ICC SPRING INTERCHANGE

Surfside Florida Building Collapse of June 2021 and ACI 318 Building Code Requirements for Structural Concrete

PART 3 OF 4

ICC INTERNATIONAL CODE COUNCIL®

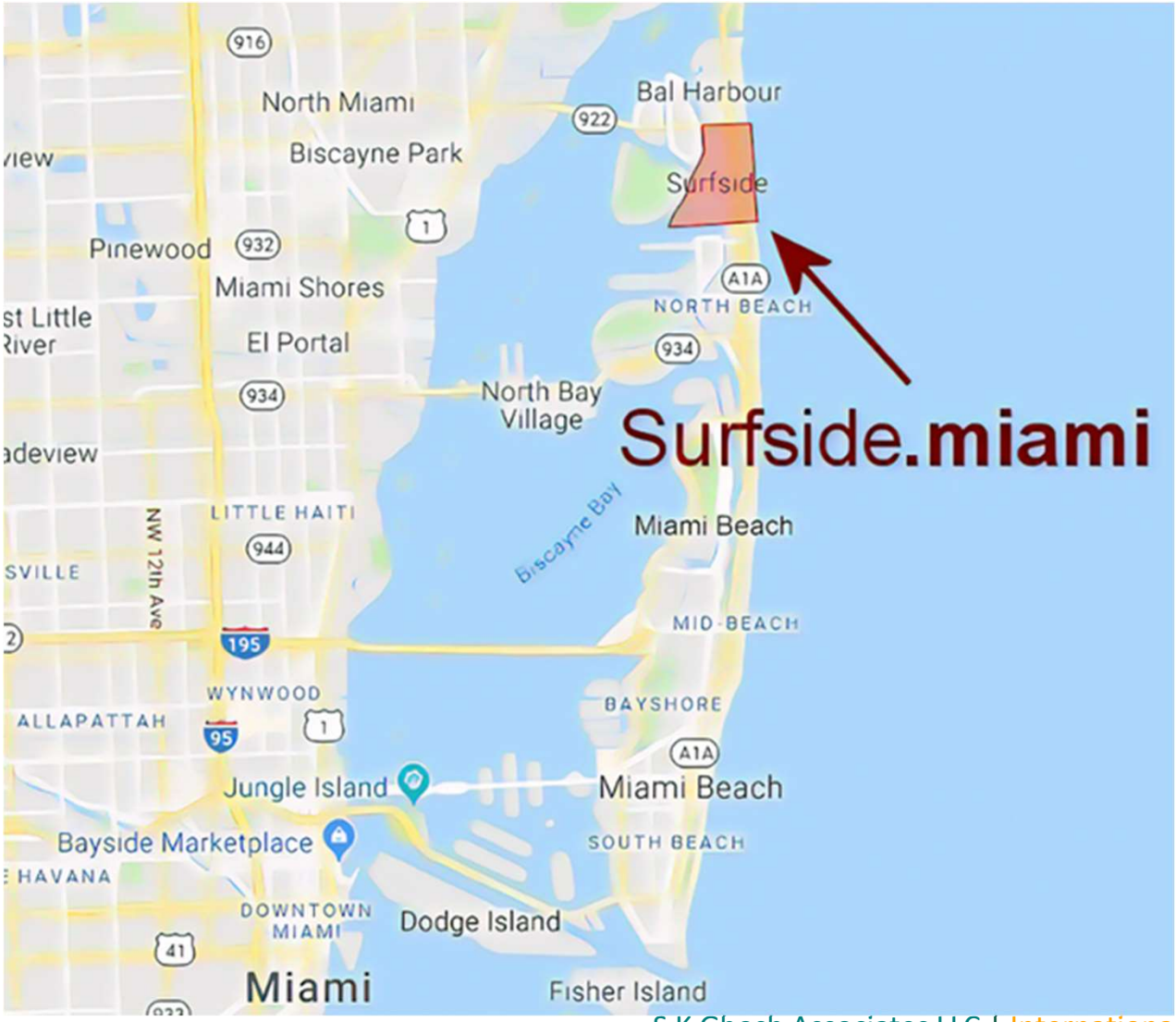
Surfside, Florida Building Collapse of June 2021 and ACI 318 Building Code Requirements for Structural Concrete: Part 3 of 4

S. K. Ghosh, S. K. Ghosh Associates LLC

Palatine, IL

The Event

On **Thursday, June 24, 2021**, at approximately 1:25 a.m. EDT, Champlain Towers South, a 12-story beachfront condominium in the Miami suburb of Surfside, Florida, partially collapsed. Ninety-eight people died.



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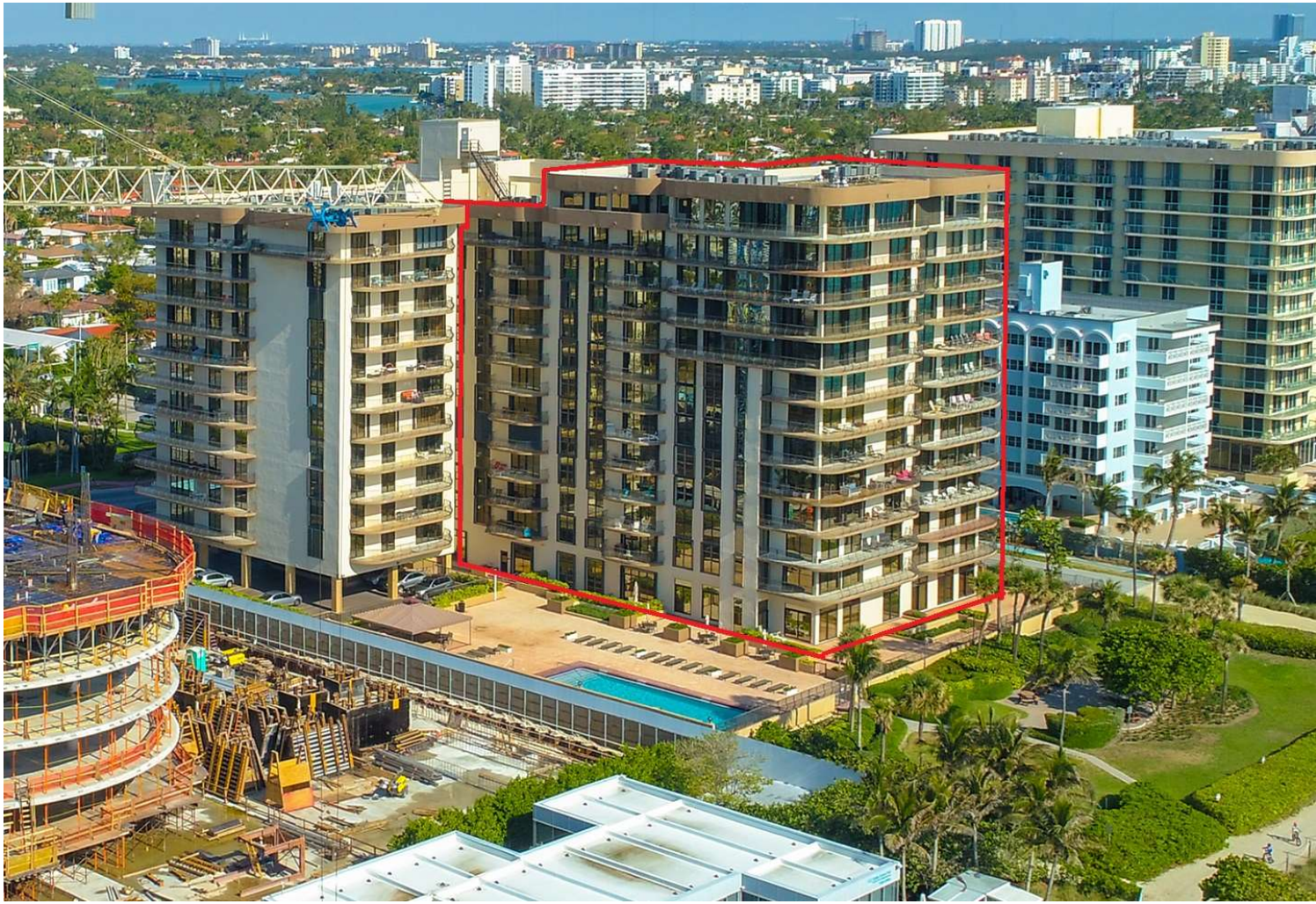
Champlain Tower South Before Collapse



Before and After Collapse

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Critical Improvements in ACI 318 since Building Was Designed

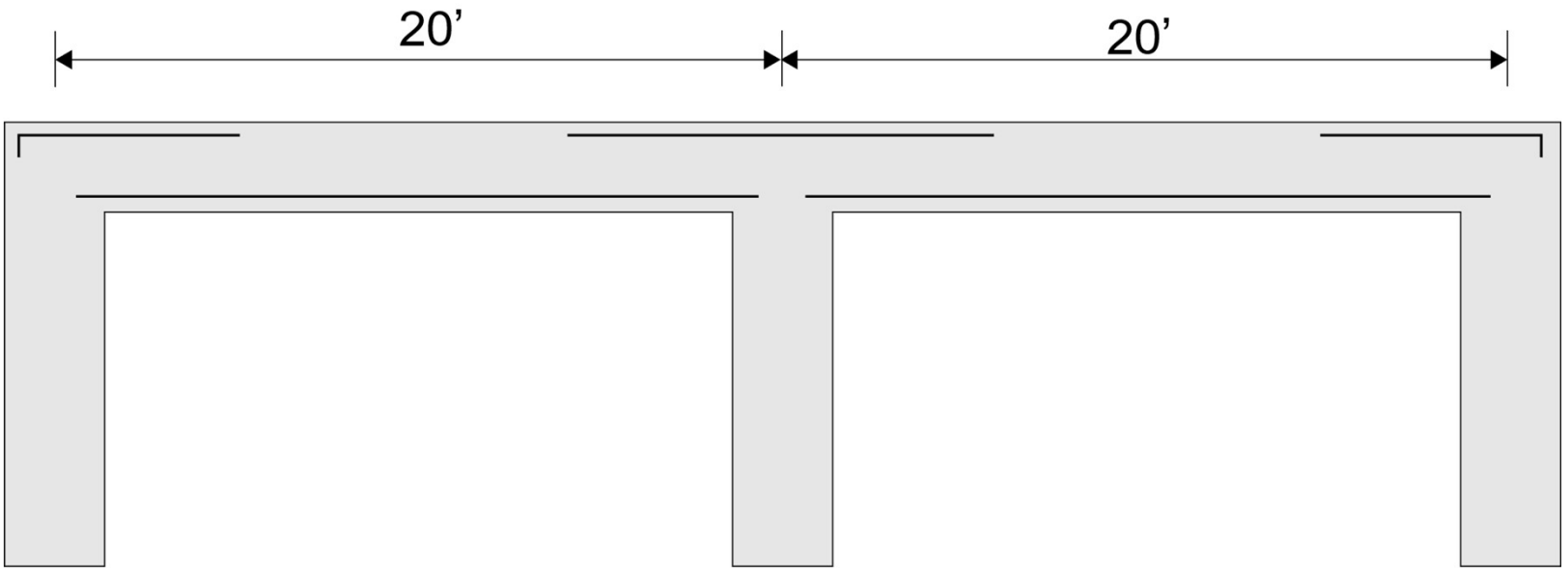
The building was likely designed under the early or mid-1970s Florida Building Code and ACI 318-71 or ACI 318-77. Concrete durability, flat plate punching shear, and structural integrity provisions of ACI 318 are critical areas of improvements that engineers, architects, and building officials must be familiar with for safe performance of concrete buildings.

STRUCTURAL INTEGRITY

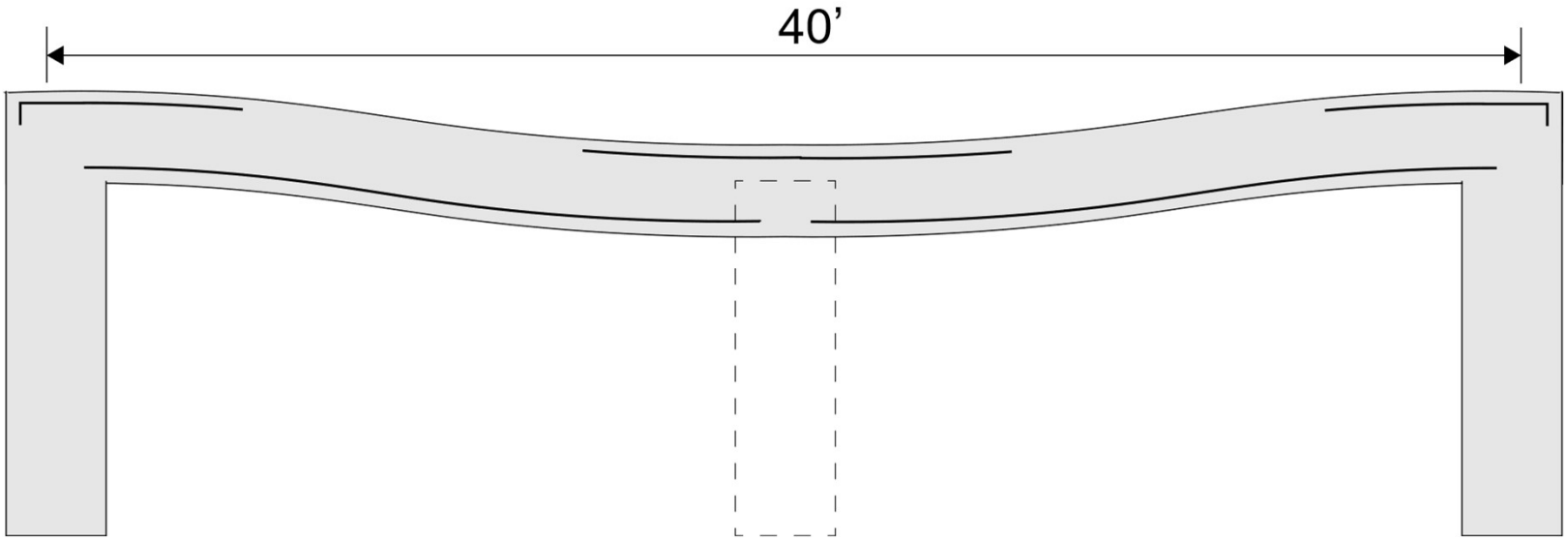
7.13 – REQUIREMENTS FOR STRUCTURAL INTEGRITY

- Introduced in ACI 318-89
- Purpose: To Enhance Overall Integrity of a Concrete Structure through Minor Changes in Detailing of Reinforcement - without Impacting Economy

WITHOUT CONTINUOUS BOTTOM REINFORCEMENT



WITHOUT CONTINUOUS BOTTOM REINFORCEMENT



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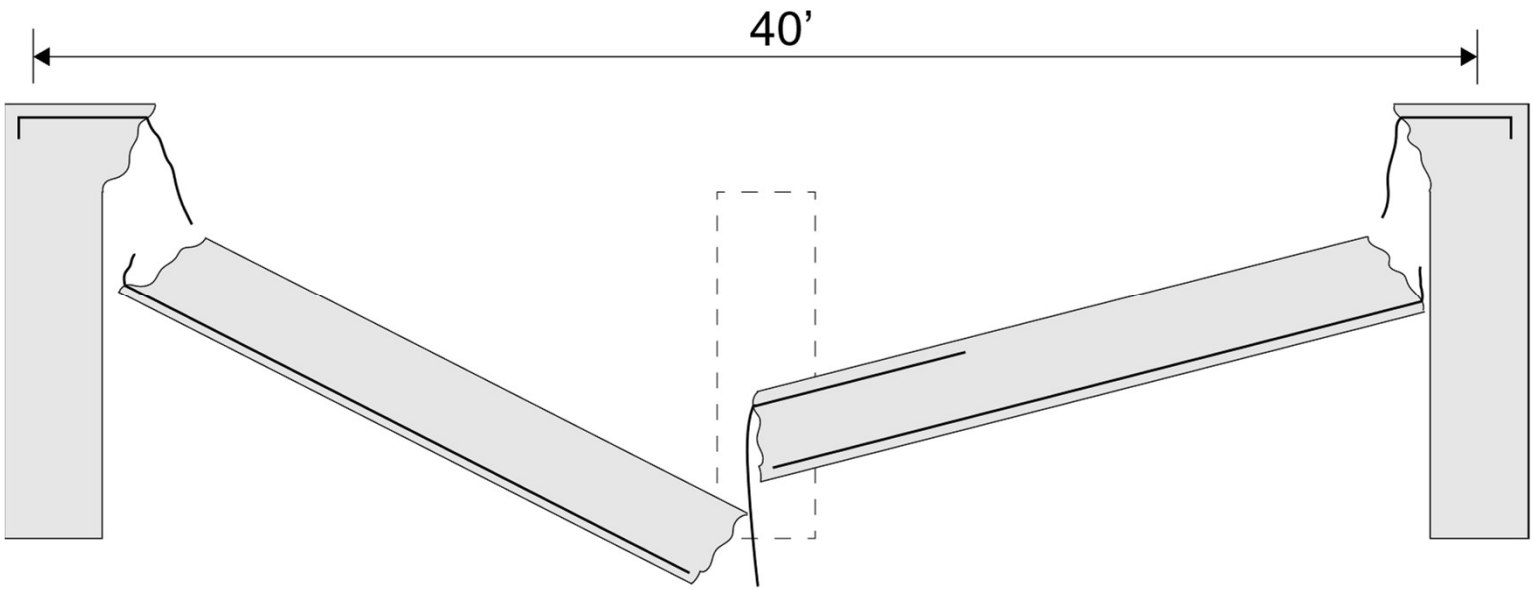
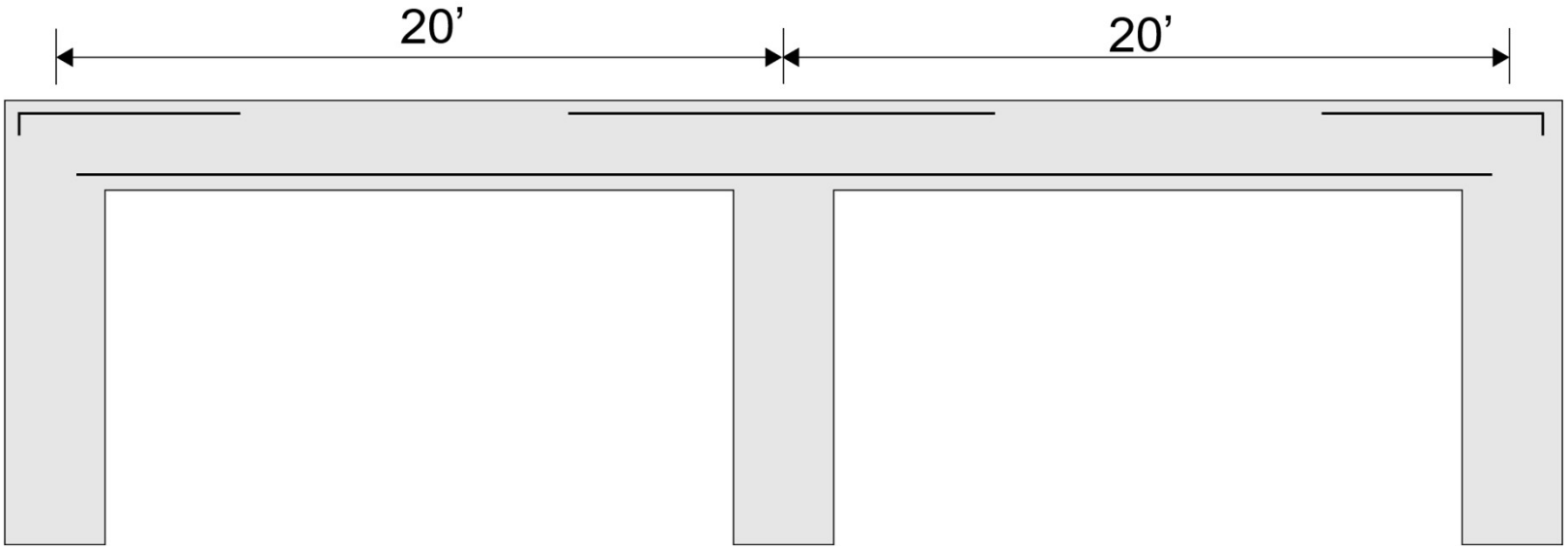
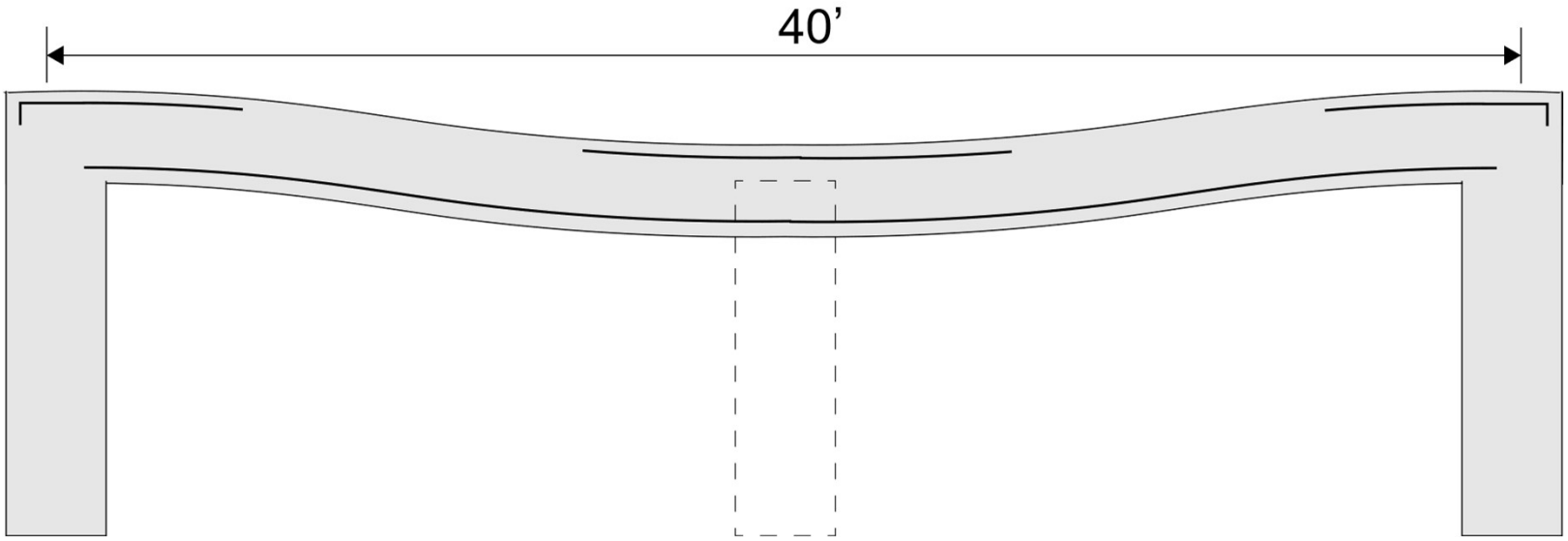


WITH CONTINUOUS BOTTOM REINFORCEMENT



WITH CONTINUOUS BOTTOM REINFORCEMENT



Ronan Point (1968) Explosion on 18th Floor of 22 Floors

Ronan Point

Load-Bearing Precast Panels

Explosion in Lower Story

Local Damage

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Progressive Collapse vs. Structural Integrity

- Design against progressive collapse requires extensive analysis and design assuming loss of one member at a time
- ACI 318 structural integrity requirements call for minor changes in detailing of reinforcement – no analysis is needed

318-89 – 318-11 7.13 - Requirements for structural integrity

7.13.1 -In the detailing of reinforcement and connections, members of a structure shall be effectively tied together to improve integrity of the overall structure.

318-89 – 318-11 R7.13 – Structural Integrity Requirements

Experience has shown that the overall integrity of a structure can be substantially enhanced by minor changes in detailing of reinforcement. It is the intent of this section of the Code to improve the redundancy and ductility in structures so that in the event of damage to a major supporting element or an abnormal loading event, the resulting damage may be confined to a relatively small area and the structure will have a better chance to maintain overall stability.

318-14 Structural Integrity Requirements after Reorganization

4.10.1.1 Reinforcement and connections shall be detailed to tie the structure together effectively and to improve overall structural integrity.

318-14 Structural Integrity Requirements after Reorganization

4.10.2 *Minimum requirements for structural integrity*

4.10.2.1 Structural members and their connections shall be in accordance with structural integrity requirements in Table 4.10.2.1.

318-14 Structural Integrity Requirements after Reorganization

Table 4.10.2.1—Minimum requirements for structural integrity

Member type	Section
Nonprestressed two-way slabs	8.7.4.2
Prestressed two-way slabs	8.7.5.6
Nonprestressed two-way joist systems	8.8.1.6
Cast-in-place beam	9.7.7
Nonprestressed one-way joist system	9.8.1.6
Precast joints and connections	16.2.1.8

Structural Integrity Requirements of ACI 318

318-89

7.13.1 – General

7.13.2 – Cast-in-place construction

- 7.13.2.1 – Joist construction
- 7.13.22 – Perimeter beams
- 7.13.2.3 – Other than perimeter beams
- 7.13.2.4 – Two-way slab construction; refers to 13.4.8.5

7.13.3 – Precast construction

Structural Integrity Requirements of ACI 318

318-89 (Revised 92)

7.13.4 – Lift-slab construction added

318-95

7.13.2.2 (Perimeter beams) – Addition inserted

7.13.2.4 (Two-way slabs) – Now refers to 13.3.8.5

7.13.3 (Precast construction) – Now refers to 16.5

318-99

No change

Structural Integrity Requirements of ACI 318

318-02

Many changes

Mechanical and welded splices added to Class A tension splices

7.13.2.2 (Perimeter beams) – Split into 7.13.2.2 and 7.13.2.3

Previous 7.13.2.3 (Other than perimeter beams) is now 7.13.2.4

Previous 7.13.2.4 (Two-way slabs) is now 7.13.2.5

318-05

No change

Structural Integrity Requirements of ACI 318

318-08

Many changes

Anchoring at discontinuous supports is now much more specific

Class A tension splice changed to Class B tension splice

7.13.2.2 (Perimeter beams) of 318-89 is now in three sections: 7.13.2.2, 7.13.2.3, 7.13.2.4

Former 7.13.2.4 (Other than perimeter beams is now 7.13.2.5)

Former 7.13.2.5 (Two-way slabs) now split into:

7.13.2.6 – Nonprestressed two-way slabs

7.13.2.7 – Prestressed two-way slabs

Structural Integrity Requirements of ACI 318

318-11

Tension splice changed to tension lap splice

318-14

Reorganization

Structural integrity of two-way joist construction added

318-19

Welded stirrups in accordance with 25.5.7

Class B tension lap splices in accordance with 25.5.2

in Sections 8.7.4.2.1 and 9.7.7.6

CAST-IN-PLACE JOISTS AND BEAMS

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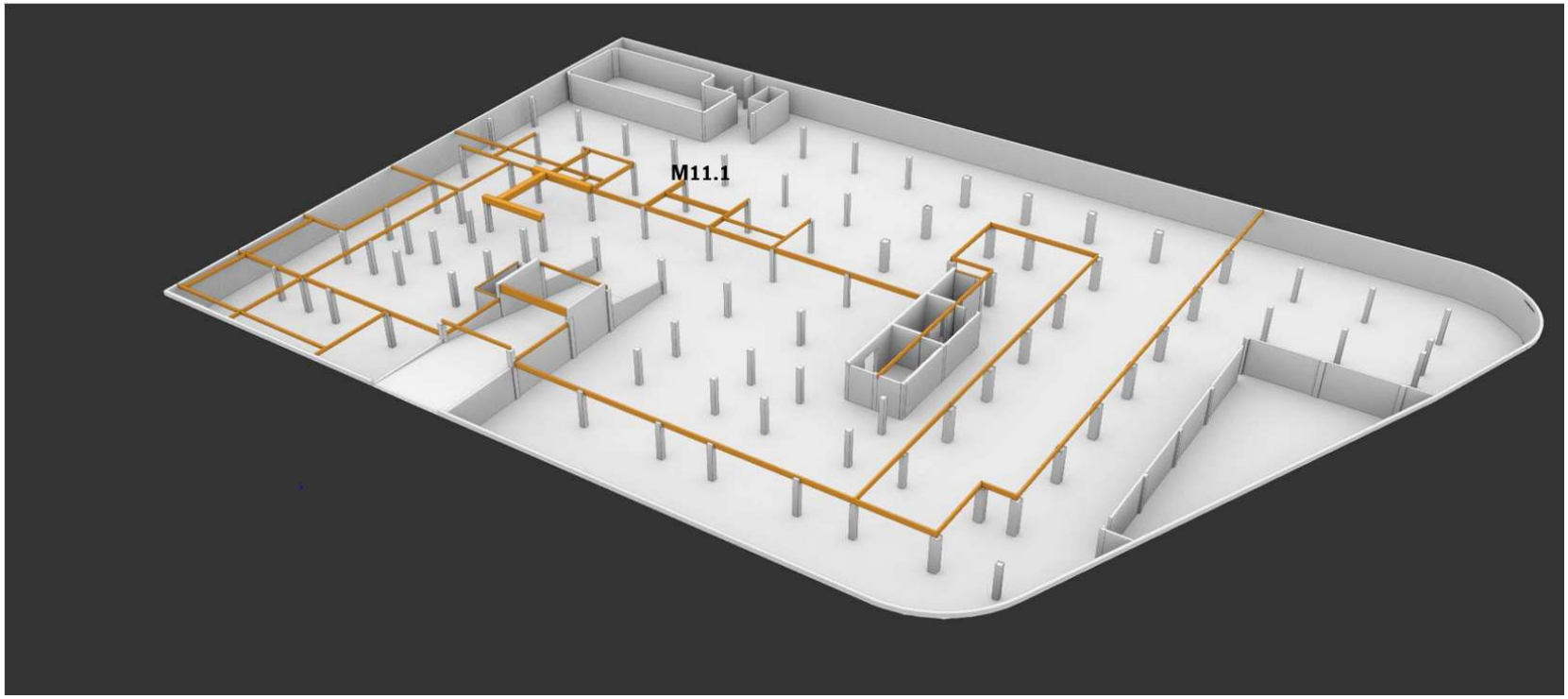
Beams Supporting Ground-Level Slab above Basement



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Cast-in-Place Construction –Joist Construction

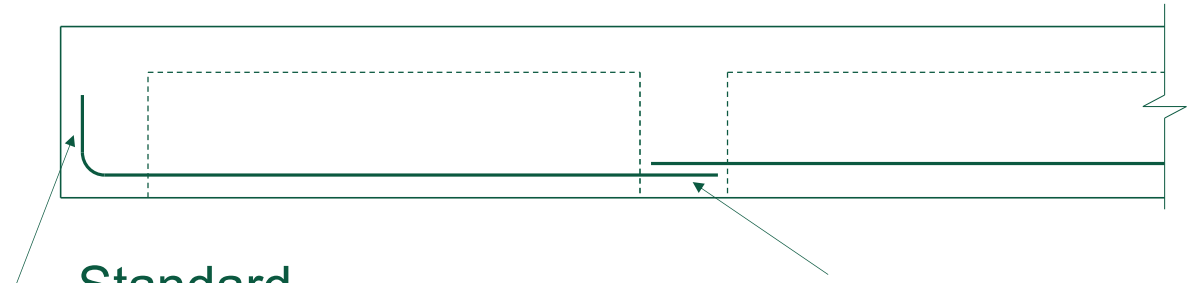
7.13.2 - For cast-in-place construction, the following shall constitute minimum requirements:

7.13.2.1 - In joist construction, at least one bottom bar shall be continuous or shall be spliced over the support with a Class A tension splice and at noncontinuous supports be terminated with a standard hook.

R7.13.2 – Structural Integrity Requirements

With damage to a support, top reinforcement that 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 continuous, catenary action can be provided.

7.13.2.1 – Joist Construction



Standard Hook

Minimum One Bottom Bar

- Continuous
- Class A Tension Splice (Class B 318-08)
- Mechanical/Welded Splice (318-02)

318-89 7.13.2.2 – Perimeter Beams

Beams at the perimeter of the structure shall have at least one-sixth of the tension reinforcement required for negative moment at the support and one-quarter of the positive moment reinforcement required at midspan made continuous around the perimeter and tied with closed stirrups, or stirrups anchored around the negative moment reinforcement with a hook having a bend of at least 135 deg [ACI 318-95]. Stirrups need not be extended through any joints. When splices are needed, the required continuity shall be provided with top reinforcement spliced at midspan and bottom reinforcement spliced at or near the support with Class A tension splices.

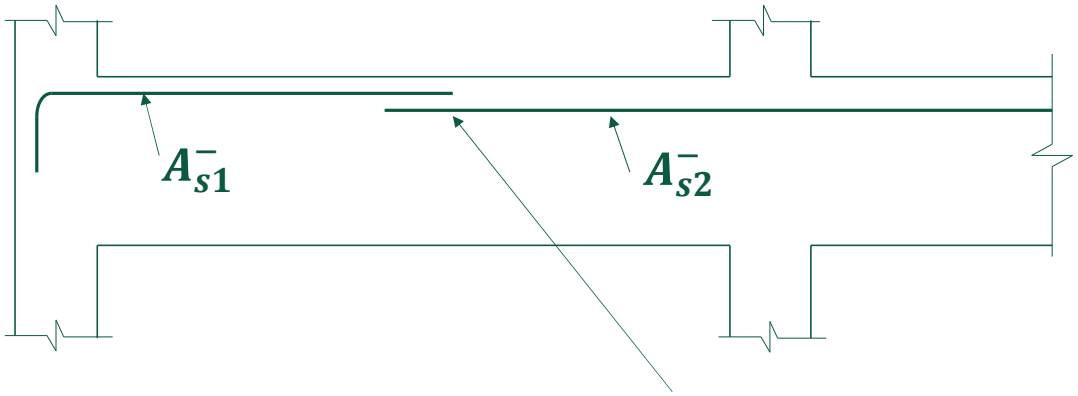
318-89 R7.13.2 – Structural Integrity Requirements

Requiring continuous top and bottom reinforcement in perimeter or spandrel beams provides a continuous tie around the structure. It is not the intent to require a tensile tie of continuous reinforcement of constant size around the entire perimeter of a structure, but simply to require that one half of the top flexural reinforcement required to extend past the point of inflection by 12.12.3 be further extended to lap splice at midspan. Similarly, the bottom reinforcement required to extend into the support by 12.11.1 must be made continuous or spliced with bottom reinforcement from the adjacent span. 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.

ACI 318-89 12.12 – Development of Negative Moment Reinforcement

12.12.3 — At least one-third the total tension reinforcement provided for negative moment at a support shall have an embedment length beyond the point of inflection not less than effective depth of member, $12d_b$, or one-sixteenth the clear span, whichever is greater.

7.13.2.2(a) – Perimeter Beams



Largest of $A_{s1}^-/6$ or $A_{s2}^-/6$ (Min 2 Bars)

- Continuous
- Class A Tension Splice (Class B 318-08)
- Mechanical/Welded Splice (318-02)

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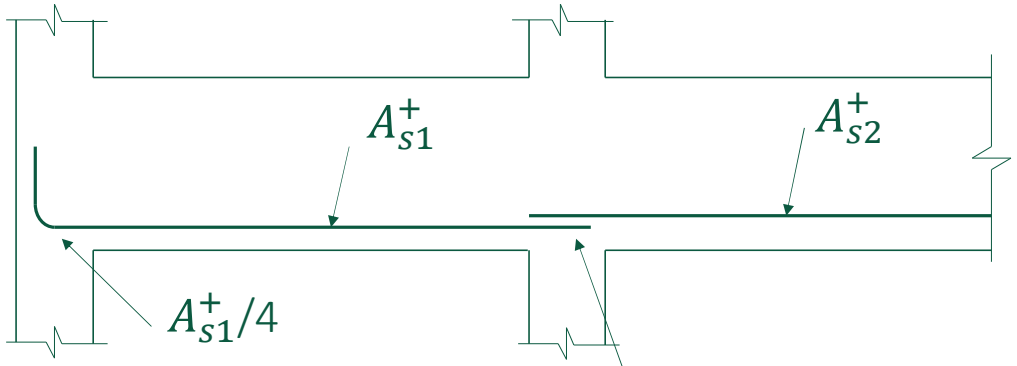
ACI 318-89 12.12 – Development of Positive Moment Reinforcement

ACI 318-89 12.11.1 — At least one-third the positive moment reinforcement in simple members and one-fourth the positive moment reinforcement in continuous members shall extend along the same face of member into the support. In beams, such reinforcement shall extend into the support at least 6 in.

7.13.2.2(b) – Perimeter Beams



$$Largest\ of\ A_{s1}^{+}/4\ or\ A_{s2}^{+}/4\ (Min\ 2\ Bars)$$

- Continuous
- Class A Tension Splice (Class B 318-08)
- Mechanical/Welded Splice (318-02)

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318-02 7.13.2.2 – Perimeter Beams

Beams along the perimeter of the structure shall have continuous reinforcement consisting of:

(a) at least one-sixth of the tension reinforcement required for negative moment at the support, but not less than two bars; and

(b) at least one-quarter of the tension reinforcement required for positive moment at midspan, but not less than two bars.

318-02 7.13.2.3 – Perimeter Beams

7.13.2.3 — Where splices are needed to provide the required continuity, the top reinforcement shall be spliced at or near midspan and bottom reinforcement shall be spliced at or near the support. Splices shall be Class A tension splices or mechanical or welded splices satisfying 12.14.3. The continuous reinforcement required in 7.13.2.2(a) and 7.13.2.2(b) shall be enclosed by the corners of U-stirrups having not less than 135-deg hooks around the continuous top bars, or by one-piece closed stirrups with not less than 135- deg hooks around one of the continuous top bars. Stirrups need not be extended through any joints.

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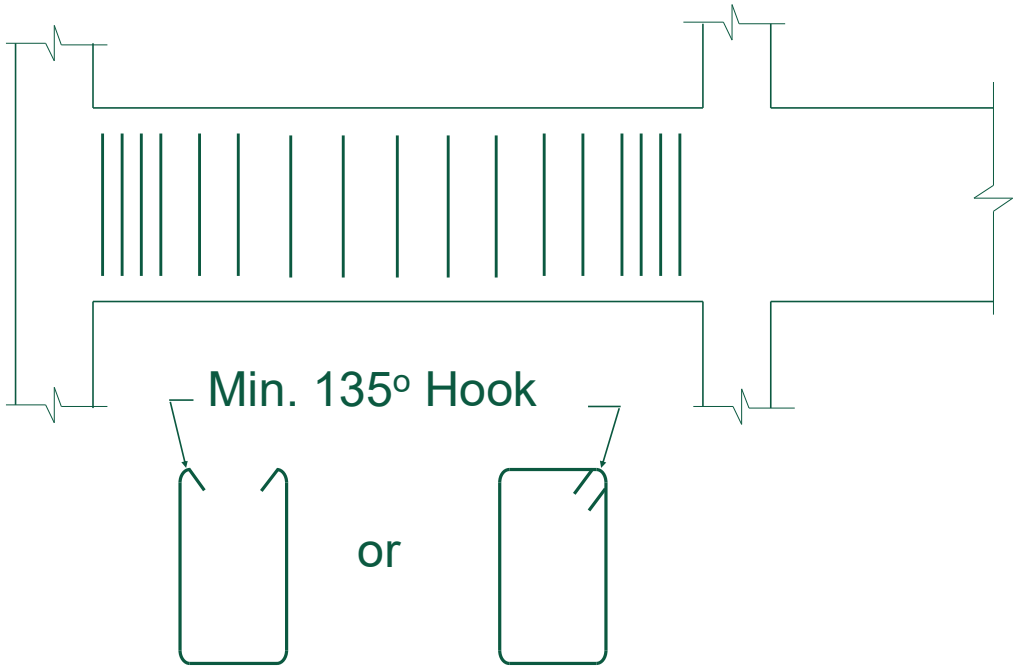
318-02 7.13.2.3 – Perimeter Beams



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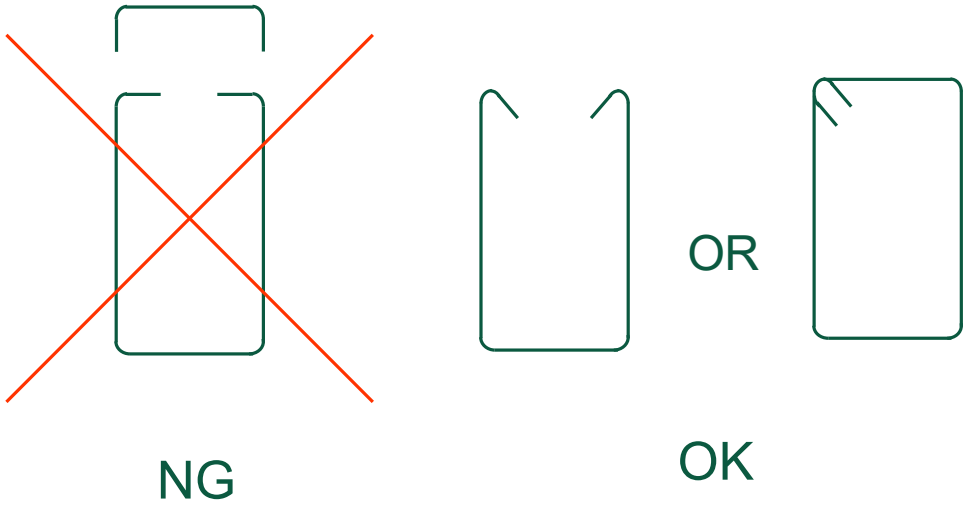
318-02 R7.13.2.3 – Perimeter Beams

Section 7.13.2 was revised in 2002 to require U-stirrups with not less than 135-deg hooks around the continuous bars, or one-piece close stirrups, because a crosstie forming the top of a two-piece closed stirrup is ineffective in preventing the top continuous bars from tearing out of the top of the beam.

R7.13.2.3 (from 318-02) – Perimeter Beams



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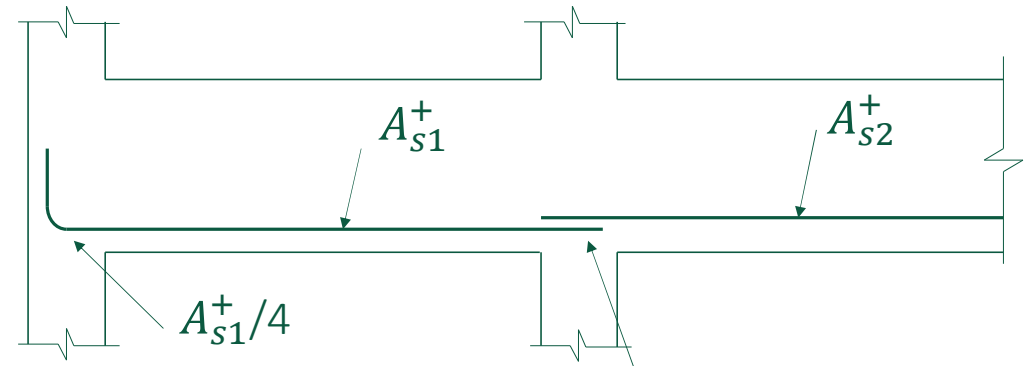
318-89 7.13.2.3 (318-02 7.13.2.4) – Other than Perimeter Beams

In other than perimeter beams, when closed stirrups are not provided, at least one-quarter of the positive moment reinforcement required at midspan shall be continuous or shall be spliced over them support with a Class A (Class B 318-08) tension splice and at noncontinuous supports be terminated with a standard hook.

318-89 7.13.2.3 (318-02 7.13.2.4) – Other than Perimeter Beams



Largest of $A_{s1}^{+}/4$ or $A_{s2}^{+}/4$ (Min 2 Bars)

- Continuous
- Class A Tension Splice (Class B 318-08)
- Mechanical/Welded Splice (318-02)

NONPRESTRESSED TWO-WAY SLABS

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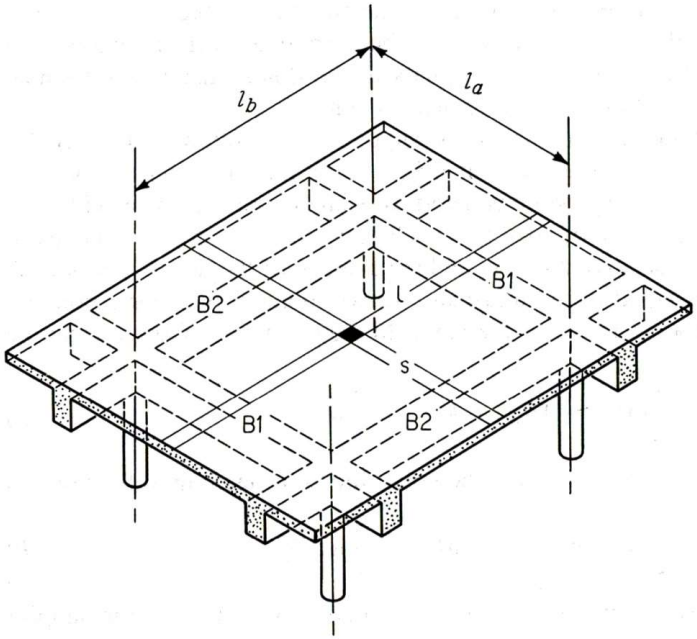
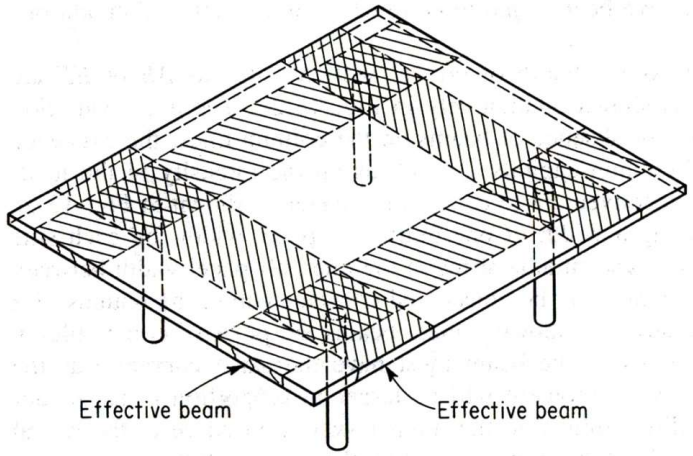
Column-Supported Two-Way Slabs



Two-Way Slab with Beams



Two-Way Slab without Beams

Source: Nilson, A., Darwin, D., and Dolan, C., *Design of Concrete Structures*, McGraw-Hill, 2009

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Punching Shear Failure of Parking Structure Slab

(PHOTO BY SAUL MARTINEZ FOR THE WASHINGTON POST)

The standing columns here suggest the columns “punched through” the deck.

318-89 7.13.2.4 – Two-Way Slab Integrity Reinforcement

For two-way slab construction, see 13.4.8.5.

13.4.8.5 — At least two of the column strip bottom bars or wires in each direction shall be continuous or spliced with Class A splices or anchored within support. These bars shall pass through the column and shall be placed within the column core.

318-95, -99 7.13.2.5 – Two-Way Slab Integrity Reinforcement

7.13.2.5 — For two-way slab construction, see 13.3.8.5.

13.3.8.5 - All bottom bars or wires within the column strip, in each direction, shall be continuous or spliced with Class A splices (or with mechanical or welded splices satisfying 12.14.3 – 318-02, -05) located as shown in Fig. 13.3.8. At least two of the column strip bottom bars or wires in each direction shall pass within the column core and shall be anchored at exterior supports.

318-08 7.13.2.6 – Two-Way Slab Integrity Reinforcement

7.13.2.6 — For nonprestressed two-way slab construction, see 13.3.8.5.

13.3.8.5 — All bottom bars or wires within the column strip, in each direction, shall be continuous or spliced with Class B tension (lap – 318 11)splices or with mechanical or welded splices satisfying 12.14.3. Splices shall be located as shown in Fig. 13.3.8. At least two of the column strip bottom bars or wires in each direction shall pass within the region bounded by the longitudinal reinforcement of the column and shall be anchored at exterior supports.

318-14 8.7.4.2 – Two-Way Slab Integrity Reinforcement

8.7.4.2 *Structural integrity*

8.7.4.2.1 All bottom deformed bars or deformed wires within the column strip, in each direction, shall be continuous or spliced with full mechanical, full welded, or Class B tension splices. Splices shall be located in accordance with Fig. 8.7.4.1.3a.

8.7.4.2.2 At least two of the column strip bottom bars or wires in each direction shall pass within the region bounded by the longitudinal reinforcement of the column and shall be anchored at exterior supports.

318-19 8.7.4.2 – Two-Way Slab Integrity Reinforcement

8.7.4.2 *Structural integrity*

8.7.4.2.1 All bottom deformed bars or deformed wires within the column strip, in each direction, shall be continuous or spliced using mechanical or welded splices in accordance with 25.5.7 or Class B tension lap splices in accordance with 25.5.2. Splices shall be located in accordance with Fig. 8.7.4.1.3.

8.7.4.2.2 [No change]

318-89 (Revised 92) 7.13.4 – Lift-Slab Construction

For lift-slab construction, see 13.4.8.6 and 18.12.6.

Unchanged in 318-95, 318-99, 318-02, 318-05, 318-08, 318-11.

Reference should be made to 8.9.1 in 318-14 and 318-19.

Not discussed

318-14 8.8.1.6 – Nonprestressed Two-Way Joist Construction

8.8.1.6 For structural integrity, at least one bottom bar in each joist shall be continuous and shall be anchored to develop f_y at the face of supports.

POST-TENSIONED TWO-WAY SLABS

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ACI 318-08 REQUIREMENTS FOR STRUCTURAL INTEGRITY

7.13.2.7 – For prestressed two-way slab construction, see 18.12.6 and 18.12.7.

18.12.6 — Except as permitted in 18.12.7, in slabs with unbonded tendons, a minimum of two 1/2 in. diameter or larger, seven-wire post-tensioned strands shall be provided in each direction at columns, either passing through or anchored within the region bounded by the longitudinal reinforcement of the column. Outside column and shear cap faces, these two structural integrity tendons shall pass under any orthogonal tendons in adjacent spans. Where the two structural integrity tendons are anchored within the region bounded by the longitudinal reinforcement of the column, the anchorage shall be located beyond the column centroid and away from the anchored span.

ACI 318-08 REQUIREMENTS FOR STRUCTURAL INTEGRITY

18.12.7 — Prestressed slabs not satisfying 18.12.6 shall be permitted provided they contain bottom reinforcement in each direction passing within the region bounded by the longitudinal reinforcement of the column and anchored at exterior supports as required by 13.3.8.5. The area of bottom Reinforcement in each direction shall be not less than 1.5 Times that required by Eq. (10-3) and not less than $300b_w d/f_y$, where b_w is the width of the column face through which the reinforcement passes. Minimum extension of these bars beyond the column or shear cap face shall be equal to or greater than the bar development length required by 12.2.1.

ACI 318-14 REQUIREMENTS FOR STRUCTURAL INTEGRITY

8.7.5.6 *Structural integrity*

8.7.5.6.1 Except as permitted in 8.7.5.6.3, at least two tendons with 1/2 in. diameter or larger strand shall be placed in each direction at columns in accordance with (a) or (b):

(a) Tendons shall pass through the region bounded by the longitudinal reinforcement of the column.

ACI 318-14 REQUIREMENTS FOR STRUCTURAL INTEGRITY

8.7.5.6.1

(b) Tendons shall be anchored within the region bounded by the longitudinal reinforcement of the column, and the anchorage shall be located beyond the column centroid and away from the anchored span.

8.7.5.6.2 Outside of the column and shear cap faces, the two structural integrity tendons required by 8.7.5.6.1 shall pass under any orthogonal tendons in adjacent spans.

PRECAST CONCRETE CONSTRUCTION

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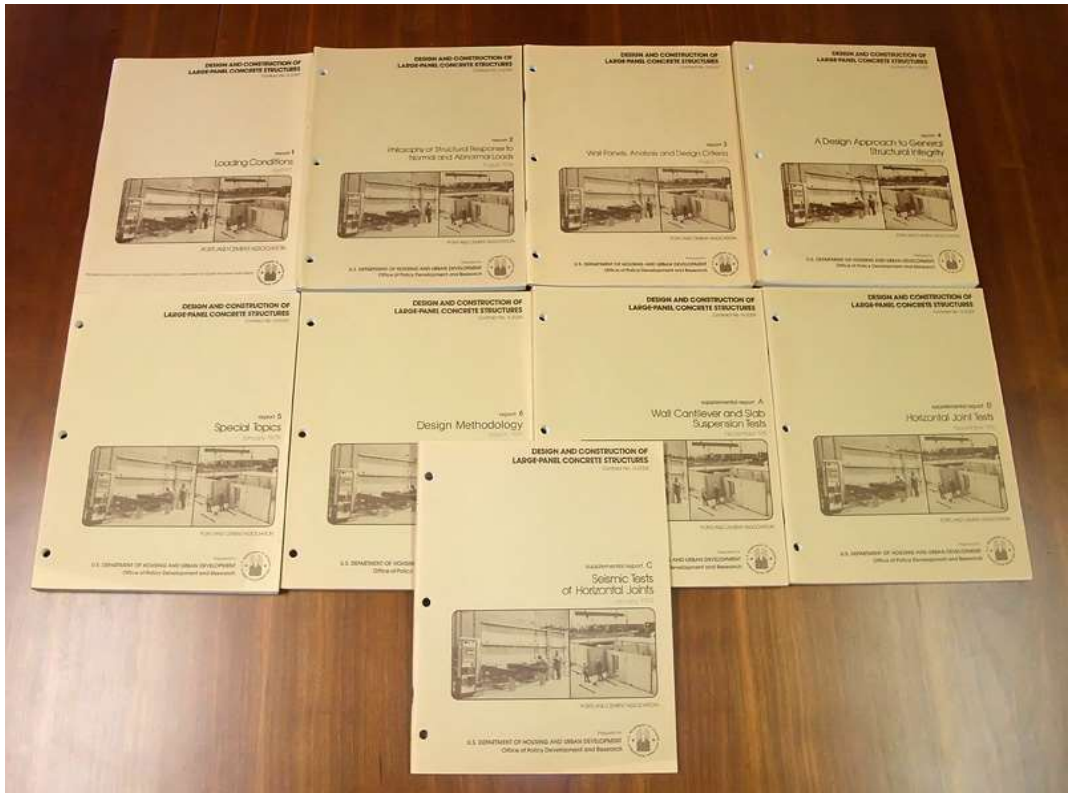
7.13.3 – Precast Concrete

- Detailed Requirements for Structural Integrity for Precast Concrete Were Introduced in Section 16.5 of ACI 318-95. This Was a Part of the Expansion and Re-write of Chapter 16 in 318-95.

HUD-Sponsored PCA Research, Reports



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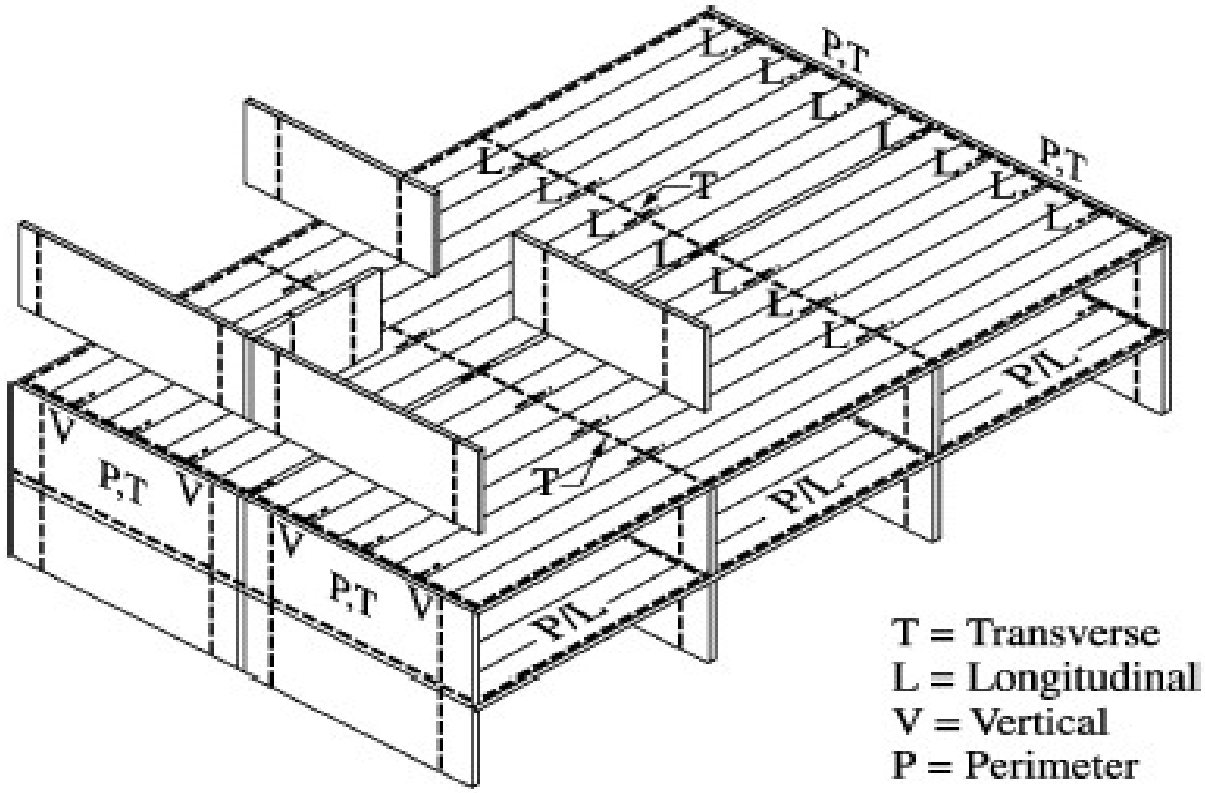
16.5 – Structural Integrity for Precast Structures

1. Members Must be Connected to the Lateral Load Resisting System. Tension Ties Shall be Provided in the Transverse, Longitudinal, and Vertical Directions and Around the Perimeter of the Structure.
2. The Lateral Load Resisting System Must be Continuous to the Foundation.

16.5 – Structural Integrity



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