Seismic Analysis, Behavior, Design, and Detailing Requirements of Special RC Moment Frames Based on ASEC 7-22 and ACI 318-19 Codes

An Online Continuing Education Course for Engineers

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Seismic Analysis, Behavior, Design, and Detailing Requirements of Special RC Moment Frames Based on ASEC 7-22 and ACI 318-19 Codes

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1. INTRODUCTION

Building structures generally comprise a three-dimensional framework of structural elements configured to support gravity and lateral loads. Although the complete three-dimensional system acts integrally to resist loads, the seismic force-resisting system is commonly conceived as being composed of vertical elements, diaphragms, and the foundation (**Figure 1-1**).

For reinforced concrete buildings assigned to the highest Seismic Design Categories (D, E, and F) in the United States, as defined in ASCE/SEI 7-22, the applicable building codes permit the vertical elements to be either special moment frames or special structural walls. This course is written to describe the use, analysis, design, and construction of special reinforced concrete moment frames.

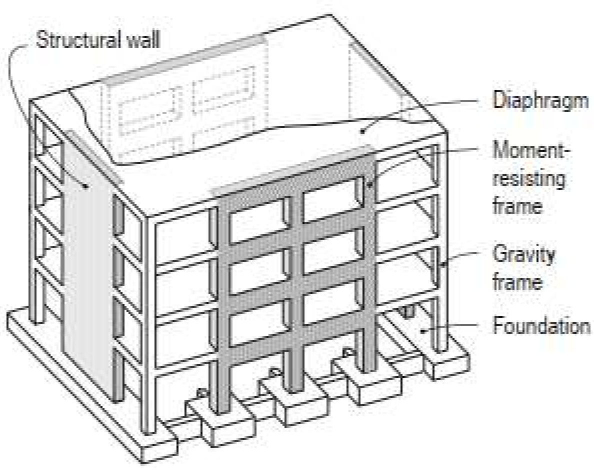


Figure 1-1. *Basic building structural system*

Reinforced concrete special moment frames are made up of beams, columns, and beam-column joints. The frames are proportioned and detailed to resist flexural, axial, and shearing actions that result as a building sways through multiple displacement cycles during earthquake ground shaking. Special proportioning and detailing requirements result in a frame capable of resisting strong earthquake shaking without significant loss of stiffness or strength. These moment-resisting frames are called "special moment frames" because of these additional requirements, which improve the seismic resistance in comparison with less stringently detailed intermediate and ordinary moment frames.

The design requirements for special moment frames are presented in the ACI 318-19 Code. The special requirements relate to inspection, materials, framing members (beams, columns, and beam-column joints), and construction procedures. In addition, requirements pertain to diaphragms, foundations, and framing members not designated as part of the seismic force-resisting system. The numerous interrelated requirements are covered in several sections of ACI 318, making their identification and application challenging for all but the most experienced designers.

This course was written for practicing structural engineers to assist in the application of ACI 318 requirements for special moment frames. The material is presented in a sequence that practicing engineers have found useful. The course will also be useful for building officials, educators, and students.

Most special moment frames use cast-in-place, normal-weight concrete without prestressing, and the member cross sections are rectilinear.

The main body of text in this course emphasizes code requirements and accepted approaches to their implementation. It includes background information and illustrations to help explain the requirements. Additional guidance is presented in sidebars. Sections 2 through 6 present analysis, behavior, proportioning, and detailing requirements for special moment frames and other portions of the building that interact with them. Section 7 presents construction examples to illustrate the detailed requirements for constructability.

2. The Use of Special Moment Frames

2.1 Historic Development

In most early applications, special moment frames were used in all framing lines of a building. A trend that developed in the 1990s was to use special moment frames in fewer framing lines of the building, with the remainder comprising gravity-only framing that was not designated as part of the seismic force-resisting system (**Figure 1-1**). Some of these gravity-only frames did not perform well in the 1994 Northridge earthquake, leading to more stringent requirements for proportioning and detailing these frames. The provisions for members not designated as part of the seismic force-resisting system are in ACI 318 §18.14 and apply wherever special moment frames are used with gravity frames in Seismic Design Category D, E, or F as defined in ASCE 7. The detailing requirements for the gravity-only elements may approach those for the special moment frame. In many cases, it may be more economical to include those elements as part of the seismic force-resisting system if they can be made to satisfy all of the applicable requirements.

Special moment frames have also found use in dual systems that combine special moment frames with structural (shear) walls. In current usage, the moment frame is required to be capable of resisting at least 25 percent of the design seismic forces. In contrast, the total seismic resistance is provided by the combination of the moment frame and the shear walls in proportion with their relative stiffnesses. The use of special moment frames to create a dual system permits the use of a larger response modification coefficient, *R*, and thereby may reduce the overall seismic strength requirements. However, the added formwork and detailing required to construct special moment frames may increase construction costs compared with the cost for a system using only shear walls.

2.2 When to Use Special Moment Frames?

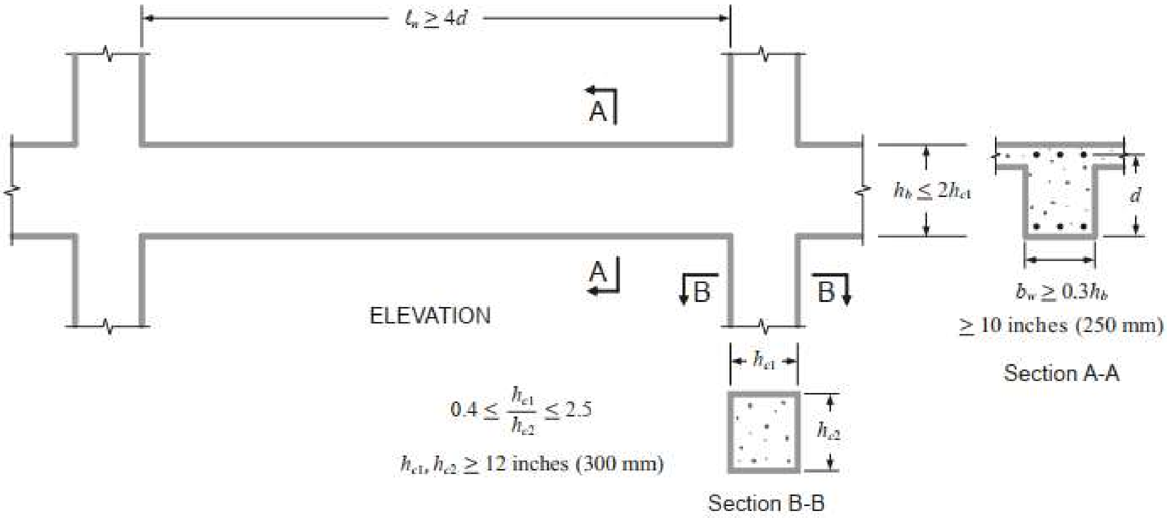
Moment frames are generally selected as the seismic force-resisting system when architectural space planning flexibility is desired. For many seismic force-resisting systems, such as special reinforced concrete shear walls, ASCE 7 §12.2.1 limits the building height. These height limits do not apply to special moment frames used alone or in combination with shear walls to create a dual system.

When concrete moment frames are selected for buildings assigned to Seismic Design Categories D, E, or F, they are required to be detailed as special reinforced concrete moment frames. Special moment frames may also be used in Seismic Design Categories A, B, and C, although this may not lead to the most economical design. If special moment frames are selected as the seismic force-resisting system, then all requirements for the frames must be satisfied to help ensure ductile behavior regardless of the Seismic Design Category.

2.3 Frame Proportioning

Special frames must be proportioned such that they are capable of providing the required lateral force resistance within specified story drift limits. The term "story drift" refers to the lateral displacement of one floor relative to the floor below it. Section 2.4, Section 4, and Section 5 of this Guide provide guidance on analysis and design to satisfy these requirements.

Typical economical beam spans for special moment frames are in the range of 20 to 30 feet (6 to 9 m). In general, this range will result in beam depths that will support typical gravity loads and the requisite seismic forces without overloading the adjacent beam-column joints and columns. Dimensional limits are covered in ACI 318 §18.6.2, §18.7.2, and §18.8.2.4. **Figure 2-1** summarizes the dimensional limits. The clear span of a beam must be at least four times its effective depth. Beam depth must not exceed twice the column depth in the framing direction, which limits the beam-column joint aspect ratio to improve force transfer. Beams are allowed to be wider than the supporting columns within ACI 318 limits, but beam width normally does not exceed the width of the column for reasons of constructability. The ratio of the cross-sectional dimensions for columns shall not be less than 0.4, and beam width b_w shall be at least $0.3h_b$, which limits the cross sections to more compact sections rather than elongated rectangles. The minimum column dimension is 12 inches (300 mm), which is often too small for practical construction.



Note: For beams wider than columns, the beam width beyond the column on each side shall not exceed the smaller of h_{c2} and $0.75h_{c1}$.
The longitudinal steel in column cross section and traverse steel in both beam and column cross sections are not shown for clarity.

Figure 2-1. *Dimensional limits of beams and columns of special moment frames according to ACI 318-19 Code*

Special moment frames with first-story heights up to 20 feet (6 m) are common in practice. For buildings with relatively tall stories, it is important to make sure that soft (low stiffness) and/or weak stories are not created (see ASCE 7 §12.3.2.2).

Slab-column moment frames generally cannot be used as special moment frames because they do not satisfy the dimensional and reinforcement requirements for special moment frames.

2.4 Strength and Story Drift Limits

Both strength and stiffness need to be considered in the design of special moment frames. According to ASCE 7, special moment frames are allowed to be designed using a response modification coefficient of R = 8. Thus, they are allowed to be designed for a base shear equal to one-eighth of the value obtained from a linear elastic response analysis. Moment frames are generally flexible lateral force-resisting systems. If the building is relatively tall, its fundamental vibration period may fall within the long-period portion of the design response spectrum, resulting in a calculated base shear that may be lower than the required minimum base shear. In such cases, the required design strength is controlled by the minimum base shear equations of ASCE 7. Base shear calculations for long-period structures, especially in Seismic Design Categories D, E, and F, are frequently controlled by the upper limit on the calculated period as defined in ASCE 7 §12.8.2. Wind loads specified in ASCE 7 must also be considered and may govern the strength requirements of special moment frames. Regardless of whether gravity, wind, or seismic forces are the largest, proportioning and detailing provisions for special moment frames apply wherever special moment frames are used.

The stiffness of the frame must be sufficient to control the story drift of the building within the limits specified by the building code. Story drift limits in ASCE 7 are a function of both the risk category (IBC §1604.5) and the redundancy factor, ρ (ASCE 7 §12.3.4), as shown in **Table 2-1.**

Table 2-1. Allowable story drift per ASCE 7, where h_{sx} is the story height.

Redundancy Factor	Risk Category		
	I and II	III	IV
$\rho = 1.0$	$0.020h_{sx}$	$0.015h_{sx}$	$0.010h_{sx}$
$\rho = 1.3$	$0.015h_{sx}$	$0.012h_{sx}$	$0.008h_{sx}$

The story drifts of the structure are to be calculated using the strength-level seismic load and amplified by C_d (ASCE 7 §12.8.6) when comparing them with the values listed in **Table 2-1**. Furthermore, the effective stiffness of framing members must be reduced to account for the effects of concrete cracking (see Section 4.2 of this course). The allowable wind story drift limit is not specified by ASCE 7; therefore, engineering judgment is required to determine the appropriate limit. Attachment of the cladding and other elements and the comfort of the occupants should be considered.

P-delta effects, addressed in ASCE 7 §12.8.7, can appreciably increase design moments and must, therefore, be considered in the frame design.

3. Principles for Design of Special Moment Frames

As noted in Section 2.4, ASCE 7 uses a design base shear that is considerably less than the base shear required for linear response at the anticipated earthquake intensity. Consequently, design-level earthquake ground motions will likely drive a building structure well beyond the linear range of response. Consistent with this expectation, ACI 318 specifies proportioning and detailing requirements for special moment frames that are intended to produce a structure capable of multiple cycles of inelastic response without critical loss of strength. Three main goals are (1) to achieve a strong-column/weak-beam design that spreads inelastic response over multiple stories, (2) to provide details that enable ductile flexural response in the intended yielding regions, and (3) to avoid nonductile failures. Additionally, connections with nonstructural elements, such as stairs and infills, must be detailed such that they do not interfere with the intended frame behavior.

3.1 Design a Strong-Column/Weak-Beam Frame

When a building sways during an earthquake, the distribution of damage over height depends on the distribution of lateral story drift. If the building has weak columns or weak beam-column joints, story drift tends to concentrate in one or a few stories (**Figure 3-1a**) and may exceed the story drift capacity of the columns. On the other hand, if columns provid... f and strong ... r the building height, story drift will be more uniformly distributed (Fi... e will be reduced. Additionally, columns in ... bove those columns, whereas the beams ... a part. Consequently, the failure of a colu... efore, building codes specify that columns ... strong-column/weak-beam principle is fun... ng earthquake ground shaking.

To view the remainder of the course material and to take the quiz for PDH credit, you must purchase the course.

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ACI 318 adopts the stro... f column moment strengths exceed the su... ion of a special moment frame. Studies ... at the full structural mechanism of ... strength ratio is relatively large (about fou... ower strength ratio of 1.2 is adopted by ... mediate mechanism (**Figure 3-1b**) i... Section 5.5 of this Guide summarizes the

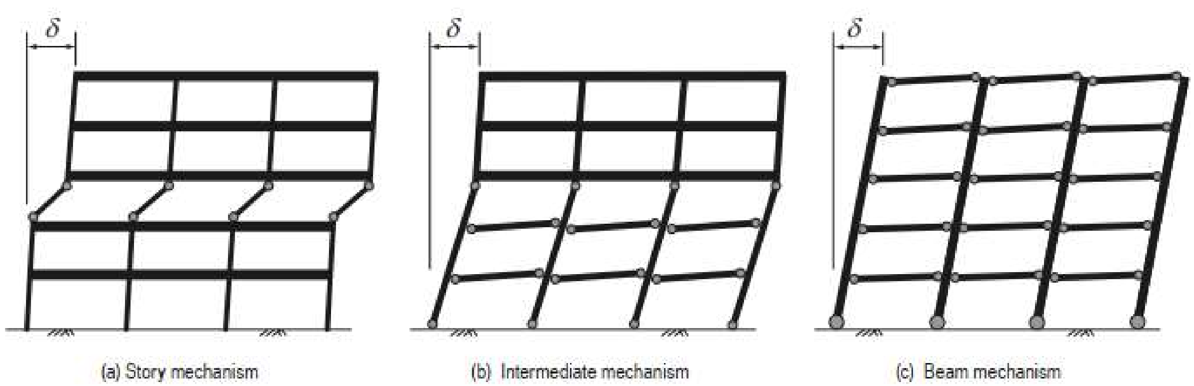

Figure 3-1. *The design of special moment frames aims to avoid the story mechanism (a) and instead achieve either an intermediate mechanism (b) or a beam mechanism (c).*