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Guide for Emulating Cast-in-Place Detailing for Seismic Design of Precast Concrete Structures

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This guide provides information for detailing precast concrete structures that should meet building code requirements for all seismic design categories by emulating cast-in-place reinforced concrete design. This guide also explains how emulative precast concrete structures can address the provisions of ACI 318-11, including those of Chapter 21, if special attention is directed to detailing the joints and splices between precast components.

Keywords: ductility; elastic design; emulation; flexural strength; joint; precast concrete; precast detailing; reinforcement.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Emulative detailing is defined as: **The design of connection systems in a precast concrete structure so that its structural performance is equivalent to that of a conventionally designed, cast-in-place, monolithic concrete structure** (Ericson and Warnes 1990).

Emulative detailing is distinct from jointed detailing, where precast elements are connected with special jointing details, such as welded or bolted plates, in that the bending stiffness of the connections differs from that of the members. As commonly applied, “emulation” refers to the design of the vertical or horizontal elements of the gravity and lateral-force-resisting system of a building or structure. Emulative detailing of precast concrete structures is applicable to any structural system where monolithic structural concrete would also be appropriate, regardless of seismic design category (Precast/Prestressed Concrete Institute 1999).

Design practice in some countries with a high seismic risk, such as New Zealand and Japan, follows design codes that address precast concrete detailed by emulation of cast-in-place concrete design. Performance of joints and related details of emulative precast concrete structural concepts has been extensively tested in Japan. Because emulative precast concrete structures have been constructed there for over several decades, emulative methods for seismic design are widely accepted.

Typical details showing proportional dimensions, as well as reinforcing steel, are schematic only and are provided solely to demonstrate the interactivity of the jointing essentials. All connection details are subject to structural analysis and compliance with code requirements. Splicing reinforcing bars by welding or lapping is not permitted by ACI 318-11 whenever the bars are subjected to stresses beyond the actual yield points of the reinforcing steel being used. Based on tests of mechanical splices reported by the California Department of Transportation (Noureddine et al. 1996), concern was expressed about staggering of mechanical splices of reinforcing bars. Staggering is not required by current codes.

Only essential reinforcing bars are shown in detail to provide clarity. Other reinforcing steel that would typically be incorporated into a conventional design is not shown. The specification and delineation of reinforcing bars or strand sizes and locations, layers, types, and numbers are the responsibility of the designer.

1.2—Scope

The purpose of this guide is to give the reader a working knowledge of emulation and emulative detailing to meet requirements in current codes. The term “emulation” has become a common concept for designers working with precast concrete systems, but has also been misinterpreted in relation to jointed systems. This guide shows a variety of emulative details and describes how they are used. Design is basically that of monolithic cast-in-place reinforced concrete converted to precast members, so no special design knowledge is required to use emulative details.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_{cv}	=	gross area of concrete section bounded by web thickness and depth of section in the direction of shear force considered
f'_c	=	specified compressive strength of concrete
M_c	=	factored moment amplified for the effects of member curvature used for design of compression member
M_{nb}	=	nominal flexural strength of beam, including slab where in tension, framing into joint
M_{nc}	=	nominal flexural strength of column framing into joint, calculated for factored axial force, consistent with the direction of lateral forces considered, resulting in lowest flexural strength
M_{pr}	=	probable flexural strength of members, with or without axial load, determined using the properties of the member at the joint faces assuming a tensile stress in the longitudinal bars of at least $1.25f_y$ and a strength reduction factor ϕ of 1.0
Ω	=	dynamic amplification factor

2.2—Definitions

element—an individual part of the structure such as a column, beam, wall, floor, or roof section that can be precast in other than its final location.

emulation—designing precast elements and their structural connections to perform as if the structure was a conventional cast-in-place concrete structure.

emulative detail—a connection in which the structural performance is equivalent to that of a continuous member or a monolithic connection.

jointed detail—a connection where the bending stiffness differs from that of the members and requires special design to collect, transfer, and redistribute forces from one member to another through the connection.

member—an individual part of the structural system, synonymous with element, such as a column, beam, floor, roof, or wall.

structure—a building or bridge built with individual elements or members.

system—a collection of elements or members that form a structure.

CHAPTER 3—GENERAL DESIGN PROCEDURES

A large body of technical information is available for the design of cast-in-place reinforced concrete structures, and extensive research and development is ongoing for all types of cast-in-place concrete technology. Numerous textbooks have been written about the behavior and design of cast-in-place reinforced concrete. Design procedures and examples for cast-in-place reinforced concrete are available (Cole/Yee/Schubert and Associates 1993). Building codes are regularly revised to reflect new research and technology developments, and the results are incorporated into teaching and working practice (International Code Council 2012; ACI 318-11). This knowledge for designing reinforced cast-in-place concrete structures is readily applicable to the design of emulative precast concrete.

The analysis and design of cast-in-place reinforced concrete structures is based on the premise that the entire system behaves monolithically. A cast-in-place concrete structure is actually built member by member with joints between concrete placements because of limitations in concrete placing, construction procedures, or schedules. Due to the continuity of the reinforcement and specific requirements for construction joints, the structure performs as a unit. The principal element of emulative detailing of precast concrete is to detail a precast structure that will exhibit structural behavior similar to that of a cast-in-place structure.

Construction joints, whether in prefabricated or cast-in-place concrete structures, should be located and detailed to ensure transmission of induced forces and loads in both the concrete and reinforcing steel. For precast concrete, emulative construction joints will likely occur at the same locations as dry joints in cast-in-place structural elements. Joints will usually be located at the ends of beams and columns, at both the ends and sides of floor elements, and between wall elements.

The essential differences between cast-in-place reinforced concrete and emulative, reinforced, precast concrete relate to field connections and assembly of the prefabricated elements. Prefabricated elements have additional design requirements for stripping, transportation, and erection loads imposed on them, but the structural analysis and element design is essentially the same for both types of construction.

Using emulative methods for connecting precast concrete elements, the detailing process follows three general steps:

1. The structural system for resisting gravity and lateral loads should be selected. A separate gravity-load-resisting frame can be combined with lateral-load-resisting shear walls, or both functions can be accomplished with moment-resisting frames. System selection is often controlled by the height of the building and the span of the components as well as architectural requirements. Some code limitations may also apply (International Code Council 2012).

2. The structure should be designed and detailed to meet the requirements of the applicable building code as if it were to be constructed of monolithic cast-in-place reinforced concrete, keeping in mind that the structure will be divided into structural elements of sizes and shapes that:

- Are suitable for plant fabrication;
- Are capable of being transported; and
- Can be erected by cranes available to the contractor.

3. The structure should be organized into precast elements of appropriate sizes and shapes to meet the aforementioned criteria. The appropriate connections should then be designed and detailed to satisfy the requirements of the applicable building code to allow the precast elements to be reconnected in a way that emulates a monolithic system.

The manufacture and construction of precast structures typically follows six steps:

1. The precast structural elements are manufactured with code-compliant mechanisms for splicing the structural reinforcing bars to provide continuity of the reinforcement throughout the structure and in accordance with approved design;
2. The prefabricated elements are transported to the project site when they are cast off-site;

3. Individual precast elements are erected and temporarily secured;

4. The reinforcing bars are connected between the precast concrete elements by completing the splices;

5. The precast concrete elements are connected with grout or concrete closures; and

6. Elements are reshored or braced as required to achieve stability.

3.1—Selecting a structural system

Selecting an appropriate structural system, such as structural walls, box structures, moment-resisting frames, and dual systems for both lateral and gravity loads, can be the most important step in achieving an economical, structurally sound design. Essentially, four types of structural elements are used in combination to form complete building systems. Horizontal elements include beams and slabs. Vertical structural elements include walls and columns or combinations of both horizontal and vertical elements, such as cruciform elements. These elements can be combined in various configurations to form commonly recognized lateral-load-resisting systems, such as structural walls and moment-resisting frames. Emulative detailing principles apply to all of them.

With precast concrete, the designer has the option to select those frames or walls necessary to resist lateral loads under the code requirements. For seismic conditions, the elements of the gravity load frame need only meet the requirements of ACI 318-11 Section 21.13.5 (frame members not proportioned to resist forces induced by earthquake motions) and the requirement that each precast member be connected to adjacent members.

3.1.1 Structural walls—Structural walls, as defined in ASCE 10 as “shear walls,” resist lateral forces parallel to the plane of the wall. Because of the relatively large in-plane depth of the wall members, significant lateral stiffness is provided.

These walls meet the requirements for ductile detailing included in ACI 318-11 Section 21.8. ASCE/SEI 7-10 assigns an R factor to the various structural systems. Systems braced with special reinforced concrete structural walls are assigned an R factor of 5.5 for load-bearing wall systems, and 6 for structural walls bracing a vertical frame. Special reinforced concrete structural walls are used in buildings in seismic performance Categories D, E, and F. Special reinforced concrete structural walls may be used in these Seismic Design Categories (SDCs) up to a maximum height of 160 ft (48.8 m) (100 ft [30.5 m] in the case of Category F). Although not required for regions of lower seismic risk, engineers can design special reinforced concrete structural walls for these regions for their increased integrity, strength, and ductility, and for the reduction of base shears afforded by the higher R factors. The R factors can be further increased where the walls are used in combination with moment frames. Used with intermediate moment frames, ordinary reinforced concrete structural walls are assigned an R factor of 5.5. Used with special moment frames, the R factor increases to 7.0.

For ordinary structural walls, emulative detailing provides a specific benefit in increasing R factors. The level of strength

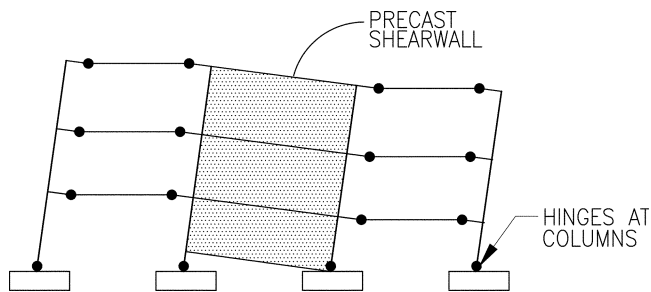


Fig. 3.1—Dual building, ductile yielding of partially debonded bars between foundation and shear wall boundary elements.

and ductility reflected by the R factors only requires that the standard details be used with precast and tilt-up construction. ASCE/SEI 7-10 recognizes precast concrete walls with three levels of detailing requirements. Ordinary Precast Concrete Shear Walls can be used only in buildings with **low seismic risk** (Seismic Design Category B) and require only detailing for structural integrity. These integrity requirements include at least two base connections for each wall rated at a nominal force of 10 kips (44.5 kN) and floor or roof anchorage based on site acceleration with a minimum threshold force. These walls are assigned an R factor that is lower by a value of 1 than the comparable ordinary reinforced concrete shear that is cast in place. For **moderate seismic risk** (Seismic Design Category C), precast walls must be Intermediate Precast Shear Walls, which have additional requirements for ductile connections. These walls are assigned an R factor that is the same as a comparable cast-in-place wall. In buildings classified with **high seismic risk** (Seismic Design Categories D, E, and F), shear walls must be Special Reinforced Concrete Shear Walls. In this case, there is no difference between monolithic cast-in-place and precast concrete walls. When precast, these walls must meet the detailing requirements for cast-in-place walls in addition to the ductile detailing requirements applied to Intermediate Precast Concrete Shear Walls. This may include boundary elements with special confinement reinforcement at close spacing that prevents the buckling of the main flexural reinforcing after yielding under cyclic loading. For special structural walls, however, only those walls that meet the ACI 318-11 Chapter 21 requirements have R factors. Precast walls can then emulate the performance and detailing of monolithic cast-in-place walls using the rules that were developed for cast-in-place construction.

The only alternative to emulation for special structural walls is the general provision of ACI 318-11 Section 21.1.1.8, which allows alternative systems if the proposed system is demonstrated by experimental evidence and analysis to have strength and toughness equal to or exceeding those provided by a comparable monolithic reinforced concrete structure. There is also acceptance of walls that use unbonded post-tensioning tendons in accordance with ACI ITG-5.1. For moment frames, the engineer can refer to ACI T1.1. This, however, is not considered emulation, but rather a newly developed jointed frame system.

Because a small rotation in a wall will create a large demand for bar elongation, ductility at the base is important.

Ductility can be increased significantly by debonding bars into and out of the foundation so that they can deform inelastically over a longer length (Soudki et al. 1995), thus resulting in greater bar elongation and wall rotational ductility (Fig. 3.1). Reinforcing steel specified for special structural walls should be ductile and have controlled strength properties. ACI 318-11 Section 21.1.5.2, requires that reinforcement resisting earthquake forces meet ASTM A706/A706M with some exceptions.

Historic background: In 2003, the *International Building Code* (IBC) (International Code Council 2003), based on the National Earthquake Hazards Reduction Program (NEHRP) “Recommended Provisions” (Building Seismic Safety Council 1997), recognized two classifications of shear walls. First, “Ordinary Reinforced Concrete Shear Walls” were walls designed in accordance with ACI 318 Chapters 1 through 18. This included Chapter 16 on precast concrete, which included provisions for structural integrity. Ordinary reinforced concrete shear walls were permitted in buildings in seismic performance Categories A, B, and C. These requirements did not include the seismic detailing provisions of Chapter 21 of ACI 318. Systems braced with ordinary reinforced concrete structural walls were assigned a response modification factor, or R factor, of 4.5 for load-bearing wall systems, and 5 for structural walls bracing a vertical frame.

Also of note, originally, the second classification of shear walls in the IBC 2003 (International Code Council 2003) was “Special Reinforced Concrete Shear Walls.” IBC 2006 (International Code Council 2006) again changed the terminology from “shear” to “structural.” Currently, the IBC 2012 (International Code Council 2012) makes the same references to the ACI 318, but changes the term “shear wall” to “structural wall.” The IBC 2012 refers to ASCE/SEI 7-10, which assigns categories for precast concrete that are distinct from cast-in-place concrete, but engineers can also use emulative detailing to meet the cast-in-place categories.

3.1.2 Box structures—Box structures are a type of structural system that may fall under the category of walls. Familiar examples of box or cellular structures, shown in Fig. 3.2 and 3.3, include stair cores, elevator cores, and some panel-type multistory residential buildings. The overlapping corners shown in Fig. 3.3 provide a strong shear component when completed. In particular cases, when the boxes include integral floors, ceilings, or both, they have been called cells. Even though a large number and variety of buildings falling under this category have been constructed in North America, it was the Architectural Institute of Japan (AIJ) that primarily formalized the classification of box structures as a structural system for earthquake-resistant buildings (Suenaga 1974).

A box is a three-dimensional cell. Monolithic cells can be emulated in precast construction with three-dimensional modules or by assembling with separately manufactured floor and wall panels using the emulative details shown in this report (refer to Fig. 3.2, 5.4, and 5.8).

3.1.3 Moment-resisting frames—Moment-resisting frames (both steel and reinforced concrete) are used for buildings over a wide range of heights.

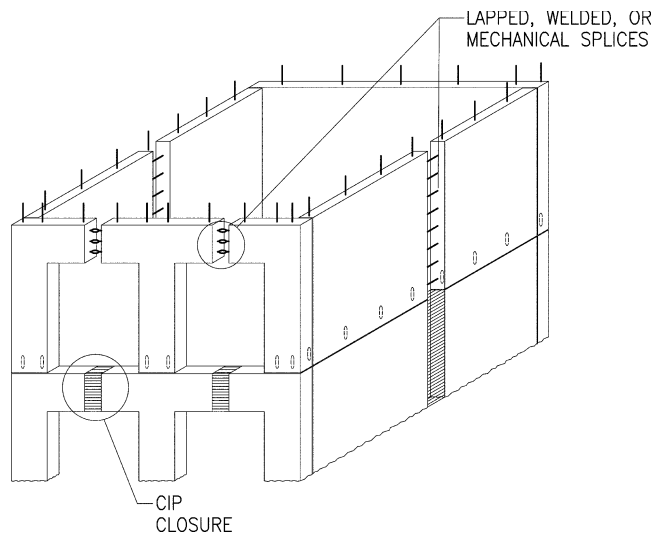


Fig. 3.2—Precast shear tower using mechanical splices and cast-in-place closure connections between elements.

When structures are required to remain elastic, design procedures require larger structural members to resist forces resulting from earthquakes. This leads to increased material costs, higher lateral forces on nonstructural elements, and probable loss of some floor and window opening space due to bulkier columns. Under elastic design provisions, beams may require greater depth, resulting in increased story heights and, consequently, taller buildings. In regions where relatively minor earthquake loads are expected, design for elastic response can be appropriate when it may not be economical to detail for ductility. Note: The NEHRP-based code provisions (Building Seismic Safety Council 1997) permit the use of ordinary moment frames for SDCs A and B.

Ductility is an important consideration where concrete moment frames subjected to lateral loads are assumed to behave inelastically. This is usually the case in SDCs D, E, and F as defined in IBC 2012 Section 1616.3 (International Code Council 2012). Special reinforced concrete moment frames may be used in these SDCs, as intermediate reinforced concrete moment frames are only permitted to be used in SDCs A, B, and C. For a complete description of permitted use of various systems, the reader is referred to IBC 2012 (International Code Council 2012) and ASCE/SEI 7-10 provisions.

Concrete frames can be readily designed to perform in a ductile manner. Full-scale tests of reinforced concrete beam-column connections have shown that such connections are ductile and can perform effectively under earthquake loading. Plastic hinging of beam-end connections is highly dependent on the type and amount of reinforcement used in the intended ductile hinge region, usually at or near beam ends.

Chapter 21 of ACI 318-11 provides prescriptive requirements for special moment frames intended to ensure strong-column/weak-beam behavior.

The "AIJ Structural Guidelines for Reinforced Concrete Buildings" (Architectural Institute of Japan 1994), a design manual for reinforced concrete frames, explains how to design concrete structures to behave elastically for equivalent

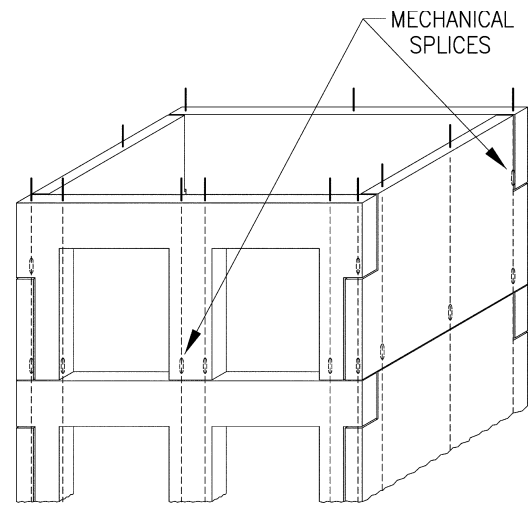


Fig. 3.3—Use of mechanical connections and interlocking precast wall elements to create a monolithic shear tower. Note: Erection sequencing must be coordinated.

earthquake loads associated with horizontal structure accelerations of up to 20% of gravity. The manual also provides for the deliberate introduction of ductile (inelastic) hinges in the beams near the beam-column junctures and at selected locations in the columns (Fig. 3.4 and 3.5). Sufficient strength is designed into the hinge regions to accommodate lateral floor accelerations up to 100% of gravity. The longitudinal reinforcement ratio of ductile hinges is intentionally limited so that the bars are capable of being strained significantly beyond their yield point, therefore inelastically elongating the bars. This mechanism absorbs and dissipates a substantial amount of seismic energy imparted to the frame.

Historic background: In June 1978, NEHRP was established. The "National Earthquake Hazard Reductions Program (NEHRP) Recommended Provisions for the Development of Seismic Regulations for New Buildings and Other Structures" (Building Seismic Safety Council 1997) was first published in 1985 and was subsequently updated. These provisions included recommendations for the evaluation of loads and general building details, and material-specific parameters and detailing provisions that are consistent with those general recommendations.

The 1994 edition of the "Recommended Provisions" was used in making major changes to the "Uniform Building Code" (UBC) (International Conference of Building Officials [ICBO] 1997). The IBC 2000 (International Code Council 2000) was the culmination of the effort initiated by the International Code Council in 1997 to develop a comprehensive set of regulations for building systems consistent with and inclusive of the scope of the existing model codes. Successive updates including the current IBC 2012 (International Code Council 2012) are updates to the IBC 2000.

3.1.4 Dual systems: frames and structural walls—Dual building systems consist of a combination of structural walls and moment frames. A dual system can be used when a moment-resisting frame alone does not provide sufficient lateral stiffness. Design attention should be directed to the probable lack of deformation compatibility in both elastic