

SEISMIC DESIGN PROVISIONS FOR PRECAST CONCRETE STRUCTURES

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BACKGROUND

Until recently, precast concrete structures could be built in areas of high seismicity, such as California, only under an enabling provision of the ACI 318 *Building Code Requirements for Structural Concrete*, which is adopted by all model codes used in the country. The provision allows precast concrete construction in a highly seismic area “if it is demonstrated by experimental evidence and analysis that the proposed system will have a strength and toughness equal to or exceeding those provided by a comparable monolithic reinforced concrete structure...”. The enforcement of this vague, qualitative requirement was, for obvious reasons, nonuniform. The need for specific enforceable design requirements for precast structures in regions of high seismicity was apparent for quite some time.

The first set of specific design provisions ever developed in this country for precast concrete structures in regions of high seismicity appeared in the 1994 edition of the *National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions*, issued by the Building Seismic Safety Council (BSSC). This paper discusses the earthquake-related design requirements for precast concrete structures of the 1994 NEHRP Provisions and how these have evolved since the publication of that document.

1994 NEHRP PROVISIONS

The 1994 *NEHRP Provisions* presented two alternatives for the design of precast lateral-force-resisting systems (Fig. 1). One choice is emulation of monolithic reinforced concrete construction. The other alternative is the use of the unique properties of precast concrete elements interconnected predominantly by dry connections (jointed precast). A “wet” connection uses any of the splicing methods of ACI 318 to connect precast or precast and cast-in-place members, and uses cast-in-place concrete or grout to fill the splicing closure. A “dry” connection is a connection between precast or precast and cast-in-place members that does not qualify as a wet connection.

Design procedures for the second alternative (jointed precast) were included in an appendix to the chapter on concrete in the 1994 NEHRP Provisions. These procedures were intended for information and trial design only because the existing state of knowledge made it premature to propose codifiable provisions based on information available at that time.

1997 UNIFORM BUILDING CODE

The Ad Hoc Committee on Precast Concrete of the Structural Engineers Association of California (SEAOC) Seismology Committee used the 1994 NEHRP requirements for precast concrete lateral-force-resisting systems as a starting point for their work in developing a code change for the 1997 UBC. However, the committee decided to limit their scope to frames only (excluding wall systems) and to the monolithic emulation option only. Jointed precast concrete is allowed only under the “unidentified structural systems” provisions of the 1997 UBC.

For emulation of the behavior of monolithic reinforced concrete construction, two alternatives are provided (Fig. 2): structural systems with “wet” connections and those with “strong” connections. Precast structural systems with wet connections must comply with all requirements applicable to monolithic reinforced concrete construction. A “strong” connection is a connection that remains elastic while designated portions of structural members (plastic hinges) undergo inelastic deformations (associated with damage) under the design basis ground motion. Prescriptive requirements are given for precast frame systems with strong connections. Such requirements for precast wall systems with strong connections are not included.

The 1994 *NEHRP Provisions* also addressed emulation of monolithic construction using ductile connections, covering both frame and wall systems, where the connections have adequate nonlinear response characteristics and it is not necessary to ensure plastic hinges remote from the connections. Usually, experimental verification is required to ensure that a connection has the necessary nonlinear response characteristics. The designer is required to consider the likely deformations of any proposed precast structure, compared to those of the same structure in monolithic reinforced concrete, before claiming that the precast form emulates monolithic construction. The 1997 UBC does not directly address emulation of monolithic construction using ductile connections.

1997 NEHRP PROVISIONS AND 2000 INTERNATIONAL BUILDING CODE

The 1997 UBC provisions concerning design of precast concrete structures in regions of high seismicity were adopted into the 1997 edition of the *NEHRP Provisions*. The first edition of the *International Building Code*, which is replacing the existing model codes as the basis of the building codes for many legal jurisdictions, has its seismic design provisions based on the 1997 *NEHRP Provisions*. The design provisions for precast concrete structures exposed to high seismic risk are included.

2000 NEHRP PROVISIONS

The 2000 *NEHRP Provisions* is in the final stages of development. The design provisions for precast structures in high seismic regions have been greatly expanded. The scope of these provisions is illustrated in Fig. 3. It should be apparent that virtually all viable options of precast concrete construction have now been considered.

The 2000 NEHRP Provisions adopts ACI 318-99 by reference to regulate concrete design and construction. Amendments are made by inserting additional provisions into, or revising the existing provisions of, ACI 318-99. In ACI 318-99, the seismic risk of a region is described as low, moderate or high. Chapter 21 contains specific requirements for the design of concrete structures in regions of high and moderate seismic risk. Structures in regions of low seismic risk need only meet the requirements of Chapters 1 through 18 of ACI 318-99. In the NEHRP Provisions, the applicability of Chapter 21 requirements depends not only on the region in which the structure is located but also on the occupancy of the structure and the characteristics of the soil on which it is founded. In the 2000 NEHRP Provisions, these three considerations are combined in terms of Seismic Design Categories (SDC) which are assigned letters A through F. ACI 318-99 recognizes SDCs A and B as being equivalent to regions of low seismic risk and needing only detailing that meets the requirements of Chapters 1 through 18. Structures assigned to SDC C are recognized as requiring detailing mandated for regions of moderate seismic risk and structures assigned to SDCs D, E and F require detailing prescribed for regions of high seismic risk.

Section numbers in Fig. 3 starting with the number 9 (for ordinary structural walls) identify specific provisions of the NEHRP Provisions. Section numbers starting with the number 21 identify specific provisions inserted into ACI 318-99.

The 2000 NEHRP Provisions requires that seismic-force resisting systems in precast concrete structures assigned to SDCs D, E and F consist of special moment frames, special structural walls, and Type Z connections (all these items are discussed later in the paper).

For structures assigned to SDC C, moment frames made from precast elements must utilize, as a minimum, Type Y connections. However, they can also have the tougher Type Z connections if the designer so chooses. Structural walls composed from precast elements can be designed as ordinary structural walls per Chapters 1 through 18 of ACI 318-99, with the requirements of Chapter 16 superseding those of Chapter 14 and with Type Y connections, as a minimum, between elements.

Special Moment Frames

The 2000 NEHRP Provisions allow the emulative and non-emulative design approaches to be used for precast and/or prestressed concrete special moment frames. Hinge locations (non-linear action locations), must be selected so that there is a strong column/weak beam deformation mechanism under seismic effects, regardless of whether emulative or non-emulative design procedures are used.

Emulative Design - Two design alternatives that were provided in the 1994 NEHRP Provisions, with minor changes, have been carried over into the 2000 NEHRP Provisions.

One procedure allows elements to be joined using ductile connections, while the other allows them to be joined using strong connections. Because a strong connection must not yield or slip, its design strength in both flexure and shear must be greater than the bending moment and shear force, respectively, corresponding to the development of probable flexural or shear strengths at nonlinear action locations. Where strong connections are used, the non-linear action location (center of the nonlinear action region) must be no closer to the near face of the strong connection by half the member depth. Any strong connection located outside of the middle half of the span of the beam must be a wet connection unless a dry connection can be justified by approved cyclic test results.

Where elements are joined using ductile connections, the aggregate interlock that is present at hinge locations in monolithic construction is unlikely to exist for precast construction. Therefore, to prevent shear slip when the moment acting at the hinge location is at its maximum probable value of M_{pr} , the co-existing shear must not exceed half the sum of the nominal shear strengths, $S_{n \text{ Connection}}$, of all the connections at the hinging section. The nominal shear strength, V_n , of the section where the connection is made must also not be less than the shear strengths of the members immediately adjacent to the connection.

Individual connections must satisfy Type Z connection requirements. Those connections can be either “wet” or “dry.” One type of ductile wet connection widely used in emulative design is the “splice sleeve” connection. Other connections with similar ductility capabilities have recently become available or are under development

Non-Emulative Design - Over the last decade many advances have been made in our understanding of the seismic behavior of precast concrete frame structures. Those advances have made possible the provisional standardization by ACI of acceptance criteria for concrete special moment frames, based on validation testing, in ACI ITG/T1.1-99. That provisional standard, together with research advances, has made possible the development of criteria for the design of frames constructed from interconnected precast elements. While criteria for such frames have existed in the NEHRP Provisions since 1994, the previous criteria were in an Appendix and contained penalties for the use of precast elements compared to monolithic concrete elements. Those penalties are eliminated in the 2000 NEHRP Provisions and the possible behavioral benefits of using precast construction are recognized.

Special Structural Walls

The studies that led to the development of the acceptance criteria of ACI ITG/T1.1-99 for special moment frames also catalyzed studies that have resulted in the development of similar acceptance criteria for special structural walls..

The 2000 NEHRP Provisions requires that the substantiating experimental evidence and analysis for special structural wall systems meet requirements similar to those of T1.1-99 for the design procedure used for the test modules, the scale of the modules, the testing agency, the test method and the test report.

Connections

Dry connections for seismic-force-resisting systems are classified into two types, Type Y and Type Z. At non-linear action locations, displacements both in the direction of action of the connection, and transverse to it, must be controlled. For example, if a sliding shear connection is to be provided between two precast members, then there must also be a tie between the two members to prevent the sliding surfaces from separating.

Type Y connections must be able to develop, for the flexure, shear, or axial load, or combinations of those quantities expected to act on the connection, a probable strength, S_{pr} , determined using a ϕ value of unity, that is not less than 125 percent of the yield strength of the connection. In essence, the connection must be able to strain-harden. Under cyclic loading the connection must be able to develop a displacement, at S_{pr} , that is at least 4.0 times its displacement at yield. The anchorage of the connection into the precast member on either side of a joint must be designed to develop in tension 1.3 times S_{pr} , and be connected directly by a Type 2 splice to the principal reinforcement of the precast or cast-in-place element.

For Type Z connections S_{pr} must be not less than 140 percent of the yield strength of the connection, and under cyclic loading the connection must be able to develop a displacement at S_{pr} that is at least 8.0 times its displacement at yield. The anchorage for the connection must also meet in both tension and compression all the requirements for Type Y connections. Equilibrium based plasticity models (strut-and-tie models), as described in Section 18.13.5 of ACI 318-99, are to be used for the design of the connection region. Confinement reinforcement in the form of closed hoops or spirals with a yield strength not less than 0.5 times the compressive force and with a spacing not greater than 3 inches must be provided around the anchorage where the local compressive stress at S_{pr} exceeds $0.7 f'_c$. The connection region is defined in the same manner as “anchorage zone” in Section 2.1 of ACI 318-99.

The testing of connections and the evaluation of results must be made in accordance with the principles of ACI ITG/T1.1-99. Connections at non-linear action locations in modules of frames and structural walls used for validation testing are deemed to satisfy the provisions for connections if the results for the test module satisfy the acceptance criteria for frames or structural walls, as appropriate.

ACI 318-02

The 2002 edition of the ACI 318 standard is expected, for the first time, to include design provisions for precast concrete structures located in regions of moderate to high seismic risk or assigned to intermediate or high seismic design categories (C, D, E, F). Figure 4 illustrates the scope of these provisions. It is evident that the scope is somewhat more limited, when compared to that of the 2000 NEHRP Provisions. When the same item is covered in both documents, the requirements are by and large similar.

CONCLUDING REMARKS

Much has been accomplished in the building codes arena to enable the satisfactory design of precast concrete structures exposed to high seismic risk. The 2000 NEHRP Provisions represents a culmination of efforts that have been underway since the late 1980's. Recent earthquakes have provided new information regarding the performance of precast concrete structures and lessons learned have been codified. With the 2000 *International Building Code*, precast concrete buildings can be designed with the necessary seismic detailing and features to ensure adequate performance. The 2002 edition of ACI 318 is expected, for the first time, to contain design provisions for precast concrete structures exposed to high seismic risk.

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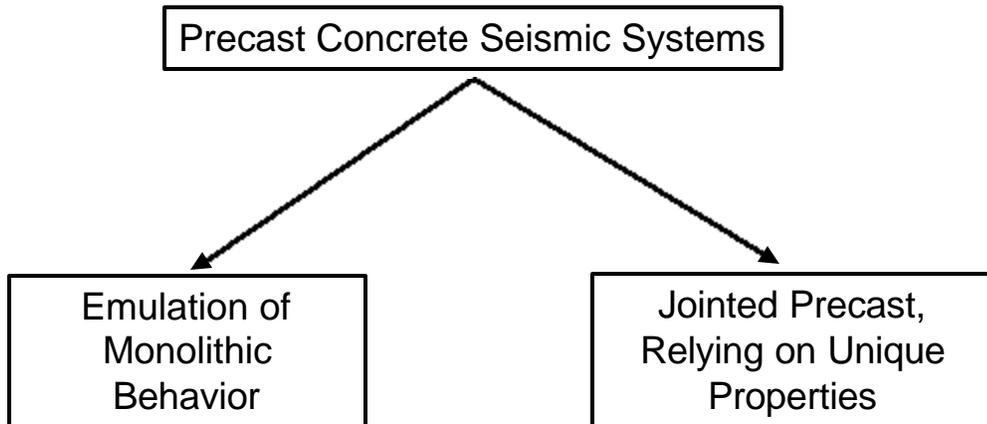


Fig. 1: Earthquake-force-resisting systems of precast concrete - options

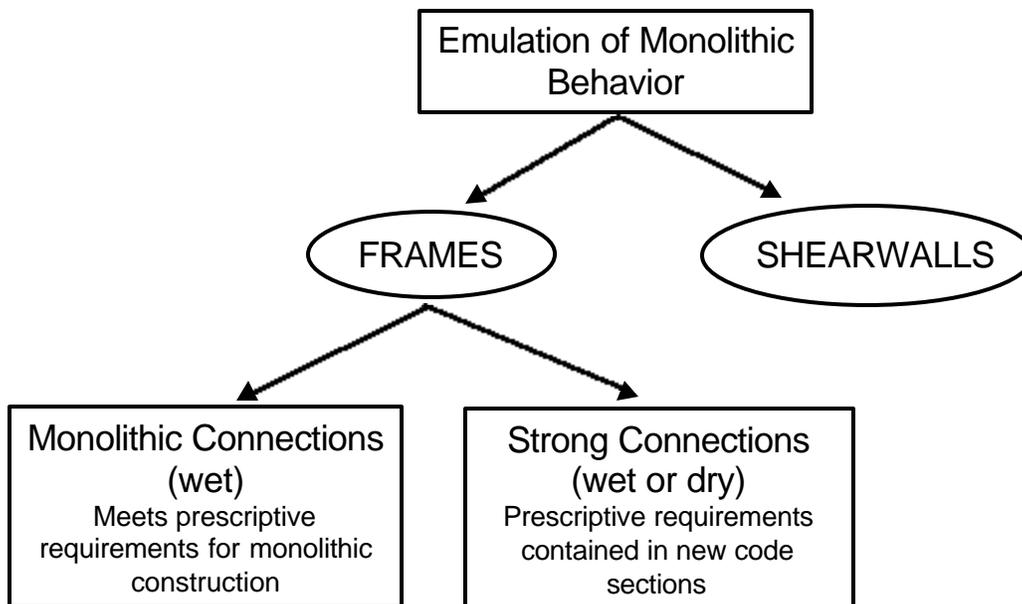


Fig. 2: Emulation of monolithic behavior - options

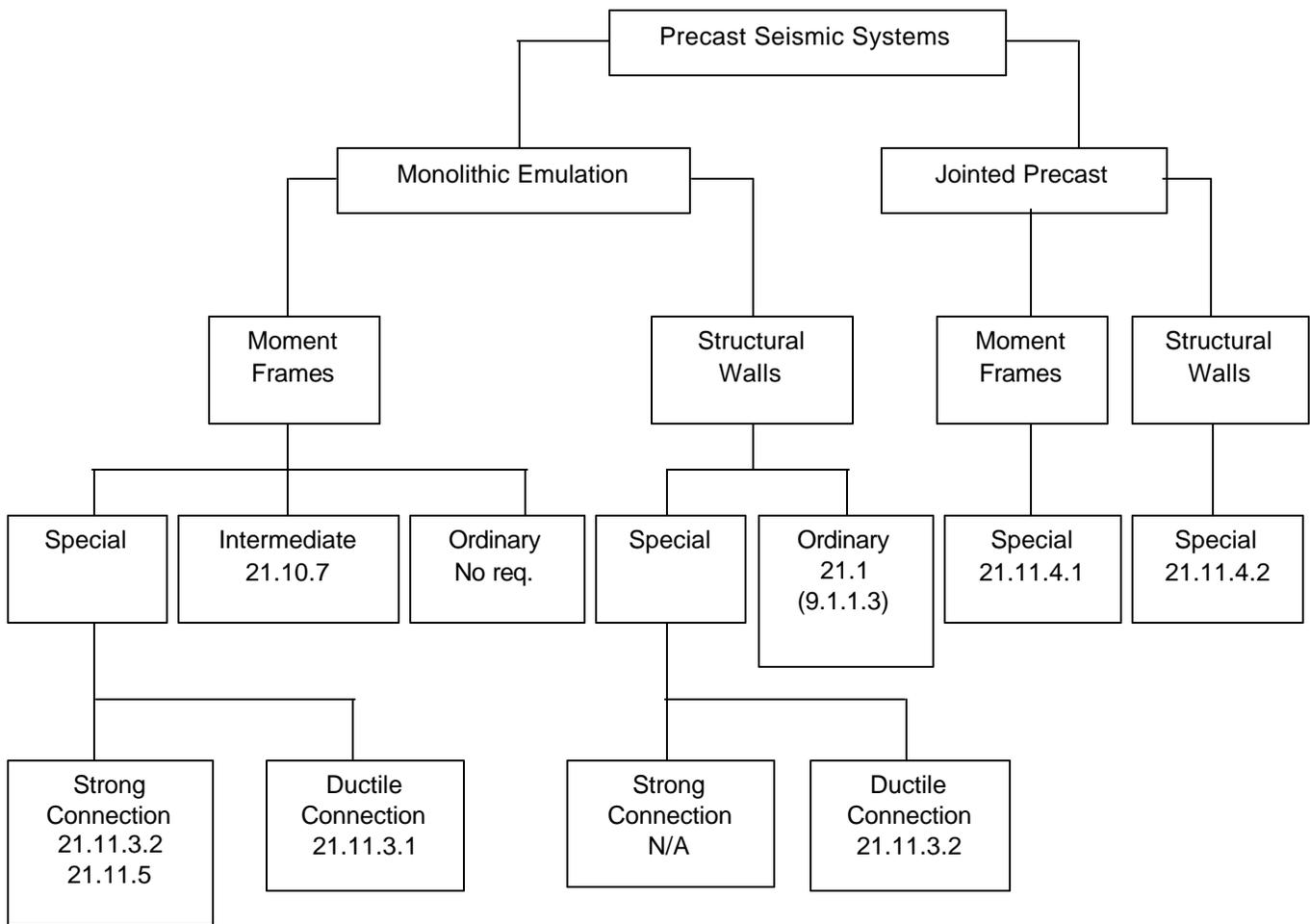


Fig. 3: Seismic design requirements for precast structures in 2000 NEHRP Provisions

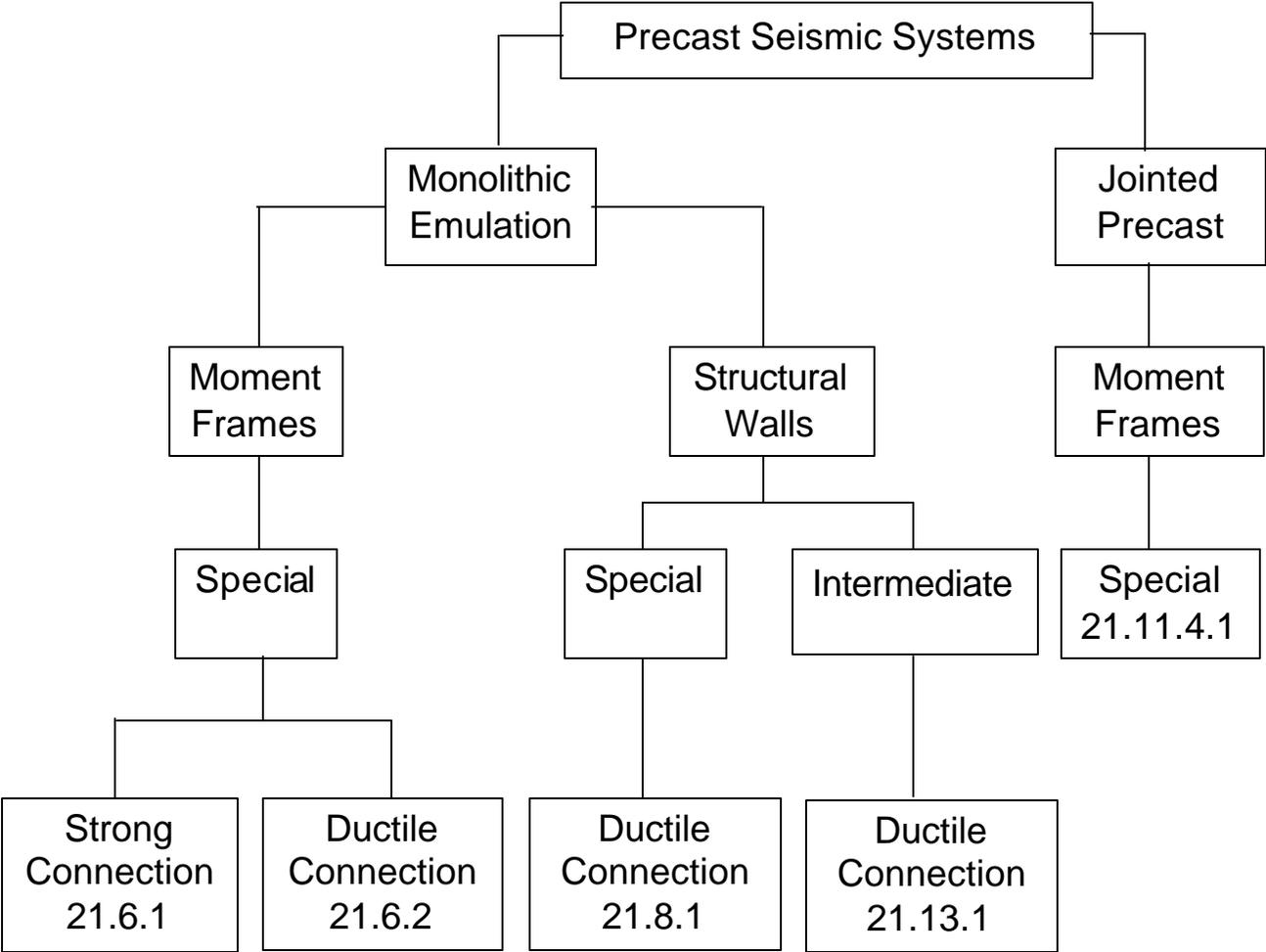


Fig. 4: Seismic design requirements for precast structures in ACI 318-02 (expected)