An efficient structural system for tall buildings to resist earthquake loads consists of reinforced concrete (RC) shear walls connected by coupling beams. Construction of coupling beams that satisfy the strength and detailing requirements set forth in ACI 318-05 for diagonally reinforced coupling beams is cumbersome and costly; therefore, ACI 318-08 provides a new detailing option that aims to improve the constructibility while maintaining adequate strength and ductility. Eight 1/2-scale specimens were tested to compare the performance of beams constructed using new and old detailing options, to compare beams with diagonal reinforcement to beams with straight bars at higher aspect ratios, and to assess the impact of reinforced and post-tensioned (PT) slabs. Test results indicate that the new detailing approach provides equal, if not improved, behavior as compared to the alternative detailing approach and that including a slab had only a modest impact on strength, stiffness, ductility, and observed damage.

**Keywords:** confinement; constructibility; coupling beam; diagonal reinforcement; experiment.

### INTRODUCTION

Tall building construction is common in metropolitan areas and it has become increasingly important to provide methods of construction that both improve seismic performance and constructibility. Core walls, with coupling beams above openings to accommodate doorways, are an efficient lateral-force-resisting system for tall buildings. When subjected to strong shaking, the coupling beams act as fuses and typically undergo large inelastic rotations.

Various testing programs have been carried out to assess the load-deformation behavior of coupling beams. The primary test variables in these studies were the beam clear span to total depth ratio (commonly referred to as the beam aspect ratio) and the arrangement of the beam reinforcement. In a majority of these studies, the load-deformation behavior of low-aspect-ratio beams (1.0 to 1.5) constructed with beam top and bottom longitudinal reinforcement were compared with beams constructed with diagonal reinforcement. Concrete compressive strengths for most tests were approximately 4 ksi (27.6 MPa). Although these tests provided valuable information, they do not address issues for current tall building construction, where beam aspect ratios are typically between 2.0 and 3.5 and concrete strengths are in the range of 6 to 8 ksi (40 to 55 MPa). In addition, none of the prior studies was a slab included as part of the test specimen, whereas the slab might restrain axial elongations and impact stiffness, strength, and deformation capacity. The use of post-tensioned (PT) slabs is also common for current construction.

The use of diagonal reinforcement in coupling beams with aspect ratios less than 4.0 was introduced in ACI 318-95. Two groups of diagonal bars are commonly assumed to form a truss, with one group serving as the tension member and the other as the compression member for a given loading direction. To enhance the compressive strength and deformation capacity of the diagonal truss members as well as to suppress buckling of the diagonal bars, the use of transverse reinforcement around the diagonal bar groups is required. The quantity of transverse reinforcement required by ACI 318-05 is the same as that used for columns, and is substantially more than used in most of the prior test programs. Nominal transverse reinforcement is also required around the entire beam cross section. Providing transverse reinforcement around the diagonal bar bundles as detailed in ACI 318-05, Section S21.7.7, is difficult, where the diagonal groups intersect at beam midspan, particularly for shallow beams, as well as at the beam-wall interface due to interference with the wall boundary vertical reinforcement (Fig. R21.9.7(a)). To combat these issues, ACI 318-08, Section S21.9.7, introduced an alternative detailing option, where transverse reinforcement is placed around the beam cross section to provide confinement and suppress buckling, and no transverse reinforcement is provided directly around the diagonal bar bundles (Fig. R21.9.7(b)). The use of this detailing option avoids the problems noted where the diagonal bars intersect and at the beam-wall interface, reducing the construction time for a typical floor by a day or two.

In beams with the aspect ratio \( l/h \) approaching 4, the angle of inclination \( \alpha \) of the diagonal reinforcement is often very small (approximately 10 degrees), making placement of the diagonal reinforcement more difficult. The use of straight (longitudinal) flexural reinforcement is common in these situations, as long as sufficient shear reinforcement can be provided to resist the shear demand.

### RESEARCH SIGNIFICANCE

Large-scale tests on diagonally reinforced coupling beam configurations typical of office and residential buildings, with and without a slab, are used to assess strength and detailing requirements. The test program fills critical knowledge gaps related to moderate aspect ratios, alternative detailing options for transverse reinforcement, and the influence of reinforced and PT slabs on beam load-deformation behavior. Findings indicate that the two detailing options in ACI 318-08 result in similar overall load-deformation response.

### EXPERIMENTAL PROGRAM

Eight 1/2-scale specimens were tested with various geometries and reinforcement configurations, including beams both with and without floor slabs (Table 1). The following sections define the design details, material properties, test...
setup, and test protocol. Additional information on the test program, including prototype beam designs, material properties, and test results, is available in Reference 13. The digital test data will be available at NEES Project Warehouse in Reference 14.

**Beam design**

The test beam prototypes were based on common tall building configurations for residential and office construction. Typical wall openings, story heights, and design loads produce coupling beams with aspect ratios of approximately 2.4 for residential buildings and 3.33 for office buildings. Cross-section dimensions are typically 24 x 30 in. (610 x 762 mm) and 24 x 36 in. (610 x 914 mm) for residential and office construction, respectively, with reinforcement consisting of two bundles of eight No. 11 diagonal bars. The nominal shear strengths of the residential and office beams, determined using ACI 318-08,11 Eq. (21-9) ($V_n = 2A_{vd} f_y \sin \alpha \leq 10 \sqrt{f'_{cu}} \frac{A_{sh}}{A_{dy}}$ psi [0.83 $\sqrt{f'_{cu}}$ MPa]), are 7.3 $\sqrt{f'_{cu}}$ and 4.8 $\sqrt{f'_{cu}}$ (0.61 and 0.40 $\sqrt{f'_{cu}}$ MPa) for aspect ratios of 2.4 ($\alpha = 15.7$) and 3.33 ($\alpha = 12.3$), respectively, and Grade 60 reinforcement. Due to geometric and strength constraints of an existing laboratory reaction frame, tests were conducted on 1/2-scale replicas of the prototype beams. Thus, the test specimens were 12 x 15 in. (305 x 381 mm) and 12 x 18 in. (305 x 457 mm) with two bundles of six No. 7 ($d_b = 22.2$ mm [7/8 in.]) diagonal bars (Fig. 1 to 4) for the residential and office beams, respectively. For aspect ratio 3.33, a 12 x 18 in. (305 x 457 mm) specimen with two groups of three No. 6 ($d_b = 19.0$ mm [3/4 in.]) straight (longitudinal) flexural reinforcement (referred to as “frame beam”) was also tested (Fig. 5). The maximum shear stress expected for the frame beam, based on reaching $M_n$ at the beam-wall interface at the beam ends, was 3.6 $\sqrt{f'_{cu}}$ psi (0.3 $\sqrt{f'_{cu}}$ MPa). This limit was selected based on input from practicing engineers; at higher shear stresses, diagonal reinforcement would typically be used.

As stated previously, the configuration of the transverse reinforcement was a primary variable of the test program. Beams with transverse reinforcement provided around the bundles of diagonal bars (referred to as “diagonal confinement”) were designed according to ACI 318-05,10 Section S21.7.4, whereas beams with transverse reinforcement provided around the entire beam cross section (referred to as “full section confinement”) were designed according to ACI 318-08,11 Section S21.9.7.4(d). Volumetric ratios of transverse reinforcement and the ratios bar spacing to bar diameter ($s/d_b$) for the 1/2-scale test beams were selected to be similar to the prototype beams. Due to spacing limits and material limitations, the volumetric ratios (Table 1) of transverse reinforcement provided in both the prototype and test beams exceed that calculated using the requirement for columns (ACI 318-08,11 Section 21.6.4.4). Additional information is provided in References 13 and 15.

### Table 1—Test matrix and material properties

<table>
<thead>
<tr>
<th>Beam</th>
<th>$l/h$, type</th>
<th>$\alpha$, degrees</th>
<th>Transverse reinforcement</th>
<th>$A_{sh}$ / $A_{dy}$,</th>
<th>$f_y$, psi</th>
<th>$f_{yd}$, psi</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB24F</td>
<td>Residential</td>
<td>2.4</td>
<td>Full section Diagonals</td>
<td>1.34 (1.25)</td>
<td>1.24 (1.09)</td>
<td>6850</td>
<td>Full section confinement ACI 318-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.24 (1.09)</td>
<td>7242</td>
<td></td>
<td>Diagonal confinement ACI 318-05</td>
</tr>
<tr>
<td>CB24F-RC</td>
<td>Residential</td>
<td>15.7</td>
<td>No. 3 at 3 in. NA</td>
<td>1.34 (1.25)</td>
<td>1.24 (1.09)</td>
<td>7305</td>
<td>Full section confinement ACI 318-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. 2 at 2.5 in. NA</td>
<td>1.92</td>
<td>2.44</td>
<td></td>
<td>Full section confinement with RC slab ACI 318-08</td>
</tr>
<tr>
<td>CB24F-PT</td>
<td>Residential</td>
<td>2.5</td>
<td>No. 3 at 3 in. NA</td>
<td>1.34 (1.25)</td>
<td>1.24 (1.09)</td>
<td>7242</td>
<td>Full section confinement with PT slab ACI 318-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. 3 at 3 in. NA</td>
<td>1.24 (1.09)</td>
<td>70,000</td>
<td>90,000</td>
<td>Full section confinement (reduced) with PT slab ACI 318-08</td>
</tr>
<tr>
<td>CB33F</td>
<td>Office</td>
<td>3.33</td>
<td>No. 3 at 3 in. NA</td>
<td>0.67 (0.63)</td>
<td>0.62 (0.55)</td>
<td>6990</td>
<td>Full section confinement ACI 318-08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. 3 at 6 in. NA</td>
<td>1.34 (1.25)</td>
<td>1.26 (1.06)</td>
<td>6850</td>
<td>Full section confinement ACI 318-05</td>
</tr>
<tr>
<td>CB33D</td>
<td>Office</td>
<td>3.33</td>
<td>No. 3 at 3 in. NA</td>
<td>1.34 (1.25)</td>
<td>1.26 (1.06)</td>
<td>6850</td>
<td>Full section confinement ACI 318-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. 2 at 2.5 in. NA</td>
<td>1.92</td>
<td>2.44</td>
<td></td>
<td>Diagonal confinement ACI 318-05</td>
</tr>
<tr>
<td>FB33</td>
<td>Office</td>
<td>0.0</td>
<td>No. 3 at 3 in. NA</td>
<td>1.34 (1.25)</td>
<td>1.26 (1.06)</td>
<td>6850</td>
<td>Six No. 6 straight bars</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>—</td>
<td>—</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calculations for full-scale prototype beams; NA is not available.

Note: 1 psi = 0.0069 MPa.
Three test specimens with an aspect ratio of 2.4 were constructed with 4 in. (101.6 mm) thick slabs. CB24F-RC contained a slab reinforced with No. 3 bars at 12 in. spacing ($d_b = 9.5$ mm [3/8 in.] at 304.8 mm), on the top and bottom in the transverse direction, and on the top only in the longitudinal direction, without post-tensioning strands (Fig. 6). CB24F-PT and CB24F-1/2-PT both contained a similar reinforced concrete (RC) slab, but also were reinforced with 3/8 in. (9.5 mm) seven-wire strands post-tensioned to apply 150 psi (1.03 MPa) to the slab in the longitudinal direction (Fig. 6 and 7). The test beam geometries and reinforcement configurations are summarized in Table 1 and Fig. 1 to 7.

Material properties

Tests on four 6 x 12 in. (152 x 304 mm) concrete cylinders and three reinforcing bar coupons were conducted to determine concrete compressive strength $f_{c}^{'}$ at test day and the yield and ultimate tensile strengths ($f_y$ and $f_u$) for reinforcement (Table 1). All of the reinforcement used to construct the test specimens was taken from a single heat (for a given bar size) to minimize variations in reinforcement properties between test specimens.

Test setup

The setup shown in Fig. 8, where the test specimen was placed in a vertical position with end blocks simulating wall boundary zones, was used for all tests. The end blocks were grouted and post-tensioned to the laboratory strong floor (bottom) and to the steel reaction frame (top) to minimize slip between the surfaces as well as to provide for fixed end conditions. Two vertical hydraulic actuators were used to ensure zero rotation at the top of the specimen, while maintaining constant (zero) axial force in the beam.

The lateral load was applied via a horizontal actuator, with the line of action of the actuator force passing through the midspan (midheight) of the test specimen to achieve zero moment at the beam midspan. To prevent out-of-plane rotation or twisting, a sliding truss system was attached between the steel reaction frame and the RC reaction wall. Linear variable differential transformers (LVDTs) were used to...
measure displacements. Crack widths were measured manually at peak and zero deformation. Additional information is provided in References 13 and 15.

**Loading protocol**

The testing procedure included load-controlled and displacement-controlled cycles (Fig. 9). Load control was performed at 0.125, 0.25, 0.50, and 0.75\(V_y\), where \(V_y = 2M_y/l_y\) to ensure that the load-displacement behavior prior to yield was captured. Beyond 0.75\(V_y\), displacement control was used in increments of percent chord rotation \(\theta\), defined as the relative lateral displacement over the clear span of the beam, \(\Delta\), divided by the beam clear span \(l_y\) (excluding any contribution of slip and rotation of the bottom support block). Three cycles were applied at each load increment for load-controlled testing, and three cycles were applied in displacement control at each increment of chord rotation up to 3%, which is approximately the allowable collapse prevention (CP) limit state for ASCE 41-06. Two cycles were applied at each increment of chord rotation exceeding 3%.

**EXPERIMENTAL RESULTS AND DISCUSSION**

Results from the eight tests are presented and discussed. Overall load-displacement relations are compared to assess the impact of providing full section confinement as opposed to confinement around the diagonal bars for both residential- and office-use beams. The role of transverse reinforcement is examined by comparing load-displacement relations for the beams, including one beam with only one-half of the required transverse reinforcement. Other comparisons are made that examine the effect of the floor slab (both RC and PT RC) on the beam load-deformation response. Additional
results, including the effective elastic bending stiffness at yield as well as the influence of scale on the test results, are addressed in References 13 and 15 and Part 2 of this paper.17

Load and deformation responses

Figure 10 is a plot of the load-deformation response of CB24F and CB24D, and is representative of the general behavior of all specimens tested with diagonal bars. The yield load for both beams occurred at approximately 1% beam chord rotation, and significant strength degradation began at approximately 8% total beam chord rotation. Strength and deformation characteristics for all beams are summarized in Table 2.

All of the test specimens exhibited similar damage states and deformation characteristics. Each specimen had hairline diagonal cracking (<1/64 in. [0.4 mm]) at beam chord rotations less than 1%, and only specimens not detailed with full section confinement experienced large shear cracks (>1/8 in. [3.2 mm]) at 6% rotation. However, each beam exhibited fairly large flexural and slip/extension cracking (>1/4 in. [6.4 mm]).
(6.4 mm) prior to 3% rotation at the beam-wall interface. Slip/extension cracks are defined as damage occurring at the beam-wall interface. Figure 11 is a plot of the relative contributions of shear, flexure, and slip/extension deformations to the overall deformation of CB24F, and is representative of the behavior of all beams tested. This plot shows that shear deformations account for less than 20% of the total beam chord rotation (at peak value), while flexure and slip/extension each account for approximately 40% of beam chord rotation at low rotations (<1%). At high rotations (>3%), slip/extension accounts for nearly 80% of measured peak beam chord rotation. Lateral strength degradation began with the buckling of the diagonal reinforcement, followed by the fracture of both the diagonal reinforcement and the hoops/cross ties at the beam-wall interface. Table 3 summarizes the measured crack widths.

Detailing

Full section confinement versus diagonal confinement—Load-deformation responses of CB24F and CB24D are very similar over the full range of applied rotations (Fig. 10). Notably, both beams achieve large rotation (approximately 8%) without significant degradation in the lateral-load-carrying capacity, and the beams achieve shear strengths of 1.25 and 1.17 times the ACI nominal strength, \( V_{n(ACI)} \) (Table 2). The shear strength of CB24D degraded rapidly at around 8% rotation, whereas CB24F degraded more gradually, maintaining a residual shear capacity of approximately 80% at rotations exceeding 10%. Figures 12 and 13 are photos of CB24F and CB24D at 6% and 10% total rotations, respectively, and measurements reveal that diagonal crack widths for CB24F were less than 0.02 in. (0.5 mm) and flexural crack widths of 0.08 and 0.12 in. (2.0 and 3.2 mm) were measured at 3% and 6% rotations, respectively (Table 3). In general, diagonal crack widths for CB24D were larger than for CB24F, possibly due to the reduced transverse reinforcement around the full section, and the majority of the damage and deformations were focused at the beam-wall interface in the form of slip/extension cracks.

Figure 14 plots load-versus-rotation relations for the 3.33-aspect-ratio beams with full section confinement (CB33F) versus diagonal confinement (CB33D). Similar to the 2.4-aspect-ratio beams, Fig. 14 reveals that the beams have similar strength (Table 2), stiffness, deformation, and damage (Table 3) characteristics.

The test results presented in Fig. 11 to 14 indicate that for beams with an aspect ratio greater than 2.0, the full section confinement option of ACI 318-08\textsuperscript{11} provides equivalent, if not improved, performance compared to confinement around the diagonals per ACI 318-05.\textsuperscript{10} Diagonal crack widths for

![Figure 10—Cyclic load-deformation: CB24F versus CB24D. (Note: 1 in. = 25.4 mm.)](image1)

![Figure 11—Shear, flexural, and slip/extension deformation contributions to overall displacement for CB24F.](image2)

### Table 2—Moment and shear-strength capacities

<table>
<thead>
<tr>
<th>Beam</th>
<th>( M_{x+} ), in-kip</th>
<th>( M_{x-} ), in-kip</th>
<th>( V@M_{x+} )</th>
<th>( V@M_{x-} )</th>
<th>( V_{(ACI)} ), kip</th>
<th>( V_{n(ACI)} )</th>
<th>( V_{n} ), kip</th>
<th>( V_{n} )</th>
<th>( V_{n} )</th>
<th>( \lambda_{c} ), in.</th>
<th>( \lambda_{c} ), in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB24F</td>
<td>2850</td>
<td>2850</td>
<td>158.3</td>
<td>10.65</td>
<td>136.3</td>
<td>9.15</td>
<td>154.9</td>
<td>10.40</td>
<td>121.3</td>
<td>0.360</td>
<td>171.0</td>
</tr>
<tr>
<td>CB24D</td>
<td>2850</td>
<td>2850</td>
<td>158.3</td>
<td>10.65</td>
<td>136.3</td>
<td>9.15</td>
<td>150.7</td>
<td>10.12</td>
<td>128.8</td>
<td>0.363</td>
<td>159.2</td>
</tr>
<tr>
<td>CB24F-RC</td>
<td>2890 (3550)*</td>
<td>2890 (3350)*</td>
<td>160.6 (191.7)*</td>
<td>10.45 (12.50)*</td>
<td>136.3</td>
<td>8.87</td>
<td>181.0</td>
<td>11.77</td>
<td>147.2</td>
<td>0.362</td>
<td>190.8</td>
</tr>
<tr>
<td>CB24F-PT</td>
<td>3160 (3960)*</td>
<td>3160 (3625)*</td>
<td>175.6 (210.7)*</td>
<td>11.45 (13.75)*</td>
<td>136.3</td>
<td>8.90</td>
<td>198.9</td>
<td>12.98</td>
<td>163.2</td>
<td>0.361</td>
<td>211.8</td>
</tr>
<tr>
<td>CB24F-1/2-PT</td>
<td>3145 (3940)*</td>
<td>3145 (3610)*</td>
<td>174.7 (209.7)*</td>
<td>11.61 (13.90)*</td>
<td>136.3</td>
<td>9.06</td>
<td>182.4</td>
<td>12.12</td>
<td>158.1</td>
<td>0.365</td>
<td>189.6</td>
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<tr>
<td>CB33F</td>
<td>3615</td>
<td>3615</td>
<td>120.5</td>
<td>6.77</td>
<td>107.8</td>
<td>6.03</td>
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<td>6.62</td>
<td>107.7</td>
<td>0.600</td>
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<tr>
<td>CB33D</td>
<td>3615</td>
<td>3615</td>
<td>120.5</td>
<td>6.77</td>
<td>107.8</td>
<td>6.03</td>
<td>114.7</td>
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<td>95.94</td>
<td>0.601</td>
<td>120.6</td>
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<td>FB33</td>
<td>1450</td>
<td>1450</td>
<td>48.3</td>
<td>2.89</td>
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<td>—</td>
<td>56.3</td>
<td>3.37</td>
<td>47.86</td>
<td>0.306</td>
<td>58.1</td>
</tr>
</tbody>
</table>

*Calculations that consider impact of slab.

Notes: 1 in.-kip = 113 mm-kN; 1 in. = 25.4 mm; 1 kip = 4.45 kN.
the full section confinement were generally less than for diagonal confinement.

**Full confinement versus half confinement**—The transverse reinforcement used for CB24F-1/2-PT was one-half that used for CB24F-PT to assess the impact of using less than the code-required transverse reinforcement, given that the requirements of ACI 318-05, Section S21.6.4, are based on column requirements. Figure 15 plots load-deformation responses and reveals similar loading and unloading relations up to 3% total rotation, which approximately corresponds to the collapse prevention limit state per ASCE 41-06. At higher rotations ($\theta \geq 4\%$), modest strength degradation is observed for CB24F-1/2-PT, whereas the strength of CB24F-PT continues to increase slightly. Both beams achieve rotations of approximately 8% before significant lateral strength degradation, defined as the point where the lateral load dropped to $0.8V_{ave}$, where $V_{ave}$ is defined as the average shear force resisted by the beam between the yield point and the onset of significant lateral strength degradation. Diagonal

### Table 3—Crack widths, in.

<table>
<thead>
<tr>
<th>Beam</th>
<th>1% Slip/extension</th>
<th>1% Flexure</th>
<th>1% Shear</th>
<th>3% Slip/extension</th>
<th>3% Flexure</th>
<th>3% Shear</th>
<th>6% Slip/extension</th>
<th>6% Flexure</th>
<th>6% Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB24F</td>
<td>0.125</td>
<td>0.065</td>
<td>Hairline</td>
<td>0.400</td>
<td>0.080</td>
<td>Hairline</td>
<td>0.750</td>
<td>0.125</td>
<td>0.015</td>
</tr>
<tr>
<td>CB24D</td>
<td>0.125</td>
<td>0.095</td>
<td>Hairline</td>
<td>0.375</td>
<td>0.125</td>
<td>0.016</td>
<td>0.500</td>
<td>0.250</td>
<td>0.125</td>
</tr>
<tr>
<td>CB24F-RC</td>
<td>0.095</td>
<td>0.045</td>
<td>Hairline</td>
<td>0.500</td>
<td>0.125</td>
<td>0.016</td>
<td>0.500</td>
<td>0.375</td>
<td>0.065</td>
</tr>
<tr>
<td>CB24F-PT</td>
<td>0.065</td>
<td>0.030</td>
<td>Hairline</td>
<td>0.250</td>
<td>0.190</td>
<td>Hairline</td>
<td>0.500</td>
<td>0.250</td>
<td>Hairline</td>
</tr>
<tr>
<td>CB24F-1/2-PT</td>
<td>0.065</td>
<td>0.015</td>
<td>Hairline</td>
<td>0.375</td>
<td>0.190</td>
<td>0.031</td>
<td>0.625</td>
<td>0.375</td>
<td>0.250</td>
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<td>CB33F</td>
<td>0.125</td>
<td>0.065</td>
<td>Hairline</td>
<td>0.315</td>
<td>0.065</td>
<td>0.016</td>
<td>0.500</td>
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<td>CB33F</td>
<td>0.125</td>
<td>0.065</td>
<td>Hairline</td>
<td>0.250</td>
<td>0.125</td>
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<td>0.500</td>
<td>0.190</td>
<td>0.125</td>
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<tr>
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<td>0.060</td>
<td>0.030</td>
<td>Hairline</td>
<td>0.250</td>
<td>0.250</td>
<td>0.125</td>
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<td>—</td>
</tr>
</tbody>
</table>

*Note: 1 in. = 25.4 mm.*

**Fig. 12**—CB24F damage photos: (a) 6% rotation; and (b) 10% rotation.

**Fig. 13**—CB24D damage photos: (a) 6% rotation; and (b) 10% rotation.

**Fig. 14**—Cyclic load-deformation: CB33F versus CB33D. (Note: 1 in. = 25.4 mm.)
crack widths for CB24F-1/2-PT (Fig. 16) are much larger than those observed for CB24F-PT (Fig. 17), especially for rotations exceeding 6%. At 4% rotation, 1/16 in. (1.6 mm) diagonal cracks were noted in CB24F-1/2-PT, whereas diagonal cracks were still hairline in CB24F-PT. Beyond 4% rotation, for CB24F-1/2-PT, spalling of cover concrete was noted and 1/4 in. (6.4 mm) diagonal cracks were noted at 6% rotation; buckling and fracture of diagonal reinforcement and crushing of the core concrete were noted for rotations between 8 and 10%. In contrast, minimal damage was observed for CB24F-PT (Fig. 17), with hairline diagonal cracks and flexural crack widths of less than 1/4 in. (6.4 mm), with most of the rotation due to reinforcing bar slip/pullout at the beam-wall interface (approximately 1/2 in. [12.7 mm] at 6% rotation). Crack widths for all beams are summarized in Table 3.

The test results indicate that coupling beams satisfying ACI 318-08\textsuperscript{11} are generally capable of achieving total rotations exceeding 8%, whereas ASCE 41 limits plastic rotation to 3% without strength degradation and 5% with 20% strength degradation. The test results indicate that there is little difference in load-deformation response between CB24F-PT and CB24F-1/2-PT; therefore, the potential to reduce the quantity of required transverse reinforcement exists, but requires further study because only one beam test was conducted with reduced transverse reinforcement.

Slab impact

Four beams with an aspect ratio of 2.4 were tested to systematically assess the impact of a slab on load-deformation responses. CB24F did not include a slab, whereas CB24F-RC included an RC slab, and CB24F-PT and CB24F-1/2-PT included PT slabs (with 150 psi [1.03 MPa] of prestress). Comparing the load-displacement responses of CB24F versus CB24F-RC, Fig. 18 reveals that the slab increases shear strength by 17% (155 to 181 kip [689 to 805 kN]); however, this strength increase can be accounted for by considering the increase in nominal moment strength due to the presence of the slab—that is, slab concrete in compression at the beam-wall interface at one beam end—and slab tension reinforcement at the beam-wall interface at the other beam end (Table 2). For example, a moment-curvature analysis considering the slab (concrete and reinforcement) produces increases of approximately 20% in the positive and negative nominal moment capacities, which also provide similar increases in beam shear (because yielding of diagonal reinforcement limits the shear forces on the beams). The results indicate that the higher test shear strength observed is primarily due to the increase in nominal moment capacity of

![Fig. 15](image1.png)

**Fig. 15**—Cyclic load-deformation: CB24F-PT versus CB24F-1/2-PT. (Note: 1 in. = 25.4 mm.)

![Fig. 16](image2.png)

**Fig. 16**—CB24F-1/2-PT damage photos: (a) 6% rotation; and (b) 10% rotation.

![Fig. 17](image3.png)

**Fig. 17**—CB24F-PT damage photos: (a) 6% rotation; and (b) 10% rotation.
the relatively slender beams when a slab is present. Refer to Reference 13 for additional calculations.

The presence of a slab, and in particular a PT slab, might impact the load-deformation behavior by restraining the axial growth along the member length. Figure 19 plots the axial growth of CB24F versus CB24F-RC and reveals that the axial growth is very similar for the two tests. Both beams grow approximately 1 in. (25 mm) over the course of the test, with relatively large cracks observed at the beam-wall interface. Strength degradation for CB24F is noted at 8%, due to the buckling and eventual fracture of the diagonal bars, leading to axial shortening, whereas the axial extension in CB24F-RC remains stable over the entire test due to the presence of the slab.

Load-deformation responses for CB24F-RC versus CB24F-PT are compared in Fig. 20 and display similar overall behavior, with CB24F-PT experiencing higher shear forces—13.0 $\sqrt{A_{w}}$ psi (1.08 $\sqrt{A_{w}}$ MPa)—than CB24F-RC—11.9 $\sqrt{A_{w}}$ psi (0.98 $\sqrt{A_{w}}$ MPa). This increase in strength is primarily due to the axial force applied to the specimen by the tensioned strands, which provided approximately 150 psi (1.03 MPa) stress to the slab and increased the nominal moment strength (Table 2). Between 8 and 10% rotations, strength degradation is more pronounced for CB24F-PT than CB24F-RC, with 30% reduction for CB24F-PT versus 10% for CB24F-RC, possibly due to the presence of precompression.

A plot of axial elongation of CB24F-RC versus CB24F-PT (Fig. 19) indicates that the PT slab with 150 psi (1.03 MPa) prestress grows 30 to 40% less than the RC slab. Additionally, the PT slab, similar to the RC slab in CB24F-RC, helps to maintain the axial integrity of the beam for chord rotations exceeding 6%.

**Frame beam**

FB33 was tested to assess the impact of providing straight bars as flexural reinforcement instead of diagonal bars in beams with relatively low shear-stress demand (<4.0 $\sqrt{A_{w}}$ psi [<0.33 $\sqrt{A_{w}}$ MPa]). A plot of load versus deformation for FB33 (Fig. 21) indicates that plastic rotations greater than 4% can be reached prior to strength degradation. These results correspond well with prior test results on similarly sized beams, which achieved maximum shear stresses of approximately 4.7 $\sqrt{A_{w}}$ psi (0.39 $\sqrt{A_{w}}$ MPa) and plastic chord rotations greater than 3.5%. Compared with CB33F and CB33D (Fig. 14), FB33 experiences pinching in the load-deformation plot, indicating that less energy is dissipated.

Additionally, the beams with diagonal reinforcement exhibited higher ductility, reaching plastic rotations exceeding 7% prior to strength degradation. However, for beams that are expected to experience shear forces less than 5.0 $\sqrt{A_{w}}$ psi (0.42 $\sqrt{A_{w}}$ MPa), frame beams with straight bars can provide significant ductility ($\theta_p > 4\%$) and are much easier to construct than diagonally reinforced beams. Therefore, adding a shear stress limit of 5.0 $\sqrt{A_{w}}$ psi (0.42 $\sqrt{A_{w}}$ MPa) for conventionally reinforced coupling beams with aspect ratios between 2 and 4 according to ACI 318-08, Section 21.9.7, might be prudent. At a minimum, ACI 318 should add commentary to note the significant difference in defor-
mation capacity between diagonally and longitudinally reinforced coupling beams.

CONCLUSIONS

Seven diagonally reinforced coupling beam specimens and one frame beam specimen with $l/b$ of 2.4 and 3.3, and varying geometries and reinforcement layouts, were tested under reversed cyclic loading and double-curvature bending. The following conclusions can be drawn from the test results for beams with an aspect ratio greater than 2.0.

1. Beams detailed according to the new provision in ACI 318-08, which allows for full section confinement, have performance, in terms of strength and ductility, that is slightly better than beams detailed according to the old provision in ACI 318-05, which requires confinement of the diagonal bar groups.

2. Including an RC concrete slab increases the beam shear strength by approximately 15 to 20%, whereas adding post-tensioning increases the beam shear strength by an additional 10% for the beams tested. The strength increase was directly related to the increase in beam moment strength, as the beam shear force was limited by flexural yielding.

3. Beams detailed to satisfy 1/2$A_{sh}$ perform well at chord rotations $\theta < 3.0\%$. However, at very large rotations ($\theta > 6.0\%$), the beams experienced greater levels of damage (that is, more spalling of cover concrete and substantially larger shear cracks). Surprisingly, beams tested to satisfy 1/3$A_{sh}$, such results indicate that the amount of transverse reinforcement required could be modestly reduced for the beam aspect ratios tested, especially for beams with lower ductility requirements ($\theta < 3.0\%$). However, further study is necessary to determine if less transverse reinforcement could be used for rotations exceeding 3%, or for beams with lower aspect ratios ($<2$).

4. Most damage experienced by coupling beams with an aspect ratio ranging from 2.4 to 3.3 is concentrated at the beam-end interface in the form of slip/extension of diagonal reinforcement, even when axial load is applied to the beam via post-tensioning. Beams not detailed with full section confinement experience more damage at large rotations ($\theta > 6.0\%$).

5. ACI 318-08 implies equivalence between diagonally reinforced coupling beams and frame beams for aspect ratios between 2.0 and 4.0. However, frame beams typically achieve maximum plastic chord rotations of 3.5 to 4.0%, for cases where the expected shear stresses are 4.0 to 5.0$\sqrt{f'c}$ psi (0.33 to 0.42$\sqrt{f'c}$ MPa), or approximately one-half the values for diagonally reinforced coupling beams tested. Changes to the ACI 318 code should be considered to reduce the shear stress allowed for frame beams (for example, 5.0$\sqrt{f'c}$ psi [0.42$\sqrt{f'c}$ MPa]), or to the ACI commentary to identify this significant difference in performance.

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NOTATION

- $A_{cw} = $ cross-sectional area of concrete beam web
- $A_{td} = $ area of transverse reinforcement provided within given spacing $s$
- $A_{sd} = $ cross-sectional area of each diagonal group of bars
- $b_w = $ width of beam web
- $d_b = $ diameter of reinforcing bar
- $E_c = $ modulus of elasticity of concrete
- $f' = $ concrete compressive strength
- $f_y = $ yield strength of reinforcement
- $h = $ beam depth
- $I_{gf} = $ effective section moment of inertia
- $I_g = $ gross section moment of inertia
- $I_p = $ clear span of beam
- $M_a = $ moment capacity of beam
- $M_y = $ yield moment of beam
- $s = $ longitudinal spacing of transverse reinforcement
- $V = $ beam shear
- $V_{ave}, V_{n} = $ beam shear at the nominal moment capacity ($2M_{y}/L$)
- $V_{ave}(<0.8\%\text{u}) = $ average beam shear between yield and onset of strength degradation
- $V_{max} = $ maximum shear force applied during test
- $V_n = $ nominal shear capacity of beam
- $\phi = $ angle between diagonal bars and longitudinal axis of beam
- $\Delta = $ relative displacement of beam end
- $\Delta_y = $ relative displacement at yield
- $\theta = $ beam chord rotation
- $\theta_y = $ beam chord rotation at yield

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