to free the anchor rods of the concrete and allow elongation of the anchors over a greater length. This needs to be coordinated with compression in the anchor rods such that buckling of the anchor rods under compression is avoided.

## 2.7. ACTUAL PERFORMANCE OF BASE PLATES SUBJECTED TO AXIAL LOAD DURING EARTHQUAKES

Until the 1994 Northridge earthquake, there were almost no reports of discovery of major structural damage to column base plates. It is possible that during past earthquakes, even if there was minor damage to base plates, it was not discovered since base plates are not generally exposed. During the 1994 Northridge earthquake a modern library building, Figure 2.13, located close to the epicenter, had sustained serious damage in its base plates. The lateral load resisting system of the structure consisted of concentrically braced frames as shown in Figure 2.14.

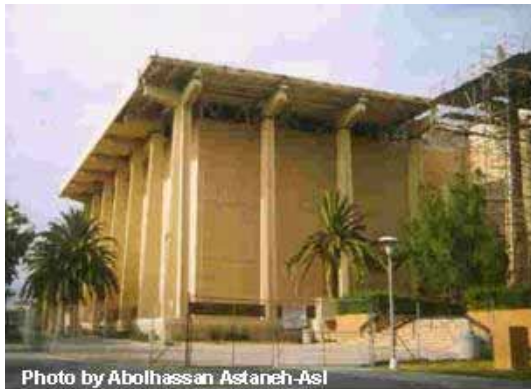


Figure 2.13. View of the Library Building



Figure 2.14. View of a Braced Frame



Figure 2.15. Fracture of Heat-Affected Zone of Base Plate



Figure 2.16. Fracture of Base Plate

Some of the boundary column base plates in this building had sustained serious structural damage. The damage, shown in Figures 2.15 through 2.18, was in the form of cracks in the welds' heat-affected zones connecting the columns to the base plate, in the base plate near the tip of the column flange, cracking of relatively thick grout under the base plate, elongation of the anchor rods, and splitting in half of the anchor rod nuts above the base plates.



Figure 2.17. Damage to the Base Plate, Grout, and Pedestal

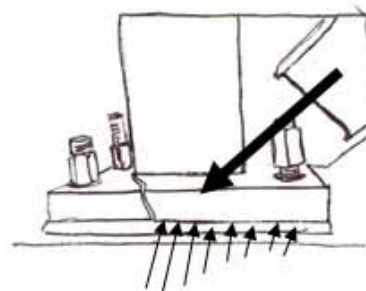
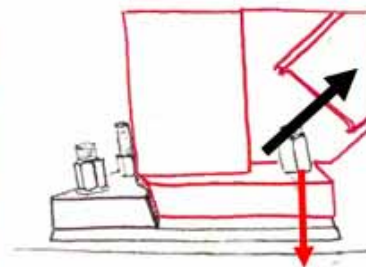


Figure 2.18. Damage to the Base Plate, Grout, and Pedestal



Fracture Line

(a)



(b)

Figure 2.19. (a) Fracture of Base Plate and (b) Uplifting and Dropping of Base Plate during the Earthquake

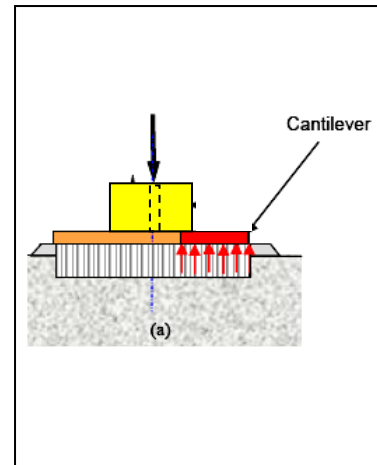
Elongation of the anchor bolts indicates that during the earthquake relatively large uplift forces might have been applied to the base plates. The crushing of grout under the base plate could be considered an indicator of large axial compressive forces acting on the base plates. The relatively thick base plates were subjected to significant bending on the opposite side of the gusset plate. During the post earthquake reconnaissance of the damage, the author concluded that, due to relatively small ductility of the thick base plates in bending when they were being uplifted, a small existing crack in the heat-affected zone of the base plates might have propagated and resulted in wider splitting of the base plate into two parts or complete separation of the column from the base plate. In either case the column had become free of the foundation to uplift without any control mechanism or damping. The uncontrolled uplift might have caused the rocking of the braced bay, creating relatively large drift at the roof level and unseating the pre-cast concrete canopy beams that had collapsed during the earthquake, Figure 2.19.

## **2.8. TESTS OF ANCHOR RODS SUBJECTED TO SHEAR AND UPLIFT**

Information on the actual testing of anchor rods subjected to shear or shear combined with tension is very limited. Adihardjo and Soltis (1979) published a paper on this topic and concluded that their test program indicated “the interdependence of grout and anchor rod in determining the capacity of a grouted base detail subjected to combined shear and tension.” They also concluded that “the existing interaction equations based on bolts embedded directly in concrete are not applicable to the grouted condition when the shear component becomes predominant.”



# 3. Seismic Design Considerations



## 3.1. Introduction

Columns in braced frames have one of the two types of base plates shown in Figure 3.1. The base plates in Figure 3.1(a) and (b) are for the columns of braced bays where, in addition to the column, bracing members from one side or both sides are connected to the base plate as well. These base plates are designed for axial force in combination with shear, while the small secondary moment present in the connection is ignored. This chapter discusses the design of these base plates. The base plate shown in Figure 3.1(c) is for the gravity columns outside the braced frame and in general carries axial compression due to gravity loads. This condition of axially loaded base plate can also occur in a braced frame at the base of a frame where the bottom bay of braces is in a “V” configuration. This column would then be subjected to cyclic compression and tension without shear. Those base plates are not considered part of lateral force resisting systems, and their design can be done following the procedures in the *AISC Manual of Steel Construction* (AISC 2005b).

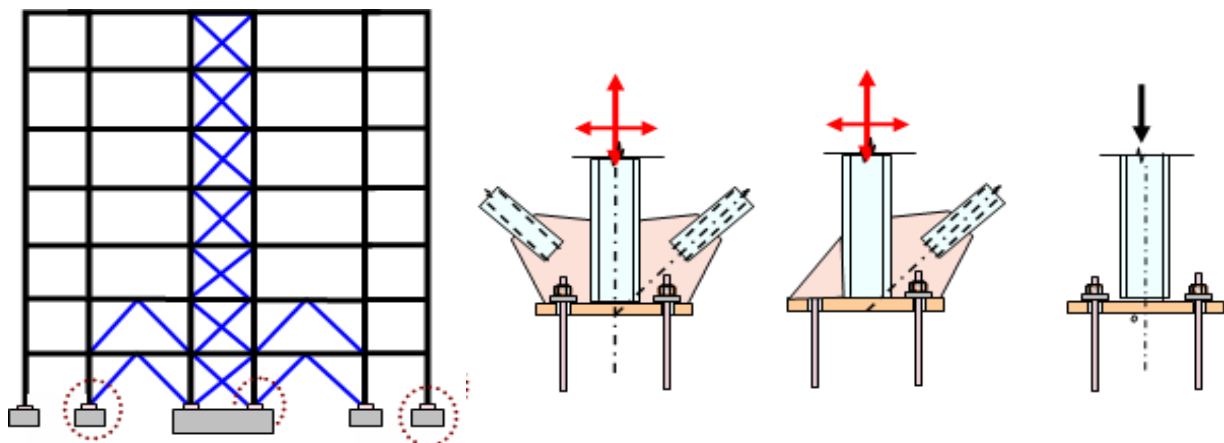


Figure 3.1. Examples of Base Plates in Braced Frames

### 3.2. SEISMIC DESIGN OF BASE PLATES IN BRACED FRAMES

This section presents the concepts and procedures for seismic design of base plates of ordinary concentrically braced frames (OCBF) and special concentrically braced frames (SCBF) that are designed using a response modification factor,  $R$ , of greater than 3.0. The procedures given below can also be used in design of base plates of eccentrically braced frames (EBF), although attention must be paid to ensure sufficient rotational ductility in the base plates since the columns in eccentrically braced frames are expected to rotate more than the columns in concentrically braced frames. For definitions of OCBF, SCBF,  $R$ , and EBF see the *AISC Seismic Provisions* (AISC 2005c).

As discussed in the previous chapter, failure modes of base plates in braced frames subjected to cyclic axial force and shear are:

- Yielding failure of the base plate due to bending
- Yielding of anchor rods in tension during uplift phase of loading
- Compression yielding of anchor rods when double nuts are used, one above and one below the base plate
- Pull-out failure of anchor rods
- Compressive failure of concrete under the base plate
- Failure of the grout under the base plate
- Cone failure of the concrete holding the anchor rod during the uplift phase
- Shear failure of anchor rods
- Shear failure of shear keys if used to transfer shear from the base plate to the foundation

To develop seismic design procedures for base plates, the preceding failure modes are divided into two categories, ductile and brittle, as shown in Figure 3.2. Failure modes a, b, and c in the preceding list are ductile, while the remaining failure modes are brittle.

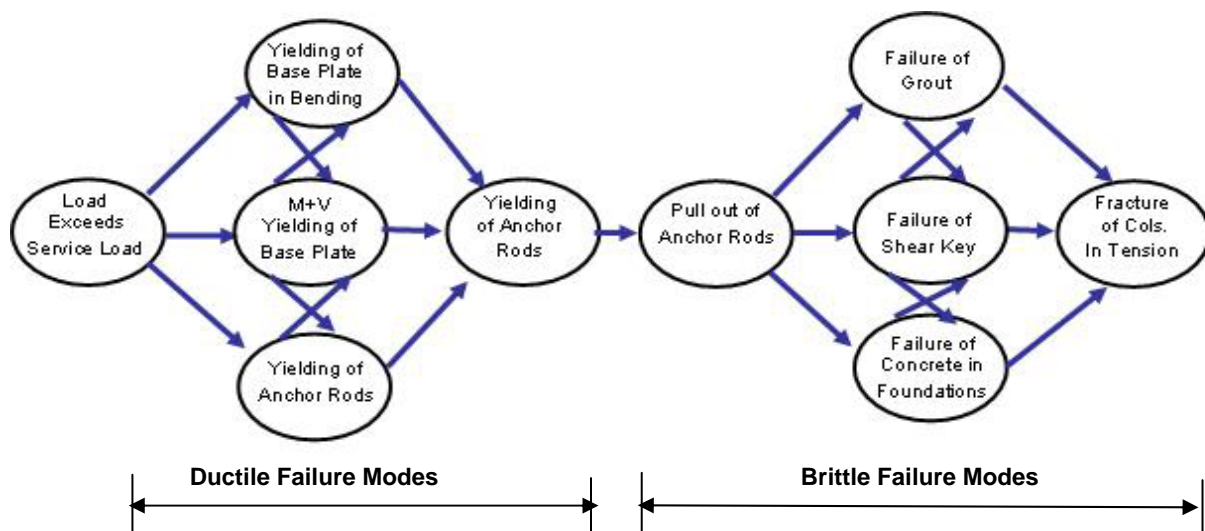


Figure 3.2. Hierarchical Order of Failure Modes in Braced Frame Base Plates

The damage due to brittle failure modes of base plates is very difficult to inspect, detect, and repair. This is because base plates in most applications are not accessible without removal of the floors or other material covering them. Therefore, in formulating the proposed seismic design procedures given in the following subsections, the approach was to ensure that the capacity of brittle failure modes is at least 1.25 times the expected capacity of the ductile failure modes. This is written as:

$$(\text{Capacity of Brittle Failure Modes}) \geq 1.25 P_u$$

$$(\text{Expected Capacity of Ductile Failure Modes}) \geq P_u$$

In terms of load and resistance factor design format, this approach can be written as:

$$(\phi_u)(P_{nu}) \geq 1.25P_u \quad (\text{for non-ductile failure modes}) \quad (3.1)$$

$$(\phi_y)(P_{ny}) \geq P_u \quad (\text{for ductile failure modes}) \quad (3.2)$$

Where,

- $P_u$  Required strength of the base plate equal to the axial load that can be delivered to the top of the base plate by the brace and column connected to the base plate when both of them reach their respective expected yield strength. In calculating the expected yield strength of the brace and column connected to the base plate, instead of  $F_y$ , the specified yield stress,  $R_y F_y$ , the expected yield stress, should be used.
- $R_y$  Ratio of the expected yield stress to the specified minimum yield stress,  $F_y$
- $F_y$  Specified minimum yield stress of the type of steel to be used
- $P_{nu}$  Nominal capacity of a brittle failure mode involving fracture of steel or failure modes of concrete
- $P_{ny}$  Nominal capacity of a ductile failure mode involving yielding of steel
- $\phi_u$  Reduction factor for brittle failure modes given by the AISC *Specifications* (AISC 2005a)
- $\phi_y$  Reduction factor for ductile yield failure mode = 0.90

In the following, design equations are provided for each of the preceding failure modes. The design equations are mostly adapted from the AISC *Specifications* (AISC 2005a) with some modifications to ensure that after completion of the design, ductile failure modes govern over the more brittle modes in accordance with the Equations 3.1 and 3.2 above.

### 3.2.a. Yielding of the Base Plate Due to Bending under Axial Compression

In design, the stress distribution under the base plate is assumed to be uniform. The portion of the base plate that is extended out of the column footprint is assumed to act as a cantilever beam subjected to uniform pressure exerted from the concrete as shown in Figure 3.3(a). To establish the length of the cantilever, the I-shaped footprint is converted to a rectangular footprint as shown in Figure 3.3(b). The rectangular footprint has dimensions of  $0.80b_f \times 0.90d$ , where  $b_f$  and  $d$  are the width of the flange and the depth of the cross section of the column, respectively.

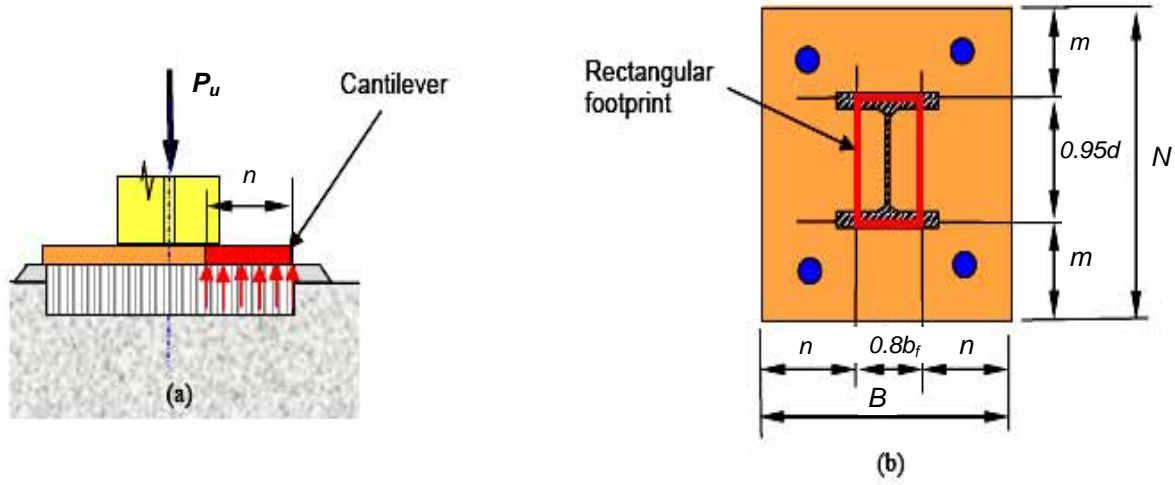


Figure 3.3. (a) Bearing Stresses Acting on the Base Plate and  
(b) Dimensions of Base Plate Used in Design

The design equation to check the failure mode of bending yielding of base plates is:

$$P_u \leq \phi_y P_{nb} \quad (3.3)$$

Where:

$P_{nb}$  Axial force that results in formation of plastic hinge in the base plate, calculated as:

$$P_{np} = p A_{BN} \quad (3.4)$$

$p$  Pressure acting under the base plate assuming a uniform distribution of pressure; see Figure 3.3. Considering the cantilever with the length of  $L$ , as shown in Figure 3.3, we can calculate  $p$  as:

$$M \leq \phi_y M_p \quad (3.5)$$

$$pL^2/2 \leq ZF_y \quad (3.6)$$

$$(P_u/A_{BN}) L^2/2 \leq (t^2/4) F_y \quad (3.7)$$

Rearranging Equation 3.7 and combining it with Equation 3.4 results in the following equation to calculate the minimum thickness of base plate:

$$t \geq L \sqrt{\frac{2P_u}{\phi_y F_y BN}} \quad (3.8)$$

In the preceding equations:

|          |   |
|----------|---|
| $M$      | Applied bending moment in the base plate  |
| $M_p$    | Plastic moment of a 1-inch strip of base plate                                    |
| $Z$      | plastic section modulus of the 1-inch-wide strip of base plate                    |
| $t$      | Thickness of the base plate   |
| $B$      | Length of the base plate parallel to the flange (Figure 3.3)                      |
| $N$      | Length of the base plate parallel to the web (Figure 3.3)                         |
| $\phi_b$ | Resistance reduction factor for yielding equal to 0.90                            |
| $L$      | Length of the base plate cantilever, the smallest of the following three numbers: |

$$m = (1/2)(N - 0.95d) \quad (3.9)$$

$$n = (1/2)(B - 0.8b_f) \quad (3.10)$$

$$n' = (1/4)(d b_f)^{1/2} \quad (3.11)$$

The last number,  $n'$ , is the length of the cantilever in lightly loaded base plates where the stress distribution under the base plate is not uniform, as shown in Figure 3.4. For more information on lightly loaded base plates subjected to axial compression see Thornton (1990) where a summary of design methods proposed for lightly loaded base plates is provided. A literature search did not find information on behavior and design of lightly loaded base plates subjected to uplift.

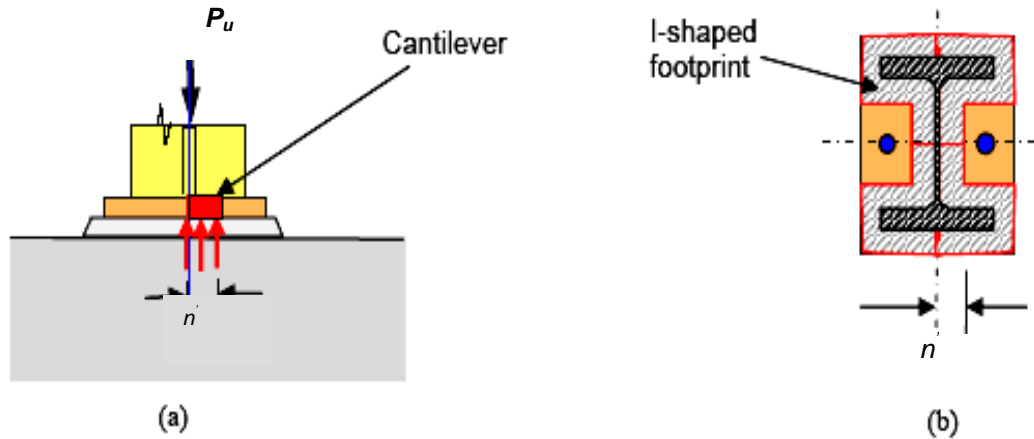


Figure 3.4. Cantilever Length  $n'$  for Lightly Loaded Columns

### 3.2.b. Yielding Failure of Base Plate Due to Bending Caused by Uplift

When a base plate is uplifted, it is subjected to bending as shown in Cases I and II of Figure 2.3. As the load increases, a collapse mechanism is reached when the two lines of plastic hinges form along the edge of the column and anchor rod line. This is shown in Figure 3.5.

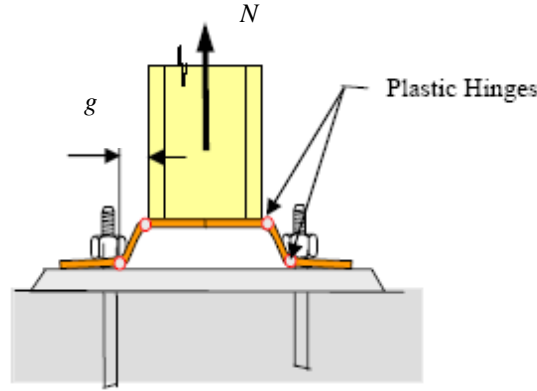


Figure 3.5. Plastic Hinge Formation in the Base Plate

The design equation to check the plastic collapse mechanism of base plates is:

$$P_u \leq \phi_y P_{nb-ut} \quad (3.12)$$

Where,

$P_{nb-up}$  Collapse capacity of the base plate in uplift given as:

$$P_{nb-up} = 4M_{pl}/g \quad (3.13)$$

$M_{pl}$  Bending capacity of one line of the plastic hinge equal to:

$$M_{pl} = (W - nd_h)(t/4)(F_y) \quad (3.14)$$

$W$  Length of the plastic hinge, smaller of  $B$  and  $N$

$n$  Number of anchor rods in one plastic hinge

$d_h$  Diameter of the anchor rod hole

It should be noted that some designers assume plastic hinge to occur at the face of the column based on the expectation that the bolts are more of a pinned support and there is little prying. Also the designer should consider the geometry of the base plate and anchor bolts before using the full width of the base plate to check the moment capacity of the base plate at the face of column. If the base plate is wide and the anchor bolts are close to the column flange, it is not reasonable to use the full width of the base plate when evaluating the base plate bending. Some designers use a critical width of base plate using a 45-degree spread from the bolts to the column flange similar to the AISC Column Base Plate Design Guide (Fisher and Kloiber, 2006), as shown in Figure 15 on page 22 of the AISC Design Guide.

### 3.2.c. Yielding Failure of the Base Plate Due to Combined Bending and Shear

In very thick and compact base plates, where the anchor rods are close to the column, it is possible that the base plate fails under the combined action of bending moment and shear. In these cases the use of the following interaction equation from ASCE (1971) is suggested. The reference has extensive discussion of the interaction of shear and bending in steel sections.

$$\frac{M}{f_y M_p} + \left( \frac{V}{f_y V_p} \right)^4 = 1.0 \quad (3.15)$$

Where,

$V$  Applied shear acting on a 1-inch-wide strip of the base plate  
 $V_p$  Shear yield capacity of the 1-inch-wide strip of base plate. According to ASCE (1971),  
 $V_p$  is equal to  $(0.50F_y)(t)(1.0 \text{ inch})$

### 3.2.d. Yielding of Anchor Rods in Tension during the Uplift Phase of Loading

The design equation to check the tension failure mode of the anchor rod is:

$$P_u \leq \phi_y P_{nar} \quad (3.16)$$

Where,

$P_{nar}$  Nominal tensile strength of anchor rod given as:

$$(a) \text{ For threaded anchor rods: } P_n = (0.75F_u) A_{ar} \quad (3.17)$$

$$(b) \text{ For upset anchor rods: } P_n = (F_y) A_{uar} \quad (3.18)$$

$A_{ar}$  Area of anchor rod based on nominal diameter  
 $A_{uar}$  Cross sectional area of upset portion of upset rods  
 $F_u$  Specified ultimate strength of anchor rod material  
 $F_y$  Specified yield stress of upset anchor rod material

One item for designers to keep in mind is if they are counting the benefit of ductility of the anchor rods, detailing in the system must be consistent with this behavior. The plate washer should be thick enough based on the hole in the base plate, and confinement of the bolts should be adequate to prevent buckling of the anchor rod.

### 3.2.e. Pullout Failure of Anchor Rods Due to Axial Uplift

To calculate the pullout capacity of an anchor rod embedded in a concrete foundation, please refer to ACI-318, where this failure mode is covered. Washer plates with nuts top and bottom should be used to create the end anchorage of all anchor rods embedded in the concrete foundation. “L” bolts and “J” bolts should not be used due to pull-out failure resulting from local crushing of the concrete at the radius of the L and J bolt bends when the anchor rods are highly loaded, allowing the anchor rod to pull out of the concrete.

### 3.2.f. Compression Yielding of Anchor Rods When Double Nuts Are Used

The equations to establish the yield capacity of anchor rods when subjected to compression are the same as those given for tension anchor rods in Section 3.2.d. The anchor rods are subjected to compression only if double nuts, one above and one below the base plate, are used.

### 3.2.g. Limit State of Compression Failure of Grout under the Base Plate

Currently, the compressive strength of grout used under the base plates is greater than the strength of concrete in the foundation. However, the grout needs also to be checked for compressive failure since the concrete in the foundation is confined and might have much higher strength than the specified  $f'_c$ , but the grout is not confined. In seismic applications, to avoid failure of grout, it is suggested that the compressive strength of the unconfined grout be greater than 1.25 times the compressive strength of the concrete in the foundation in confined conditions. The reader is referred to the next section for elaboration on the “confined condition”.

The design community typically uses a grout with a minimum strength of 5,000 psi at 28 days. So, this requirement should be easy to satisfy, unless the foundation strength is to be in excess of  $f'_c = 4,000$  psi. Even then, many of the commonly used grouts achieve 5,000 psi in 3 days or less, with an ultimate strength of 9,000 to 13,000 psi in 28 days, depending on the amount of water used when the grout is made and placed (plastic, flowable, or liquid grout placement).

In addition, to avoid crushing of the grout under the base plate due to cyclic compression and the uplift expected at the base of braced frame columns, the thickness of the grout should be less than 2 inches. For thicker grouts, either reinforcing mesh or, preferably, fiber reinforcement may be used to prevent damage to grout under dynamic impact of column base plate during a severe earthquake.

When a base plate is subjected to uplift, due to bending of the base plate and development of prying forces at the edges of the base plate, those areas of grout may be subjected to large compressive forces. The force acting on the grout, shown in Figure 2.3, Cases I and II, can be calculated from the equilibrium of the free body diagram of the base plate. The force is the prying action force. Following the procedures discussed earlier for the base plates under compression, the bearing pressure on the grout is checked to ensure that it does not exceed  $0.85f'_c$  with a  $\phi$  factor of 0.6 for concrete bearing compression.

### 3.2.h. Compressive Failure of Concrete under the Base Plate

The design equation to check the failure mode of compressive crushing of the concrete under the base plate is:

$$P_{uc} \leq 1.25\phi_c P_{nc} \quad (3.19)$$

Where:

$P_{uc}$  Required strength of the base plate in compression equal to the axial load in compression that can be delivered to the top of the base plate by the brace and column connected to



the base plate when both of them reach their respective compressive strength. In calculating the compressive strength of the brace and column connected to the base plate, instead of  $F_y$ , used in the AISC *Specifications* (AISC 2005a),  $R_y F_y$  should be used.

$\phi_c$  Resistance reduction factor for concrete supporting a base plate = 0.60  
 $P_{nc}$  Nominal compressive strength of the concrete under the base plate given as:

$$P_{nc} = (0.85k f'_c) A_{BN} \quad (3.20)$$

$A_{BN}$  Area of base plate equals  $B$  times  $N$ ; see Figure 3.3  
 $f'_c$  Specified compressive stress of concrete  
 $k$  A factor representing the confinement effects of large foundations given by:

$$k = (A_f/A_{BN})^{0.5} \leq 2.0 \quad (3.21)$$

$A_f$  Area of the foundation or pedestal supporting the base plate

### 3.1.i. Shear Failure of Base Plates to Foundation Connection

The design equation to check the shear failure mode of base plates is:

$$P_u \leq \phi_s P_{ns} \quad (3.22)$$

Where:

$P_u$  Factored applied compressive force  
 $\phi_s$  Resistance reduction factor for shear failure modes  
 $P_{ns}$  Nominal shear strength of the base plate concrete under the base plate given by Equation (3.23)

Shear force applied to a base plate can be transferred to the foundation by either friction between the base plate and the foundation or by mechanical means such as anchor rods and, if necessary, shear keys. Compared to mechanical means, using friction to transfer shear is not reliable. In fact most seismic codes do not allow the use of friction to transfer seismic shear force. Instead of friction we can use the shear capacity of the anchor bolts and, if necessary, the shear keys to transfer shear. The shear strength of the anchor rods is not also very reliable and can create a weak link in design. This is due to the fact that holes for the anchor rods are usually oversized for ease of construction, so for the rods to carry shear they need a welded plate washer. But, the bolts will be in bending over the height of the anchor rod, and bending to some amount over the grout depending on the amount of confinement of the grout. So, although shear capacity of anchor rods may be used in tight design conditions or in evaluating the available shear strength of an existing structure to be retrofitted, it is not a preferred solution. For those rare cases, where shear strength of anchor rods are used, in the following equations shear strength of anchor rod is also included.

The value of  $\phi_s P_{ns}$  in Equation 3.22 will be equal to the summation of the reduced shear resistance provided by the anchor rods and the shear keys:

$$\phi_s P_{ns} = \phi_y (A_{ar})(0.60F_{yar}) + \phi (P_{sh-key}) \quad (3.23)$$

Where

- $A_{ar}$  Area of anchor rod at shear plane  
 $F_{yar}$  Specified minimum yield stress of anchor rod material  
 $\phi$  Reduction factor for shear key = 0.90  
 $P_{sh-key}$  Capacity of the shear key to transfer shear

Shear capacity of the shear key can be established by considering the shear key to be a cantilever beam bearing against the reinforced concrete, as shown in Figure 3.6. It should be mentioned that the governing failure mode of the shear key should be the ductile failure mode of yielding under combined shear and bending and not brittle failure mode. Some designers prefer a tee section, I-section or a stiffened plate for shear key instead of a single plate when the shear force is large and using a single plate can result in the thickness of shear key plate to be quite large.

The shear key stiffener or the use of sections instead of plate can reduce the shear key thickness, but the sections create difficulty in placing the foundation top steel.

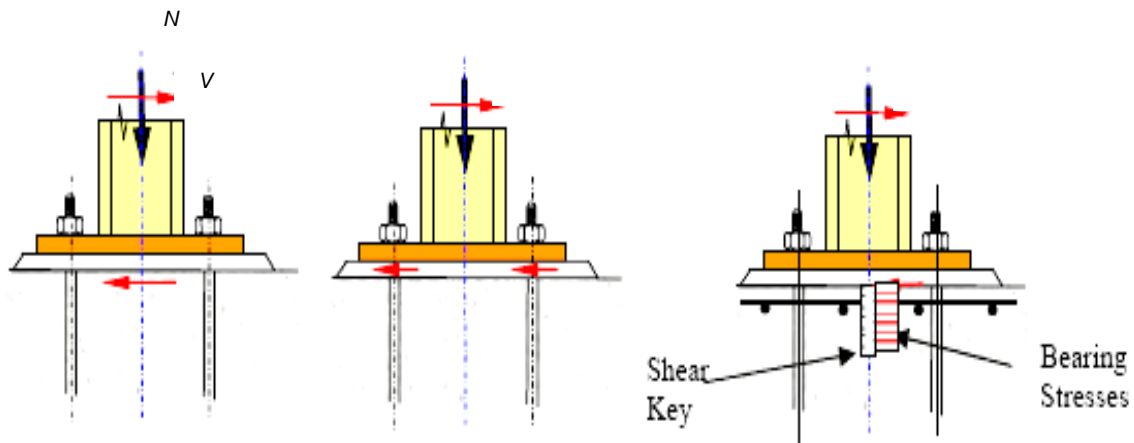


Figure 3.6. Shear Transfer Using Friction, Anchor Rods, and Shear Keys

Shipp and Haninger (1983) provide information on design of anchor bolts subjected to shear and propose a design method for headed anchor bolts subjected to shear and tension. The method ensures ductility of the anchor bolts subjected to combined shear and tension by making yielding of the anchor bolt the governing failure mode over the fracture of the concrete cone in tension. Such philosophy of yielding being the governing failure mode over fracture failure modes, is routinely used in seismic design, therefore, these ductile anchor bolts also fit well with ductile seismic design and can be used for base plates in braced frames.

### 3.3. BASE PLATES WITH ONE-SIDED GUSSET PLATES

The discussion in previous section was focused on base plates that are double symmetric. In some cases, the column is eccentric with respect to the center of the base plate. This can occur in

base plates that are near the property line, Figure 3.7(a) or in base plates where gusset plate is only on one side of the column, Figure 3.7(b). This section discusses these two cases.

### 3.3.a. Axially-Loaded Base Plates with Eccentricity

When column is eccentric with respect to center of the base plate, the eccentricity will create bending moment that need to be resisted by the base plate, the column and the foundation. For this case as shown in Figure 3.8, we can place the “Work Point (W.P.)”, where the axis of column and brace intersect, at the top surface of the base plate, under the bottom surface of the base plate or inside the foundation. Wherever we place the W.P., in design of base plate and the anchor bolts, we need to apply the correct axial load, shear and bending moment to the bottom surface of the base plate, where it bears against the grout and design it for the bearing pressures acting on this surface. In Figure 3.8(a), W.P. is placed on the bottom surface of the base plate and as a result, the forces acting on this surface are shear, axial load and bending moment. In Figure 3.8(b) the W.P. is placed somewhere in the foundation, and below the base plate, such that the resultant force passes through the center of the base plate bottom surface resulting in only axial load and shear acting on this surface. In Figure 3.8, forces in the column and the brace are compression forces. When the lateral load is reversed, depending on the magnitude of forces in the column and bracing member, magnitude and direction of the resultant reaction force acting on the bottom surface of the base plate will change although the reaction still will pass through the Work Point as shown in Figure 3.9 for a case where the bracing member is in tension and the column is steel under compression because of uplift not being able to cancel the downward gravity force in the column. In this case, for both cases of (a) and (b), the reaction under the base plate is eccentric with respect to the center of the base plate and creates bending under the base plate that need to be taken into account in design. The point here is that we can choose the

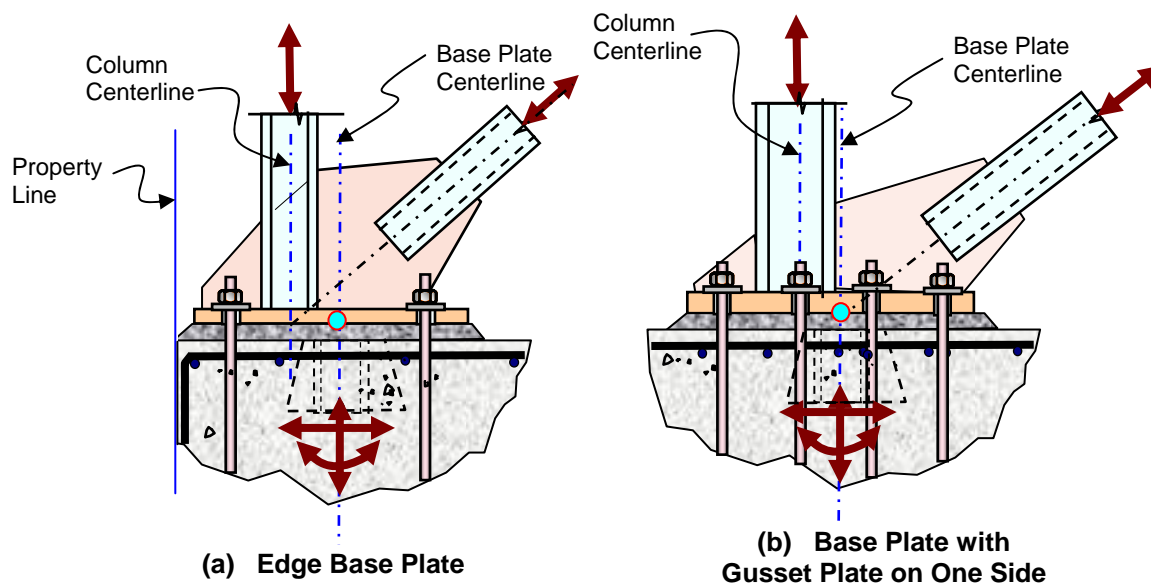


Figure 3.7. Examples of Axially Loaded Base Plates with Eccentricity of Load

location of Work Point to eliminate eccentricity for one condition of loading and need to establish the eccentricity for other load conditions and take the bending moment that might exist into account.

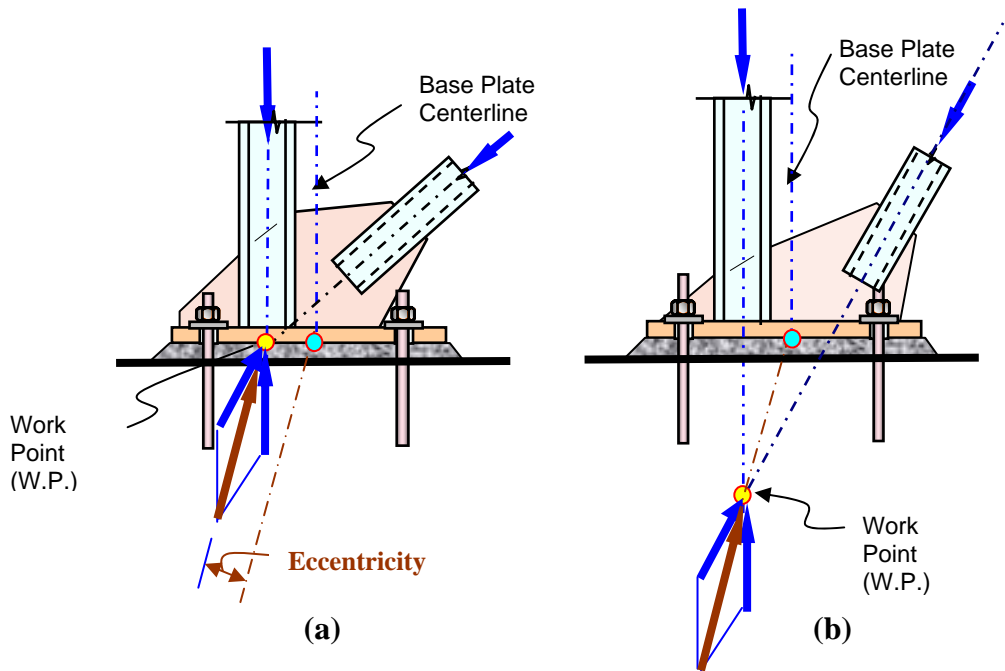


Figure 3.8. (a) Work Point under the base Plate Creating Eccentricity and;  
(b) Work Point Inside Foundation to Eliminate Eccentricity of Resultant Acting on the Base Plate

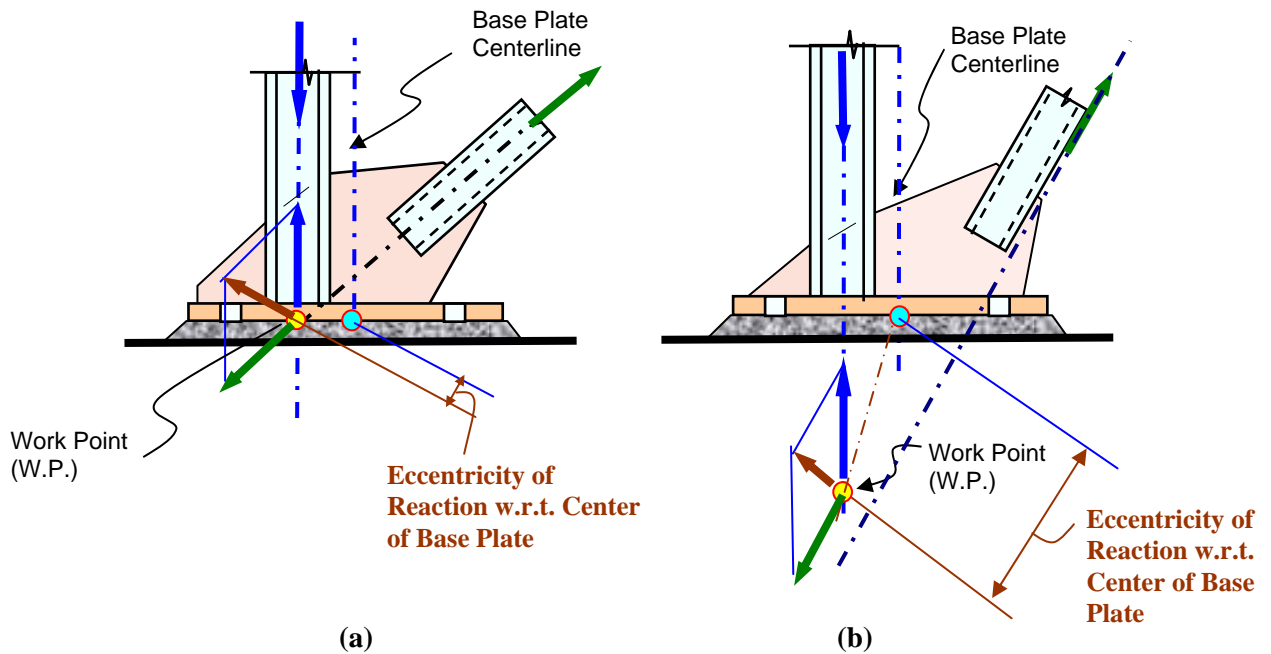


Figure 3.9. (a) Work Point under the Base Plate Creating Eccentricity and;  
(b) Work Point Inside Foundation Still Creating Eccentricity

After establishing axial force, shear and bending moment (if any) acting on the bottom surface of the base plate (the same surface as the top surface of the grout), the stresses under the base plate can be established and the base plate and anchor bolts can be designed following the concepts and design procedures discussed earlier in this chapter on design of base plates subjected to bearing stresses under the base plate. If the forces acting on the bottom surface of the base plate are axial force shear and bending moment, the procedure for design of base plates subjected to combined axial load, shear and bending moment should be sued. Such procedures are discussed in references AISC (2006) and Astaneh-Asl (2008).

### 3.3.b. Notes on Base Plates at the Intersection of Two Braced Frames

In some cases, two braced bays share a common column and common base plate, Figure 3.10. In these cases if base plate is a corner base plate, the center of base plate and column will be eccentric as shown in Figure 3.10. As discussed in previous section, such eccentricities need to be considered in design.

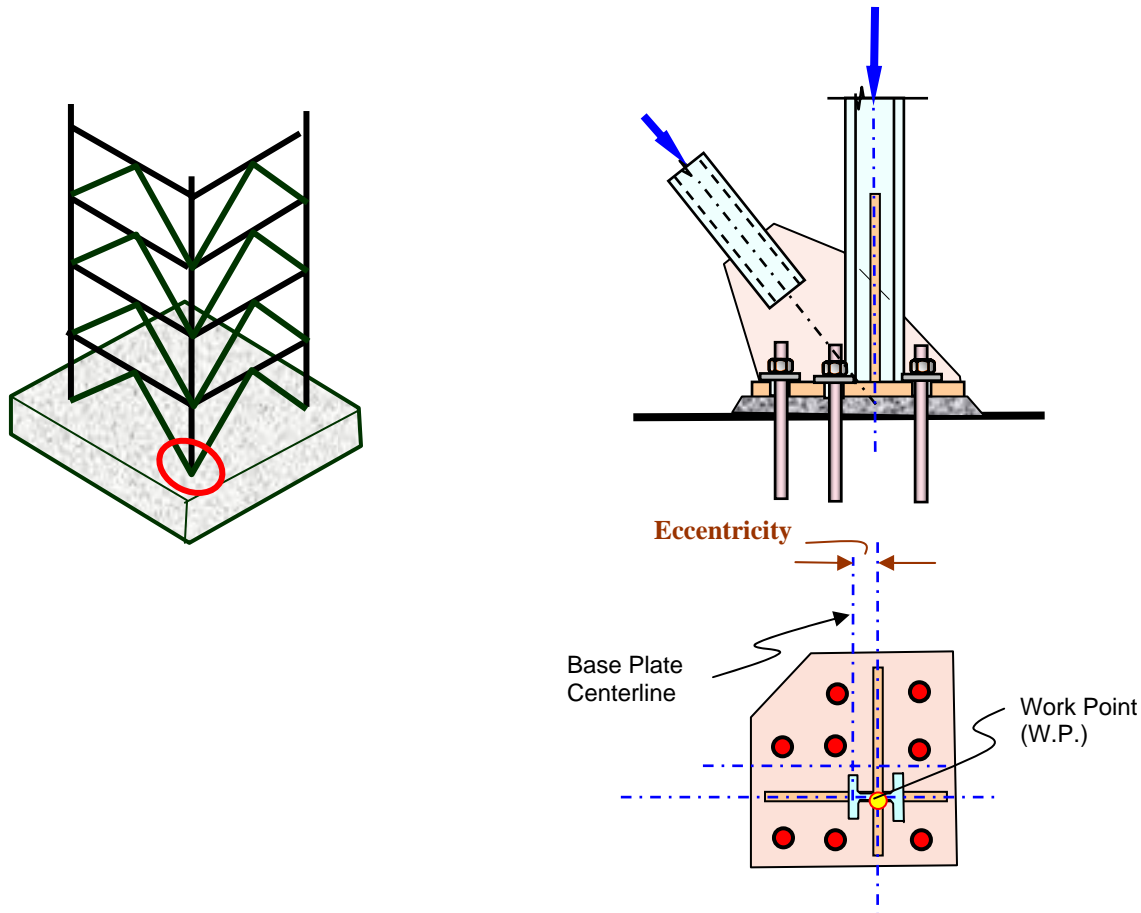
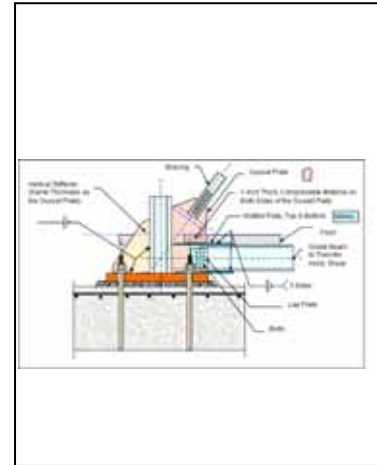


Figure 3.10. Base Plate at the Corner of Intersecting Braced Bays

## 4. Suggested Base Plate Details



### 4.1. Suggested Details

Following is the suggested detailing for braced frame base plates in seismic applications. The details have been developed with input from structural engineers and fabricators. There are other viable details used in design offices and the suggested details below are not by any means the best. It is developed to provide sufficient strength, stiffness, and ductility for a reasonable cost while making the fabrication and erection of the base plates easy. A number of publications offer very useful tips and suggestions for proper detailing of base plates among them Ricker (1989), Shneur (2006) and (Fisher and Kloiber, 2006). As a reminder, just as the column base plate can have uplift, so can the concrete foundation, which has to be considered in design of the brace frame column uplift. Uplift forces may require the placement of top reinforcing in the foundation, in addition to the required bottom reinforcing in the bottoms of footings and foundations. Figure 4.1 shows a suggested detail for a base plate where the horizontal component of the brace force is transferred to the foundation by embedded base plate and gusset plate.

Figures 4.2 and 4.3 show two suggested details where the horizontal component of the brace force is resisted by a horizontal member connecting the base plates of the two braced columns. The horizontal member can be reinforced concrete, Figure 4.2, or steel member, Figure 4.3. The reinforced concrete horizontal beam is expected to be more economical than the steel beam. For one to four story buildings most designers will not bury a steel beam in the ground as a grade beam. They will most likely tie the foundations together with concrete grade beams (if they tie them together at all). For 1-4 story brace frame buildings it might be most economical to use A706 rebars welded to base plates as one continuous piece between the base plates with no rebar splices unless welded splices or couplers are used. The rebars are designed to take the column horizontal shear through tension /compression of the rebar. There can be 2 – 6 rebars (#9 to #11) typically between the columns, welded to both the gusset plate and the base plate. The rebars are preferred to have stirrups to help confine the concrete for compression and prevent buckling of the rebars. The concrete grade beam is probably a less expensive solution than the steel beam since we still have to encase the steel beam in concrete. It also allows us to raise the top of the footing to within about 12 inches of the finish floor, whereas with a steel

beam in the foundation, the top of the footing would be down 24 inches or more below the finished floor. The deeper footing depth makes for larger gusset plates.

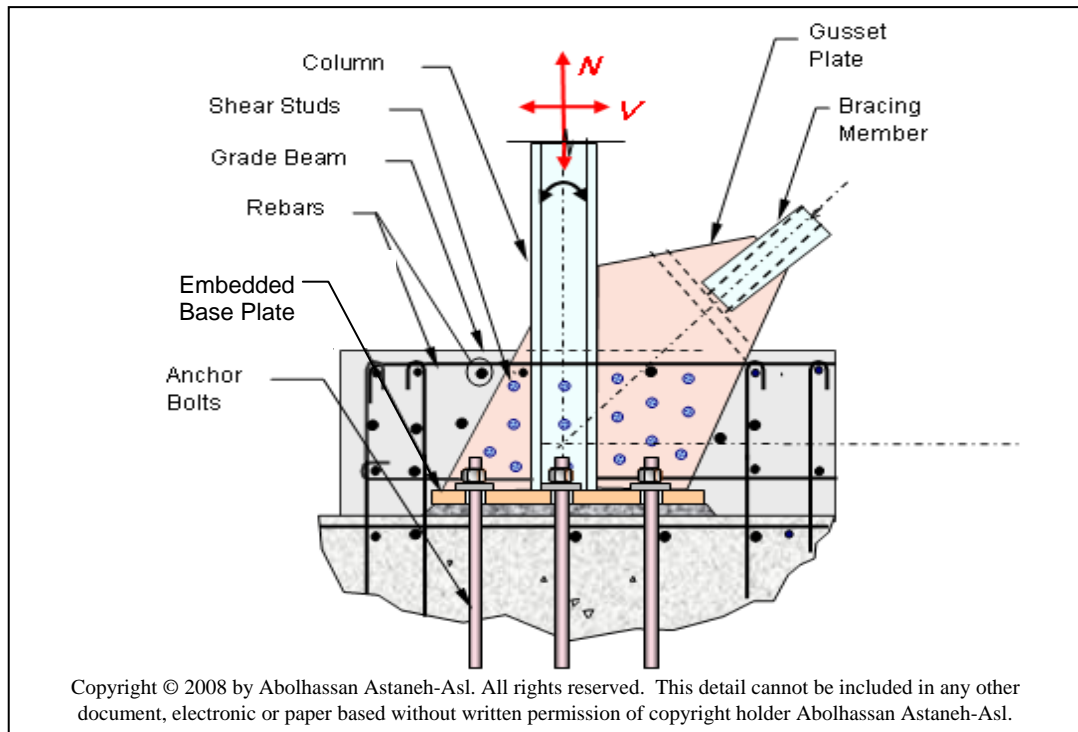


Figure 4.1. A Suggested Detail for Embedded Base Plate

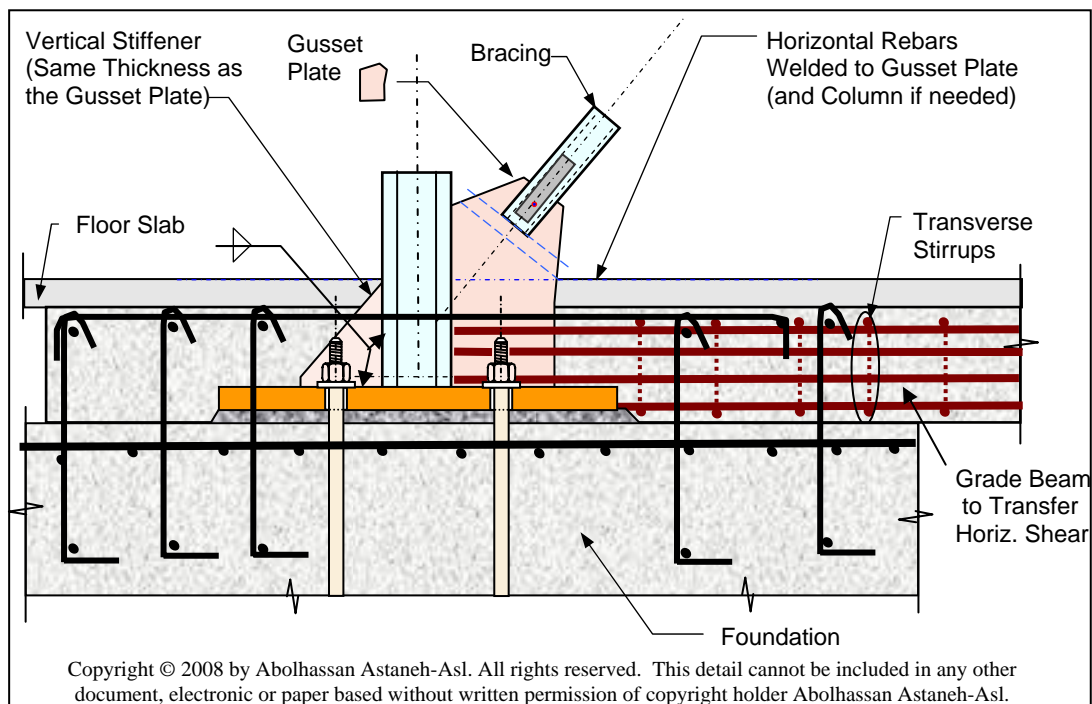


Figure 4.2. A Suggested Detail for Base Plate with Horizontal Reinf. Concrete Grade Beam

In tall buildings with larger shear and uplift forces, we would probably have the column buried in a concrete wall, if available, with the diagonal brace framing starting at the top of the wall where the horizontal steel beam of the braced bay would frame to the gusset plate/column as discussed in details of gusset plates for braced frames in the Steel TIPS report by Astaneh-Asl, Cochran and Sabelli (2006). The base plate will be located below the R/C wall at the bottom of the column.

As mentioned earlier, in the steel case, the steel horizontal member is normally embedded in a concrete grade beam or thickened slab and has headed studs on each side to transfer the shear forces into the concrete.

Normally, the yield line in the gusset plate, starting at the top of the concrete, is shown to avoid having to put in the foam at this location and to separate a yield line from the top of the embedded steel element. The use of an embedded steel element seems essential for larger steel buildings where the transfer of shear via anchor bolts does not seem viable, especially since one must develop the yield capacity of the bracing member in tension. When using an embedded steel element some structural engineers mandate that the plate washers on top of the base plate are NOT welded to the base plate to limit the amount of shear transferred into the column anchor bolts.

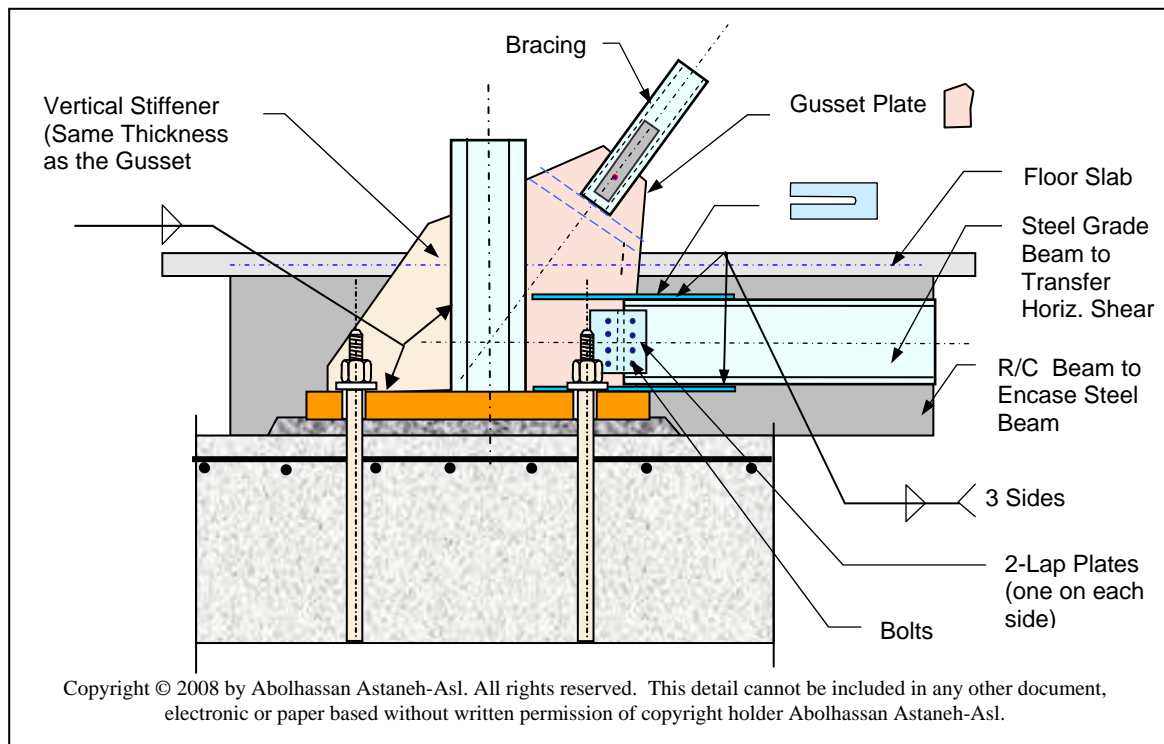


Figure 4.3. A Suggested Detail for Braced Frame Base Plates with Horizontal Steel Beam



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### *About the Author:*



Abolhassan Astaneh-Asl, Ph.D., P.E., is a professor of structural engineering at the University of California, Berkeley. He is the winner of the 1998 T. R. Higgins Lectureship Award of the American Institute of Steel Construction. From 1968 to 1978 he was a structural engineer and construction manager in Iran designing and constructing buildings, bridges, water tanks, transmission towers, and other structures. During the period 1978–1982, he completed his M.S. and Ph.D. in structural engineering, both at the University of Michigan in Ann Arbor under the supervision of Professors Subhash C. Goel and Robert D. Hanson. Since 1982, he has been a faculty member of structural engineering involved in teaching, research, and design of both building and bridge structures, both in steel and composite, in the United States and abroad particularly with respect to the behavior and design of such structures under gravity combined with seismic effects. He has conducted several major projects on seismic design and retrofit of steel long span bridges and tall buildings. Since 1995, he has also been studying the behavior of steel and composite structures, both buildings and bridges, subjected to blast and impact loads and has been involved in testing and further development of technologies and design concepts to reduce blast damage and to prevent progressive collapse of steel and composite building and bridge structures subjected to terrorist blast (car bombs) or impact (planes and rockets) attacks.

After the September 11, 2001 tragic terrorist attacks on the World Trade Center and the collapse of the towers, armed with a research grant from the National Science Foundation, he conducted a reconnaissance investigation of the collapse and collected perishable data. As an expert, he later testified before the Committee on Science of the House of Representative of the U.S. Congress on his findings regarding the collapse of the World Trade Center towers. His current research includes studies of blast effects on steel and composite long-span bridges and elevated freeways with the aim of developing technologies to prevent progressive collapse of these important transportation links.

Since 2004 he has been doing research on earthquake hazard reduction in the Middle East, particularly in developing low- cost steel frame buildings for rural areas of highly seismic countries in the Middle East. His current projects, in addition to protection of buildings and bridge structures against seismic effects and terrorist blast attacks, includes investigation of the April 29<sup>th</sup>, 2007 collapse of the two spans of the Mac Arthur Maze elevated bridge intersection in Northern California due to fire, funded by the National Science Foundation and study of the progressive collapse of the I-35W steel deck truss bridge in Minnesota which occurred on August 1, 2007 and development of procedures on design, evaluation and retrofit of gusset plates in steel truss bridges.

His most recent work on buildings include development of rational procedures for seismic design of steel shear walls.

Contact the author at:

E-mail: [Astaneh@ce.berkeley.edu](mailto:Astaneh@ce.berkeley.edu)

Web: <http://www.astaneh.net> and <http://www.ce.berkeley.edu/~astaneh>

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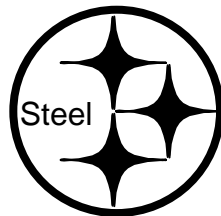
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