Significant Changes between ACI 318-11 and ACI 318-14

Part 2: Technical Changes

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The American Concrete Institute (ACI) published the *Building Code Requirements for Structural Concrete* (ACI 318-14) and *Commentary* (ACI 318R-14) in the Fall of 2014. ACI 318-14 has been adopted by reference into the 2015 International Building Code (IBC). There are very significant organizational as well as technical changes between ACI 318-11 and ACI 318-14. This is the second of a two-part article on these changes: Part 1 (STRUCTURE, April 2016) described the organizational changes, and this Part is devoted to the technical changes.

Overview of Technical Changes

In view of the effort involved in the complete reorganization of ACI 318-14, the initial expectation was that the number of technical changes in ACI 318-14 would be minimal. However, it did not end up that way. ACI 318-14 contains a number of significant technical changes, with some of the most significant ones discussed below.

Chapter 1 – General

The new Section 1.5 – *Interpretation* is an important addition to Chapter 1. This section tells the user how to properly interpret ACI 318 provisions.

Chapter 2 – Notation and Terminology

A new sentence has been added to the definition for "hoop." It reads: "A closed tie shall not be made up of interlocking headed deformed bars." The term "special seismic systems" has been newly defined as: "structural systems that use special moment frames, special structural walls, or both."

Chapter 4 – Structural System Requirements

This new chapter contains sections on: Materials, Design Loads, Structural System and Load paths, Structural Analysis, Strength, Serviceability, Durability, Sustainability, Structural Integrity, Fire Resistance, Requirements for Specific Types of Construction, Construction and Inspection, and Strength Evaluation of Existing Structures. Most of these sections refer to other chapters in ACI 318-14. The section on Construction and Inspection, for instance, refers to Chapter 26. ACI 318-14 does not have specific requirements concerning sustainability and fire resistance. The section on *Sustainability* permits the licensed design professional to specify sustainability requirements in the construction documents. The strength, serviceability, and durability requirements of ACI 318-14 are required to take precedence over sustainability considerations. In the section on *Fire Resistance*, ACI 318 refers to the fire protection requirements of the general building code, which is the legal code used by the authority having jurisdiction over the structure.

Chapter 5 – Loads

For many code cycles, ACI 318 retained provisions for service-level earthquake forces in design load combinations. Any reference to service-level earthquake forces has been deleted from ACI 318-14.

A requirement to include secondary moments was rightly included in the ACI 318-11 section on *Moment Redistribution* but was not included anywhere else. Since secondary moments are a significant consideration in member design even when moments are not redistributed, they should be included in the member chapters. Also, the effects of reactions induced by prestressing include more than just secondary moments. Thus, Section 5.3.11 now states: "Required strength U shall include internal load effects due to reactions induced by prestressing with a load factor of 1.0." In the chapter on one-way slabs, Section 7.4.1.3 now requires: "For prestressed slabs, effects of reactions induced by prestressing shall be considered in accordance with 5.3.11." Sections 8.4.1.3 and 9.4.1.3 have similarly been added to the chapters on two-way slabs and beams, respectively.

Chapter 6 – Structural Analysis

ACI 318-11 and prior editions were silent on the use of finite element analysis (FEA). Chapter 6 has added a new Section 6.9 with provisions that are intended to explicitly allow the use of FEA and to provide a framework for future expansion of FEA provisions. The added provisions are not meant to serve as a guide for selection and use of FEA software. The new chapter on *Diaphragms and Collectors* makes an explicit reference to the use of FEA. This made it imperative for ACI 318 to recognize the acceptability of its use.

Chapter 8 – Two-Way Slabs

ACI 318-11 Section 18.9.1 required a minimum area of bonded reinforcement to be provided in all flexural members with unbonded tendons. ACI 318-14 Section 8.6.2.3 requires the same minimum bonded reinforcement in slabs with unbonded or bonded tendons, except that the area of bonded tendons is considered effective in controlling cracking.

The structural integrity requirements in ACI 318-11 Section 18.12.6 applied to two-way post-tensioned slab systems with unbonded tendons only. The structural integrity requirements in ACI 318-14 Section 8.7.5.6 apply to two-way post-tensioned slab systems with unbonded as well as bonded tendons.

Chapter 9 – Beams

An extensive PCI-sponsored experimental and analytical research program was conducted at

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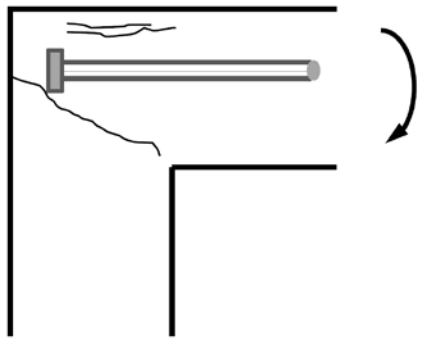

Figure 1. Knee joint with headed beam reinforcement.

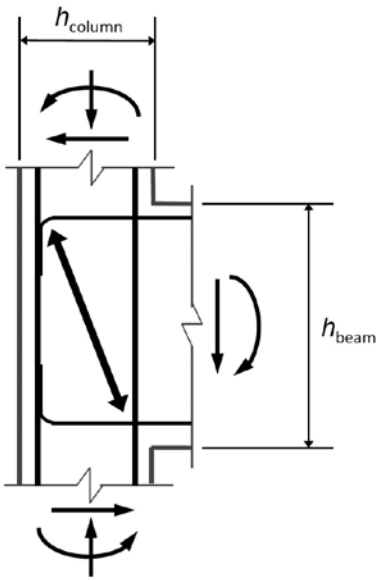

Figure 2. Compression strut in joint with high aspect ratio.

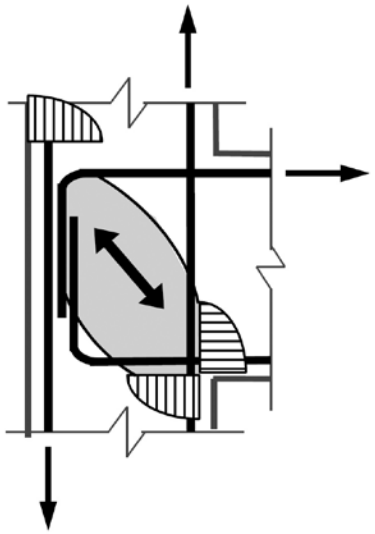

Figure 3. Bending of hooks into a joint.

North Carolina State University. The results of this research demonstrated that properly designed open web reinforcement is a safe, effective, and efficient alternative to traditional closed stirrups for slender precast spandrels. A simple, rational design procedure was developed. This proposed procedure significantly reduces reinforcement congestion, especially in the end regions of slender spandrels, while maintaining a desired level of safety. This led directly to the inclusion in ACI 318-14 of new Section 9.5.4.7, which reads: "For solid precast sections with an aspect ratio $h/b_t \geq 4.5$ [b_t = width of that part of cross section containing the closed stirrups resisting torsion, in.], it shall be permitted to use an alternative design procedure and open web reinforcement, provided the adequacy of the procedure and reinforcement have been shown by analysis and substantial agreement with results of comprehensive tests. The minimum reinforcement requirements of 9.6.4 and detailing requirements of 9.7.5 and 9.7.6.3 need not be satisfied."

Chapter 12 – Diaphragms

ACI 318 has, for many editions, contained design and detailing requirements, found in ACI 318-14 Section 18.12, for diaphragms in structures assigned to Seismic Design Category (SDC) D, E, or F, defined in ACE 7-10. ACI 318-14 has, for the first time, added design provisions in the new Chapter 12 for diaphragms in buildings assigned to SDC C and lower. The new chapter applies to the design of nonprestressed and prestressed diaphragms. The diaphragms may be cast-in-place as well as precast with or without topping. The topping may be composite or non-composite with the precast units.

Chapter 18 – Earthquake Resistant Structures

Some of the most important technical changes are found in Chapter 18, *Earthquake Resistant Structures*, and include the following:

1) Confinement requirements for columns of special moment frames with high axial load or high concrete compressive strength are significantly different for the regions of potential plastic hinging at the two ends. The changes are in recognition of the dependence of the amount of required confinement on the magnitude of the axial load imposed on a column and on the strength of concrete in the column. The new requirements also recognize the fact that longitudinal reinforcement that is well distributed and laterally supported around the perimeter of a column core provides more effective confinement than a cage with larger, widely-spaced longitudinal bars. The new confinement requirements will be the subject of a separate paper in a subsequent issue of the STRUCTURE magazine.
2) For beam-column joints of special moment frames, the new items are (a) restrictions on joint aspect ratio, (b) requirements for knee joints with headed beam reinforcement, (c) hooking of beam reinforcement within a joint, and (d) requirements for headed longitudinal reinforcement within joints.
   a) The case of knee joints with headed beam reinforcement (*Figure 1*) requires special consideration. ACI 318 joint design provisions are based on the assumption that joint shear strength is provided mainly by a diagonal compression strut that develops across the joint. Joint transverse reinforcement confines the concrete strut, enabling it to resist shear under force reversals. The strut is most effective if the joint aspect ratio h_{beam}/h_{column} (*Figure 2*) is close to 1.0. ACI 318-14 Section 18.8.2.4 restricts h_{beam}/h_{column} to a value of two or less.
   b) In such joints, joint failure can occur by a diagonal crack that extends beyond the headed bars, or by top-face blowout above the beam bars. ACI 318-14 Section 18.8.3.4, therefore, requires that in such joints, "the column shall extend above the top of the joint a distance at least the depth h of the joint. Alternatively, the beam reinforcement shall be enclosed by additional vertical joint reinforcement providing equivalent confinement to the top face of the joint."
   c) The tail of 90-degree hooks is now required to be bent into the joint (Section 18.8.5.1), as shown in *Figure 3*.
   d) ACI 318-14 now explicitly permits use of headed reinforcement in beam-column joints of special moment frames and permits the clear spacing in such joints to be as small as $3d_b$ for bars in a layer (Section 18.8.5.2).
3) Section 18.10, previously Section 21.9, has been extensively revised in view of the performance of buildings in the Chile earthquake of 2010 and the Christchurch, New Zealand earthquakes of 2011, as well as performance observed in the 2010 E-Defense full-scale reinforced concrete building tests.

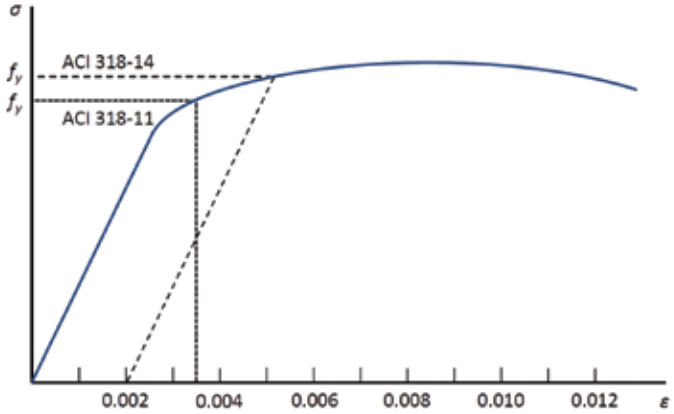

Figure 4. Definition of yield strength of high-strength reinforcement.

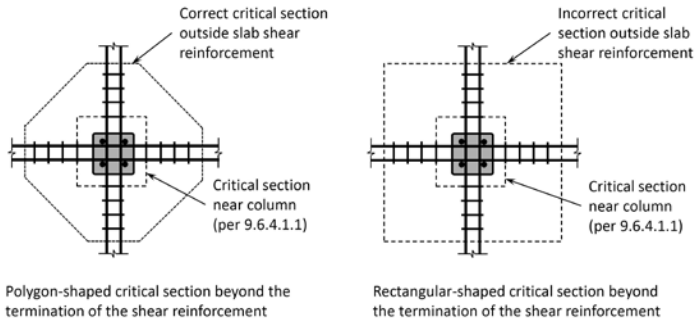

Figure 5. Critical section for two-way shear around discontinued punching shear reinforcement (adapted from ACI 318-14 Figures R22.6.4.2a and R22.6.4.2b).

4) In these earthquakes and laboratory tests, concrete spalling and vertical reinforcement buckling were at times observed at wall boundaries. Wall damage was often concentrated over a wall height of two or three times the wall thicknesses, much less than the commonly assumed plastic-hinge height of one-half the wall length. Out-of-plane buckling failures over partial story heights were also observed; this failure mode had previously been observed only in a few, moderate-scale laboratory tests. Design requirements for special shear walls have changed in significant ways in ACI 318-14 in view of the above observations.

These changes will also be the subject of a separate paper in a subsequent issue of the STRUCTURE magazine and are not discussed here any further.

Chapter 19 – Concrete: Design and Durability Requirements

ACI 318-11 Table 4.2.1 – *Exposure Categories* and Classes is now ACI 318-14 Table 19.3.1.1. A number of changes have been made in this table.

e) The column titled "Severity" has been deleted from the table.
f) Conditions describing Exposure Classes F1, F2, and F3 have changed. "Occasional exposure to moisture" has been replaced by "limited exposure to water."
g) "Continuous contact with moisture" has been replaced by "frequent exposure to water."
h) Exposure Classes P0 and P1 (P for Permeability) are now W0 and W1 (W for contact with Water) because permeability is not an exposure condition.

ACI 318-11 Table 4.3.1 – *Requirements for Concrete by Exposure Class* is now Table 19.3.2.1.

The maximum water-cementitious materials ratio and the minimum compressive strength requirements for Exposure Classes F1 and F3 have changed. The cementitious materials types that are allowed in concrete assigned to Exposure Classes S1, S2, and S3 have changed because ASTM C595 has included requirements for binary (IP and IS) and ternary (IT) blended cement since 2009.

New *Commentary* Section 19.3.3.2 clarifies that ACI 318 requirements for air content apply to fresh concrete sampled at the point of discharge from a mixer or a transportation unit upon arrival on site. If the licensed design professional requires sampling and acceptance of fresh concrete air content at another point, appropriate requirements must be included in the construction documents.

Chapter 20 – Steel Reinforcement Properties, Durability, and Embedments

Section 3.5.3.2 of ACI 318-71 through 318-08 defined the yield strength of reinforcement "with f_y exceeding 60,000 psi" as the stress corresponding to a strain of 0.35%. ACI 318-11 defined the yield strength of reinforcement "with f_y at least 60,000 psi" as the stress corresponding to a strain of 0.35%. This definition has changed in a major way in ACI 318-14. For reinforcement without a sharply defined yield point, it is now 0.2 percent proof stress (*Figure 4*), as in ASTM Specifications.

A third supplementary requirement is now added for ASTM A615 Grade 60 reinforcement to be permitted for use in special moment frames and special shear walls. The minimum elongation in 8 inches must now be the same as that for ASTM A706 Grade 60 reinforcement.

The stress in prestressing steel at the stage of strength, f_{ps}, can be calculated based on strain compatibility, or is permitted to be calculated in accordance with Eq. (20.3.2.3.1) for members with bonded prestressed reinforcement if the effective prestress is no smaller than one-half the tensile strength of the prestressing reinforcement. ACI 318-14 now requires that all prestressing reinforcement be located in the tension zone for Eq. (20.3.2.3.1) to be applicable.

Chapter 22 – Sectional Strength

For prestressed members, a new equation for the nominal axial strength at zero eccentricity, P_o, has been introduced in Section 22.4.2.3.

ACI 318-14 has also added Section 22.4.3.1, which requires that the nominal axial tensile strength of a nonprestressed, composite, or prestressed member, P_{nt}, be taken greater than $P_{nt,max}$, calculated by the new Eq. (22.4.3.1).

In ACI 318-14, the two-way shear provisions are all expressed in terms of stress (v_n, v_c, v_s, used in ACI 318-11 for slab-column connections subject to axial load and moment), never force (V_n, V_c, V_s, used in ACI 318-11 for slab-column connections subject to concentric axial load only).

Section 22.6.4.2 now reads: "For two-way members reinforced with headed shear reinforcement or single- or multi-leg stirrups, a critical section with perimeter b_o located $d/2$ beyond the outermost peripheral line of shear reinforcement shall also be considered. The shape of this critical section shall be a polygon selected to minimize b_o." The last sentence is new in ACI 318-14 (*Figure 5*).

Chapter 25 – Reinforcement Details

Two changes are made in ACI 318-14 Table 25.3.2 to eliminate the difference between the required tail extension of a 90-deg or 135-deg standard hook ($6d_b$ in ACI 318-11) and that of a seismic hook ($6d_b$, subject to a minimum of 3 inches). The 3-inch minimum requirement now applies to standard hooks as well.

Mechanical or welded splices with strengths below 125% of the yield strength of the spliced reinforcing bars are no longer permitted. The associated stagger requirements have been

deleted. Thus, there is no longer a need to specify "full" mechanical or "full" welded splices.

ACI 318-11 referred to the 17th Edition of the AASHTO *Standard Specification for Highway Bridges* (2002) for the design of local zone reinforcement in post-tensioned anchorage zones. However, AASHTO is no longer updating the *Standard Specification for Highway Bridges*. Therefore, in Section 25.9.4.3.1, reference is now made to the AASHTO *LRFD Bridge Design Specifications*.

Chapter 26 – Construction Documents and Inspection

There was no direct counterpart to this chapter in ACI 318-11. The first paragraph of the Commentary to Chapter 26 gives a very good idea as to what the chapter is about: "…This chapter establishes the minimum requirements for information that must be included in the construction documents as applicable to the project. The requirements include information developed in the structural design that must be conveyed to the contractor, provisions directing the contractor on required quality, and inspection requirements to verify compliance with the construction documents. In previous editions of the Code through 2011, these provisions were located throughout the document. Starting with the 2014 edition, with the exception of Chapter 17, all provisions relating to construction have been gathered into this chapter for use by the licensed design professional. Construction and inspection-related provisions associated with anchors are in Chapter 17 and are called out within Sections 26.7 and 26.13, as appropriate."

There are some substantive changes made to the ACI 318-11 provisions covered in Chapter 26.

The ACI 318-11 (Section 3.5.1) language "Discontinuous deformed steel fibers shall be permitted only for resisting shear under conditions specified …" has been interpreted to restrict other applications in which discontinuous deformed steel fibers could potentially be used. The wording has been improved to indicate that ACI 318-14 only addresses the use of deformed steel fibers for shear. Other applications are not prohibited, but rather fall under ACI 318-14 Section 1.4.

ACI 318-11 Sections 5.3 – *Proportioning on the basis of field experience or trial mixtures, or both*, 5.4 – *Proportioning without field experience or trial mixtures*, and 5.5 – *Average compressive strength reduction* contained prescriptive requirements for mixture proportioning. These requirements are no longer found in ACI 318-14; instead, ACI 301-10, *Specifications for Structural Concrete*, is referenced from Section 26.4.3.

Requirements for post-tensioning ducts and grouting have also been removed as being outdated. The Commentary now provides specification guidance.

Conclusions

Contrary to the widely held perception that in view of a complete reorganization of ACI 318-14, technical changes were held to a minimum, ACI 318-14 contains a number of significant technical changes, some of the most important of which are found in Chapter 18, *Earthquake Resistant Structures*, and Chapter 19, *Concrete: Design and Durability Requirements*.▪

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