# Requirements for the Use of PRESSS Moment-Resisting Frame Systems

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*This article explores the relation between the design requirements of ACI T1.1-01, ACI T1.2-03, and Section 21.6.3 of ACI 318-02 for hybrid connections and explains limitations in the use of pretensioned connections of the type used in the upper floors of the PRESSS Test Building.*

In the July-August 2003 issue of the PCI JOURNAL,[1] the authors discussed PCI's strategy for codification of PRESSS structural systems with emphasis on the strategy for non-emulative design of special precast concrete shear walls. Such shear walls were used in one direction of the PRESSS five-story building tested at the University of California at San Diego.[2]

In the perpendicular direction, non-emulative special moment frames were used. On one face of the building, frames with hybrid and pretensioned connections were used, while on the other parallel face, tension-compression yielding (TCY) frames were used. At the end of testing, the appearance of the frames with the hybrid and pretensioned connections was superior to that of the TCY frames. Further, on first analysis, it also appeared that the structural performance of the former frames was superior to that of the TCY frames. Therefore, for implementation of the PRESSS program results, efforts with respect to frames have concentrated first on expediting the utilization of frames with hybrid and pretensioned connections.

For the face of the PRESSS Test Building where frames with hybrid and pretensioned connections were used, hybrid connections were used for the frames of the lower three floors and pretensioned connections for the frames of the upper two floors. The typical hybrid frame interior joint and the pretensioned frame interior joint for the PRESSS Test Building are shown in Figs. 1 and 2, respectively.[2] The frame with hybrid connections uses multistory columns and single-bay beams. That frame is appropriate for floor-by-floor construction typical of multistory buildings. The frame with pretensioned connections uses multi-bay beams and single-story columns typical of "up-and-out" low-rise construction.

The hybrid connection was developed by the National Institute for Standards and Technology (NIST),[3] working in conjunction with Pankow Builders, the University of Washington, and others. That developmental test program used small-scale specimens and had an extensive analysis component. At the completion of the NIST study, ACI in 1996 undertook the task of evaluating the significance of this new technology and facilitating the transfer of the technology into practice through its Innovation Task Group (ITG) process. Because the ITG process was new, and the technology had far-reaching implications that generated considerable input from many parties, the technology transfer process was not as rapid as might have been desired.

Initially, a mechanism had to be found for addressing the restrictions of Section 21.2.1.5 of ACI 318.[4] That provision requires that a reinforced concrete structural system not satisfying the detailing requirements of Chapter 21 be demonstrated by experimental evidence and analysis to have strength and toughness equal to or exceeding those provided by a comparable monolithic reinforced concrete structure that satisfies the detailing requirements of Chapter 21.

The need to satisfy that restriction was met by the development of the Standard "Acceptance Criteria for Moment Frames Based on Structural Testing (ACI T1.1-01) and Commentary (ACI T1.1R-01)."[5] In particular, it is to be noted that ACI T1.1-01 defines minimum acceptance criteria only. Further, as was the case for the Pankow connection, the standard requires that prior to testing, a design procedure shall have been developed for prototype moment frames having the generic form for which acceptance is sought and that the same procedure be used to proportion the test modules.

As explained in the Commentary, T1.1R-01, the test program specified in the Standard is not for the purpose of creating basic data on the strength and deformation properties required for the design of a new type of special moment frame. The creation of such data generally requires that test modules be loaded to failure, as was the case in the NIST development program. For the testing specified in T1.1-01, an existing design procedure is being validated and, therefore, each and every test module must not fail prior to satisfaction of the acceptance requirements specified in T1.1-01. There is no requirement that the test modules be taken to failure.

With a mechanism developed for addressing the equivalency requirement of Section 21.2.1.5 of ACI 318, the task group ITG-1 was then able to address directly the technology transfer issue for hybrid connections. A design procedure for one specific type of hybrid moment frames had been developed through the NIST work and analytical studies. Validation testing of half-scale modules satisfying the requirements of T1.1-01 had been conducted by Pankow Builders for the construction of the 39-story Paramount Building in San Francisco.[6]

The above results and those for the similar hybrid connection types used in the PRESSS building could be used to define requirements for one specific type of hybrid frame that, while not satisfying the prescriptive requirements of Chapter 21 of ACI 318, did satisfy the requirements of T1.1-01. The characteristics required of that frame are specified in the ACI Standard "Special Hybrid Moment Frames Composed of Discretely Jointed Precast and Post-Tensioned Concrete Members (ACI T1.2-03) and Commentary (ACI T1.2R-03)," published in December 2003.[7]

With that publication, the technology transfer process for hybrid connections, of the type developed by NIST and Pankow, is now complete. The precast industry can use such frames in regions of high seismic risk or for structures assigned to high seismic performance or design categories, provided the requirements of Section 21.6.3 of ACI 318-02 concerning special moment frames constructed using precast concrete are satisfied.

The objective of this article is to further explore the relation between the requirements of T1.1-01, T1.2-03, and Section 21.6.3 of ACI 318-02 for hybrid connections, and to explore limitations in the use of pretensioned connections of the type used in the upper floors of the PRESSS Test Building.

## RELATION BETWEEN ACI T1.1-01, ACI T1.2-03, AND ACI 318

Standard T1.1-01 was completed prior to the adoption of ACI 318-02. Therefore, the ACI 318 standard referenced in T1.1-01 is the 1999 edition. Differences between ACI 318-99 and ACI 318-02 that affect the provisions of T1.1-01 are minimal. However, the significance of the provisions of Section 21.6.3 of ACI 318-02 for the implementation of T1.1-01 and T1.2-03 are large.

Standard T1.1-01 had to be written, and adopted by the ACI Standards Board, before its use could be considered by ACI Committee 318. Therefore, the preamble to T1.1-01 notes that "This document defines the minimum experimental evidence that can be deemed adequate to attempt to validate the use of ... weak beam/strong column frames not satisfying fully the prescriptive requirements of Chapter 21 of ACI 318-99." Because ACI 318-02 has now referenced T1.1-01 in Section 21.6.3, T1.1-01 can now unequivocally be said to define the minimum experimental evidence that must be available in order to construct jointed precast special moment frames.

Section 21.6.3 of ACI 318-02 also contains two requirements beyond those in T1.1-01: "(a) Details and materials used in the test specimens shall be representative of those used in the structure; and (b) The design procedure used to proportion the test specimens shall define the mechanism by which the frame resists gravity and earthquake effects, and shall establish acceptance values for sustaining that mechanism. Portions of the mechanism that deviate from code requirements shall be contained in the test specimens and shall be tested to determine the upper bound for acceptance values." These two provisions are important and affect directly the implementation of T1.2-03.

Standard T1.2-03 defines a connection as hybrid when it combines both post-tensioned and precast construction and, in its Section 4, T1.2-03 describes several key considerations for hybrid frames in general. However, the document provides detailed guid-

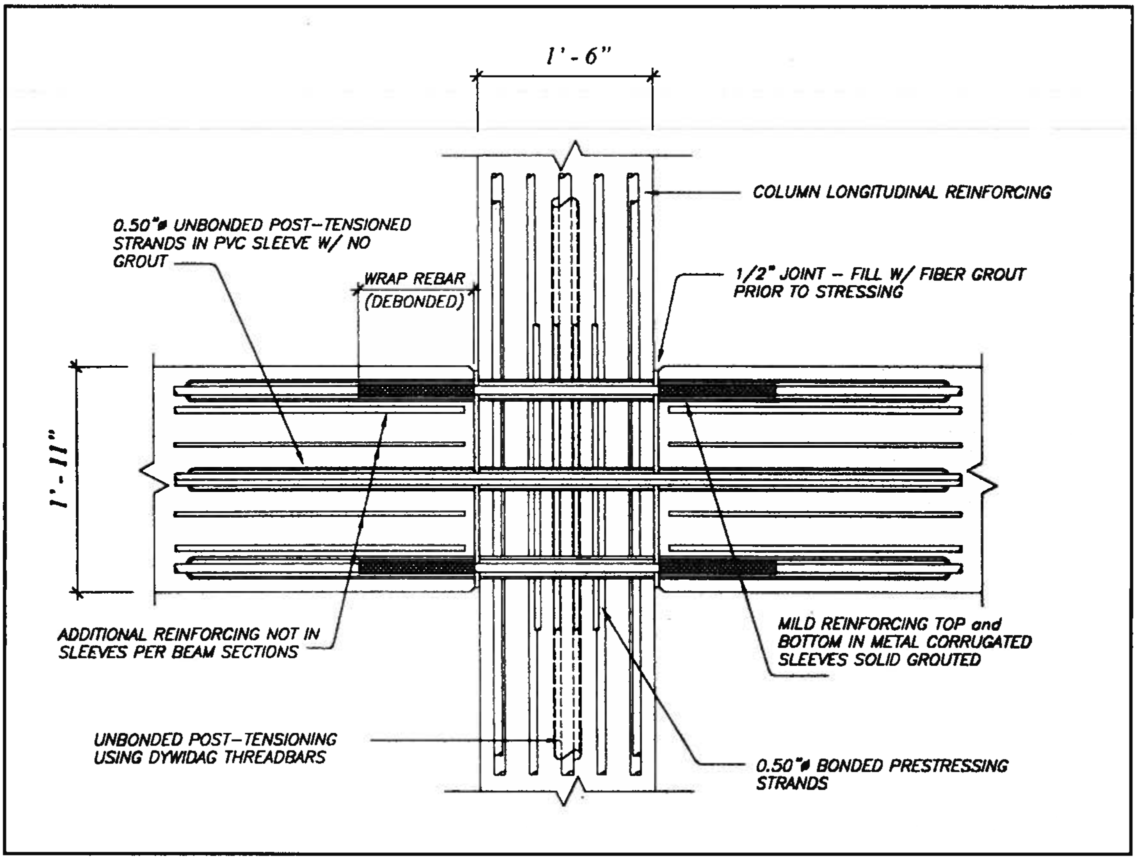


Fig. 1. Idealization of interior column hybrid connection used in the PRESSS Test Building (transverse joint reinforcement not shown for clarity only).

ance for mechanism requirements for one specific type of hybrid frame only. That is the frame developed through the efforts of NIST, Pankow Builders, and the University of Washington and typified by the connection shown in Fig. 1.

There are two key features to hybrid frames in general. One is that the primary connection between the precast beam and the column is made by post-tensioning. Another is that horizontal deformed reinforcing bars are placed across the beam-column interface to ensure adequate energy dissipation, provide additional continuity between beam and column, and add to the moment strength of the beam.

However, for the specific type of hybrid frame covered by T1.2-03, there are three essential requirements. First, the post-tensioning steel must be unbonded anchor to anchor and centrally located within the beam. Second, the horizontal top and bottom deformed bar energy dissipating reinforcement crossing the beam-column interface must have equal areas. Third, those bars must be grouted in ducts located in the column and the beam and be deliberately debonded for a short distance in the beam adjacent to the beam-column interface.

The debonded length is a crucial design element. Debonding is essential to reducing the high cyclic strains that would otherwise occur in those bars at the beam-column interface. The longer the debonded length, the lower the period of the structure and, therefore, the smaller the inertia force it feels.

However, too large a debonded length can allow buckling when the bar is loaded inelastically in compression. Additional information on assessment of bond for bars grouted in ducts such as those used in the frame of Fig. 1 can be found in Reference 8.

Sections 5, 6, and 7 of T1.2-03 define design requirements for the beams of the moment frames, the beam-column interfaces, and the frame joints, respectively, and include associated acceptable limiting strains and forces in order that a hybrid frame of the type shown in Fig. 1 can sustain under high seismic excitations the mechanism by which it resists seismic forces.

However, Section 21.6.3(a) of ACI 318-02 limits the use of T1.2-03 to the characteristics of those frames for which validation tests have been successfully completed. Therefore, until additional validation tests are made that satisfy T1.1-01, the use of T1.2-03 is limited to frames with material and engineering design characteristics (considering shear, flexure, and axial load) not exceeding the bounds of the properties used in the validation tests reported in Reference 6.

Reference 6 reports on validation tests that were made on an interior column-beam connection of the type shown in Fig. 1, on an exterior column-beam connection that had the beam attached to one face of the column only, and on a corner column-beam connection that had beams framing into the columns in two perpendicular directions. Hybrid frames with all of those seismic-force-resisting beam-column configurations are now available for use with T1.2-03.

However, note that the tests conducted to date limit the footprint of such frames to a layout where perpendicular frames meet at a corner only. Until additional validation tests are

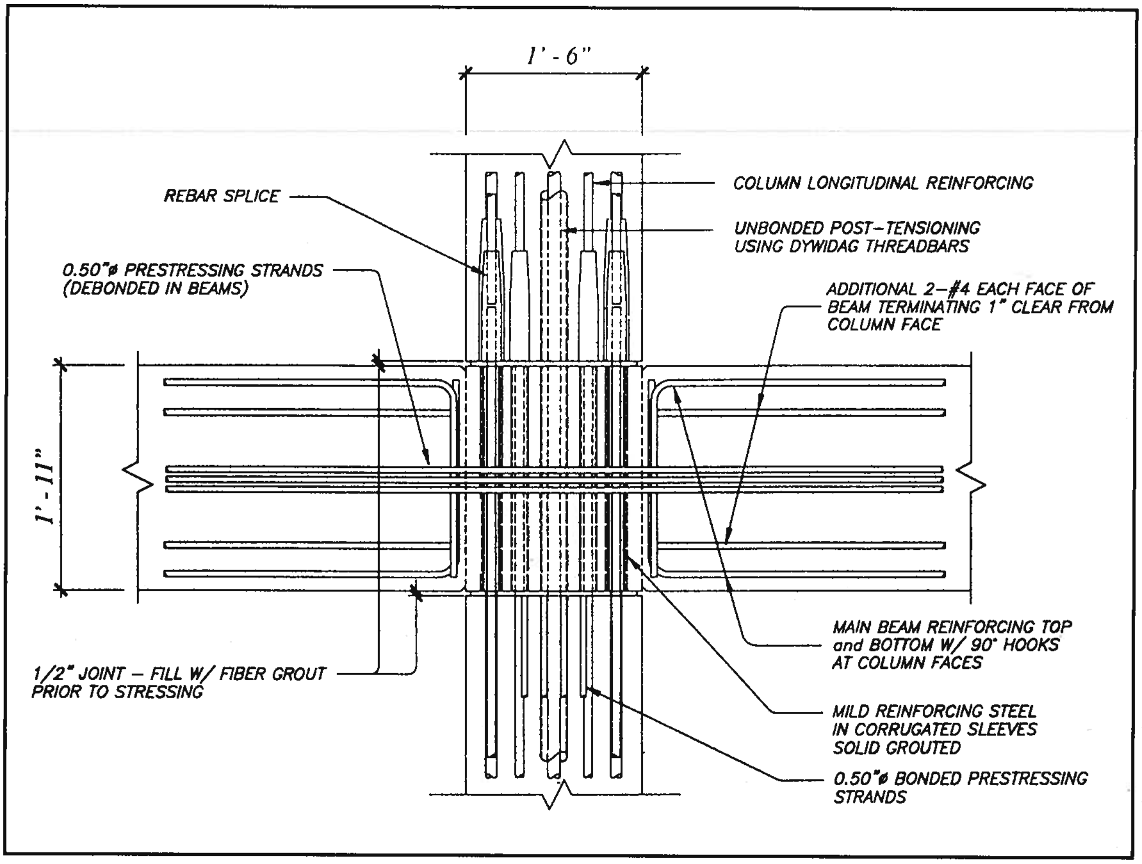


Fig. 2. Idealization of interior column pretensioned connection used in the PRESSS Test Building (transverse joint reinforcement not shown for clarity only).

made satisfying T1.1-01, seismic-force-resisting frame systems intersecting at an interior column or at an exterior column, other than a corner column, are not permitted.

Normal weight concrete was used in the validation tests of Reference 6. The specified concrete compressive strengths were 6000 psi (41 MPa) for the columns and 5000 psi (34 MPa) for the beams of the interior and exterior column specimens, respectively. The specified strengths for the corner column specimen were 8000 psi (55 MPa) for the column and 6000 psi (41 MPa) for the beam. Lower limits to the measured strengths were 6016 and 5931 psi (41.49 and 40.90 MPa) for the columns and beams of the interior and exterior column specimens, respectively, and 8638 and 6548 psi (59.57 and 45.16 MPa) for the column and beams of the corner column specimen, respectively.

The prestressing steel used for the post-tensioning consisted of nine seven-wire, low-relaxation strands conforming to ASTM A 416 Grade 270. Note that T1.2-03 prohibits the use of post-tensioning bars due to concerns with the stress concentration that can occur with kinking of the bar at the beam-column interface. The reinforcement for energy dissipation and the column longitudinal steel conformed to ASTM A 706. The longitudinal reinforcement in beams (excluding the reinforcement for energy dissipation) and all transverse reinforcement in beams and columns conformed to ASTM A 615 Grade 60.

The grout used at the beam-column interface of the specimens had a compressive strength approximately equal to the compressive strength of the beam, and it was reinforced with polypropylene fibers. The grout used to bond the energy dissipation bars was a high-fluidity cable grout with a compressive strength of about 8000 psi (55 MPa).

A constant axial load was applied to the columns, equal to 10 percent of the compressive strength of the gross concrete area. Available evidence from tests on the joints of monolithic concrete frames indicates that higher values of axial stress have little effect on the nominal shear strength limits specified in Section 21.5.3 of ACI 318-02.

However, until additional validation tests are completed, because of the presence of the prestressing duct, the column axial stress values used should not be significantly less than the 10 percent used in the tests of Reference 6. The joints of the validation tests of Reference 6 were designed to the ACI stress limits. In particular, the joint for the interior column specimen, with the area of the prestressing duct [having an internal diameter of 3 in. (76 mm)] deducted from the joint area, as required by Section 7.1 of T1.2-03, was stressed in the validation testing to the limit of $15\sqrt{f_c'}$ permitted by Section 21.5.3.

The result was that the joint was severely cracked by the end of testing. Therefore, if the axial stress were reduced below the 10 percent level, joint shear failure would have been likely. Further, because one of the more favorable characteristics of the hybrid frame is its potential ability to resist seismic forces simply by opening and closing of the joint at the beam-column interface, with minimal damage to the concrete, the use of nominal joint shear stresses less than those permitted in

Section 21.5.3 of ACI 318 is recommended in Section 7.1.2 of T1.2-03.

Finally, the maximum value of the factored shear stress applied to the beams of the modules during the validation tests of Reference 6 was approximately $3\sqrt{f'_c}$. Therefore, factored shear stress levels in beams need to be limited to that value until additional validation tests demonstrate that higher values can be used.

As long as the provisions of T1.2-03 are used to determine hybrid frame properties, and the limitations of the prior paragraph are satisfied as required by Section 21.6.3 of ACI 318, hybrid frame designs can be made using the same values for the response modification factor, $R$, deflection amplification factor, $C_d$, and system overstrength factor, $\Omega_o$, as those specified for monolithic special reinforced concrete moment frames in the governing building code.

There is one practical aspect of hybrid frame construction that needs to be appreciated by designers. The location of ducts and embedments must be carefully controlled if the hybrid frame is to perform successfully. Therefore, precast manufacturers need to be contacted early in the design phase to ensure that their knowledge of tolerances and construction requirements and how to achieve them are utilized. Of particular importance is satisfying the requirement that ducts in the columns and beams line up correctly.

## PRETENSIONED CONNECTIONS

Pretensioned connections of the type shown in Fig. 2 were used for the frames of the upper two levels on one face of the PRESSS building. Because of their position on that face, those frames were not as severely deformed as the hybrid frames in the lower three stories. However, while those frames performed satisfactorily in the severest test applied to the building, they would not be permitted under Section 21.6.3 of ACI 318 to be used alone as the seismic-force-resisting system in regions of high seismic risk or for structures assigned to high seismic performance or design categories.

That restriction is because T1.1-01 requires that test modules possess a relative energy dissipation ratio of not less than one-eighth for the third complete cycle to a drift ratio equal to or greater than 3.5 percent. Tests on modules made from precast beams connected to columns by post-tensioning alone[9] and analyses of the seismic response for frames with such connections[10] have demonstrated that energy dissipation ratios will be significantly less than one-eighth.

While satisfactory seismic performance can be provided by such connections, a given seismic excitation will result in drift levels for frames with such connections greater than those for frames with connections meeting the requirements of T1.1-01. Thus, contrary to the situation for frames containing connections satisfying T1.1-01, the appropriate response modification factor $R$ and the deflection amplification factor $C_d$ for frames containing pretensioned connections similar to those of Fig. 2 are not the same as those for monolithic construction.

In addition, the toughness requirement of Section 21.2.1.5 of ACI 318 is customarily interpreted as requiring a minimum amount of bonded deformed bar reinforcement connecting beams to columns, which satisfies Section 16.5 of ACI 318. Frames constructed using connections of the type shown in Fig. 2 are not acceptable for special moment frames as defined by Section 21.1 of ACI 318.

Moment frames with pretensioned connections of the type shown in Fig. 2 can be designed to satisfy all the requirements of Section 21.12 of ACI 318-02 for intermediate moment frames. Further, the results reported in References 9 and 10 suggest that frames constructed using such pretensioned connections should be acceptable for intermediate moment frames when designed using the same $R$ and $C_d$ factors as those specified in the governing building code for cast-in-place concrete construction.

Analyses need to be made to verify that conclusion, and acceptance criteria proposed for intermediate moment frames based on structural testing. Probably, the same acceptance criteria as those for special moment frames can be used with only the relative energy dissipation ratio requirement of Section 9.1.3 of T1.1-01 deleted. Reference to those criteria can then be inserted in ACI 318, and the definition for intermediate moment frame in Section 21.1 of ACI 318 amended to a wording similar to that for the definition for special moment frames where both cast-in-place and precast construction are recognized.

In the interim, the results of References 9 and 10 and the satisfactory performance of the pretensioned frame in the PRESSS Test Building can be used in conjunction with the provisions of Section 1.4 of ACI 318-02 to seek building department approval of a pretensioned frame system for moderate seismic risk zones or for structures assigned to intermediate seismic performance or design categories.

Alternatively, seismic resistance in moderate seismic zones can be provided by a framing system consisting of moment frames with pretensioned connections paralleled by cast-in-place frames satisfying ACI 318 Section 21.12 or hybrid frames satisfying T1.2-03. If this is done, the parallel cast-in-place frames or the hybrid frames would make up for the deficiency in the energy dissipation capacities of the frames with the pretensioned connections.

It is believed that this very phenomenon accounted for the satisfactory performance of the frames with pretensioned connections in the PRESSS Test Building under severe seismic excitation. The use of the same $R$ and $C_d$ factors as applicable to monolithic construction would then be totally justified in the design of the frames with pretensioned connections used in parallel with cast-in-place frames satisfying ACI 318 Section 21.12 or hybrid frames satisfying T1.2-03.

There can be situations in practice where it is cost effective to use special, rather than intermediate, moment frames in regions of moderate seismic risk. The reason for this is that the higher $R$ and $C_d$ factors permitted with special detailing allow the use of less material than for frames with intermediate detailing. Use of T1.2-03 is restricted to special hybrid moment frames composed of precast beams connected by post-tensioning tendons to columns continuous past the joints of the frame. However, given the good performance of the pretensioned frames in combination with such special hybrid frames in the five-story PRESSS Test Building, it is reasonable to assume that the provisions of T1.2-03 can also be used to design pretensioned hybrid moment frames where the details of Fig. 1 are combined with the details of Fig. 2.

The concentrically pretensioned beams would then be continuous through the columns, and would have special energy-dissipating mild steel reinforcement placed top and bottom in the beam in the joint region and deliberately debonded for a specified length adjacent to the beam-column interface. Provision would need to be made to ensure cracking at the beam-column interface. However, that could be readily accomplished using a thin styrofoam or plastic sheet extending at least 1 in. (25.4 mm) into the beam for each of its faces at the beam-column joint.

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