

ACI 224.4R-13

Guide to Design Detailing to Mitigate Cracking

Reported by ACI Committee 224



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Guide to Design Detailing to Mitigate Cracking

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Guide to Design Detailing to Mitigate Cracking

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Recommendations made in this guide offer performance-based details that can mitigate and control concrete cracking. Structural elements are reviewed individually to identify crack causation and to offer design and detailing recommendations to mitigate crack development. In addition, standard details for various structural members within a building are offered that have been used effectively to mitigate and control crack development in concrete members.

Keywords: cast-in-place; crack mitigation; crack control; cracking; detailing; environmental structure; foundation; prestressed; reinforcement; restraint; shrinkage; slab; tensile stress; thermal effects; wall.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

- 1.1—Introduction, p. 2
- 1.2—Objective, p. 2
- 1.3—Scope, p. 2

CHAPTER 2—NOTATION AND DEFINITIONS, p. 2

- 2.1—Notation, p. 2
- 2.2—Definitions, p. 3

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CHAPTER 3—DESIGN-DETAILING CONSIDERATIONS, p. 3

- 3.1—Concrete member type and reinforcement, p. 3
- 3.2—Overall and local regions, p. 3
- 3.3—Framing compatibility, p. 3

CHAPTER 4—DETAILING OF TWO-WAY REINFORCED CONCRETE SLAB SYSTEMS, p. 3

- 4.1—General, p. 3
- 4.2—Causes and types of restraint cracking, p. 3
- 4.3—Crack mitigation and control, p. 5

CHAPTER 5—DETAILING OF ONE-WAY REINFORCED CONCRETE SLAB SYSTEMS, p. 9

- 5.1—General, p. 9
- 5.2—Causes and types of restraint cracking, p. 10
- 5.3—Crack mitigation and control, p. 11

CHAPTER 6—DETAILING OF COLUMNS, p. 12

- 6.1—General, p. 12
- 6.2—Short columns, p. 12
- 6.3—Columns between walls, p. 13
- 6.4—Corner and exterior columns, p. 13
- 6.5—Slender columns, p. 13
- 6.6—Multistory columns, p. 13
- 6.7—Column/slab joints, p. 14
- 6.8—Oversized or unique-shaped columns (architectural columns), p. 14

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CHAPTER 7—DETAILING OF WALLS, p. 15

- 7.1—Gravity load-bearing walls, p. 15
- 7.2—Non-load-bearing walls, p. 15
- 7.3—Shear walls, p. 15
- 7.4—Walls intended to contain liquid, p. 15

CHAPTER 8—DETAILING ON SLABS-ON-GROUND, p. 16

- 8.1—General, p. 16
- 8.2—Contraction joints, p. 16
- 8.3—Construction joints, p. 18
- 8.4—Expansion and isolation joints, p. 19

CHAPTER 9—REFERENCES, p. 20

Cited references, p. 20

CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

This guide addresses how to reduce potential cracking in reinforced concrete buildings in the design process through judicious consideration of building layout, selection of appropriate connections and joint types, and use of good reinforcement details. Each member within a structure may be subject to different types of cracks. Once the building design is developed, the type of framing system and its geometry selected, and appropriate code-required loads considered, it is then possible for the engineer to understand and identify the possible predominate crack development, crack types, and crack locations for each member within the structure. Predicting possible crack development for members within a building typically allows application of appropriate design details to mitigate and control cracking. Effective detailing of concrete members can improve strength, serviceability (deflection and durability), and aesthetics of a concrete structure.

The terms “crack mitigation” and “crack control” as used in this document have distinct meanings. Crack mitigation involves measures that are intended to prevent cracking from occurring. This includes concepts intended to minimize or eliminate restraint, such as consideration of building layout, the use of connection or element releases, or both. Crack control involves measures that are intended to control where cracks occur, or to limit the width and spacing of cracks. Crack control approaches include the use of joints and reinforcement detailing. The term “design details” in this document is a broad term intended to include all design measures intended to mitigate and control cracking.

Some of the crack mitigation and control measures described in this document involve reinforcement details and other requirements that may already be required by the Building Code for structural reasons. Other measures recommended in this document may require details and reinforcement amounts in excess of that required by ACI 315.

1.2—Objective

The *ACI Detailing Manual* (ACI Committee 315 2004) provides standard reinforcement details to aid the designer

in addressing concrete cracking. The *ACI Detailing Manual* shows individual details in isolation, which may be used for a particular member, joint, or cross section. In contrast, the objective of this document is to address the mitigation and control of cracking by considering the overall nature of a structure and how members may experience additional cross-sectional stresses due to the restraint caused by the structural system. The effect of the geometry and layout of the concrete framing system on the cracking of individual members or joints is discussed, and recommendations for more favorable arrangements of structural framing to minimize restraint are presented. Additionally, specific framing conditions where the cracking of a particular part of the structure is directly or indirectly affected by the neighboring elements or the overall framing system are discussed, and suggested reinforcement and release details to avoid or minimize such cracking are provided.

1.3—Scope

This document provides recommendations for design details and structural framing guidelines to mitigate, control, or distribute crack development in concrete members and structural systems. The recommendations and guidelines are presented in terms of concepts and effective practices that have been successfully implemented to mitigate and control cracking. Specific reinforcement details are presented for some situations, but not all, as the document is intended to illustrate concepts and approaches rather than to provide comprehensive details for all situations.

The reinforcement details shown in this document are for Grade 60 deformed steel reinforcing bars. Note that these reinforcement details may not be sufficient when other types of reinforcement are used, and in particular where the elastic properties (for example, fiber-reinforced polymer), bond properties, or strength of the bars are different.

This document specifically excludes the review of concrete member cracking due to unique or special materials used, concrete mixture proportions, or placing and finishing practices. The design details presented herein are limited to building structures and may not apply to special structures or nonbuilding structures. This document is limited to cast-in-place concrete frames only, not to precast concrete and masonry elements.

CHAPTER 2—NOTATION AND DEFINITIONS**2.1—Notation**

- S_1, S_2 = horizontal spacing of contraction joints in slabs on ground, in. (mm)
- S_{Dowel} = center-to-center spacing of dowel bars used for vertical joint load transfer in slabs on ground, in. (mm)
- S_{Plate} = center-to-center spacing of steel plates used for vertical joint load transfer in slabs on ground, in. (mm)
- ρ = steel reinforcement ratio

2.2—Definitions

“2013 ACI Concrete Terminology” provides a comprehensive list of definitions that is available online at: <http://www.concrete.org/Tools/ConcreteTerminology.aspx>.

CHAPTER 3—DESIGN-DETAILING CONSIDERATIONS

3.1—Concrete member type and reinforcement

A detailed review of each concrete member type is required to mitigate or control localized and global cracking. Each member should be reviewed for its predominant cracking behavior. The most common cracks are caused by:

- a) Restrained concrete volume changes (creep, shrinkage, elastic shortening, and thermal effects)
- b) Concrete member restraint effects
- c) Loading effects (flexure, shear, axial tension/compression, and torsion)

This guide addresses horizontal floor framing members such as one- and two-way slab systems, vertical elements of concrete structures such as walls and columns, and nonstructural slabs-on-ground. This guide may call for minimum reinforcement in excess of that noted in ACI 318 for increased serviceability performance.

3.2—Overall and local regions

Due to the variety of member types and geometries and the various factors that cause cracks, it is imperative that each concrete member be reviewed individually and as part of the overall framing system during the design-detailing process. Concentrated load application and vulnerable member joint conditions may require a localized review of concrete details. On the other hand, the overall framing layout may cause indirect load transfer due to geometry or member incompatibility that results in concrete cracking based on overall behavior of the framing system. Chapters 4 through 8 describe a localized and overall performance review of members.

3.3—Framing compatibility

Framing compatibility is one of the basic premises of a properly performing structure. The relative proportioning of member shapes plays an important role in mitigating concrete cracking. An example of framing incompatibility would be found in a structure where concrete member sizes are simply out of scale, such as where oversized architectural columns are used to support a thin slab. The restraining effects of oversized members on their surrounding members can be significant. For this reason, it is advisable to maintain compatible member sizes and connections to mitigate restraint cracking during concrete shortening. If geometry or architectural considerations dictate such incompatibility, special consideration should be given to incompatible member connections. Alternatively, incompatible framing geometry resulting from architectural considerations can be addressed by using built-up nonstructural foam sections or shapes added to the completed concrete frame to obtain

the architectural shapes desired (for example, to increase column size for aesthetic purposes).

CHAPTER 4—DETAILING OF TWO-WAY REINFORCED CONCRETE SLAB SYSTEMS

4.1—General

ACI 318-11 provides minimum requirements related to shrinkage and temperature reinforcement (7.12) and outlines the need for restraint crack control (7.12.1.2, 7.12.3, 10.6, 11.6.7, 18.2.4, and 18.10.2). However, specific requirements for structural and restraint crack control in two-way reinforced concrete slab systems are not provided. As a result, some designers use the provisions in 10.6 of ACI 318-11 for flexural crack control in beams and one-way slabs in both principal directions for two-way slab systems. The ACI 318 provisions for one-way action may not be adequate for two-way slab systems, where the effects of restrained volume changes from shrinkage and thermal strains are significant. Crack-control equations for beams and one-way slabs generally underestimate the crack widths developed in two-way slabs. ACI 224R and Nawy (2005) present specific procedures for determining conventional flexural crack control in two-way slab systems.

In contrast to cracking that may be induced by the action of structural loading, unintended cracking due to restraint of slab shortening by structural elements can be quite pronounced. This type of cracking tends to be through-slab cracking because it results from direct in-plane tension (ACI 224.2R). This chapter covers restraint cracking and mitigation strategies for two-way slab systems. Much of the information presented has been adapted from the work by Aalami and Barth (1989) on post-tensioned building structures.

4.2—Causes and types of restraint cracking

Several factors can combine to lead to restraint cracks in two-way reinforced concrete slabs. Structurally stiff elements such as walls, elevator and stairwell cores, and columns restrain the slab from shortening. If the tensile stress resulting from the restrained shortening exceeds the tensile strength of the concrete, a restraint crack occurs (ACI 224.2R). Depending on the stiffness of the restraining elements and the length of the slab spans, multiple restraint cracks may form.

The specific factors that cause shortening of concrete slabs include:

- a) Shrinkage of concrete
- b) Creep of concrete due to sustained loads
- c) Temperature decrease
- d) Elastic shortening (post-tensioned slabs only)

Figure 4.2a illustrates typical restraint cracking that may occur in two-way slab systems. The figure illustrates that for reinforced concrete, the bonded reinforcement in the column strips tends to control restrained shrinkage cracking and more cracks of smaller size tend to form because of the bonded reinforcement. In contrast, in unbonded post-tensioned construction, restrained shrinkage cracking tends

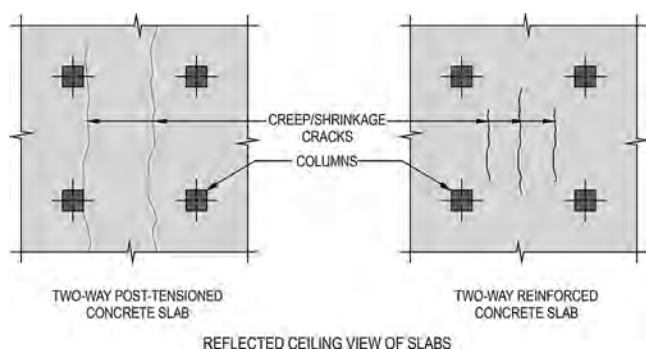


Fig. 4.2a—Typical restrained-shrinkage cracks in two-way slabs.

Table 4.2—Contributions to typical slab shortening (Martin and Perry 2004)

Item	Percentage contribution of total shortening
Shrinkage	70
Creep	12
Temperature	18
Total	100

to be less distributed because there is less bonded mild reinforcement used.

To illustrate the potential total restraint that can develop in an 8 in. (200 mm) slab with a standard 4000 psi (28 MPa) normalweight concrete mixture, consider a 100 x 200 ft (30 x 60 m) concrete slab subjected to 70 percent ambient humidity. Table 4.2 summarizes the anticipated total contributions of various factors to shortening of the slab based on Martin and Perry (2004). As noted in the table, a significant portion of the slab shortening after 1 year results from concrete shrinkage.

For illustration purposes, the total long-term unrestrained concrete shrinkage for the slab is assumed to be approximately 400 microstrain (accounting for slab characteristics and ambient humidity; refer to ACI 209.2R for more information on estimation of shrinkage). If the slab is fully restrained, the elastic stress in the slab is calculated as the product of the unrestrained strain times the modulus of elasticity. Based on an estimated modulus of elasticity of 3.6×10^6 psi (25,000 MPa), then the induced elastic stress, when the slab is fully restrained, is approximately 1400 psi (9.6 MPa). Because this calculated tensile stress will greatly exceed the tensile strength of concrete, restraint (tension) cracks will occur. Of course, no slab is fully restrained, and a countervailing effect of long-term creep is a reduction in effective modulus, which reduces the theoretical computed tensile stress by at least half (Kim and Lee 1998; Altoubat and Lange 2001). It is clear, however, that the interaction of restraining structural elements is the critical factor in crack formation.

A secondary factor that can predispose a restraint crack to form at a specific location is the termination (cutoff) of reinforcement and location of combined maximum flexural and axial shortening tensile stress, as illustrated in Fig. 4.2b. The termination of all or most slab reinforcement at a single

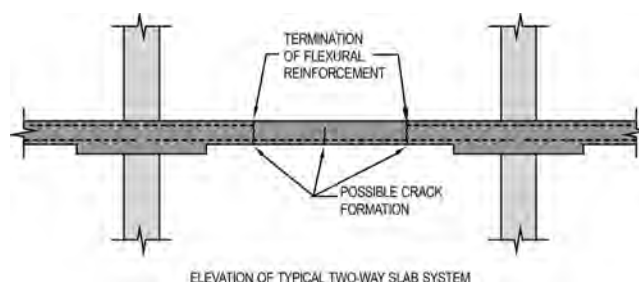


Fig. 4.2b—Probable restraint crack formation near reinforcement termination or location of maximum combined tensile stresses.

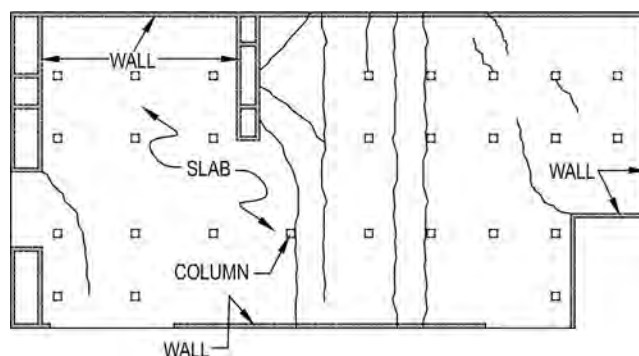


Fig. 4.2.1—Illustration of possible restraint cracking in two-way slab.

location tends to produce a stress discontinuity that can define the location of cracks. Section 13.3.8 of ACI 318-11 prescribes requirements for termination of top (negative moment) reinforcement in the column and middle strips of two-way slabs. Potential crack formation can be minimized by extending alternating bar termination locations beyond the minimum requirements. In structures where restraint is significant, it is recommended to make some portion of the top reinforcement continuous over the slab length to control restrained shrinkage and temperature cracks.

4.2.1 Overall slab cracks—The primary cause of overall restraint cracking in two-way slab systems is the layout of gravity- and lateral-load-carrying structural elements, the manner in which the slab is tied into those elements, and irregularities in the slab geometry. Figure 4.2.1 illustrates the probable locations of restraint cracks in a two-way slab system relative to the location of structural elements and discontinuities. The two-way concrete slab will shorten toward the center of rigidity or point of no movement. The wall surrounding the slab limits possible shortening movement, resulting in cracking along the length of the slab wall connection. Note that restraint may result in top, bottom, or through cracking of the slab.

4.2.2 Localized slab cracks—Figure 4.2.2 presents examples of localized cracks in slabs. This type of cracking is associated with slab openings and reentrant corners where there is an abrupt change in stiffness of adjoining elements. Two-way slab cracking at corners that are tied to walls may result from gravity loading as well as from restrained shrinkage and thermal actions. The wall will restrain the

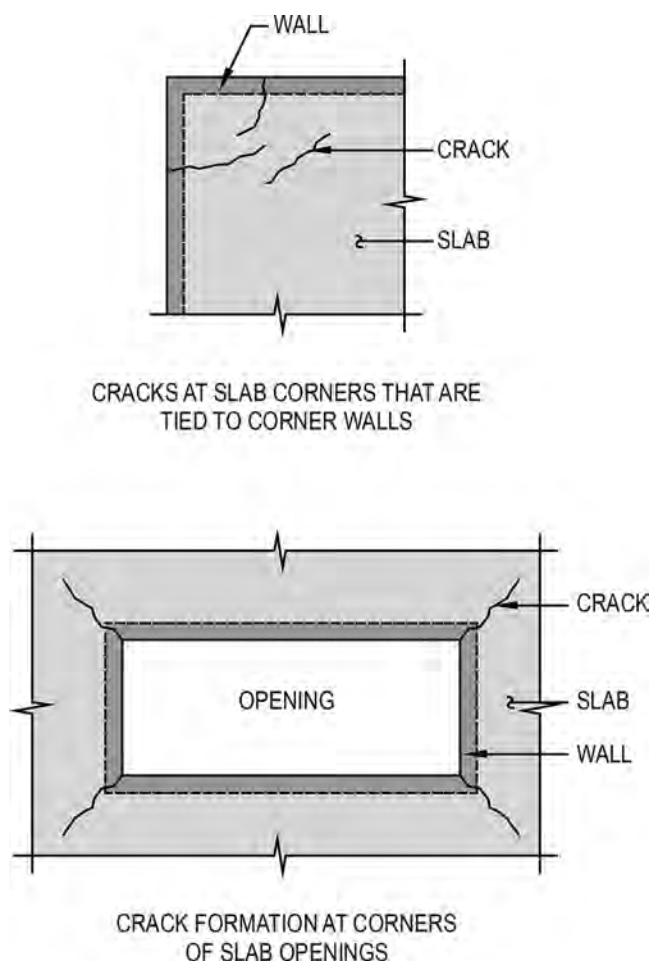


Fig. 4.2.2—Localized cracking in two-way slabs.

tendency of the slab corner to lift when subjected to out-of-plane (gravity) loading, producing localized moments, and cracking in the slab.

4.3—Crack mitigation and control

The principal approaches to mitigate and control restraint cracking in two-way slabs are the judicious arrangement of supporting members that may restrain the slab, and the use of structural separations and joints, releases between the slab and supporting elements, and special reinforcement details.

4.3.1 Restraining member layout—One of the most effective methods of restraint crack mitigation in two-way slabs is through the selection of favorable column and wall locations. The tendency of the slab is to shrink toward its geometric center. A symmetric positioning and selection of an equal number of walls located at a point of zero movement is most favorable for crack mitigation purposes. Figure 4.3.1a contrasts the more favorable to less favorable arrangement of walls to mitigate slab cracking. Figure 4.3.1b shows differences between a more favorable and less favorable column layout for mitigation of slab cracking. In general, it is best to have the center of rigidity of the two-way system coincide with the center of mass of the slab. This is illustrated by each of the more favorable wall arrangements in Fig. 4.3.1a. Uniform column layouts with equal column

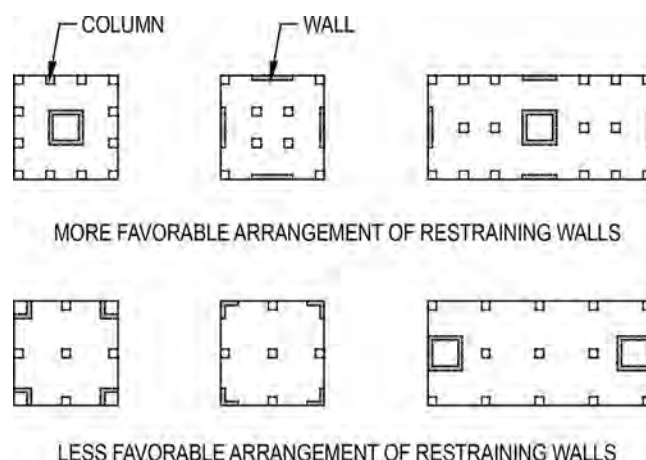


Fig. 4.3.1a—Influence of restraining wall location on cracking.

spacing will also tend to locate the center of rigidity with the slab geometric center. It is understood that, in most cases, architectural functionality dictates the location of vertical supporting elements. It is important, however, for the engineer to inform the architect and owner of improved performance (from a cracking point of view) if walls and other restraining elements are placed favorably. Less favorable arrangement of restraining elements, however, can be accommodated by providing temporary wall releases or through the installation of pour strips, which will allow a significant amount of shortening to take place before the slab is locked into place.

4.3.2 Structural separation and expansion joint location—Slabs of irregular geometry are more susceptible to restraint cracking. Figure 4.3.2 shows a logical location to separate slab areas to avoid cracking at the reentrant corner. This separation can be detailed as an expansion joint. By separating slab areas, the centers of rigidity and mass for each area coincide, thus providing two smaller and regular slab areas instead of one irregular large slab area.

4.3.3 Structural element releases—Providing mechanisms that allow relative movement between the slab and supporting elements can be an effective means of crack mitigation, particularly when a favorable arrangement of columns and walls is not fully possible. The relative movements can be accomplished through appropriate design of slab-to-wall connections, column-slab connections, slab joints, or wall joints.

4.3.3.1 Slab-to-wall connections—Figure 4.3.3.1 shows a fixed or rigid slab-to-wall connection and three types of commonly used connections to facilitate slippage at slab and wall interfaces. These types of slab-to-wall releases are applicable to both exterior and interior locations. It is recommended that some form of tie be made between the slab and wall to allow for shear transfer. This provides stability for intended or unintended lateral loads and overall structural integrity.

A temporary release allows the two-way slab system to experience the majority of its shortening before being permanently fixed. A temporary release is typically provided for a

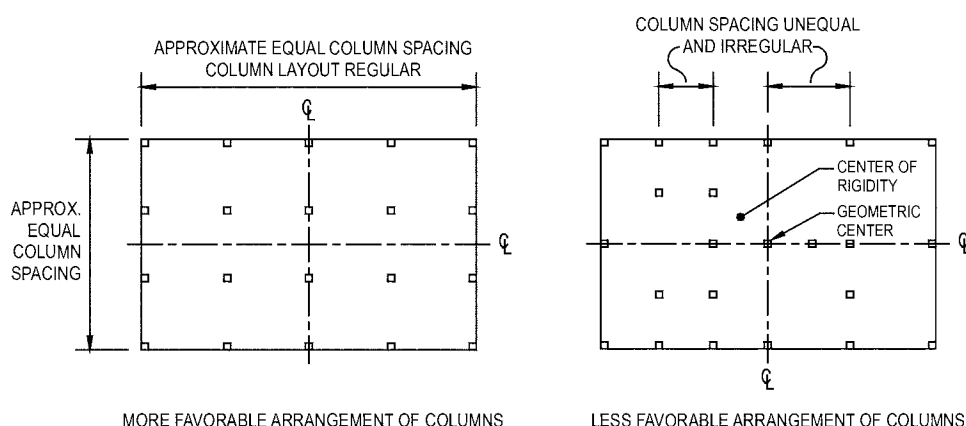
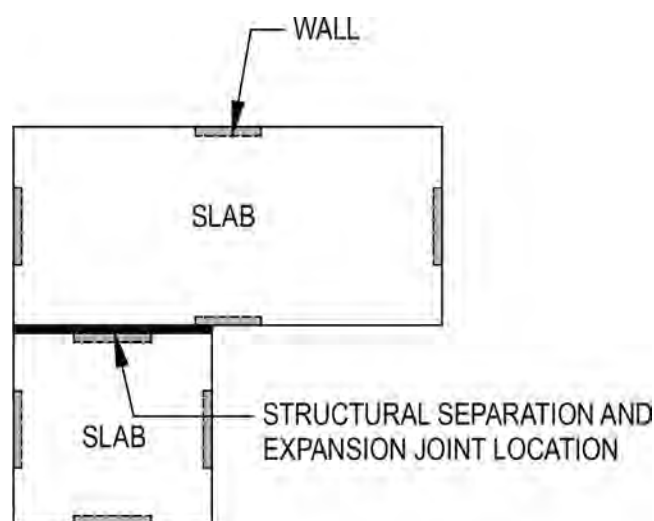


Fig. 4.3.1b—Influence of column arrangement on cracking.



SEPARATION BETWEEN LARGE IRREGULAR AREA FORMING TWO REGULAR AREAS

Fig. 4.3.2—Structural separation of irregular slab area.

duration of approximately 20 to 50 days during construction to accommodate the initial shortening. For example, this duration can reduce the overall effects of shortening due to creep and shrinkage of a post-tensioned slab by 35 to 50 percent. The temporary release is achieved by disengaging the vertical reinforcement extending from the lower wall into the slab using a 3 in. (75 mm) diameter pocket at the dowel bar tail locations, as shown in Fig. 4.3.3.1(b) for a concrete wall. The pocket is empty during the release period, and is later grouted to achieve continuity once the release duration has ended. The pocket is normally made the full depth of the slab thickness to facilitate grouting. Temporary releases are primarily used in single-story structures, as illustrated in Fig. 4.3.3.1(b). Temporary releases are rarely used in multistory buildings because the time delay between the upper wall and slab pour is typically minimal (7 days or less), thus requiring complex details to facilitate grouting of the pocket at the end of the release period (20 to 50 days) if the upper wall is already in place.

Fig. 4.3.3.1(c) and (d) show permanent release details for concrete and masonry wall systems, respectively. The permanent release is created by filling the pocket at the dowel bar locations with a compressible material (for example, closed-cell extruded polystyrene foam) at the time of construction, thus permanently disengaging the dowel bar between the lower wall and the slab. Note the L-shaped, or hooked, reinforcing bars that provide continuity between the slab and the upper wall are located beyond, not aligned with, the foam-filled pocket.

The performance of the release is dependent on the materials selected and workmanship. The top of the walls must have a smooth trowelled surface, as a concrete surface that is simply struck off provides too much interlock. A single sheet of polyethylene plastic is inadequate to provide the necessary slip plane. A 1/8 to 1/4 in. (3 to 6 mm) thick tempered wood particle board or two layers of heavy polyethylene sheeting with a thickness of at least 20 mils (0.5 mm) is generally adequate. For the case of masonry (concrete-filled block) construction, there is a need to provide a compressible material that will allow for relatively free movement of the concrete slab, as the interfacial concrete and block surface could be too rough to allow for movement (refer to Fig. 4.3.3.1(d)).

4.3.3.2 Column-slab connection—In reinforced concrete two-way slab construction, the column-slab connections are generally not released. In some cases where a relatively stiff system of shear walls is used, columns should be released, as shown in Fig. 4.3.3.2, to allow for slab shortening. A release is provided at the base of the end column and is typically also provided at each upper level for very long slabs where large lateral movement of end columns can occur due to shortening of the slab, or for structural systems having very stiff, oversized end columns. The slab/column/wall system should be analyzed to ensure overall structural stability, and the bearing pad should have sufficient bearing and rotational capacity.

4.3.3.3 Slab joints—Slab joints provide a separation in the slab between openings and other discontinuity locations. A slab joint extends only along the slab, and does not extend into the supporting structure. These joints are neither strong enough to resist the forces due to shortening nor flexible