Structural Integrity Requirements for Concrete Buildings

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Concrete Thinking for a sustainable world

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Structures capable of safely supporting all conventional design loads may suffer local damage from severe, local abnormal loads, such as explosions caused by gas or industrial liquids, vehicle impact, or impact of local effects from very high winds such as those recorded in tornadoes. Generally, such abnormal loads or events are not design considerations.

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Learning Objectives

This article presents structural integrity requirements for reinforced concrete buildings in accordance with the American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-05). The reader will learn the detailing provisions to achieve structural integrity for cast-in-place joists, beams, two-way slabs, lift slabs, and precast concrete construction. All referenced items are from ACI 318-05, unless noted otherwise.

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Local failure of a major structural support may spread from element to element, resulting in the collapse of the entire structure. This sequence of failure is usually termed progressive collapse. Except for specially designed protective systems, it is impractical to design structures to resist this kind of collapse. However, minor changes in reinforcement detailing can be made to provide continuity and redundancy, and to increase the ductility of the structure, and thus limit the effects of local damage to help prevent or minimize progressive collapse. The overall ability of a reinforced concrete structure to withstand such abnormal loads can be enhanced substantially by providing relatively minor changes in the detailing of the reinforcement, without impacting the overall economy.

The American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-05) Section 7.13 sets forth provisions intended to improve the redundancy and ductility of structures. This is achieved by providing, as a minimum, some continuity reinforcement or tie between horizontal framing members. In the event of damage to a major supporting element or an abnormal loading, the integrity reinforcement is intended to confine any resulting damage to a relatively small area, thus improving overall stability.

It is not the intent of Section 7.13 that a structure is designed to resist partial or progressive collapse caused by gross misuse, or to resist severe abnormal loads acting directly on a large portion of the structure. General collapse of a structure as the result of abnormal events, such as wartime or

ACI 318-05 includes provision to improve structural stability, such as providing perimeter beams with continuous top and bottom reinforcement to ensure a continuous tie around the structure.

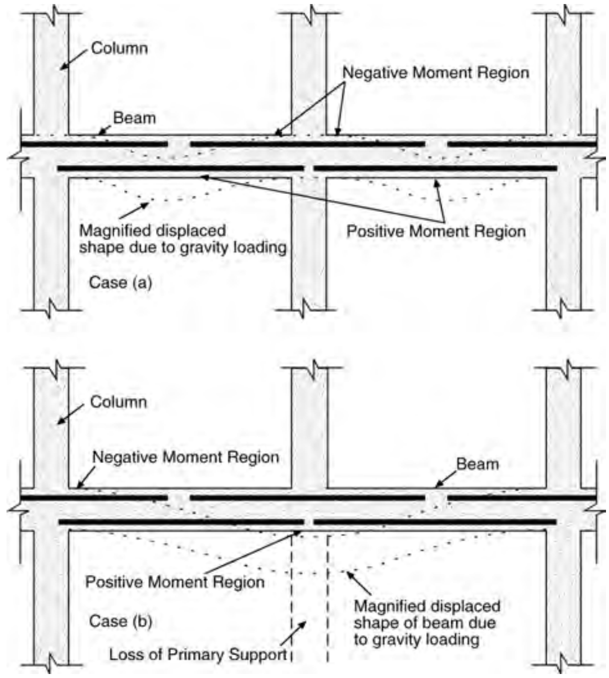


Figure 1: Lack of continuous reinforcement across the beam-to-column connection can lead to progressive collapse. (See Reference 4 on page 6)

Progressive Collapse vs. Structural Integrity

- Design against progressive collapse requires analysis and design assuming loss of one member at a time.
- ACI 318-05 Structural Integrity Requirements call for minor changes in detailing of reinforcement — no analysis is needed.

terrorist bombing and landslides, is beyond the scope of conventional/typical design criteria.

General structural integrity

Damage to a major supporting element of a structure caused by accident or abnormal loading can lead to collapse of a large portion of the structure or total collapse of the structure. Since accidents are normally unforeseeable events, they cannot be defined precisely; likewise, providing general structural integrity to a structure is a requirement that cannot be stated in simple terms. The performance provision outlined in the American Society of Civil Engineers' Minimum Design Loads for Buildings and Other Structures (ASCE 7-05) states that "members of a structure shall be effectively tied together to improve integrity of the overall structure." This provision will require a level of judgment on the part of the designer and will generate differing opinions among designers as to how effectively to provide a structural integrity solution for a particular framing system. It is obvious that all conditions that might be encountered in design cannot be specified in the code. The code, however, does set forth specific requirements for reinforcement details for cast-in-place joists, beams, two-way slab construction, and precast structures.

Consider the continuous beam in Figure 1 Case (a), where bottom reinforcement is provided only along the length of the beam where positive moment is induced by downward loads. As shown in Case (b) it is unlikely that the beam will be capable of redistributing the loads in case of damage to, or loss of, a supporting column. Minor changes in reinforcement detailing without much impact on the cost of the structure can prevent such collapse. ACI 318-05 includes provisions for structural integrity reinforcement that require some top and bottom beam reinforcement to be continuous.

An example of vulnerability addressed by Section 7.13 is potential damage to a support. With damage to a support, the top reinforcement — which is continuous over the support, but not confined by stirrups — will tend to tear out of the concrete and will not provide the catenary action needed to bridge the damaged support. By making a portion of the bottom reinforcement in beams continuous over supports, some catenary action can be provided. In edge or perimeter beams, providing some continuous top and bottom reinforcement creates tying action and provides continuity. The continuous tie provided to perimeter beams will toughen the exterior portion of a structure, should an exterior column be severely damaged.

There are other conditions and structural configurations where the designer should evaluate the necessary integrity requirements for a framing system to carry loads around a severely damaged support. The designer will need to evaluate the design conditions and incorporate the necessary integrity requirements through proper detailing. The concept of providing general structural integrity is also discussed in the commentary of ASCE 7-05, and in the commentary to Section 7.13.

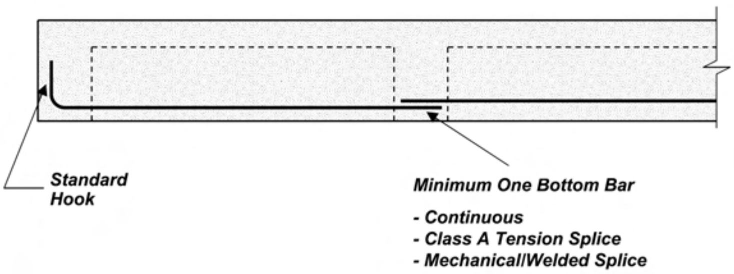


Figure 2: In joist construction, at least one bottom bar must be continuous or must be spliced with a Class A tension splice or mechanical or welded splice. At a non-continuous end of the joist, the bars must be terminated with a standard hook. Structural integrity requirements for joist construction are provided in Section 7.13.2.1.

Cast-in-place joists and beams

Joist construction conforming with Sections 8.11 and 7.13.2.1 requires at least one bottom bar to be continuous or spliced with a Class A tension splice or a mechanical or welded splice satisfying Section 12.14.3. At a non-continuous end of the beam, the bottom bars must be terminated with a standard hook. The structural integrity requirements for joists are depicted in Figure 2.

For perimeter or spandrel beams, the code requires some of the top and bottom reinforcement to be continuous. The continuous top and bottom reinforcement provides a continuous tie around the structure, and would act as a catenary in case of loss of a support. Section 7.13.2.2 sets forth the requirements for continuous reinforcement in perimeter beams; these requirements are illustrated in Figures 3 and 4 and are based on the following:

- At least one-sixth of the tension reinforcement required for negative moment at support, but not less than two bars, must be continuous or spliced at or near midspan.
- Section 12.11.1 requires that at least one-fourth of the positive moment reinforcement in continuous members extend into the support 6 inches. Section 7.13.2.3 requires that same amount of reinforcement to be continuous or spliced at or near the support. If the depth of a continuous beam changes at a support, the bottom reinforcement in the deeper member should be terminated with a standard hook and bottom reinforcement in the shallower member should be extended into and fully developed in the deeper member.

Section 7.13.2.3 requires that the continuous top and bottom reinforcement required for structural integrity of perimeter beams be enclosed by the corners of U-stirrups having not less than 135-degree hooks around the continuous top bars, or by one-piece closed stirrups with not less than 135-degree hooks around one of the continuous top bars. Size and spacing of stirrups are based on shear and torsion design requirements. Stirrups need not be extended through any joints. Figures 4 and 5 illustrate these requirements.

The structural integrity requirement for interior beams, Section 7.13.2.4, follows the positive moment tension reinforcement requirements for perimeter beams (see Figure 6). At least one-quarter of the positive moment reinforcement, but not less than two bars, must be continuous. This reinforcement may be spliced over or near the support with a Class A tension splice or a mechanical or welded splice satisfying Section 12.14.3, and standard hooks must be used to terminate reinforcement at noncontinuous ends. Interior beams are not required to provide stirrups as defined in Section 7.13.2.3.

Background of 318-05 Structural Integrity Requirements

- Section 7.13, Requirements for Structural Integrity, was introduced in ACI 318-89.
- Purpose: To enhance overall continuity, redundancy, and ductility of a structure through minor changes in detailing of reinforcement — without impacting economy.

Cast-in-place two-way slabs

For two-way slab construction, Section 7.13 refers to 13.3.8.5 for structural integrity requirements. Section 13.3.8.5

Figure 3: Continuous top reinforcement in conjunction with bottom bars in perimeter beams provides continuous tie around the structure. Structural integrity requirements for top bars of perimeter beams are provided in Section 7.13.2.2(a).

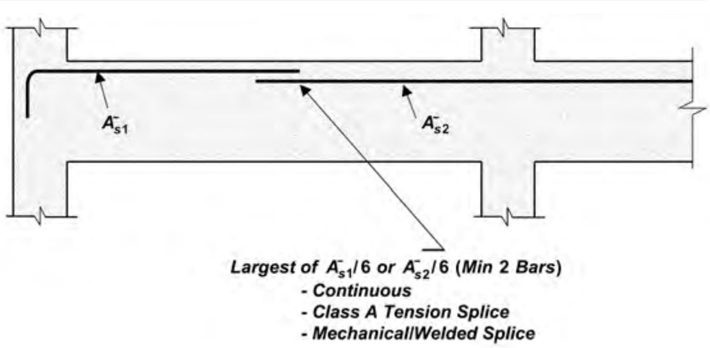
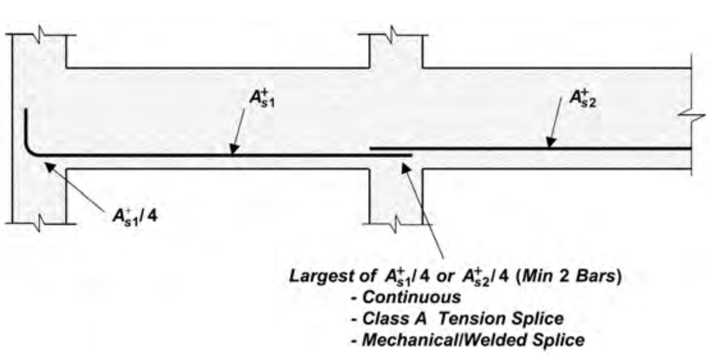
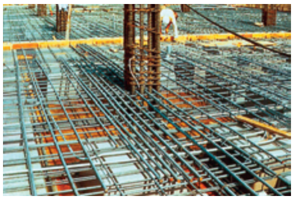


Figure 4: Catenary action can be provided by extending a portion of the bottom reinforcement and making it continuous. The portion of bottom reinforcement required to be extended into the support must be made continuous or spliced with bottom reinforcement from the adjacent span. Structural integrity requirements for bottom bars of perimeter beams are provided in Section 7.13.2.2(b).





Continuous column strip bottom bars through the column core give the slab some residual capacity in case of a punching shear failure at a single support, per Section 13.3.8.5.

requires that all bottom bars or wires within the column strip, in each direction, be continuous or spliced with Class A tension splices or with mechanical or welded splices satisfying Section 12.14.3. (see ACI 318-05 Figure 13.3.8 for permissible locations for splices). In addition, at least two of the column strip bottom bars or wires in each direction must pass within the column core, and must be anchored at exterior supports. The continuous column strip bottom reinforcement provides the slab some residual ability to span to the adjacent supports should a single support be damaged. The two continuous column strip bottom bars or wires through the column are provided to give the slab some residual capacity following a punching shear failure at a single support.

In slabs where shearheads are used as shear reinforcement and it is not practical to pass the bottom bars required by section 13.3.8.5 through the column, at least two bonded bottom bars or wires in each direction must pass through the shearhead as close to the column as practicable and be continuous or spliced with a Class A splice. At exterior columns, the reinforcement must be anchored at the shearhead.

In some instances, there is sufficient clearance so that the bonded bottom bars can pass under shearheads and through the column. Where clearance under the shearhead

Requirements for Structural Integrity in ACI 318-05

- Cast-in-place (CIP) joist (Section 7.13.2.1)
- CIP perimeter beams (Section 7.13.2.2-.3)
- CIP other than perimeter beams (Section 7.13.2.4)
- CIP slabs (Section 13.3.8.5)
- Lift-slabs (Section 13.3.8.6, 18.12.6)
- Precast structures (Section 16.5)

is inadequate, the bottom bars should pass through holes in the shearhead arms. Shearheads should be kept as low as possible in the slab to increase their effectiveness.

Lift slabs

In lift-slab construction where it is not practical to pass the bottom bars required through the column, at least two bonded bottom bars or wires in each direction must pass through the lifting collar as close to the column as practicable and be continuous or spliced with a Class A splice. At exterior columns, the reinforcement must be anchored at the lifting collar.

Precast concrete construction

Because of the segmental construction of precast structures, the code requires tension ties in the transverse, longitudinal, and vertical directions for precast concrete buildings of all heights to tie elements together effectively. The trans-

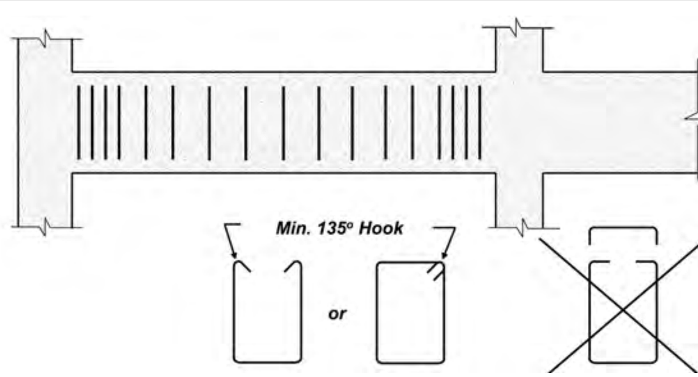


Figure 5: To prevent the top continuous bars from tearing out of the top of the beam, U-stirrups with 135-degree hooks, or one-piece closed stirrups must be used around the continuous bars. Structural integrity requirements for stirrups in perimeter beams are provided in Section 7.13.2.3.

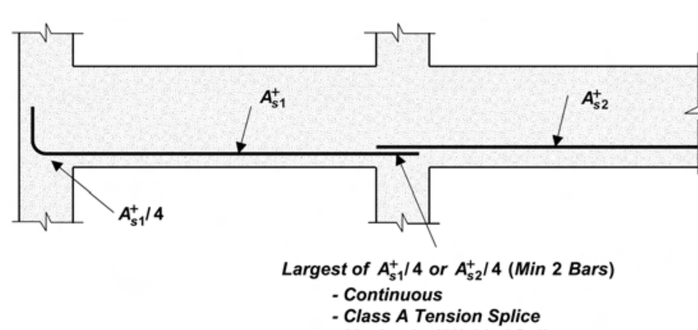


Figure 6: Structural integrity requirements for bottom reinforcement interior beams are provided in Section 7.13.2.4.

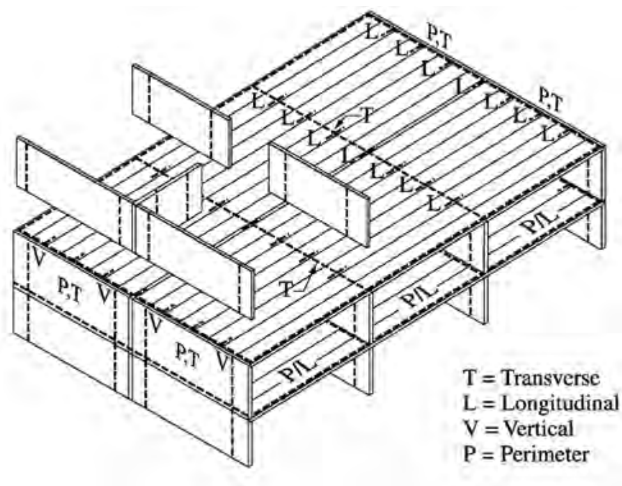


Figure 7: Typical arrangement of tensile ties in precast bearing wall structures, include typical transverse, longitudinal, vertical, and perimeter arrangements. (See Reference 7)

verse and longitudinal ties must connect individual precast members to a lateral load resisting system. Connections that rely solely on friction due to gravity forces are not permitted. The connections between the diaphragm and the members being laterally supported must have a nominal tensile strength of at least 300 pounds per linear foot. The general requirement for structural integrity in Section 7.13.1 states that "… members of a structure shall be effectively tied together …"

The overall integrity of a precast structure can be substantially enhanced by minor changes in the amount, location, and detailing of member reinforcement, and in detailing of connection hardware. With that in mind, the ACI 318-05 Commentary cautions that for precast concrete construction, connection details should be arranged so as to minimize the potential for cracking from restrained creep, shrinkage, and temperature movements. See Section 16.5 for detailed structural integrity design requirements for precast construction, including requirements for precast bearing wall structures three or more stories in height. The commentary refers the designer to the Precast/Prestressed Concrete Institute's Manual Design and Typical Details of Connections for Precast and Prestressed Concrete (MNL-123-88) for information on connections and detailing requirements. Figure 7 shows the typical arrangement of tension ties in precast bearing wall structures, often called large panel structures. The ties for this structural system are intended to provide catenary hanger supports in the event of loss of bearing wall support. The ACI 318-05 requires these ties to be designed to carry a minimum of 300 pounds per linear foot.

Conclusion

The Structural Integrity provisions set forth by the ACI 318-05 are intended to improve the redundancy and ductility of structures by including minor changes to standard detailing practice. Furthermore, these provisions are crafted to provide this added continuity without economical implications. ■

ASCE 7-05 Section 1.4 General Structural Integrity

- Design buildings to sustain local damage and prevent other damage disproportionate to the local damage.
- Arrange structural elements to provide stability to the entire structure.
- Transfer loads from locally damaged region.
- Provide continuity, redundancy, and ductility.

Resources

1. Building Code Requirements for Structural Concrete ACI 318-05 and Commentary-ACI 318R-05, American Concrete Institute, Farmington Hills, Mich., 2005.
2. Notes on ACI 318-05 Building Code Requirements for Structural Concrete, EB705, Portland Cement Association, Skokie, Ill., 2005.
3. Minimum Design Loads for Buildings and Other Structures, ASCE 7-05, American Society of Civil Engineers, New York, 2005.
4. Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects, U.S. General Services Administration, November 2003.
5. Design of Concrete Structures, 13th Edition, Arthur H. Nilson et al, McGraw Hill, 2003.
6. Design and Typical Details of Connections for Precast and Prestressed Concrete, MNL-123-88, Precast/ Prestressed Concrete Institute, Chicago, 1988.
7. Design and Construction of Large-Panel Concrete Structures, EB092, Portland Cement Association, Skokie, Ill., 1976.
8. An Engineering Guide to Concrete Buildings and Progressive Collapse, IS545, Portland Cement Association, Skokie, Ill., 2005.

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Quiz questions

1. **In which edition of ACI 318 were the Structural Integrity provisions first included?**
   a) 2005 b) 2002 c) 1989 d) 1983

2. **Structural Integrity provisions of ACI 318 are minimum requirements for what types of buildings?**
   a) Residential b) Commercial c) Federal d) All

3. **Structural Integrity provisions of ACI 318 are intended to:**
   a) Prevent progressive collapse
   b) Improve ductility, redundancy, and continuity
   c) Supersede GSA/DoD provisions
   d) Increase the seismic Ω-factor

4. **For cast-in-place construction, perimeter beams should have continuous top reinforcement consisting of at least ___ of the tension reinforcement for negative moment at the support.**
   a) 2 inches^2 b) 1/2 A_s c) M_u / 4d d) 1/6 A_s

5. **For cast-in-place construction, perimeter beams should have continuous bottom reinforcement consisting of at least ___ of the tension reinforcement for positive moment at midspan.**
   a) 1/2 A_s b) two continuous bars c) 1/4 A_s d) b and c

6. **For cast-in-place construction, where splices are needed to provide continuity, the top reinforcement shall be spliced at or near the:**
   a) Support b) Plastic hinge c) Midspan d) Point of inflection

7. **For cast-in-place construction, where splices are needed to provide continuity, the bottom reinforcement shall be spliced at or near the:**
   a) Support b) Plastic hinge c) Midspan d) Point of inflection

8. **For cast-in-place construction, the continuous top reinforcement shall be enclosed by:**
   a) Hoop stirrups having standard hooks
   b) U-stirrups having 90-degree hooks
   c) U-Stirrups having 135-degree hooks
   d) Hoop stirrups with cross-ties

9. **For two-way slab construction, at least ___ of the column strip bars should pass within the core of the column and shall be anchored at exterior supports.**
   a) One b) Two c) Three d) Four

10. **For precast concrete construction, the connections between diaphragm and the members being laterally supported shall have a nominal tensile strength capable of resisting at least:**
    a) 10 kips
    b) 300 pounds per linear foot
    c) 300 pounds
    d) 3 kips per linear foot

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2)	a	b	c	d	7)	a	b	c	d
3)	a	b	c	d	8)	a	b	c	d
4)	a	b	c	d	9)	a	b	c	d
5)	a	b	c	d	10)	a	b	c	d

Required contact information

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Signature: Date: