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Changes in the ACI 318 Anchoring to Concrete Seismic Provisions

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The American Concrete Institute (ACI) *Building Code Requirements for Structural Concrete* (ACI 318) includes provisions for anchoring to concrete in Appendix D (ACI 318-02 through ACI 318-11) and Chapter 17 (ACI 318-14). Anchorages designed to resist seismic load conditions require special consideration. This article discusses the changes between ACI 318-08 Appendix D seismic provisions and ACI 318-11 Appendix D/ ACI 318-14 Chapter 17 seismic provisions, and includes a brief discussion about the *International Building Code* (IBC) seismic anchoring provisions.

ACI 318 Seismic Provisions for Anchors

ACI 318-08 seismic anchoring provisions are given in Part D.3.3, which is included in **Part D.3 – General requirements**. ACI 318-11 seismic anchoring provisions are given in **Part D.3.3 – Seismic design requirements**. ACI 318-14 seismic anchoring provisions are given in **Section 17.2.3 – Seismic design**. ACI 318-08 Part D.3.3 defines seismic anchor design as that which "includes earthquake forces for structures assigned to Seismic Design Category C, D, E, or F". ACI 318-11 Part D.3.3.1 and ACI 318-14 Section 17.2.3.1 define seismic anchor design as that for "anchors in structures assigned to Seismic Design Category C, D, E, or F".

The ACI 318 and IBC codes assume cracked concrete conditions for the design of cast-in-place and post-installed anchors because the existence of cracks in the anchor vicinity can result in a reduced ultimate load capacity and increased displacement at ultimate load. ACI 318 requires post-installed anchors to be qualified for seismic load conditions via testing in cracked concrete. Flexural crack widths corresponding to the onset of reinforcing yield under seismic loading are assumed to equal 0.02 inches. Post-installed anchor qualification standards are referenced in ACI 318-08 Part D.3.3.2, ACI 318-11 Part D.3.3.3 and ACI 318-14 Section 17.2.3.3.

ACI 318-08 seismic anchoring provisions must be satisfied for both tension and shear. In contrast to these provisions, ACI 318-11 and ACI 318-14 seismic anchoring provisions permit design for either tension, or shear, or both tension and shear.

ACI 318-08 Seismic Provisions

ACI 318-08 Appendix D seismic design consists of three options defined by the provisions given in Part D.3.3.4, Part D.3.3.5 and Part D.3.3.6. The provisions in the option selected must be satisfied for both tension and shear load conditions.

ACI 318-08 Appendix D seismic design criteria can be summarized as follows:

- calculate nominal strengths corresponding to possible anchor failure modes per Part D.4.1.
- apply a strength reduction factor (ϕ-factor) to each nominal strength per Part D.4.1.2.
- apply a seismic reduction factor of 0.75 to non-steel design strengths per Part D.3.3.3.

The commentary RD.3.3.3 notes that the 0.75 factor is applied "to account for increased damage states in the concrete resulting from seismic actions." When the design is controlled by non-ductile anchor strengths, an additional reduction factor must be applied to the calculated anchor design strengths corresponding to brittle failure modes. This criterion will be covered when discussing Part D.3.3.6.

Part D.3.3.4 can be used if the anchorage design is governed by the steel strength of a ductile steel element. The design steel strength in tension, defined by the parameter ϕN_{sa}, must be the controlling tension design strength compared to the non-steel tension design strengths defined by the parameter $(0.75)(\phi N_N)$. Likewise, the design steel strength in shear, defined by the parameter ϕV_{sa}, must be the controlling shear design strength compared to the non-steel shear design strengths defined by the parameter $(0.75)(\phi V_N)$. **Part D.1 – Definitions** defines a ductile steel element as having a tensile test elongation of at least fourteen percent measured over a specified gauge length, and a reduction in cross-sectional area of at least thirty percent. Anchor elements that do not satisfy these criteria, or for which these criteria are not determined, are assumed to be brittle steel elements, which precludes them from design with the provisions of D.3.3.4.

Part D.3.3.5 can be used if the anchorage design is controlled by ductile yielding of the attachment. The force calculated to yield the attachment must be less than or equal to the calculated anchor design strengths. Tension anchor design strengths are defined as ϕN_{sa} for steel failure and $(0.75)(\phi N_N)$ for non-steel failure. Shear anchor design strengths are defined by ϕV_{sa} for steel failure and $(0.75)(\phi V_N)$ for non-steel failure.

Part D.3.3.4 and Part D.3.3.5 are both predicated on a ductile failure mode controlling the anchorage design. The ACI 318 code recognizes, however, that an anchorage design controlled by a ductile failure mode may not be possible. For example, anchor spacing and edge distance, concrete member thickness, or base plate properties may preclude an anchorage design controlled by a ductile failure mode. Therefore, Part D.3.3.6 provides another option that waives any ductility requirement and permits the anchorage design to be controlled by a brittle failure mode. The provisions of Part D.3.3.6 include an additional

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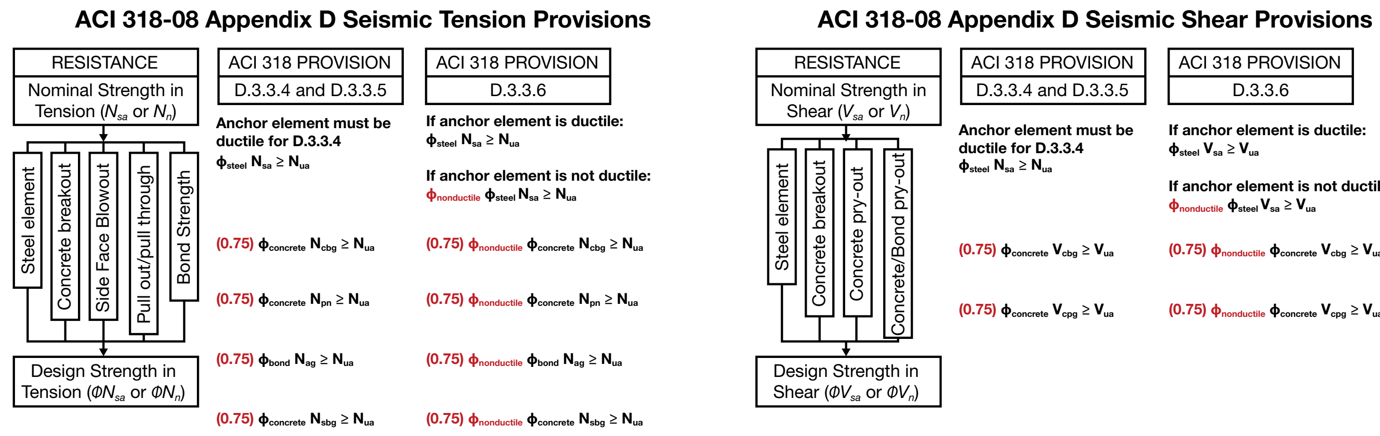

Figure 1.

reduction factor which must be applied to anchor design strengths corresponding to brittle failure modes. For simplicity, this factor will be referred to in this article as $\phi_{nonductile}$.

$\phi_{nonductile}$ is applied to non-steel anchor design strengths ($\phi_{nonductile}$ 0.75 ϕN_N and $\phi_{nonductile}$ 0.75 ϕV_N) as well as to steel design strengths for anchor elements considered to be brittle ($\phi_{nonductile}$ ϕ_{steel} N_{sa} and $\phi_{nonductile}$ ϕ_{steel} V_{sa}). The default value for $\phi_{nonductile}$ is 0.4; however, it can vary depending on the design conditions being considered. Part D.3.3.6 notes that a $\phi_{nonductile}$ value of 0.5 can be used for "anchors of stud bearing walls" because this application typically consists of multiple anchors capable of load redistribution. The 2009 IBC Section 1908.1.9 waives the use of $\phi_{nonductile}$ for anchorage of nonstructural components and anchors designed to resist wall out-of-plane forces. *Figure 1* summarizes ACI 318-08 Appendix D seismic calculations.

ACI 318-11 and ACI 318-14 Seismic Provisions

ACI 318-11 anchor provisions are given in **Appendix D – Anchoring to Concrete**. ACI 318-14 anchor provisions are given in **Chapter 17 – Anchoring to Concrete**. Other than the numbering system, there is no difference in content between ACI 318-11 Appendix D and ACI 318-14 Chapter 17 anchoring provisions. This section discusses ACI 318-11 Appendix D seismic anchor provisions and references the corresponding ACI 318-14 Chapter 17 section in parentheses.

ACI 318-11 and ACI 318-14 seismic anchor calculations do not have to be performed if the earthquake component of the factored load acting on the anchorage is less than or equal to twenty percent of the total factored load acting on the anchorage. Unlike ACI

318-08 Appendix D seismic provisions, ACI 318-11 and ACI 318-14 seismic anchor provisions permit design for either tension conditions, or shear conditions, or both tension and shear conditions.

ACI 318-11 and ACI 318-14 Seismic Tension Provisions

ACI 318-11 **Part D.3.3.4 – Requirements for tensile loading** (ACI 318-14 **Section 17.2.3.4**) permits a tiered approach to seismic design. Part D.3.3.4.1 (Section 17.2.3.4.1) waives the requirement to design for seismic tension if the "tensile component of the strength-level earthquake force" is less than or equal to 20 percent of the total factored tension load. Equations consisting of factored load combinations are given in ACI 318-11 **Section 9.2 – Required Strength** (ACI 318-14 **Section 5.3 – Load factors and combinations**). The parameter E in these equations corresponds to the earthquake force component of the factored load. When considering tension loads that include E, if the value calculated for E is less than or equal to twenty percent of the total factored load, no seismic calculations are required for tension. In this case, the tension design for the anchorage will be per Table D.4.1.1– **Required Strength of Anchors** (ACI 318-14 Table 17.3.1.1). If E is greater than twenty percent of the total factored tension load, Part D.3.3.4.2 (Section 17.2.3.4.2) requires the tension design for the anchorage to be performed using one of the options given in Part D.3.3.4.3 (Section 17.2.3.4.3).

ACI 318-11 Appendix D and ACI 318-14 Chapter 17 seismic tension provisions can be summarized as follows:

- calculate design strengths corresponding to possible anchor failure modes per Table D.4.1.1 (Table 17.3.1.1).
- apply a seismic reduction factor of 0.75 to non-steel tension design strengths per Part D.3.3.4.4 (Section 17.2.3.4.4).

Seismic tension options include anchorage design controlled by the strength of the attachment (ductile or brittle failure), or anchorage design controlled by the anchor design strengths (ductile or brittle failure). When the anchorage design is controlled by a brittle anchor failure mode, an overstrength factor (Ω_0) must be applied to the earthquake component (E) of the factored load.

Part D.3.3.4.3(a) (ACI 318-14 Section 17.2.3.4.3(a)) provisions are only relevant to ductile anchor elements. A ductility check must first be performed. The purpose of this check is to provide a reasonable expectation, based on nominal strengths, that the anchor element will have yielded when ultimate load is reached. The check requires the ratio ($N_{ua,i}$ /$1.2N_{sa}$), corresponding to steel failure, to exceed the ratio (N_{ua} /N_N), corresponding to non-steel failure. The check defines non-steel failure as "concrete-governed strengths". Note that bond strength is considered a "concrete-governed" tension strength for purposes of this check. $N_{ua,i}$ corresponds to the highest-loaded anchor in tension, and the steel strength of the anchor is defined as 1.2 times the nominal steel strength (N_{sa}). N_{ua} corresponds to the factored tension load, and N_N corresponds to the nominal concrete breakout strength, nominal bond strength, nominal pullout strength or nominal side-face blowout strength for the anchorage. If ($N_{ua,i}$ /$1.2N_{sa}$) for steel failure is greater than (N_{ua} /N_N) for all possible non-steel failure modes, the ductility check is satisfied, and the calculated design strengths will be (ϕN_{sa}) for steel failure and (0.75)(ϕN_N) for non-steel failure modes.

ACI 318-11 Part D.3.3.4.3(b) (ACI 318-14 Section 17.2.3.4.3(b)) requires the anchorage design to be controlled by ductile yielding of the attachment. ACI 318-11 Part D.3.3.4.3(c) (ACI 318-14 Section 17.2.3.4.3(c)) permits the anchorage design to be controlled by the strength of a non-yielding attachment, e.g. crushing of a wood sill plate. The calculated design strengths for both options will be defined by the parameters (ϕN_{sa}) for steel failure and (0.75)(ϕN_N) for non-steel failure modes.

ACI 318-11 Part D.3.3.4.3(d) (ACI 318-14 Section 17.2.3.4.3(d)) requires anchor design strengths to be greater than or equal to the factored tension load inclusive of an Ω_0 overstrength factor in the earthquake component (E) of the factored load.

ACI 318-11 and ACI 318-14 Seismic Shear Provisions

ACI 318-11 **Part D.3.3.5 – Requirements for shear loading** (ACI 318-14 **Section 17.2.3.5**) also permits a tiered approach to seismic design. Part D.3.3.5.1 (Section 17.2.3.5.1) waives the requirement to design for seismic shear if the "shear component of the strength-level earthquake force" is less than or equal to 20 percent of the total factored shear load. When considering shear factored load equations that include E, if the value calculated for E is less than or equal to 20 percent of the total factored load, no seismic calculations are required for shear. In this case, the anchorage design will be per Table D.4.1.1 (ACI 318-14 Table 17.3.1.1). If E is greater than 20 percent of the total factored shear load, Part D.3.3.5.2 (Section 17.2.3.5.2) requires the shear design for the anchorage to be performed using one of the options given in Part D.3.3.5.3 (Section 17.2.3.5.3).

Unlike ACI 318-08 Appendix D, ACI 318-11 Appendix D and ACI 318-14 Chapter 17 seismic shear provisions do not apply a reduction factor of 0.75 to non-steel design strengths. The calculated shear design strengths are defined by the parameters ϕV_{sa} for steel failure, and ϕV_N for non-steel failure modes. Another difference between ACI 318-11/ACI 318-14 seismic shear anchoring provisions and ACI 318-08 seismic shear anchoring provisions is that anchorage design based on yielding of a ductile anchor element is not offered as a seismic shear option in either ACI 318-11 or ACI 318-14.

ACI 318-11 Part D.3.3.5.3(a) (ACI 318-14 Section 17.2.3.5.3(a)) requires the anchorage design to be controlled by ductile yielding of the attachment. If this cannot be satisfied, ACI 318-11 Part D.3.3.5.3(b) (ACI 318-14 Section 17.2.3.5.3(b)) provides an option that permits the anchorage design to be controlled by the strength of a non-yielding attachment.

ACI 318-11 Part D.3.3.5.3(c) (ACI 318-14 Section 17.2.3.5.3(c)) requires the calculated anchor design strengths to be greater than or equal to the factored shear load inclusive of an Ω_0 overstrength factor in the earthquake component (E) of the factored load. *Figure 2* summarizes ACI 318-11 Appendix D and ACI 318-14 Chapter 17 seismic calculations.

IBC Seismic Provisions Versus ACI 318 Seismic Provisions

The IBC references codes and standards that are considered part of the requirements of that particular IBC version. **Chapter 35 – Referenced Standards** in the 2012 IBC and 2015 IBC references ACI 318-11 and ACI 318-14 respectively. **Chapter 19 – CONCRETE** references ACI 318 anchoring provisions; however, the 2012 IBC was published prior to the publication of ACI 318-11, which resulted in the 2012 IBC seismic anchoring provisions given in Section 1905.1.9 referencing ACI 318-08 Appendix D seismic provisions instead of ACI 318-11 Appendix D seismic provisions. This situation illustrates the importance of understanding the local codes, because jurisdictions may make amendments to the IBC model codes. For example, jurisdictions can amend the 2012 IBC Chapter 19 anchor provisions prior to adopting the 2012 IBC,

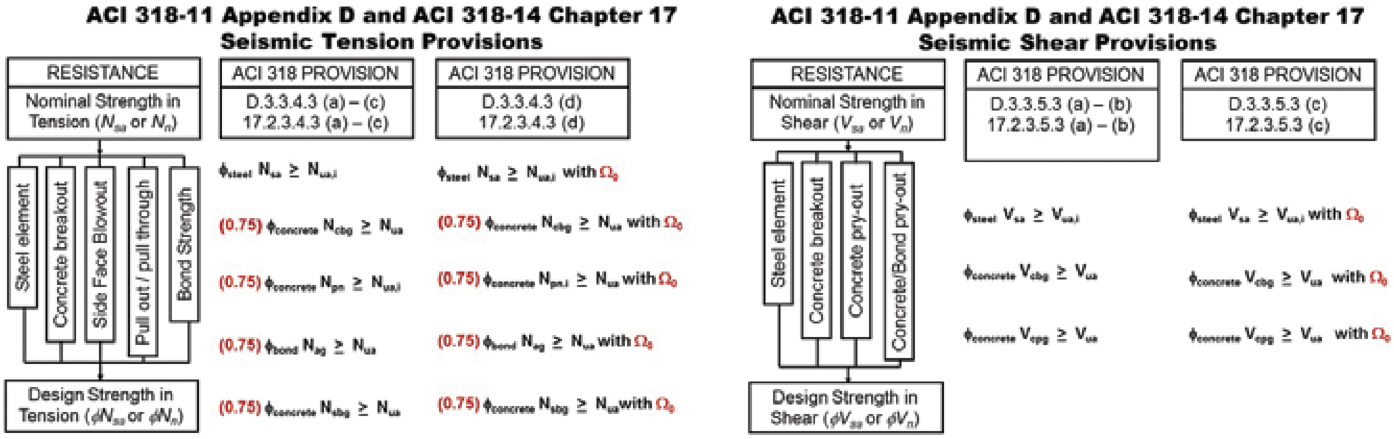

Figure 2.

or jurisdictions that have adopted the 2012 IBC without amendments can permit design per ACI 318-11 Appendix D via approval by the authority having jurisdiction. 2015 IBC Chapter 19 seismic anchoring provisions reference ACI 318-14 Chapter 17 seismic anchoring provisions.

Summary

ACI 318 seismic anchoring provisions provide options for a design that is controlled by the strength of the attachment or by the strength of the anchors. A design controlled by some form of ductile failure is preferable; however, a design controlled by a non-ductile failure mode is permissible if additional provisions relative to either the load or resistance calculations are satisfied. Post-installed anchors must be qualified by testing for use with the seismic anchor provisions of ACI 318.

ACI 318-08 seismic anchoring provisions must be satisfied for both tension and shear load conditions. ACI 318-11 and ACI 318-14 seismic anchoring provisions can be performed for tension only, shear only, or tension and shear.

The 2012 IBC seismic anchoring provisions reference ACI 318-08 Appendix D provisions instead of ACI 318-11 Appendix D provisions due to a difference in the publication date of each code. This discrepancy has been eliminated with harmonization of the 2015 IBC and ACI 318-14 Chapter 17 seismic anchoring provisions.▪