ANCHOR ROD DESIGN FOR NONBUILDING STRUCTURES

R. Drake\textsuperscript{1} and R. Bachman\textsuperscript{2}

ABSTRACT

The design of structural steel column base plates supported by exposed concrete foundations is an important aspect of the design of nonbuilding structures. The design of anchor rods is an important part of the base plates design process when lateral loads must be transferred from the steel structure to the concrete foundation. Design procedures for embedded anchor rods have evolved greatly over the past 50 years. This paper is intended to provide a brief history and summary of the anchor rod design procedures as they apply to nonbuilding structures including large industrial buildings.

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Anchor Rod Design For Nonbuilding Structures

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ABSTRACT

The design of structural steel column base plates supported by exposed concrete foundations is an important aspect of the design of nonbuilding structures. The design of anchor rods is an important part of the base plates design process when lateral loads must be transferred from the steel structure to the concrete foundation. Design procedures for embedded anchor rods have evolved greatly over the past 50 years. This paper is intended to provide a brief history and summary of the anchor rod design procedures as they apply to nonbuilding structures including large industrial buildings.

INTRODUCTION

Design of steel anchor rods embedded in concrete requires the use of the design specifications of two different trade organizations. The American Institute of Steel Construction (AISC) specification and material standards apply to the design of the steel rod and nut elements. The American Concrete Institute (ACI) specification and material standards apply to the design of the concrete embedment and associated reinforcing steel.

AISC uses the term “anchor rod” for anchors embedded in concrete. ACI use the term “anchor bolt” for the same anchors. The term “rod” is intended to indicate that they are threaded rods (usually only partially threaded) and not structural bolts. For this paper, the term anchor rod is used to describe the anchors embedded in concrete.

There are two basic types of anchor rods, cast-in or cast-in place (CIP) anchors and post-installed anchors (anchors installed in drilled holes after the concrete has hardened). There are many type of vendor proprietary post-installed anchors and the capacities of these anchors are established by testing in conjunction with vendor supplied software. On the other hand, CIP anchors are typically specified on the design drawings and the design capacity is determined by calculation based on the AISC and ACI design procedures. Almost all nonbuilding structures are anchored to concrete by CIP anchor rods with diameters of 1.5 inches or greater, while typically nonstructural components are anchored to concrete by post-installed anchors with diameters of 1 inch or less. This paper will therefore focus on the design procedures for CIP anchors although the same procedures supplemented by testing also apply to post-installed anchors.

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Brief History Of Anchor Rod Design

Until the early 1970s, the design of CIP anchor rods for nonbuilding structure applications were based on the design procedures of the ACI 318 building code [1] based procedures for development length for smooth (not deformed) reinforcing steel and bond. Typically, large diameter anchor rods were J shaped while smaller diameter anchor rods were L shaped and the rods were fabricated of ASTM A307 steel [10].

In 1976, design criteria developed specifically for anchorage was published in ACI 349 Appendix B [2]. This Appendix introduced several new design concepts to the design of anchor rods including:

- headed anchor rods
- a 45 degree concrete tension failure surface (same as used in shear failure for beams)
- procedures for providing supplemental reinforcing steel to improve the capacity in tension and shear and
- requiring that the concrete capacity (with supplemental reinforcing) exceed the ultimate strength steel rod capacity in both tension and shear.

Because many of the companies who design nonbuilding structures also designed nuclear facilities, they became aware of the rational and somewhat easy to use procedures of ACI 349 Appendix B into their office design procedures by the early 1980s. The essence of the design concepts of ACI 349 Appendix B for CIP anchors rods was codified for all structures with the introduction of Section 1925.3 into the 1988 Uniform Building Code (UBC) [16].

In 1994, the decision was made to merge the three model building codes in the United States (including the UBC) into one building code to be called the International Building Code (IBC) [14] to be first published in 2000. It was thought the 2000 IBC would utilize Section 1925.3 of the UBC for anchorage design but instead new design procedures were proposed by ACI which were adopted that were radically different based on testing performed on anchors in Europe. These procedures incorporated fracture mechanics principles, size effects and cracked concrete assumptions. Because most jurisdictions in the United States outside those on the west coast do not review the design of industrial facilities and because California did not adopt the IBC as its building code until 2007 (the 2006 IBC version), most companies designing anchorage for structures continued to use the procedure of the UBC and ACI-349 Appendix B.

In 2002, ACI decided to incorporate the anchor rod design procedures there were introduced into the 2000 IBC as Appendix D of ACI 318-02. In ACI 318-05, Appendix D was updated. ACI 318-05 was adopted by reference into 2006 IBC and design procedures were removed from Chapter 19 of the IBC. However, design procedures for ACI 318-05 Appendix were adopted into the 2006 IBC with several exceptions. There were also exceptions taken in ASCE 7-05 [9], the design standard that provide the minimum design loads and other associated criteria in the design of structures. Both the ASCE 7-05 and IBC exceptions that provided additional but unintended conservatism with regards to the design of anchor rods particularly for earthquake design applications. These were a coordinated effort to remove this conservatism in the adoption of the 2015 IBC; and all the adopted documents from ACI, AISC and ACI removed unintentional and
double dipping of conservatisms along with clarifying exceptions to the ACI 349-Appendix D in the IBC. This document summarizes the 2015 IBC anchor rod procedures rather than the details of previous procedures.

**Differences Between Buildings and Nonbuilding Structures**

Buildings are generally regarded as enclosed structures, designed to house and support a commercial or residential occupancy. Anchor rods are usually not exposed to the outside environment. For larger buildings especially in high seismic areas, steel columns are often embedded deeply in concrete foundations and development length concepts are used to justify their concrete embedment design and anchor rods are not used to resist design forces. Also, in high seismic areas, structural steel buildings utilize capacity design concepts which results in very high embedment design forces.

Nonbuilding structures are generally regarded as either unenclosed or enclosed structures, designed to support an industrial operation. Anchor rods are often exposed to the outside environment. Many nonbuilding structures rely on the ductile behavior of the anchor rods to provide at least some of the system ductility and to justify the seismic response modification factor (R).

Often, the nonbuilding structures design community develops criteria to interpret the building code requirements for the unique types of structures found in industrial, chemical, and petrochemical facilities [8][13][17].

**Observed Anchor Rod Behavior In Past Extreme Events**

Anchor rods anchoring nonbuilding structures have performed will in past extreme events have performed well and anchor rod failures of CIP bolts designed for tension and shear design forces for the extreme event are rarely reported. Of particular interest is the performance of tall steel vessels, stacks, storage tanks and large single story industrial buildings subjected to very strong ground motions during large earthquake events. A common observation by during most earthquakes made regarding many of these nonbuilding structures was the nonlinear stretch of anchor rods several inches with virtually no damage to the nonbuilding structures themselves. The fix for these structures apart from some minor foundation spalling was to often simply tighten the nut or unloosen the nut, add washers and retighten the nut. Where anchorage damage was observed was to pier (stub columns) type foundations with limited edge distances and minimal confinement reinforcing. Virtually no damage has been observed where the piers have been designed to the procedures of ACI 349-Appendix B and the 1988 or later versions of the UBC.

**Issues With Current Anchor Rod Design Requirements**

The current anchor rod design procedures provided in ACI 318-14 Chapter 17 result in much deeper embedment requirements that previously required by ACI 349 Appendix B for larger diameter anchor bolts particularly in high seismic regions where additional factors to account for cracked concrete are applied and the desire for anchorage not to be the failure point is applied.
The additional requirements do not seem to be justified based on actual performance in past earthquakes.

Also, the concept of ductile anchorage needs to be re-examined. Ductile anchorage makes sense where ductile mode (tension) is a primary part of the lateral force resisting system and contributes significantly to total inelastic displacement of the structure at effective center of mass. However it makes little sense for shear modes or cases where anchor rod design force is multiplied by an amplified design force (omega zero factor). Also, overall system ductility is insignificantly affected by shear mode anchorage inelastic deformations. It would therefore be judged more rational if the ductile anchorage were eliminated from ACI 318 except for tension were the anchorage is required to stretch nonlinear to obtain the design performance of the nonbuilding structure.

CURRENT CODE AND SPECIFICATION REQUIREMENTS

Purpose

The purpose of most building codes and material specifications is to establish minimum life safety requirements for the general public. For structural engineers, this means that loads are prescribed that shall be safely resisted without exceeding material strength and without excessive deformation.

Design Philosophies of Current Codes

Most current building codes and material specifications have requirements for both Strength Design and Allowable Strength Design.

\[
\text{Demand} \leq \text{Capacity} \\
\text{Required Strength} \leq \text{Design Strength} \\
\text{Factored Loads} \leq \text{Factor} \times \text{Nominal Strength}
\]

For simplicity, this paper only considers strength design, the 2015 International Building Code (IBC) requirements, and the material specifications incorporated by code reference.

2015 IBC

Required Strength

The IBC prescribes Dead Loads (D) and Live Loads (L, \(L_t\)). The IBC also prescribes Snow Loads (S), Wind Loads (W), and Earthquake Loads (E) by reference to ASCE 7. The loads are combined using strength load combinations prescribed in the IBC. Load effects on individual structural members are determined by an appropriate structural analysis that considers equilibrium, stability, geometric compatibility and material properties.

Design Strengths
In general, design strengths are prescribed by reference to material specifications.

**ACI 318-14**

ACI 318-14 Chapter 17 (formerly Appendix D) applies to both cast-in and post-installed anchors. Cast-in anchors are defined as headed bolts, headed studs, or hooked bolts installed before the concrete is placed. Post-installed anchors are defined as anchors installed in hardened concrete, including adhesive, expansion, and undercut anchors.

**Required Strength**

The required strength for nonseismic applications is generally as prescribed in the building code.

**Materials**

For seismic applications, ACI 318 requires that Anchors rods shall transmit tensile loads via a ductile steel element with a stretch length of at least eight anchor diameters otherwise determined by analysis. Ductile steel elements are defined as an element with a tensile test elongation of at least 14 percent and reduction in area of at least 30 percent. Alternatively, the anchor rods can be designed for load combinations that include the overstrength factor ($\Omega_o$).

**Design Strength**

Tension design strengths are prescribed for steel anchor strength ($\Phi N_{sa}$), concrete breakout strength ($\Phi N_{cb}$), pullout strength ($\Phi N_{pm}$), concrete sideface blowout strength ($\Phi N_{sb}$), and adhesive anchor bond strength ($\Phi N_a$). Shear design strengths are prescribed for steel anchor strength ($\Phi V_{sa}$), concrete breakout strength ($\Phi V_{cb}$), and concrete pryout strength ($\Phi V_{cp}$).

When anchor reinforcement is provided and developed on both sides of potential tension or shear breakout surfaces, the concrete breakout design strengths need not be considered, provided that the reinforcement design strength is multiplied times 0.75. Use of anchor reinforcement is usually economical when anchor rods are placed in pedestals or near the edges of foundations, both common for nonbuilding structures.

Equations presented in ACI 318 were developed for rectangular foundations, with anchors having uniform edge distances. Many nonbuilding structures, such as vertical vessels and their ancillary structural steel platform structures have round or octagonal shaped foundations. In these cases, anchor edge distances may not be constant and ACI 318 equations must be modified to meet their intent.

**Interaction Of Tension And Shear Forces**

Interaction acceptance criteria are provided for anchors when the required strength to design strength ratios for tension and shear are both greater than 0.20.
Seismic Considerations

Anchors subjected to earthquake forces shall not be located in the expected plastic hinge zones of concrete structures. For anchors in structures assigned to Seismic Design Categories A and B, and anchors where the earthquake contribution is less than 20% of the total anchor load there are no additional seismic requirements beyond those prescribed in the building code. For anchors in structures assigned to Seismic Design Categories C, D, E, and F, four tension force options and three shear force options are presented. Some options require that the required strength be determined considering material overstrength ($\Omega_o$). Some options require that concrete design strengths be multiplied by 0.75. Some options require both. Post-installed anchors must meet the additional seismic qualification requirements of either ACI 355.2 [3] or ACI 355.4 [4].

ASCE 7-16

General

Anchors in concrete for nonbuilding structures shall be in accordance with ACI 318-14.

Seismic Considerations

Post-installed anchors in concrete shall be qualified in accordance with either ACI 355.2 or ACI 355.4. Connections between anchor rods and tanks or vessels shall be designed for the lesser of the calculated anchor rod design force from load combinations with the overstrength factor ($\Omega_o$) or the anchor rod tensile strength. Load combinations with the overstrength factor ($\Omega_o$) are not to be used to size the anchor rods. To permit anchor rod yielding, the minimum rod gauge length is eight times the rod diameter.

AISC 360-16

Materials

AISC 360 [6] prescribes acceptable steel materials for anchor rods. The preferred material is ASTM F1554 [11], which is produced in three yield strengths, 36, 55, and 105 ksi. Note that ASTM F1554 Grade 55 or Grade 105 bolts do not meet the previously described anchor rod elongation test requirements and cannot be considered ductile steel elements.

Required Strength

The required strength for anchor rods and column bases is as prescribed in the building code. Anchor rod loads shall consider the tensile component of any bending moments.

Design Strength

Design strength for the anchor rods shall be as prescribed for threaded rods, including consideration of the interaction of shear and tension loads. The design strength of anchor rod
and column base interaction with concrete shall be in accordance with either ACI 318 or ACI 349. Additional design guidance is provided in AISC Design Guide 1.

Seismic Considerations

Seismic considerations for anchor rods are prescribed in AISC 341 for structural steel seismic force resisting systems (SFRS) that require seismic detailing.

AISC 341-16

AISC 341 [5] prescribes seismic detailing requirements for steel structures and is a supplement to the requirements of AISC 360, when required by either ASCE 7 Table 12.2-1 or ASCE 7 Table 15.4-1.

Required Strength

The required shear strength of column bases shall be the summation of the required connections strengths for diagonal braces and columns at the base. The required shear strength for the column is the lesser of the expected column plastic shear and the shear calculated using the overstrength seismic load. There is a minimum shear summation equal to 0.7 times the expected column plastic shear, not applicable for Ordinary Concentrically Braced Frames. The required flexural strength of columns bases, including the tension load on anchor rods, is summation of the required connections strengths for diagonal braces and columns at the base. The required flexural strength for the column is the lesser of the expected plastic moment and the moment calculated using the overstrength seismic load.

Design Strength

Design strength for the anchor rods shall be as prescribed in AISC 360. The design strength of anchor rod and column base interaction with concrete shall be in accordance with either ACI 318. A User Note is provided to remind the designer that when anchor reinforcement is provided, it should be developed on both sides of potential tension or shear breakout surfaces.

SPECIFIC DESIGN REQUIREMENTS

Supplementary And Anchor Reinforcing

In nonbuilding structures, it is common that structural steel columns are anchored to reinforced concrete pedestals, which are in turn anchored to a supporting foundation. In these cases, the standard practice is to design the pedestal reinforcing as anchor reinforcement to transfer all of the design loads. Use of supplementary anchor reinforcing to take part of the design load is not common.

The tension design loads are transferred between the pedestal and foundation by developing the pedestal vertical reinforcing steel on both sides of the construction joint. Usually the vertical reinforcing steel is hooked into the foundation resting on the lower level of reinforcing steel.
The tension design loads are transferred between the vertical reinforcing steel and the anchors by developing the reinforcing steel on both sides of the 35 degree tension breakout cone originating at the anchor. It is unusual to hook the vertical reinforcing steel at the top of the pedestal because of the rebar congestion at that location. As a result, anchors are usually long to allow straight bar development of the vertical reinforcing steel. Key elements of the tension design load transfer are shown in Figure 1.

The shear design loads are usually transferred between the pedestal and foundation by roughening the foundation concrete at the construction joint. For higher shear forces, the vertical reinforcing steel can be used to develop shear friction resistance. The shear design loads are transferred between the shear reinforcing steel (ties) and the anchors by developing the reinforcing steel on both sides of the 35 degree shear breakout cone originating at the anchor. Closed ties are both standard construction practice and necessary to develop the reinforcing steel. Key elements of the shear design load transfer are shown in Figure 2.

![Figure 1. Anchor Reinforcement In Pedestal To Preclude Concrete Tension Breakout.](image1.png)

![Figure 2. Anchor Reinforcement In Pedestal To Preclude Concrete Sideface Blowout](image2.png)

In addition, ACI 318 requires that the anchors be enclosed at the top of the pedestal by either two No. 4 tie sets or three No. 3 tie sets.

**Pretensioning**

Some engineers employ pretensioning of anchor rods for tall vessels and stacks particularly if they are concerned with low cycle fatigue. One concern with pretensioning is the loss of pretension forces caused by concrete creep and shrinkage and the relatively short anchor rod length. Fang provides a more thorough discussion of pretensioned anchor rods.
Minimum Stretch Length

As noted above, the inelastic stretching of anchor rods is important in the seismic design of several nonbuilding structures. The need for adequate stretched length (also sometimes referred to as gauge length) was first recognized in New Zealand requirements for nonbuilding structures in the early 1980s and the first testing to determine the stretched length and strain capacity of anchor rods made of different materials for nonbuilding structure applications was done in 1985. The concept of stretch length was first introduced in ACI 318-11 Appendix D based on observations in the 2010 Chile Earthquake and suggested a minimum stretch length of eight times the bolt diameter for the minimum stretched length were structures rely on bolt stretch during earthquakes. Engineers often require that anchor rod be wrapped with Teflon tape or be coated with bond breaker to insure that for the embedded portion of an anchor is not bonded to the concrete and that the stretch and freely occur. The amount of stretch length needed for a given nonbuilding structure in seismic event is a function of many factors. A suggested procedure for determining the needed stretched length for a given nonbuilding structure in a given design earthquake event is provided in a paper by Trautner, et al [15].

Design Of Column Base Plates

A good summary of the design of column base plates can be found in AISC Design Guide 1 [7], including example problems for base plates with axial load only, axial load in combination with moments, and shear loads. The design example includes development of required tension and shear strengths for the anchor rods. Additional background reading for column base plates with axial load in combination with moments can be found in the paper by Drake and Elkin [12].

SUMMARY AND CONCLUSIONS

This paper provides a brief history of past anchor rod design procedures and a summary of current anchor rod design procedures as they apply to nonbuilding structures including large industrial buildings.

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