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Cyclic performance of precast coupling beams with bundled diagonal reinforcement

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ABSTRACT

Diagonally reinforced coupling beams designed according to current codes are expected to endure significant inelastic deformations during earthquakes. However, it is very difficult to fabricate the coupling beams in a construction site due to the congestion of reinforcement and the complex arrangement of diagonal reinforcement. For resolving the problems, this study developed precast coupling beams with bundled diagonal reinforcement. To verify the effectiveness of the proposed design method, experimental tests were conducted on four 1/2-scale coupling beam specimens subjected to cyclic loading. The test results suggest that the precast coupling beams with bundled diagonal reinforcement exhibited good ductility and energy dissipation capacities similar to those having code-specified diagonal reinforcement.
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1. Introduction

A coupled wall system that consists of separate structural walls linked together by coupling beams is effective to resist lateral forces in high-rise buildings [1,2]. Coupling beams designed according to current codes [3–6] are expected to endure significant inelastic deformations under design-level earthquakes. Thus, coupling beams should be provided with appropriate reinforcing details to execute sufficient seismic performance such as ductility and energy dissipation.

Conventionally reinforced coupling beams, which have longitudinal bars parallel to the span of the beam, may suffer sliding shear failure at the beam ends [7]. Transverse reinforcement could not prevent sliding shear failure because vertical cracks propagated across the entire depth of the beam between stirrups [8]. A good example of the sliding shear failure of coupling beams can be found in the failure of coupling beams in Mount McKinley building in Anchorage, Alaska due to the 1964 Anchorage Earthquake [9]. Since then, many studies have been conducted to resolve this problem. Historically, Paulay and Binney [10] first developed diagonal reinforcement for coupling beams. Diagonally reinforced coupling beams were proven to not suffer sliding shear failure and have superior ductility and energy dissipation capacities and stiffness retention than conventionally reinforced beams [10–12].

From the previous studies mentioned above, Section 21.9.7 of ACI 318 [3] specifies two confinement options for coupling beams with diagonal reinforcement, as shown in Fig. 1. In the first option in Fig. 1(a), each group of diagonal reinforcement comprises at least four longitudinal bars enclosed by transverse reinforcement. This confinement method requires very complex bar arrangement, especially near the mid-span of the beam where diagonal reinforcement groups cross each other. Also, according to Harries et al. [13], arranging diagonal bars enclosed by transverse reinforcement is practically difficult when the average shear stress in the beam is greater than $0.5\sqrt{f'_c}$ (where f'_c is the concrete compressive strength in MPa). Due to such shortcomings, the second confinement option in Fig. 1(b) is allowed in Section 21.9.7.4(d) of ACI 318 [3] that transverse reinforcement required for beams and columns of special moment frames should be provided for the entire cross section of the beam.

Shui et al. [14] reported that diagonal reinforcement would generally be less effective in coupling beams with large length-to-depth ratios (l_n/h) that cause the small angles of diagonal reinforcement [15,7]. For a similar reason, ACI 318-11 [3] allows to use conventional reinforcement layout in shallow coupling beams. As an example, for a coupling beam with l_n/h larger than 2, diagonal reinforcement is not required by ACI 318 [3].

In efforts to resolve the difficulty of fabricating diagonal reinforcement in coupling beams, various reinforcing details have been proposed and tested to date [12,16,17]. Recently, steel and composite coupling beams have been developed [18,19]. In this

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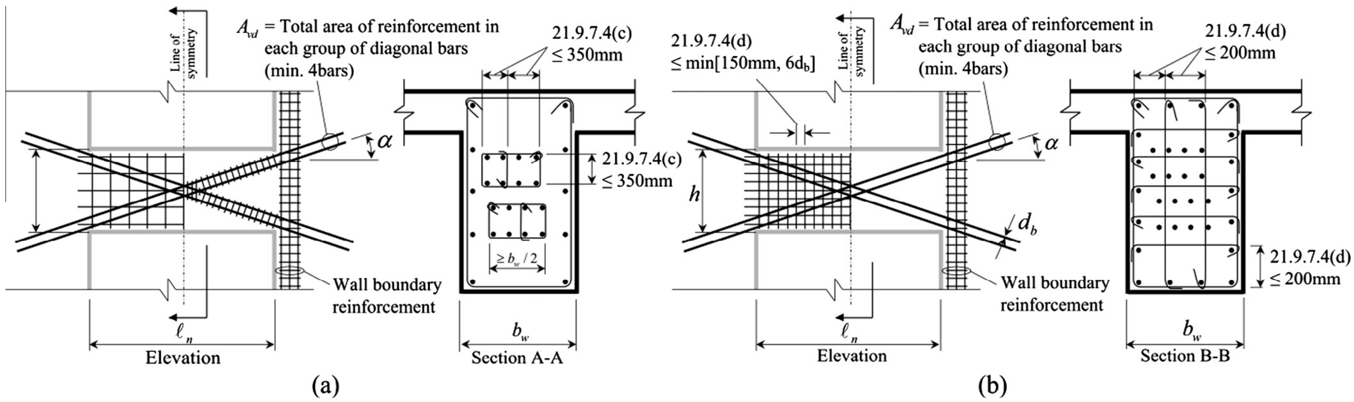

Fig. 1. Two confinement methods for diagonally reinforced coupling beams specified in ACI 318-11: (a) 1st confinement option and (b) 2nd confinement option.

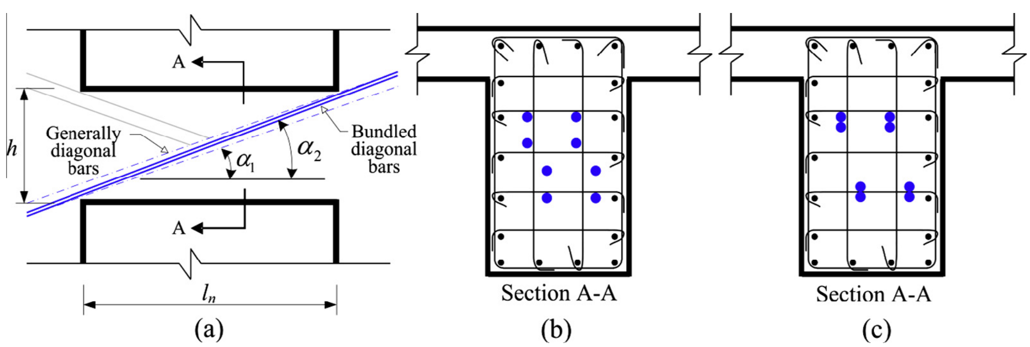

Fig. 2. Advantages in the use of bundled diagonal reinforcement: (a) increase in the angle of bundled diagonal bars, (b) reinforcement detail according to ACI 318-11, and (c) reinforcement detail with bundled diagonal bars.

study, the use of bundled diagonal reinforcement is investigated as a modification to the second reinforcement details in Fig. 1(b). As illustrated in Fig. 2, bundled diagonal reinforcement secures sufficient internal space so that it will enhance workability and promote simplified construction, compared with code-specified diagonal reinforcement, in which spacers are needed to maintain the gaps between separate diagonal bars. Bundling also increases the angle of diagonal reinforcement from the longitudinal axis of the beam (Fig. 2), which will lead to improvement in both flexural and shear strengths. In addition, the feasibility of precast coupling beam construction is explored for the purpose of maximizing construction simplification. Four approximately 1/2-scale coupling beam specimens are tested subject to earthquake-type cyclic loading, to verify the seismic performance of precast RC coupling beams with bundled diagonal reinforcement.

2. Experimental program

2.1. Specimen design and test variables

To evaluate the seismic performance of RC coupling beams having bundled diagonal reinforcement, four 1/2-scale coupling beam specimens were tested. The use of bundled diagonal reinforcement described in Fig. 2 was taken as the most important test variable. Also, the aspect ratio of coupling beams varied to be 2.0 or 3.5. The aspect ratio (l_n/h) of the beam was defined as the beam span length divided by the height of the beam (Fig. 1).

Fig. 3 illustrates the dimensions and reinforcing details of coupling beam specimens. Specimens SD-2.0 and SD-3.5, with the aspect ratio of 2.0 and 3.5 respectively, were designed following the requirements in Section 21.9.7.4 of ACI 318 [3]. The confinement of diagonal reinforcement was executed by arranging horizontal and transverse reinforcement over the entire section of the coupling beam as shown in Fig. 1(b), which is specified in Section 21.9.7.4(d) of ACI 318 [3]. Specimens BD-2.0 and BD-3.5 had the same design details with SD-2.0 and SD-3.5 respectively, except for bundling the diagonal reinforcement. The tests were mainly intended to assess the effectiveness of bundled diagonal reinforcement in comparison to code-specified diagonal reinforcement, in both deep and shallow coupling beams.

Specimen details and test variables are summarized in Table 1. The length of the beam was 1050 mm in all specimens, and the height of the beam was 525 mm or 300 mm, so that the aspect ratio was 2.0 or 3.5. The amount of diagonal reinforcement was determined to have the maximum average shear stress in the coupling beam approximately equal to $0.5\sqrt{f'_c}$. Reinforcing D13 with a diameter of 13 mm was used for horizontal and transverse reinforcement. The spacing of transverse reinforcement was 120 mm and 110 mm in the specimens with the aspect ratio of 2.0 and 3.5 respectively, not exceeding six times the diagonal bar diameter as required in ACI 318-11. The inclination angles of code-specified diagonal reinforcement in Specimens SD-2.0 and SD-3.5 were about 20.4° and 8.9° respectively, while the angles of bundled diagonal reinforcement in specimens BD-2.0 and BD-3.5 were about 22.1° and 10.7°, respectively.

To evaluate the feasibility of precast construction of coupling beams, the beam portion was constructed first, and the stubs playing the role of shear walls at the ends of the beam were fabricated about a week later. To ensure the load transfer between the beam and stubs, 50-mm deep rectangular shear keys were provided at the beam ends, and U-shaped reinforcement was added at the connection between the beam and stubs (Fig. 3). Sufficient reinforcing

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