SEISMIC DESIGN PROVISIONS FOR PRECAST CONCRETE STRUCTURES IN ACI 318

by

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BACKGROUND

This is a follow-up to a series of three prior papers discussing significant modifications approved for inclusion in the 2000 NEHRP Provisions, dealing with the design of precast concrete seismic-force-resisting systems. This paper discusses the corresponding provisions that are expected to be included, for the first time, in the 2002 edition of the ACI 318 Building Code Requirements for Structural Concrete, and describes the relation between the ACI and NEHRP provisions.

In the May-June 2000 issue of the *PCI JOURNAL*, the history and development of the requirements of the NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions[1] for precast and prestressed concrete structures were discussed. In the September-October 2000 and November-December 2000 issues of the *PCI JOURNAL*, the specifics of the requirements of the proposed 2000 NEHRP Provisions concerning precast concrete seismic-force-resisting frames and shear wall systems, and untopped diaphragms, respectively, were given and the bases of those provisions were documented.

This paper first summarizes (from the second paper in the above series) the requirements of the proposed 2000 NEHRP Recommended Provisions for seismic-force-resisting frame and shear wall systems composed of precast concrete elements. It then presents and discuses the corresponding design provisions that are expected to be included in ACI 318-02[2], and points out certain similarities and differences.

The ACI and NEHRP documents have fundamentally different purposes. The NEHRP Provisions is intended as a resource document for use by code and standard writers. By contrast, ACI Committee 318 is a standard writing group publishing requirements intended as suitable for adoption into codes.

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 from prior editions of the document. The scope of these provisions is illustrated in Fig. 1.

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. In the 2000 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. 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. 1 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. In Fig. 1 precast systems are divided between "monolithic emulation" and "jointed". In this article the design processes for those systems are described as "emulative" and "non-emulative" respectively. Conceptually that differentiation between the two systems is arbitrary since the global deformations of a jointed frame system should also emulate those for monolithic frame construction. However, as implied by the terminology used in this article, it is the design process that differs for the two systems; the process for "jointed" construction is less emulative of that for cast-in-place construction than that for "monolithic emulation".

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).

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 emulative as well as non-emulative design approaches to be used for precast 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 have been carried over from prior editions 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. 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.

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, $S_{n\ Connection}$, 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[3]. 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 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 (as defined in ACI 318-99) 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 in advanced stages of preparation. Although all necessary approvals have not been obtained and all necessary processes have not been completed, which means that the contents are still subject to change, the 2000 edition 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 2 illustrates the scope of these proposed provisions. It is evident that the scope is somewhat more limited, when compared to that of the 2000 NEHRP Provisions.

New provisions for special moment frames and structural walls constructed of precast concrete are provided. Although new provisions are also given for the design of intermediate precast structural walls (an item not included in the 2000 NEHRP Provisions), general building codes that address seismic design categories currently do not recognize intermediate structural walls. In part that is because the difference between the R^{-} values currently used for ordinary and special structural walls is small. By contrast the difference between the R^{-} values for ordinary and special moment frames is much larger and the introduction of an intermediate moment frame category is economically desirable.

Special Moment Frames

Emulative Design - The detailing provisions in Sections 21.6.1 and 21.6.2 are intended to produce frames that respond to design displacements (displacements expected when structure is subjected to the design-basis earthquake) essentially like monolithic special moment frames.

Precast frame systems composed of concrete elements with ductile connections are expected to experience flexural yielding in connection regions. Precast concrete frame systems composed of elements joined using strong connections are intended to experience flexural yielding outside the connections. Strong connections include the length of the coupler hardware. Capacity design techniques are used to ensure that the strong connection remains elastic following the formation of plastic hinges. Additional columns requirements are provided to avoid hinging and strength deterioration of column-to-column connections.

Examples of brittle fracture of reinforcing bars at the faces of mechanical splices, caused by strain concentrations, have been observed in laboratory tests of precast beam-column connections[4]. Therefore, designers are cautioned to carefully select locations of strong connections or take other measures, such as debonding of reinforcing bars in highly stressed regions, to avoid strain concentrations that have the potential to cause premature fracture of reinforcement.

Non-Emulative Design - Special moment frames constructed using precast concrete and not satisfying the requirements of Sections 21.6.1 and 21.6.2 are permitted, provided they satisfy the requirements of ACI Provisional Standard ITG/T1.1-99[3], "Acceptance Criteria for Moment Frames Based on Structural Testing." Two additional criteria, not part of ITG/T1.1-99 or the 2000 NEHRP Provisions, are imposed. First, details and materials used in the test specimens must be representative of those used in the structures. Second, the design procedure must identify the load path or mechanism by which the frame resists gravity and earthquake effects. The tests must be configured to examine initial behavior modes, and the measured quantities must establish upper-bound acceptance values for components of the load path, which may be in terms of limiting stresses, forces, strains, or other quantities. The design procedure used for the structure must not deviate from that used to design the test specimens, and acceptance values must not exceed values that were demonstrated by tests to be acceptable.

Intermediate Precast Structural Walls

Connections between precast wall panels or between wall panels and the foundation are required to resist forces induced by earthquake motions and to provide for yielding (of steel elements or reinforcement only) in the vicinity of the connections. Elements of connections that are designed not to yield must develop at least 1.5 times the specified yield strength of the reinforcement. It may be noted that the Type Y and Z connections of the 2000 NEHRP Provision are not recognized or used in ACI 318-02.

It has been noted earlier that general building codes, based on the various model codes currently in existence, do not recognize Intermediate Precast Structural Walls.

Special Structural Walls

Special structural walls constructed using precast concrete must satisfy all ACI 318 requirements for cast-in-place special structural walls (Section 21.7), and must also satisfy the connection requirements imposed on Intermediate Precast Structural Walls.

Vertically coupled precast concrete shear walls and post-tensioned precast concrete shearwalls, as utilized in the PRESSS program, are permitted under the 2000 NEHRP Provisions. The ACI 318-02 provisions will make use of such systems difficult. However, that difficulty may be consistent with the concept that the NEHRP Provisions is a resource document whereas ACI 318 is intended for regulatory use. For 'jointed precast concrete special moment' frames several commercial structures completed in the field have demonstrated the viability of that form of construction. The corresponding structures isong special structural walls have yet to be built.

ADOPTION INTO MODEL CODES AND STANDARDS

It is expected as of this writing that the seismic design provisions of the 2003 International Building Code (IBC)[5] are going to be based on the 2000 NEHRP Provisions. However, since ACI 318-02 is now going to have design provisions for precast concrete structures assigned to high seismic design categories, these will become part of the 2003 IBC, since ACI 318-02 is going to be adopted by reference into that code to regulate concrete design and construction. In other words, the precast concrete design provisions of the 2000 NEHRP Provisions are going to be superseded by those of the 2000 NEHRP Provisions in the 2003 IBC.

The above remarks can also be made with respect to ASCE 7-02[6], which is currently under development and which is expected to be referenced by NFPA 5000 the model building code that the National Fire Protection Association is in the process of developing.

REFERENCES

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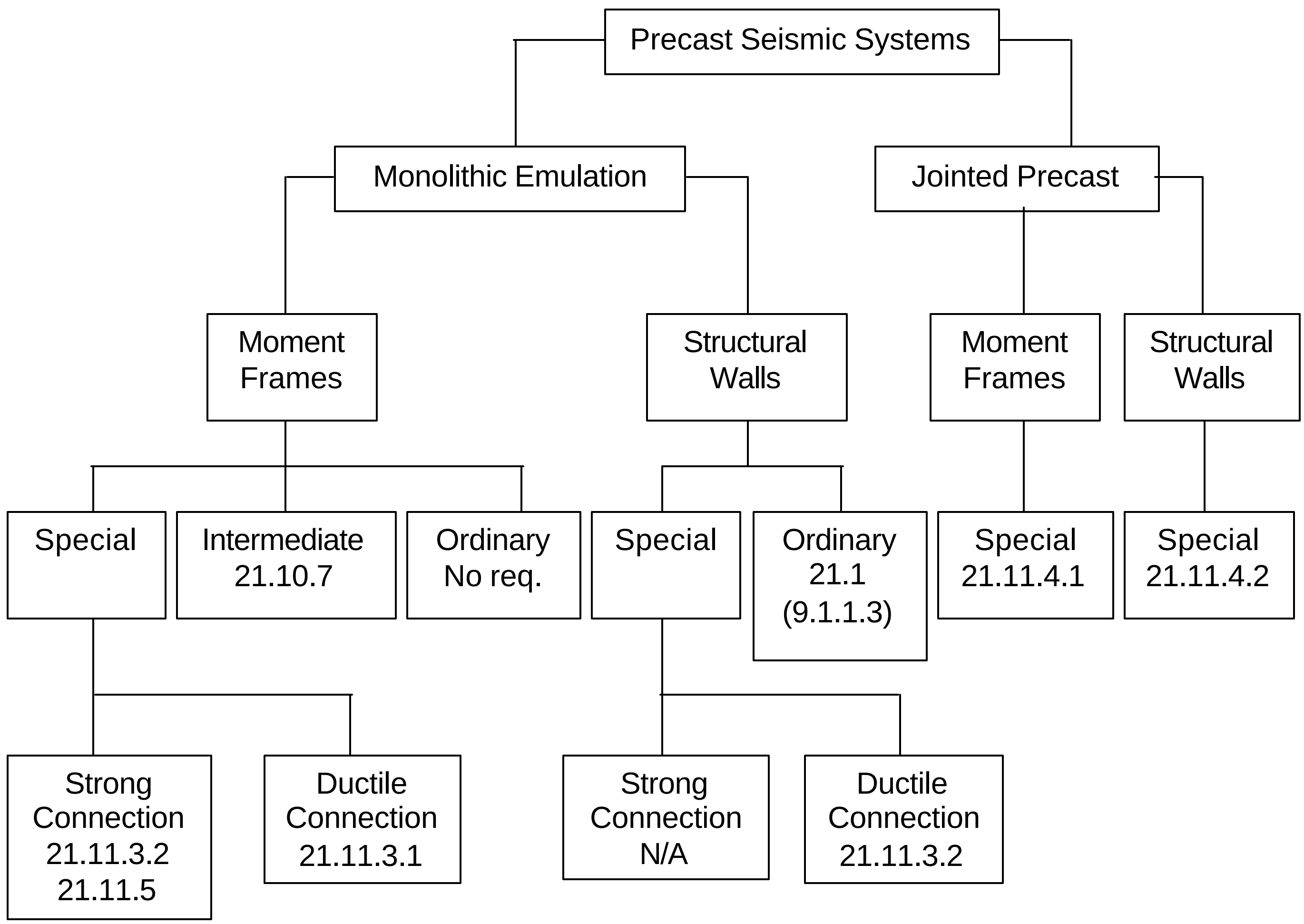

Fig. 1: Seismic design requirements for precast structures in 2000 NEHRP Provisions

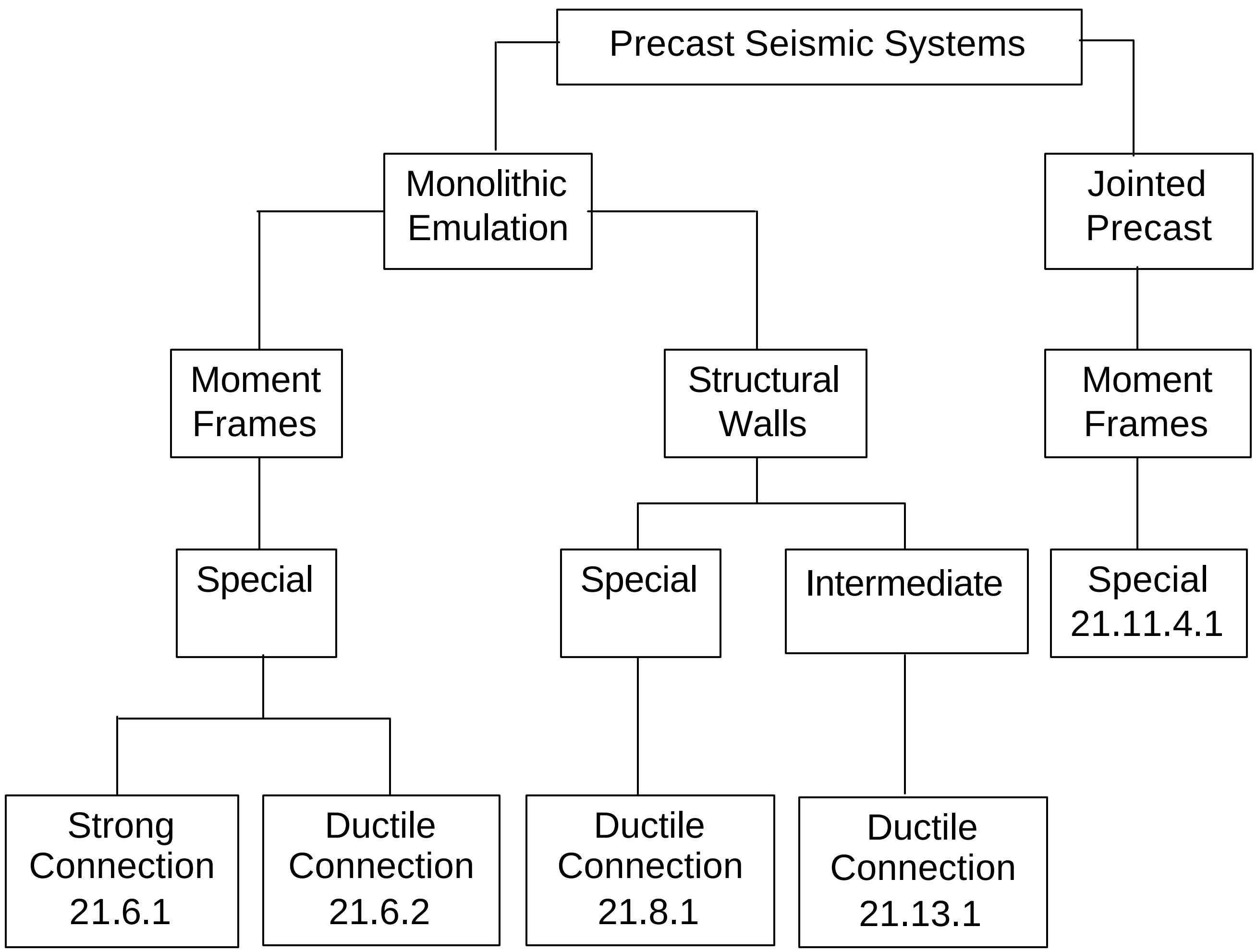

Fig. 2: Seismic design requirements for precast structures in ACI 318-02 (expected)