*** POOR QUALITY ***

SIMPLIFIED DESIGN PROVISIONS FOR HYBRID PRECAST CONNECTIONS

by

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ABSTRACT

A rational design procedure is presented to compute the probable moment, the nominal moment, and the story drift capacities of a hybrid precast moment-resisting beam-to-column connection. The hybrid connections consist of mild steel which is used to dissipate energy by yielding and high strength prestressing steel which is used to provide the shear resistance through friction developed at the beam-column interface by the post-tensioning force. The design procedure is based on 1/3-scale hybrid precast beam-to-column connections tested at the National Institute of Standards and Technology (NIST). The simplified procedure relies on the stress-strain behavior of mild steel up to its ultimate strength and is based on equilibrium considerations at the beam-column joint.

KEYWORDS: Building technology, beam-column, concrete, connection, joint, drift capacity, moment capacity, precast, post-tensioning, seismic design procedure.

1.0 INTRODUCTION

Current building codes (such as the American Concrete Institute and Uniform Building Codes) used in high seismic areas of the United States have evolved toward sets of prescriptive rules which codify design provisions for a few building systems. Seismic resistant reinforced concrete systems have, in effect, been limited to cast-in-place shear walls and special moment resisting frames (SMRF). While these two systems have been shown to perform well during earthquakes, implementation of the details prescribed for a monolithic system into a prefabricated building is difficult.

The current UBC code [ICBO, 1994] allows alternative seismic systems to be used if the following requirements are met:

> "1627.9.2 **Undefined structural systems.** Undefined structural systems shall be shown by technical and test data which establish the dynamic characteristics and demonstrate the lateral-force resistance and energy absorption capacity to be equivalent to systems listed in Table 16-N for equivalent R_W values."

The precast moment frame using hybrid connections, shown in Figure 1, was developed to meet the requirements of an R_W = 12 system. The connection consists of mild steel [f_y = 414 MPa (60 ksi)] located at

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the top and bottom of the beam and high strength prestressing steel [f_{pu} = 1862 MPa (270 ksi)] located at mid-depth of the beam. The mild steel is used to dissipate energy by yielding, and the prestressing steel is used to provide the shear resistance from the friction developed by the post-tensioning (PT) force. The mild steel is fully bonded except for a very short length and the PT steel is unbonded or partially debonded. The purpose of the short unbonded length of the mild steel is to delay fracture of the mild steel bars and the unbonding of the PT steel is intended to delay yielding of the PT steel. The term hybrid refers to the simultaneous use of two types of steel with different roles.

This paper briefly describes design procedures for the hybrid connections that ensure that both the required strength and story drift capacities are achieved. More details on the design procedure may be found in Cheok et al. (1996). The experimental program and connection details may be found in Stone et al. (1995).

2.0 DESIGN CONCEPT

The precast moment frame using the hybrid connection is based upon the following:

1. Multi-story columns are used with single bay beams requiring a connection at the beam column interface, which is also the location of maximum seismic moment.
2. A ductile connection is developed at the beam-column interfaces, causing all yielding at this location and minimal damage to the precast beams.
3. Post-tensioned reinforcement is used to provide a reliable clamping force at the beam-column interface to resist gravity loads.
4. Vertical shear resistance at the beam-column interface is provided by friction created by a combination of the PT clamping force and the compression portion of the moment couple.
5. At the required maximum drift, the PT steel remains elastic.
6. The concrete in the end regions of the beam is confined so that it will not spall at the required maximum drift.
7. Mild steel reinforcement provides a portion of the flexural strength in addition to providing energy dissipation.
8. Sufficient mild steel reinforcement is provided to resist the gravity loads on the beam in the unlikely event of strand anchorage failure. This is provided as a backup collapse prevention mechanism.

3.0 DESIGN FORCES

3.1 General

The drift requirements, strength reduction factors, and base shear may be calculated or obtained as prescribed by the UBC (ICBO, 1994). In a prestressed system, prior to decompression (zero tension stress in concrete), the system will behave in a manner comparable to a cast-in-place system, except that the beams are not likely to crack. Gross section properties should be used to develop a representation of system stiffness. For the interval between decompression and yield, the section properties are between that of an uncracked section and a cracked section.

3.2 *Maximum Drift Demand*

The drift demand as used in this section differs from the UBC drift requirement both in purpose and calculation. The UBC drift requirement is a serviceability requirement and is based on drifts of an elastic structure subjected to UBC design forces. The proposed drift demands are estimates of story drifts that a structure may undergo in an earthquake and were computed from non-linear time history analyses of models subjected to a suite of acceleration records obtained from past earthquakes. Drift demands calculated from the non-linear time history analyses are shown in Figures 2 - 4. Based on the dynamic analyses (Figures 2 - 4) the following story drift demands are recommended:

1. 1.5% for UBC soil type 1
2. 3.5% for UBC soil type 2
3. 4.0% for UBC soil type 3

In lieu of the proposed drift demands, non-linear time history analyses using a site specific response spectrum may be used to determine the required drift demand.

4.0 VERTICAL SHEAR RESISTANCE

Vertical shear resistance at the column interface is provided by two mechanisms:

- Friction created by the clamping force provided by the PT force (F_p).
- Friction created by the compression portion of the moment couple induced by gravity, wind, or seismic moments at the beam column interface (C).

The shear demand at the beam column interface is a function of both the applied gravity loads and the induced seismic moments which are limited to the probable moment capacity of the connection (see Notation and Symbols for definitions of variables).

$$V_u \leq \phi V_n \qquad (1)$$

$$V_u \leq 1.4\, V_D + 1.7\, V_L + \frac{M_{pr1} + M_{pr2}}{L_{clear}} \qquad (2)$$

The frictional shear resistance is provided at the interface by the two mechanisms described above.

$$V_n = \mu (F_p + C) \qquad (3)$$

where μ, defined in Notation and Symbols, depends on the surface characteristics of the beam and column at the interface. A roughened surface [6 mm (0.25 in.)] per UBC 1911.7.9 (ACI 11.7.9) is recommended for this connection (μ = 1.0).

4.1 Minimum Clamping Force

Using Eqs. 1, 2, and 3, the minimum required clamping force, after losses, F_p, is

$$\phi \mu F_p = 1.4 V_D + 1.7 V_L$$

$$F_p = \frac{1.4 V_D + 1.7 V_L}{\phi \mu} \qquad (4)$$

Losses as defined in ACI 318-95, Section 18.6.1 should be considered.

4.2 Span-to-Depth Ratio

To ensure that no slip occurs between the beam and column, the minimum clear span to overall thickness of member, L/h, ratio shall be

$$\frac{L_{clear}}{h} \geq \frac{1}{\phi \mu} \qquad (5)$$

for $\gamma = d/h$,

$$\frac{L_{clear}}{d} \geq \frac{1}{\phi \mu \gamma} \qquad (6)$$

but not less than the required clear span to effective depth, L/d, ratio of 4 [UBC 1921.3.1.2 (ACI 21.3.1.2)]

5.0 MAXIMUM PRESTRESS

To safeguard against loss of the clamping force during load reversal, the maximum stress in the PT steel must be limited to ensure that no yielding of the PT steel occurs at maximum drift capacity. Lower initial prestress allows for greater strain capacity in the PT steel to accommodate the large story drift demands expected in a major earthquake.

The maximum limit on the concrete prestress is controlled by concrete strength and by the confinement in the compression zones.

6.0 PROBABLE MOMENT CAPACITY

6.1 Limit State Description

The proposed calculation procedure is intended to ensure that the hybrid connection is able to accommodate the story drift demands (See Section 3.2) while retaining at least 80% of its maximum capacity.

The performance requirement for the connection are as follows:

- The PT steel must not yield.
- The mild steel may yield but must not fracture before reaching the required drift demand.
- The compression region of the beam must be able to sustain large strains without degradation of its load carrying capacity.

These requirements are satisfied by limiting the initial stress in the PT steel, providing sufficient unbonded length of both PT and mild steels, and developing appropriate confinement details for the concrete compression zone.

6.2 Calculation Procedure

Assumptions:

1. The Whitney stress block is used for calculation of the concrete compression force.

2. The post-tensioning (PT) steel is located at mid-depth of the beam.

3. The mild steel debonds over a distance equal to 2.75 d_b on either side of the intentionally unbonded length when the beam moment is equal to the probable moment.[3]

4. Neglect the contribution of the compression steel.

The following variables are assumed to be known: A_{ps}, f'_c, $L_{u,ps}$, A_s, f_y, $\epsilon_{ps,ini}$, b, f_u, ϵ_u, d, h, d_b, L_u.

Procedure:

Step 1:

A. Compute the maximum force capacity of the mild steel, T_s.

$$T_s = A_s f_u \quad (7)$$

The minimum area of bonded steel at the bottom of the connection shall satisfy:

$$A_s \geq \frac{V_D + V_L}{f_y} \quad (8)$$

B. Determine the value of ϵ_u corresponding to f_u from a σ-ε curve for the mild steel.

C. Compute the elongation of the mild steel, Δ_s. The strain is assumed to be equal over the unbonded length.

$$\Delta_s = \epsilon_u (L_u + 5.5 d_b) \quad (9)$$

Step 2:

A. Assume a neutral axis depth, c. The pivot for the joint rotation is assumed to occur at the neutral axis (see Figure 5).

B. Compute the elongation of the PT steel, Δ_{ps}, due to flexure.

$$\Delta_{ps} = \left[\frac{\frac{h}{2} - c}{d - c}\right] \Delta_s \quad (10)$$

C. Compute the strain in the PT steel, ϵ_{ps}.

$$\epsilon_{ps} = \frac{\Delta_{ps}}{L_{u,ps}} + \epsilon_{ps,ini} \quad (11)$$

D. Obtain the stress in the PT steel, f_{ps}, from the σ-ε curve for Grade 270 prestressing strands. Check that $f_{ps} < 0.9 f_{pu}$ to prevent yielding.

$$f_{ps} \leq 0.9 f_{pu} \quad (12)$$

If $f_{ps} > 0.9 f_{pu}$, then:

[3] Tests at NIST have shown that mild steel bars grouted in ducts and subjected to cyclic loading will debond beyond the intentionally unbonded length. This distance varies and can be approximated by assuming the additional debond length will be equal to 2.75 d_b on either side of the intentionally unbonded length.

1. Increase the unbonded length of the PT steel or
2. Increase the amount of PT steel, or
3. Decrease the amount of mild steel.

Return to Step 1 if A_s is changed or to Step 2C if $L_{u,ps}$ is changed.

E. Compute the force in the PT steel, T_{ps}.

$$T_{ps} = A_{ps} f_{ps} \qquad (13)$$

Step 3:

A. Compute the concrete compression force, C_c.

$$C_c = T_s + T_{ps} \qquad (14)$$

B. Compute the neutral axis depth, c.

$$c = \frac{C_c}{0.85 f'_c\, b\, \beta_1} \qquad (15)$$

C. Compare the computed value of c from Step 3B with the assumed value of c from Step 2A.

D. If the computed value of c does not agree with the assumed value of c, set c to the value from Step 3B and repeat Steps 2 and 3 until the value of c has converged.

Step 4:

A. Compute the probable moment, M_{pr}, by summing moments about the concrete compressive force.

$$M_{pr} = M_s + M_{ps} \qquad (16)$$

$$M_s = T_s \left(d - \frac{\beta_1 c}{2} \right) \qquad (17)$$

$$M_{ps} = T_{ps} \left(\frac{h}{2} - \frac{\beta_1 c}{2} \right) \qquad (18)$$

Step 5:

A. Check M_s/M_{pr} ratio. To ensure that during load reversal the gap between the beam and the column is closed at zero drift, there has to be sufficient PT force to cause compression yielding of the mild steel. A limit of 0.5 is proposed based on equations developed by Mole [Mole, 1994].

$$\frac{M_s}{M_{pr}} \leq 0.5 \qquad (19)$$

If M_s/M_{pr} is greater than 0.5, reduce A_s and return to Step 1 or increase A_{ps} and return to Step 2E.

6.3 Maximum Drift Capacity

The maximum drift capacity is calculated by setting the mild steel strain equal to the steel strain corresponding to the ultimate tensile strength. This calculated maximum drift capacity is a lower bound.

6.3.1 Computation of Maximum Drift Capacity

The procedure given in Section 6.2, Steps 1 to 3, is used to compute the location of the neutral axis and the following additional procedure is used to obtain the maximum drift capacity.

A. Compute beam rotation, θ (Figure 5).

Using the value of c obtained in the calculation of the probable moment capacity, determine the beam rotation which is taken as the drift capacity.

$$\theta = \frac{\Delta_s}{d - c} \qquad (20)$$

B. The story drift capacity equals the beam rotation, θ, at the probable moment capacity. Since this procedure yields a lower bound for the story drift capacity, no capacity reduction factor is used.

$$Story\ drift = \theta \qquad (21)$$

C. Check that the drift capacity is greater than the drift demand as specified in Section 3.2. If the drift capacity does not meet the drift demand, then increase L_u.

7.0 NOMINAL MOMENT CAPACITY

The nominal moment capacity may be calculated using the two methods presented below. The nominal moment capacity as obtained using Method 2 (Eq. 22) is recommended for its simplicity.

<u>Method 1</u>

The nominal moment capacity is calculated following the procedure outlined in Section 6.2 with the following changes:

- The mild steel stress equal to f_y. Change Equation 7 to read:
  $T_s = A_s f_y$.
- Set the strain in the mild steel strain equal to the strain at the onset of strain hardening, ϵ_{sh}. ϵ_{sh} = 0.01 typically for Grade 60 bars.
- The total unbonded length is set equal to the intentionally unbonded length, L_u, of the mild steel. Change Equation 9 to read:
  $\Delta_s = \epsilon_{sh} L_u$.

<u>Method 2</u>

$$M_n = 0.70\ M_{pr} \qquad (22)$$

where M_{pr} is calculated following the procedure outlined in Section 6.2.

8.0 BEAM AND COLUMN DESIGN

The body of the beam away from the connection region shall be designed in accordance with UBC 1994 or ACI 318-95.

Column design for the precast moment frame using the hybrid connections must satisfy capacity design requirements [UBC 1994 and ACI 318-95].

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NOTATION AND SYMBOLS

A_{ps}	=	Area of PT steel.
A_s	=	Area of mild tension steel.
b	=	Beam width.
C	=	Total compression force.
C_c	=	Concrete compression force.
C'_s	=	Compressive force contribution from the mild compressive steel.
c	=	Depth from the extreme compression fiber to the neutral axis.
d	=	Effective depth.
d_b	=	Diameter of reinforcing bar.
f'_c	=	Concrete compressive strength.
f_{ps}	=	Stress in PT steel.
f_{pu}	=	Ultimate tensile strength of PT steel.
f_u	=	Ultimate tensile strength of mild steel.
f_y	=	Yield strength of mild steel.
F_p	=	Post-tensioning force.
h	=	Overall member thickness.
L_{clear}	=	Beam clear span.
L_u	=	Intentional unbonded length of mild steel.
$L_{u,ps}$	=	Unbonded length of the PT steel.
M_n	=	Nominal moment capacity.
M_{pr}	=	Probable moment capacity of beam = $M_s + M_{ps}$.
$M_{pr1,pr2}$	=	Probable beam end moments as determined in Section 6.
M_{ps}	=	Beam moment capacity contributed by post-tensioned steel.
M_s	=	Beam moment capacity contributed by mild steel.

T_{ps}	=	Tension force in PT steel.
T_s	=	Tension force in mild tension steel.
V_D	=	Unfactored shear force due to dead load.
V_L	=	Unfactored shear force due to live load.
V_n	=	Nominal shear strength.
V_u	=	Required shear strength.
β_1	=	Factor defined in UBC Section 1910.2.7.3 (ACI 10.2.7.3).
Δ_{ps}	=	Elongation of the PT steel.
Δ_s	=	Elongation of the mild steel.
ϵ_{sh}	=	Strain at onset of strain hardening of mild steel.
ϵ_{ps}	=	Strain in the PT steel.
$\epsilon_{ps,ini}$	=	Initial strain in the PT steel after losses due to post-tensioning force.
ϵ_u	=	Mild steel strain at ultimate stress, f_u.
γ	=	Ratio of d/h.
ϕ	=	Strength reduction factor.
μ	=	Coefficient of friction as defined in UBC Section 1911.7.4.3 (ACI 11.7.4.3).
θ	=	Beam rotation.