IN-LB	Inch-Pound Units
SI	International System of Units

Integrity and Collapse Resistance of Structural Concrete Floor Systems—Report

Reported by ACI Committee 377

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This report provides a summary of the present understanding of collapse-resisting mechanisms of reinforced concrete and post-tensioned flat plates, flat slabs, slabs with beams, joist floor systems, and precast floor systems following initial local failures.

Keywords: beam growth; catenary action; collapse resistance; collapse-resisting mechanisms; column removal; compressive membrane action; emulative connection; flat plate; flat slab; floor systems; joist floor; post-punching capacity; post-tensioned; precast; punching; structural integrity.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Progressive or disproportionate collapse of structures happens with low probability but may cause large-scale—relative to the extent of the initial damage—structural failure. The following are some notable collapse examples that occurred previously in different types of reinforced concrete (RC) buildings during different abnormal events:

Ronan Point building in the United Kingdom in 1968—This 22-story precast concrete wall panel building suffered collapse when the partial collapse of one floor due to an accidental explosion propagated down to the rest of the floors.

Alfred P. Murrah Building in Oklahoma City, OK, in 1995—The explosion of a truck bomb destroyed an exterior column supporting a transfer girder and the blast may have also destroyed two adjacent exterior columns (Corley 2004). The loss of these columns led to the collapse of nearly half the RC frame building and 168 deaths.

A flat-plate office building in Jackson, MI, in 1956—The collapse occurred when concrete placement on the fourth floor resulted in punching failures at the second floor (Feld 1964).

A flat-plate structure in Boston, MA, in 1971—The punching failure of a slab-column connection at the roof level propagated all the way to the ground level, resulting in the collapse of two-thirds of the building. Construction overload, poor material properties in cold weather, and inappropriate positioning of slab top reinforcement precipitated this failure (King and Delatte 2004).

L'Ambiance Plaza in Bridgeport, CT, in 1987—The 16-story building collapsed during construction. The lift-slab method was used for construction with the floors supported by steel columns. Several potential causes of the collapse were identified, but the triggering collapse mechanism was never established (Martin and Delatte 2000). However, the anomalous design details of the slab unbonded post-tensioning tendons was considered a major factor in the propagation of the collapse after it had begun (Poston et al. 1991).

The aforementioned incidents indicate that, even though collapse takes place with low frequency, disproportionate structural collapse may cause severe consequences. Given that collapse is defined as loss of vertical-load-carrying capacity of structure, floor systems are critically important in providing structural integrity and redistributing gravity loads away from failing components. Once collapse is initiated, often due to column loss, the remaining structural system should be capable of resisting the progression of the collapse. The way in which the floor system redistributes the loads varies with the type of collapse initiation and the type of floor system. Current integrity provisions are intended to aid in redistributing gravity load after an initial failure.

This report is meant to assist engineers and practitioners in addressing an increasing desire by clients demanding designs beyond the integrity requirements in ACI 318.

1.2—Scope

The report seeks to summarize our present understanding of collapse initiations, collapse-resisting mechanisms, collapse-resisting strengths of floor systems, and to discuss the role of current integrity provisions in providing resistance to collapse.

This report is designed to be used by engineers, practitioners, and researchers. It will be used to improve understanding of how concrete floor systems redistribute gravity loads following the onset of initial failure. This report can also be used by educators to describe the mechanics of collapse resistance and direct them to the applicable code provisions currently in place.

Each chapter details possible causes of collapse initiation, collapse-resisting mechanisms, collapse-resisting strengths of floor systems, and discussion of relevant code requirements. Chapters 3 and 4 mainly correspond to cast-in-place concrete structures without and with beams, respectively. The focus of Chapter 5 is on precast concrete structures. The report also presents relevant integrity provisions in ACI 318, and CSA A23.3, and the New York City Building Code (2014).

If an engineer is required to perform a comprehensive progressive collapse analysis, including the determination of collapse initiation scenarios, the design guidelines provided by the General Services Administration (GSA) or the Department of Defense (DoD) should be used. Furthermore, this report can be used to supplement current material-specific GSA and DoD guidelines with the approval of the authority having the jurisdiction over the project.

This report is developed based on analytical and experimental studies conducted on RC elements and structures with uniaxial concrete compressive design strength of approximately 3 to 8 ksi (21 to 55 MPa). Application of the collapse-resisting mechanisms discussed herein to high-strength concrete or high-strength reinforcement requires further study.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_{sb} = area of bottom slab and beam reinforcement passing through each face of column
A_{sm} = area of integrity reinforcement required in each principle direction
F = beam vertical load-carrying capacity
f_y = specified yield strength of reinforcement
L = span length of beam or one-way slab
L_1 = governing bay length
L_n = length of clear span measured face-to-face of supports
ℓ_1 = center-to-center span length
ℓ_2 = center-to-center span width (perpendicular to ℓ_1)
ℓ_x = clear span length in the short direction
ℓ_y = clear span length in the long direction
M = moment at right end of beam
M' = moment at left end of beam
P = beam axial force

V_{se} = post-punching resistance of a slab-column connection
T_x = force per unit length in the reinforcement in the short direction
T_y = force per unit length in the reinforcement in the long direction
t = outward lateral movement at beam end due to support flexibility
$w_{y,\ell}$ = slab capacity as predicted by yield-line theory
Δ = generalized deflection
ε_x = strain in the short direction
ε_y = strain in the long direction
ω = uniform floor load per unit area
ω_u = factored uniform floor load per unit area

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

beam growth—tendency in concrete elements to grow in length as flexural cracking and yielding occur, which, if restrained, results in the development of axial compressive force or compressive membrane action.

collapse—partial or complete loss of vertical load-carrying capacity of a portion of or the entirety of the structure.

disproportionate collapse—collapse that is characterized by a pronounced disparity between the original cause and the ensuing collapse of a large (relative to the initial damage) part or the whole of a structure.

emulative design—design method in precast construction to provide continuity between adjacent flooring elements by using splices or field topping with continuous reinforcement over the connection, which emulates cast-in-place construction.

failure—partial or complete loss of load-carrying capacity of an individual element or component.

progressive collapse—spread of an initial local failure from element to element, resulting eventually in partial or complete collapse of a structure.

CHAPTER 3—REINFORCED CONCRETE AND POST-TENSIONED FLAT PLATES AND SLABS

3.1—Introduction

Reinforced concrete (RC) flat plate and flat slab floor systems are two-way framing systems composed of an RC slab directly connecting to columns. Drop panels, shear caps, or column capitals, which are the characteristics of flat slab construction, may be used at the columns to resist heavier loads or provide longer spans. The slab may be reinforced with nonprestressed two-way reinforcement or unbonded post-tensioning reinforcement. The slab may have steel decking; however, the role of decking is not considered in this report. This section does not cover floor systems that have intermediate beams. Floor systems may have perimeter beams; however, this chapter only pertains to the interior portion with no beams. Floor systems with nonprestressed reinforcement, prestressed reinforcement, or both, are considered. Floor systems with interior beams are discussed in Chapter 4.

3.2—Collapse initiation and resisting mechanisms

3.2.1 *Collapse initiation*—The collapse of flat plate or flat slab floor systems may be initiated by: 1) punching shear failure of the slab around a column; 2) failure of a column; or 3) flexural failure of the slab. Progressive collapse may occur if:

a) Subsequent punching shear failures occur near surrounding columns

b) Slab(s), supporting columns, or both, fail, which may lead to impact on the floor below, thereby causing additional failures, depending on the floor at which the failure initiates

c) Tendons in unbonded post-tensioned (PT) floors fail, resulting in the loss of tension throughout the length of the tendons covering multiple spans and leading to failure across those spans

Previous collapses have been primarily due to Case (a) such as the Sampoong Department store (1995), Commonwealth Avenue, Boston, MA (1971); Skyline Plaza/Bailey's Crossroads in Virginia (1973); and Harbour Cay Condominiums in Cocoa Beach, FL (1981). As such, Case (a) is the focus of this report and current integrity provisions. Case (b) was also observed in the Murrah building as a result of the Oklahoma City bombing (Sozen et al. 1998).

3.2.2 *Collapse-resisting mechanisms*—Collapse can be resisted for Case (a) in 3.2.1 if the slab near surrounding columns has sufficient punching or post-punching capacities; for Case (b), if the slab has sufficient tensile capacity to prevent floor collapse or the floor below is able to withstand the impact of a collapsed floor; and for Case (c), if the remaining tendons and conventional reinforcement are able to redistribute and carry the load. The amount of load transferred to the adjacent columns can be estimated by using static analysis for the case with the removed column. Analysis of these mechanisms is generally conducted under the following load combination ($1.2D + (0.5L$ or $0.2S)$) per U.S. General Services Administration (2016) and UFC 4-023-03. Dynamic effects may need to be considered. The U.S. General Services Administration (2016) and UFC 4-023-03 analysis guidelines include dynamic load amplification. Research (Qian and Li 2012, 2014; Orton and Kirby 2013; Peng et al. 2018) has found the dynamic increase factors in the guidelines to be conservative.

3.2.3 *Collapse resisting mechanism strengths*

3.2.3.1 *Punching capacity*—The progression of collapse can be limited by resisting punching failure at the surrounding slab-column connections. The punching capacity of the connections can be evaluated by code provisions such as those in ACI 318 and *fib* MC2010. In addition, research conducted by Muttoni (2008) and Broms (2016) specifically consider the deformation limits of the connection. Unbalanced loading due to an initial punching shear failure or loss of a column should be considered in the surrounding connections. Dynamic effects at the connection may need to be considered.