Reduction of reinforcement congestion in slender coupling beam using bundled diagonal bars

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The current design method in the ACI building code 318M-14 for reinforced concrete coupling beams requires complex details, which leads to reinforcement congestion and difficulty in construction. As an original solution for this issue, the use of steel fibres to reduce the amount of transverse and bundled diagonal reinforcement in coupling beams is investigated in this study. In order to estimate the effect of the expected design method, four coupling beam specimens with 2/3 scale subjected to cyclic lateral loads were tested. All specimens were made of steel-fibre-reinforced concrete. One specimen complied with ACI code-specified reinforcement details (for all diagonal, transverse and horizontal bars) and three specimens used bundled diagonal reinforcement with variation in the spacing of stirrups. The global behaviours of the tested coupling beams are discussed, especially focusing on the strength, ductility and energy dissipation capacity as displacement demand increases. The test results illustrate that the lateral force-resisting performance of coupling beams was effectively improved by using steel fibres and bundled diagonal reinforcement, even with a reduced amount of stirrups, compared to that designed following ACI code-specified reinforcement details.

Notation

\[ A_v \] area of transverse reinforcement (including crossties) within spacing \( s \)

\[ A_{vd} \] area of diagonal reinforcement in each group

\[ b \] beam web width

\[ d \] nominal diameter of bar

\[ F \] force

\[ F_{\text{max}} \] maximum force

\[ F_{\text{min}} \] minimum force

\[ f_c \] specified compressive strength of concrete

\[ f_y \] specified yield strength of diagonal reinforcement

\[ f_{yt} \] specified yield strength of transverse reinforcement

\[ h \] height of beam

\[ l \] length of clear span measured face-to-face of support

\[ s \] centre to centre spacing of transverse reinforcement

\[ V_{\text{ACI}} \] nominal shear strength calculated by ACI code

\[ V_{\text{Binney}} \] nominal shear strength calculated by Binney

\[ V_C \] shear strength carried by concrete

\[ V_f \] force at failure

\[ V_{\text{Han}} \] nominal shear strength calculated by Han

\[ V_S \] shear strength calculated by transverse reinforcement

\[ V_u \] ultimate shear strength of coupling beam

\[ V_y \] force at yielding

\[ \alpha \] angle between diagonal bars and longitudinal axis of the beam

\[ \gamma \] transverse reinforcement factor

\[ \theta \] drift ratio

\[ \theta_f \] drift ratio at failure

\[ \theta_{\text{min}} \] minimum drift ratio

\[ \theta_{\text{max}} \] maximum drift ratio

\[ \theta_y \] yield drift ratio

\[ \mu \] ductility ratio

\[ \rho_t \] transverse reinforcement ratio

Introduction

Reinforced concrete (RC) coupled wall structures are usually used as the essential resistant systems against lateral forces for high-rise buildings. The common coupled wall system is made up of separate structural shear walls linked together by relatively short and deep beams called coupling beams. These coupling beams play an essential role in the seismic performance of the coupled walls and the whole structure, because they can significantly affect the displacement, ductility and internal force demands of individual members in earthquakes. Therefore, the proper design of RC coupling beams is extremely important to secure the overall performance of structures subjected to seismic excitations.

The seismic design and construction of coupling beams still remain challenging owing to the presence of large reversed cyclic rotation demands causing significant shear deformations. The conventional coupling beam (having horizontal
and transverse reinforcement) failures in the McKay building during the March 1964 Anchorage earthquake demonstrated the need for new designs to prevent sliding shear failure (Berg and Stratta, 1964). Since then, many studies have been conducted to resolve this problem. Paulay and Binney (1974) first proposed diagonal bars for coupling beams. The application of diagonal reinforcement in coupling beams led to superior ductility, energy dissipation and stiffness retention capacities compared with conventionally reinforced coupling beams (Barney et al., 1980; Tassios et al., 1996). However, the diagonal reinforcement detail creates major construction difficulties because of reinforcement congestion, especially in the mid-span area of the coupling beam, where the groups of diagonal reinforcement cross each other.

Researchers have recently looked upon the application of steel fibres for simplifying the reinforcement detail of coupling beams. Canbolat et al. (2005) tested four coupling beams, including three made of high-performance fibre-reinforced cement composites (HPFRCCs), and concluded that the application of advanced fibre-reinforced cementitious materials allowed the elimination of transverse reinforcement enclosing each group of diagonal bars (ACI 318M-14 (ACI, 2014)) without compromising the seismic performance. Lequesne et al. (2009) tested four coupling beams to investigate the impact of HPFRCCs on the behaviour of coupled wall structures. Kuang and Bączkowski (2009) conducted tests of steel-fibre-reinforced concrete coupling beams. The experimental studies conducted by Shin et al. (2014) and Han et al. (2015a) were among limited studies investigating the confinement effect of HPFRCCs in coupling beams detailed following ACI 318M-14 (ACI, 2014). They all implied the potential of HPFRCCs that may contribute to the reduction of reinforcement congestion in coupling beams (Kim et al., 2016; Le-Trung et al., 2011; Quang et al., 2016).

In recent years, the use of slender coupling beams, which have a length-to-depth ratio larger than 2, has become popular due to limitations in storey height. In such beams, the contribution of diagonal reinforcement to shear strength decreases owing to the small angle with the longitudinal axis of the coupling beam, although these beams exhibited much higher ductility and energy dissipation than those with conventional reinforcement (Han et al., 2015a; Hindi and Hassan, 2004; Shin et al., 2014). For this reason, ACI 318M-14 (ACI, 2014) allows the use of a conventional reinforcement layout in slender coupling beams. In efforts to resolve the construction difficulty of code-specified distributed diagonal reinforcement, Han et al. (2015b) tested four precast coupling beam specimens at 1/2-scale using bundled diagonal reinforcement. The test results suggested that the bundled diagonal coupling beams secured sufficient internal space, and exhibited ductility and energy dissipation capacity similar to those with code-specified diagonal reinforcement layout.

As part of the authors’ comprehensive test programme, this study considered the use of steel fibres and bundled diagonal reinforcement as an innovative method of enhancing the construction workability and simplicity, as well as improving the seismic performance, of slender coupling beams. The important advantages of bundled reinforcement over distributed reinforcement are to promote simplified construction and to increase the beam shear strength by increasing the angle between the diagonal bars and longitudinal axis of the coupling beam. To accomplish the research objectives, four 1/2-scale steel fibre coupling beams with a length-to-depth ratio of 3.5 were tested, subjected to cyclic lateral loading. Of these, one specimen used ACI code-specified reinforcement details for all diagonal, transverse and horizontal bars, and three specimens used bundled diagonal reinforcement with variation in the amount of transverse bars. The global behaviours of the tested coupling beams are discussed, focusing in particular on the ductility, strength and energy dissipation capacity.

**Experimental programme**

**Material properties**

To investigate the material properties of steel fibres, both compressive and tensile tests were conducted. Table 1 shows the physical properties of the steel fibre; the steel fibre mix proportions used for the specimens are provided in Table 2. In total, four cylinder specimens with 1% volumetric ratio of steel fibre were made and tested. The compressive test procedures corresponded to ASTM C39, ‘Standard test method for compressive strength of cylindrical concrete specimens’ (ASTM, 2015a). The compressive strength of the concrete was calculated by the average of four cylinder specimens with sizes of 200 mm × 100 mm (height × diameter). The top and bottom surfaces of the cylinder specimens were ground flat and capped using a neoprene pad (ASTM C1231) to provide uniform load distribution (ASTM, 2015b). Figure 1(a) exhibits the strain–stress curves obtained from the compressive tests. The average compressive strength of fibre-reinforced specimens is 49.6 MPa, and the secant modulus elasticity is calculated at 40% of compressive strength, with the value being 25.2 GPa.

**Table 1. Properties of steel fibres**

<table>
<thead>
<tr>
<th>Tensile strength: MPa</th>
<th>Elastic modulus: GPa</th>
<th>Diameter: mm</th>
<th>Length: mm</th>
<th>Length-to-diameter ratio</th>
<th>Volume fraction Vf: %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3070</td>
<td>210</td>
<td>0.38</td>
<td>30</td>
<td>79.0</td>
<td>1.0</td>
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</table>

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Dog-bone-shaped specimens, which had sectional dimensions of 25 x 50 mm, were tested in order to determine the tensile performance of steel fibres. In total, three mixture types were examined, and two or three similar results for each type were acquired. The tensile strength of the steel fibre was determined as the average of three specimens based on experimental results. The average of the two linear variable differential transformer (LVDT) measurements, which were mounted along the specimens’ sides in the load direction, was used to estimate the tensile strain. Figure 1(b) shows the stress–strain curves of mixture type no. 2; the experimental results are provided in Table 3. In general, the fibre-reinforced specimens showed high ductility, and formed numerous well-distributed microcracks. The maximum tensile strength was about 4.89 MPa, and the tensile strain was approximately 0.5%.

The coupling beam specimens were constructed using reinforcement with diameters D13 and D25. Table 4 summarises the mechanical properties of reinforcement. The tensile strength ($f_y$) of reinforcement for D25 and D13 are 607 MPa and 620 MPa, respectively.

Specimen description

All the coupling beam specimens in this experiment have the same reinforcement details except for the stirrup spacing and arrangement of diagonal reinforcement. The main function of transverse reinforcement is to transfer tension stresses and thus resist the opening of diagonal cracks, and to confine the concrete core. Therefore, different spacing of the stirrup in the coupling beam can result in serious effects related to shear failure. Moreover, with an increase in spacing of transverse bars, less confinement in coupling beams would be provided, which may lead to non-ductile behaviour and a sudden brittle failure of the specimens.

In this study, four 1/2-scale fibre-reinforced coupling beam specimens with section of 250 mm x 300 mm and 1050 mm long were tested to investigate the performance of a coupling beam under seismic load. Among the four specimens, one specimen (SD-SF1-S100) was a standard specimen, which was used as conventional diagonal reinforcement, as specified in ACI 318-14 (ACI, 2014), and the three remaining coupling beams were applied with a bundled diagonal layout. The length-to-depth ratio (aspect ratio) of all specimens was 3.5, which is representative of slender coupling beams. The volumetric ratio of steel fibre was approximately 1% for all coupling beams in order to assess principally the effectiveness of bundled diagonal reinforcement in slender coupling beams using fibres.

Figure 2 illustrates the dimensions and the reinforcement detail for the coupling beam specimens; the processing of specimen construction is shown in Figure 3. Two different types of reinforcement layout were used for the experiment: distributed diagonal reinforcement and bundled diagonal layout. For the

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**Table 2. Concrete mixture proportion**

<table>
<thead>
<tr>
<th>W/B^a: wt%</th>
<th>S/A^b: Vol%</th>
<th>Unitary quantity: kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.8</td>
<td>60</td>
<td>Water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>223</td>
</tr>
</tbody>
</table>

^aW/B, water/binding material; ^bS/A, sand/aggregate; ^cPC, portland cement; ^dHPMC, hydroxy propyl methyl cellulose
diagonal reinforcement layout, four longitudinal reinforcements were arranged as a diagonal group, and two opposite groups of diagonal reinforcements came across each other at the coupling beam centre (Figure 2(d)). In the bundled diagonal layout, the longitudinal bars were grouped closely to secure sufficient internal space. Transverse bars were arranged for the entire beam section, and the intermediate horizontal beam reinforcements used to anchor the transverse reinforcements were extended a short embedded length into the beam stubs to prevent yielding, as specified in ACI 318M-14 (ACI, 2014).

The three specimens that use bundled diagonal bars are termed ‘BD’; the others are termed ‘SD’ to indicate that standard diagonal reinforcement was used. The notation SF1 means that a 1% volume of steel fibres was used. The terms S100, S75 and S50 denote 100%, 75% and 50% as the amount of stirrups required for the second confinement option specified in ACI 318M-14 (ACI, 2014), respectively. The angle of diagonal bars, $\alpha$, is the angle between the diagonal reinforcement groups and the longitudinal axis of the coupling beam.

![Figure 2](image-url)
Test set-up

Figure 4 illustrates the experimental set-up adopted for the testing of the coupling beams. For convenience of testing, the specimen was arranged vertically, and the bottom stub was fixed to the floor of the laboratory to avoid sliding and overturning during the test. Reversed cyclic loading was imposed horizontally by a hydraulic actuator of 1000 kN on the steel reaction frame connected to the top stub of the coupling beam. In order to prevent out-of-plane axis rotation from the top of the coupling beams, four roller supports were placed at the ends of the experimental frame. Therefore, only horizontal movement was introduced during the test. In addition, stopper blocks were provided at the top and bottom stubs to prevent the coupling beam specimens from sliding.

A load cell was installed in the actuator to control the applied load. To measure the diagonal and transverse reinforcement strain, strain gauges were placed into the specimens at various locations, as illustrated in Figure 2. The deformations correlating with flexure and shear forces of the coupling beam were estimated by LVDTs, which were vertically and diagonally installed on the faces of the coupling beams (Figure 4).

To characterise the coupling beam responses, cyclic lateral displacement was applied at the top of the specimen, with forces steadily increasing. Figure 4 also illustrates the quasi-static displacement cyclic loading imposed to the coupling beams. Two cycles were used for each of the drift loading cases from 0.25% to 12%. The drift ratio is determined as a lateral drift divided by the length of the coupling beam. Repeating two cycles for each drift ratio level allowed information to be captured for a better understanding of the strength and stiffness degradations of the specimens.

Analysis of the test results

Using visual observation and the recorded information, the crack patterns and failure modes, lateral load–displacement responses, strength evaluation, energy dissipation and stiffness degradation of coupling beam specimen are discussed. The effects of the main test variables on the performance measurements are highlighted below.

Hysteretic comparison

In the structural dynamic analysis, ductility ratios, which are determined as the maximum drift ratio ($\theta_u$) divided by the corresponding drift when yielding occurs, were used for expressing several response factors related to deformations, rotations and curvatures. The yield drift ratio ($\theta_y$) and maximum drift ratio ($\theta_u$) were determined in accordance with the procedure proposed by Pan and Moehle (1989). In this methodology, the yield drift ratio ($\theta_y$) corresponds to the intersection point between the line of secant stiffness and the horizontal line at the maximum load point. The maximum drift ratio ($\theta_u$) is defined by the point where the maximum lateral strength was...
reduced by 20%, and ductility ratio (μ) is calculated by the following formula

1. \[ \mu = \frac{\theta_y}{\theta_f} \]

The ductility ratios of each specimen were calculated and are shown in Table 5. In general, the bundled diagonal specimen with 1% volumetric of steel fibres had a high ductility capacity compared with the distributed diagonal specimen using 1% of steel fibres. To be more specific, the ductility ratio of coupling beams with the bundled diagonal layout applied all exceed 5.0% for the positive direction, which is greater than the 4.72% for the specimen using diagonal reinforcement. With the same 100% of stirrups (120 mm for transverse reinforcement spacing), the maximum drift ratio of specimen BD-SF1-S100 is 10.5%, whereas that of specimen SD-SF1-S100 is only 8.97%.

Figures 5(a)–5(c) plot the envelopes of the hysteretic curves for the coupling beams BD-SF1-S100, BD-SF1-S75 and BD-SF-S50, which applied the bundled diagonal layout with the only difference being in the stirrup spacing. In general, all of the specimens exhibit full and stable hysteresis loops and reached almost the same level of yielding drift ratio between 1.8% and 2.0%. Their drift ratios (\(\theta_u\)) for the positive direction were 10.52%, 9.95% and 12.02%, respectively. It is worth noting that specimen BD-SF1-S50, with half the lateral...
reinforcement as used in the BD-SF1-S100 (having the same amount of stirrups as the code-specified standard specimen), had almost identical hysteretic behaviour compared with the latter coupling beams. Their drift ratios for the positive direction ($\theta_f$) were 12.02% and 11.68%, respectively. In addition, specimen BD-SF1-S75 had a spacing of transverse bars...
(180 mm) which was 2/3 smaller than that of specimen BD-SF1-S100 (120 mm); the maximum drift ratio of both specimens were quite similar, with 9.95% for the former and 10.52% for the latter. Thus, the appearance of steel fibre in the coupling beam can significantly reduce the amount of lateral transverse reinforcement without a dramatic loss of cyclic performance.

Cracking and failure modes
The cracking patterns were visually observed in the four specimens and are shown in Figure 6. For all specimens, inclined cracks started in the region near the middle of the coupling beam and horizontal cracking was detected near the interface between the beam and stub. Figures 6(a) and 6(d) exhibit the cracking patterns of specimens BD-SF1-S100 and SD-SF1-S100. During the first and second loading cycles, specimen SD-SF1-S100 had fewer relatively small cracks than specimen BD-SF1-S100, which had both flexural and diagonal cracks. However, the cracks on the former specimen developed a little bit faster than the latter specimen as the drift increased. At around 1% drift ratio, inclined cracks developed over the entire part of both specimens and then some of the diagonal bars yielded at 2% drift ratio. Significant concrete crushing and spalling at the beam bottom end was observed at 3% drift ratio for specimen SD-SF1-S100, whereas less severe damage was observed in specimen BD-SF1-S100. From this point, additional shear cracks could not clearly be seen for either of the coupling beams, and further loading led to wider flexural-shear cracks at the end of the specimens. Finally, the specimen using conventional diagonal reinforcement completely failed at 10% drift ratio, compared with 12% drift ratio for the specimen with the applied bundled diagonal layout.

The cracking patterns of specimens BD-SF1-S75 and BD-SF1-S50 were quite similar to that of specimen BD-SF1-S100 (see Figures 6(b) and 6(c)). During the first cycle (0.25% drift ratio), several horizontal and diagonal cracks propagated throughout the coupling beam BD-SF1-S50, as opposed to only a few horizontal cracks in specimen BD-SF1-S75. This could be explained by the difference in stirrup spacing in the coupling beams, at 250 and 180 mm for the former and latter specimen, respectively. At about 2% drift ratio, some of the bundled diagonal bar yielded in both specimens, and after that both of them exhibited a similar cracking and failure pattern. It may be said that steel fibre has a favourable effect on the crack resistance of coupling beams, even when the tie spacing is reduced.

Based on the crack and failure patterns, it was concluded that the bundled diagonal reinforcement was effective in a slender coupling beam. Also, the use of steel fibre in a slender coupling beam may allow the amount of stirrups to be significantly reduced without affecting the crack formation pattern.

Strength, stiffness deterioration and energy dissipation capacity
For the purpose of estimating the cyclic strength of all specimens, envelope curves were extracted from the hysteretic curves and these are shown in Figure 7. The coupling beam specimens using bundled diagonal bars achieved greater maximum lateral loads than those applying code-specified reinforcement. To be more specific, the load capacity of specimen BD-SF1-S100 was 482.36 kN, whereas that of SD-SF1-S100 was 451.97 kN. The two remaining specimens using bundled diagonal layout (BD-SF1-S75 and BD-SF1-S50) also achieved high load capacities with 512.16 kN and 474.96 kN, respectively. The test results indicate that bundled diagonal reinforcement was more effective than code-specified reinforcement. The main reason is that the angle between the diagonal reinforcement and the coupling beam longitudinal axis has been increased with the use of the bundled layout. This angle effect leads to greater expected moment and shear demand carried by the diagonal reinforcements, resulting in improvement in the flexural and shear strengths of slender coupling beams.

The nominal shear strength of coupling beams with diagonal reinforcement may be determined based on Section 21.9 of ACI 318-14 (ACI, 2014).

2. \[ V_{ACI} = 2A_{sv}f_y \sin \alpha \]

Here, \( A_{sv} \) is the total area of reinforcement in each group of diagonal bars; \( \alpha \) is the angle between the diagonal bars and the longitudinal axis of the beam; and \( f_y \) is the yield stress of diagonal reinforcement. The contribution of horizontal reinforcement, as well as the effects of the concrete and transverse reinforcement on the strength of diagonal coupling beams are not considered in ACI 318-14 (ACI, 2014). To account for these effects, the approaches developed by Binney (1972), and recently by Han et al. (2016), were used to accurately estimate the shear strength of slender coupling beams.

3. \[ V_{Binney} = V_{ACI} + V_c + V_s \]

4. \[ V_s = \frac{A_{sv}f_y d}{s} \]

5. \[ V_c = 0.17 \sqrt{f_c bd} \]

6. \[ V_{Han} = V_{ACI} + \gamma V_s \]
Here $A_v, f_y$, and $s$ are the area, yield strength and spacing of transverse reinforcement, $d$ is the effective depth of the coupling beam and $\rho_t = A_{vt}/bs$ is the transverse reinforcement ratio. Table 6 compiles the diagonal reinforcement coupling beam tests found in the literature. The ratio of $V_u$ to $V_{ACI}$ is much greater than 1, which means that the slender diagonal coupling beams designed based on ACI 318-14 (ACI, 2014) could achieve higher strength than those expected by the current code. The Binney method considered the contribution of transverse reinforcement but overestimated the ultimate strength.
shear strength of the slender coupling beams by between 12 and 63%. Much better agreement would have been obtained by using the proposed shear strength equation by Han et al. (2016). Although it may have underestimated the ultimate shear strength, a comparative agreement is observed within a margin of 16%. In short, the new shear strength equation could conservatively estimate the shear capacity for slender diagonal coupling beams, even for those using bundled diagonal layout.

The three coupling beam specimens that used bundled diagonal reinforcement were similar in cyclic strength and stiffness.
Figure 7. Load–displacement envelope curves: (a) first cycle envelope curve; (b) second cycle envelope curve

Table 6. Shear strength of diagonally reinforced coupling beam tests

<table>
<thead>
<tr>
<th>Author</th>
<th>Specimen name</th>
<th>Aspect ratio (L/h)</th>
<th>ρt: %</th>
<th>Avd: mm²</th>
<th>Fy: MPa</th>
<th>Vu: kN</th>
<th>Vu:ACI: kN</th>
<th>Vu:Binney: kN</th>
<th>Vu:Han: kN</th>
<th>Aνd: mm²</th>
<th>Fy: MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shimazaki (2004)</td>
<td>N1</td>
<td>2·5</td>
<td>0·21</td>
<td>804</td>
<td>476</td>
<td>351</td>
<td>237</td>
<td>394</td>
<td>301</td>
<td>1·48</td>
<td>0·89</td>
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<tr>
<td>Shin et al. (2014)</td>
<td>1DF0Y</td>
<td>3·5</td>
<td>0·81</td>
<td>2027</td>
<td>478</td>
<td>473</td>
<td>300</td>
<td>629</td>
<td>411</td>
<td>1·58</td>
<td>0·75</td>
</tr>
<tr>
<td>Han (2015a)</td>
<td>RC-3·5</td>
<td>3·5</td>
<td>1·32</td>
<td>2027</td>
<td>442</td>
<td>507</td>
<td>277</td>
<td>764</td>
<td>424</td>
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<tr>
<td>Naish et al. (2013)</td>
<td>CB33D</td>
<td>3·5</td>
<td>0·33</td>
<td>2322</td>
<td>482</td>
<td>537</td>
<td>423</td>
<td>717</td>
<td>525</td>
<td>1·72</td>
<td>0·75</td>
</tr>
<tr>
<td>Present study</td>
<td>SD-SF1-S100</td>
<td>3·5</td>
<td>1·21</td>
<td>2027</td>
<td>442</td>
<td>451·9</td>
<td>277</td>
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<td>415</td>
<td>1·63</td>
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<tr>
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<td>BD-SF1-S100</td>
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<td>2027</td>
<td>442</td>
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<td>333</td>
<td>662</td>
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<td>1·42</td>
<td>0·81</td>
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</table>

Figure 8. Normalised peak-to-peak stiffness

Figure 9. Cumulative energy dissipation
Summary and conclusions

The primary purpose of this research was to investigate the contribution of steel-fibre-reinforced concrete and bundled diagonal reinforcement to the simplification of construction and the seismic performance of coupling beams in special moment frames. In order to reach these goals, four approximately 1/2-scale coupling beam specimens were constructed and tested under quasi-static cyclic lateral loadings. The following conclusions are drawn from the results of this investigation.

(a) The strength and ductility of the coupling beam specimens using bundled diagonal bars were generally improved compared to the standard specimen applying ACI-specified (i.e. distributed) diagonal reinforcement. Furthermore, the application of the bundled diagonal layout in coupling beams could also increase drift capacity at failure.

(b) The specimen with distributed diagonal reinforcement had very similar initial stiffness to those with bundled diagonal reinforcement. However, the application of the bundled reinforcement layout led to an angle change effect (the angle of diagonal bars \( \alpha \) increased from 8.9° to 10.7°), which increased shear strength and allowed coupling beams to delay stiffness degradation at higher drift ratios.

(c) With the presence of 1% volumetric ratio of steel fibres, the three specimens with bundled diagonal reinforcement exhibited similar strengths and failure drift ratios, regardless of variation in the stirrup spacing (i.e. amount of stirrups). Therefore, the application of steel fibres in coupling beams with bundled diagonal layout may considerably reduce the amount of transverse reinforcement required without a loss of seismic performance.

Finally, it is worth emphasising that, together with previous RC coupling beam experiments conducted by the same authors (Han et al., 2015b), this study proposes that bundled diagonal reinforcement could be used in slender coupling beams for the purposes of ensuring satisfactory seismic performance and simplified construction.

Acknowledgement

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