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Behavior and Design of Steel Reinforced Concrete (SRC) Coupling Beams: A Review

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Abstract

Recently, steel reinforced concrete (SRC) coupling beams have been recognized as a viable alternative to diagonally reinforced concrete (RC) coupling beams used in special shear wall systems to solve the construction difficulties such as reinforcement placement and concrete casting. It is noted that specially, SRC coupling beams are very effective in case that height restrictions, higher stiffness and strength are required. This paper reviews test results of SRC coupling beams from available literatures to provide the methodology for the design and anchorage of SRC coupling beams. It is found that the SRC coupling beams can be a viable solution for construction problems due to the reinforcement congestion of traditional RC coupling beam with diagonal bar groups.

Keywords: Coupling beam, Structural performance, Steel reinforced concrete (SRC), Diagonally reinforced concrete coupling beam, Coupled shear wall system

1 Introduction

Reinforced concrete (RC) coupled shear walls in medium and high-rise buildings have been commonly used as the main lateral load resisting elements. RC coupled shear walls under earthquake attacks should behave with high shear strength, high stiffness, high ductility and high energy dissipation capacity without collapsing. To ensure these performances of coupled shear walls during an earthquake, coupling beams between adjacent shear walls need to sustain high shear force and dissipate energy dissipation effectively. Coupling beams were initially reinforced with conventional reinforcement layout consisting of longitudinal and transverse bars.

After Alaska earthquake occurred in 1964, it was recognized that a new reinforcement detail for shear-dominant RC coupling beam was required to improve the seismic performance of orthogonally reinforced concrete coupling beams. Paulay and Binney [1] proposed the diagonal reinforcement layout for short coupling beams. Based on their study result, American Concrete Institute (ACI) in 1999 (ACI 318-99) introduced a new reinforcement layout, which includes two confined diagonal bar groups and transverse reinforcement around the entire beams section, for RC coupling beams with aspect ratio less than four. Each diagonal bar group was required to confined by the same transverse reinforcement as that for columns to prevent buckling and increase the deformability of diagonal bar group in compression. The diagonal reinforcing detail for short coupling beam led to the difficulties of placing diagonal bar group and transverse reinforcement along diagonal bar group. In 2008, ACI (ACI 318-08) proposed an alternative detailing option confining the full beam cross section with transverse reinforcement without hoops along diagonal bar group to simplify the complicated detailing. However, the difficulty to placing the steel bars of short coupling beams has not been solved in practice.

Recently, various types of steel and concrete composite coupling beams have been proposed as viable alternatives to diagonally reinforced concrete coupling beams and the structural performance of these composite coupling beams was experimentally evaluated by many researchers. These composite coupling beams can be categorized as encased steel plate coupling beam, SRC coupling beam [2-6], structural steel concrete coupling beam, and concrete filled steel plate coupling beam.

Steel reinforced concrete (SRC) coupling beam is popularly used in RC coupled shear wall of high-rise building constructed in Korea. SRC coupling beam is an effective option for diagonally reinforced concrete coupling beam because SRC coupling beam with shallower depth exhibits higher stiffness and strength than RC coupling beam with diagonal bar groups.

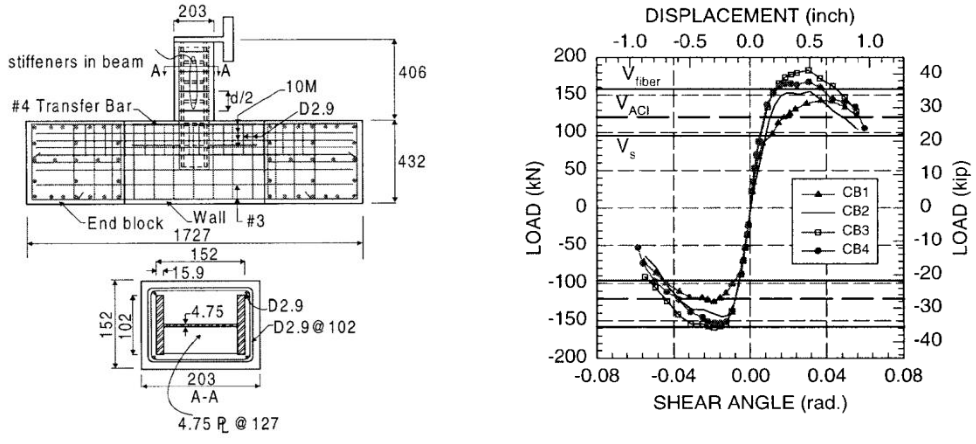
Structural design methodology for SRC coupling beam is not distinctly provided in the current Korean Building Code (KBC 2016). Therefore, this review summarizes and discusses the reported findings on the structural performance and design method of SRC coupling beams from existing research literatures.

2 Literature Review

Studies on SRC coupling beams were started by Gong and Shahrooz [2] at the University of Cincinnati. The main objectives of their study were to investigate the effect of concrete encasement on the strength, ductility and stiffness of SRC coupling beams with shear yielding steel beam. The research results indicated that reinforced encasement around the shear-yielding steel coupling beams enhanced the strength and stiffness. Harries et al [3] reviewed the state of the art for the design of conventional RC, diagonal RC, and steel-concrete composite coupling beams. Song et al [4] proposed a new detail for the connection between RC wall and SRC coupling beam and tested three SRC coupling beams with different embedment length. Their test results indicated that SRC coupling beams with only anchor bolts exhibited more strengths than that calculated with current PCI Code. Oh et al [5] developed the prestressed composite coupling beams and conducted the tests on two prestressed composite coupling beams with different amount of shear reinforcements. Baek [6] proposed the SRC coupling beam with a steel hysteresis damper and investigated experimentally the seismic performance of the special coupling beam.

Structural performance

Gong and Shahrooz [2] tested four one-third-scale SRC coupling beams to investigate the contribution of concrete encasement to the strength and stiffness of steel coupling beams. The test variables were the presence of concrete encasement around steel coupling beam, and number and spacing of web stiffeners in steel coupling beams. Figure 1 shows the load and shear strain curves of coupling beam specimens. In the study, CB1 was a steel coupling beam with stiffeners. CB2, CB 3 and CB4 specimens were SRC coupling beams. CB2 had the same amount of stiffeners as CB1 specimen. CB3 had a half of stiffener reinforcement that CB1 had. CB4 did not have stiffeners.



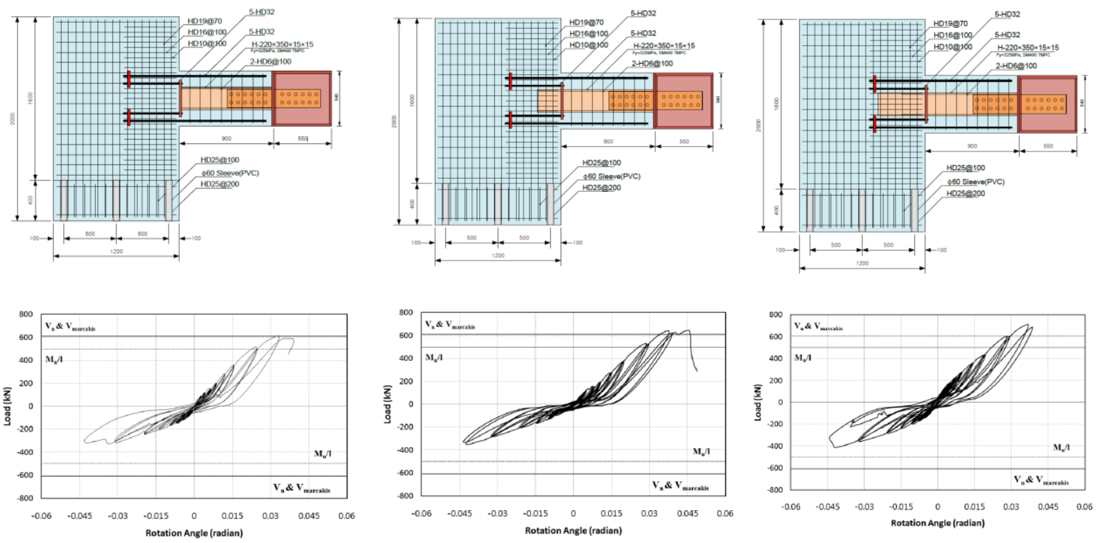
(a) Specimens' details (unit : mm) (b) Load-deflection envelope curves

Figure 1. Effect of encased concrete on the behavior of SRC coupling beam [2]

Figure 1(a) shows a typical detail of SRC coupling tested by Gong and Shahrooz [2]. Experimental results showed that encasement concrete around steel beams contribute to the prevention of flange and web buckling as shown in Figure 1(b).

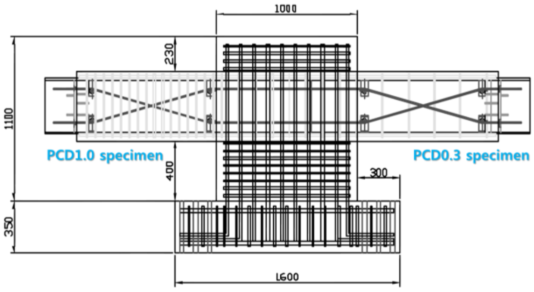
Figure 2 shows the configuration and structural responses of SRC coupling beams tested by Song et al [4]. They proposed a new detail for SRC coupling beams to reduce the embedment length of steel beam and increase the rotation-resistant capacity of connection between shear wall and SRC coupling beam as shown in Figure 2. The 32mm longitudinal bars with end plates in the SRC coupling beams were anchored into RC wall. In the ND-EL1 specimen, steel beam did not embedded into RC wall and was connected through the longitudinal bars of SRC coupling beam. The steel beams of ND-EL2 and ND-EL3 coupling beams had the embedment length of 225 mm and 450 mm. At initial loading stage, flexural and shear cracks were occurred in the SRC coupling beams. As the loading cycles in the SRC coupling beam specimens embedded into RC wall increased, the cracks propagated into the RC wall. As shown in Figure 2, the proposed detail of embedment for SRC coupling beams was effective but as the embedment length increase, the strength and stiffness of SRC coupling beam were a little improved.

Oh et al [5] introduced the prestressing system into SRC coupling beams to enhance the structural efficiency. Figure 3(a) shows the configuration and reinforcement details of prestressed SRC coupling beams. PCD 0.3 and 1.0 specimens had the same sectional details. PCD1.0 specimen was reinforced with shear reinforcement ratio of 1.0% while PCD0.3 specimen was reinforced with 0.3% shear reinforcement. Prestressing force for both specimens was $0.75f_{py}$ (f_{py}: yielding strength of prestressing tendon), 137 kN. The loading setup for SRC coupling beams was presented in Figure 3(b).

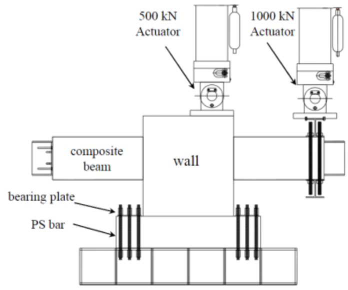


(a) ND-EL1 (b) ND-EL2 (c) ND-EL3

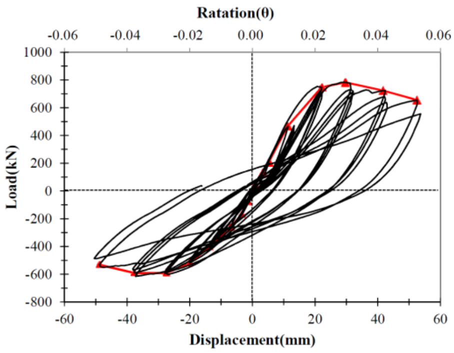
Figure 2. Effect of embedment length on the behavior of SRC coupling beam [4]



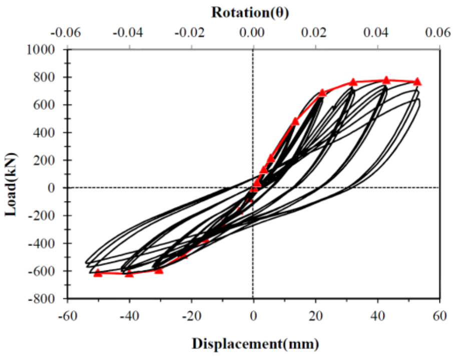
(a) Specimens' details (unit : mm)



(b) Setup for loading

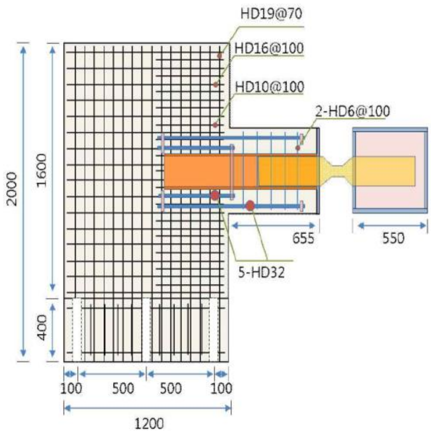


(c) Response of PCD1.0

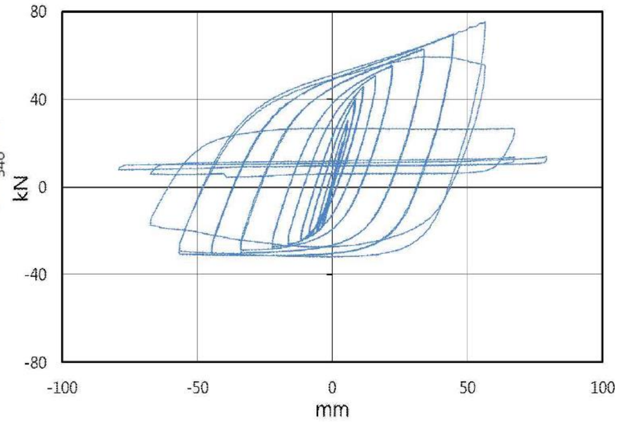


(d) Response of PCD0.3

Figure 3. Effect of stirrup on the behavior of prestressed SRC coupling beam [5]



(a) Specimens' details



(b) Load-deflection curve

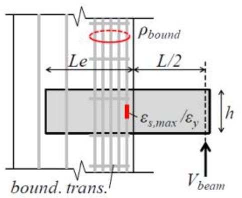
Figure 4. Response of SRC coupling beam with steel damper [6]

Figures 3(c) and (d) show the load and deflection curves of both specimens. As presented in Figures 3(c) and (d), PCD1.0 coupling beam with higher shear reinforcement ratio exhibited 12% higher shear strength than PCD0.3 with lower shear reinforcement ratio. After maximum strength, PCD1.0 specimen exhibited more abrupt strength reduction than PCD0.3 coupling beam. PCD1.0 failed to the flexural compression at the interface between coupling beam and RC wall while PCD0.3 specimen showed the spalling of web concrete under the flange of steel beam. Shear reinforcement in the prestressed SRC coupling beam had not significant effect on the structural response.

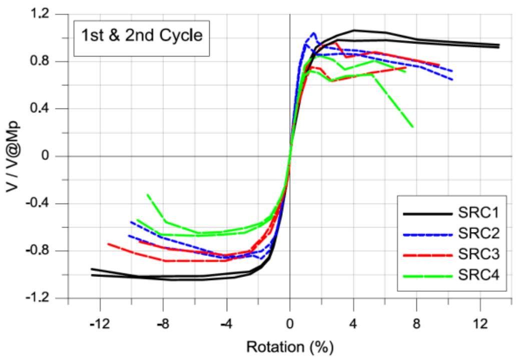
Baek [6] introduced the steel hysteretic damper into SRC coupling beam to increase the energy dissipation capacity and mitigate the crack damage in the SRC coupling beam and RC wall. Figure 4 presents typical configuration and hysteresis behavior of SRC coupling beam with steel hysteretic damper. The response of SRC coupling beam with steel damper showed a stable behavior as shown in Figure 4(b).

Motter[7] investigated the effects of embedment length, span-depth ratio, reinforcement ratio of boundary element and the loading condition of RC wall on the structural behaviors of SRC coupling beams. They tested four large-scale SRC coupling beams as shown in Figure 5(a). Figure 5(b) indicates that the embedment length, reinforcement details of boundary element and span-depth ratio had a significant effect on the structural performance of SRC coupling beams.

	$\alpha = L/h$	L_e (in.)	ρ_{bound}	bound trans.	f'_c (ksi)	$\varepsilon_{s,max}/\varepsilon_y$
SRC1	3.33	32	0.024	OBE	7.4	0.53
SRC2	3.33	24	0.033	OBE	7.4	0.83
SRC3	2.40	26	0.017	OBE	5.0	1.09
SRC4	3.33	24	0.006	Other	4.6	0.57



(a) Specimens' variables



(b) Backbone curve

Figure 5. Response of SRC coupling beam [7]

Strength capacity of SRC coupling beams

Gong and Shahrooz [2] proposed the expected shear strength equation of SRC coupling beams. The equation includes the contribution of steel beam and the reinforced concrete encasement.

$$V_n = 1.6\left[0.6F_y(d-2t_f)t_w + \frac{\sqrt{f'_c}}{6}b_c d_c + \frac{A_v f_{yt} d_c}{s}\right]$$

where F_y is the specific minimum yield strength of structural steel, d, t_f and t_w are the depth, flange thickness and web thickness of steel beam section. b_c and d_c are the effective depth and width of encasement concrete section. A_v, f_{yt} and s are the area, the specific yield strength and spacing of transverse reinforcement.

EI-Tawil et al [8] modified Gong and Shahrooz's equation for shear-yielding SRC coupling beams.

$$V_n = 1.1\frac{F_{ye}}{F_y}(0.6F_y d t_w) + 1.56\left[\frac{\sqrt{f'_c}}{6}b_c d_c + \frac{A_v f_{yt} d_c}{s}\right]$$

where F_{ye} is the expected yield strength of structural steel.

The 2010 AISC Seismic Provisions for Structural Steel Buildings provide design guidelines for SRC composite coupling beams embedded into RC walls. AISC guidelines propose different shear strength equations depending upon boundary walls; ordinary or special structural walls. For ordinary structural walls, expected shear strength of SRC coupling beams prescribed in ASCE is calculated as:

$$V_n = \frac{F_{ye}}{F_y}\left(0.6F_y d t_w\right) + \left[\frac{\sqrt{f'_c}}{6} b_c d_c + \frac{A_v f_{yt} d_c}{s}\right]$$

For special structural walls, shear strength of SRC coupling beams is computed by the equation proposed by EI-Tawil et al [8].

Embedment length of SRC coupling beams

The SRC coupling beam should sufficiently be embedded into RC wall to develop the required shear strength ($V_{required}$) of the connection between beam and wall. The equations for calculating the embedment length are driven based on the force transfer mechanism of steel members embedded in the concrete construction.

Marcakis and Mitchell [9] assumed a rigid-body motion of steel member embedded in the concrete and proposed the required embedment length (L_e) calibrated based on the experimental data.

$$V_{required} = \frac{0.85 f'_c b' (L_e - c)}{1 + \frac{3.6e}{(L_e - c)}}$$

where e is the eccentricity from the midspan of SRC coupling beam to the center of the effective embedment.

In the 2010 AISC Seismic Provisions, the required embedment length (L_e) of SRC coupling beam in the ordinary or special structural walls is proposed as following;

$$V_{required} = 4.5\sqrt{f'_c}\left(\frac{b_w}{b_f}\right)^{0.66} \beta_1 b_f L_{ec}\left[\frac{0.58 - 0.22\beta_1}{0.88 + \frac{L_c}{2L_{ec}}}\right]$$

where b_w and b_f are wall thickness and the flange width of steel coupling beam, respectively. β_1 is a factor relating depth of equivalent rectangular compressive stress block to neutral axis depth. L_c and L_{ec} are the modified net span (L_c = net span L + 2 concrete cover thickness c) including the concrete cover thickness and the modified embedment length ($L_{ec} = L_e - c$) excluding the concrete cover thickness, respectively.

3 Conclusions

This paper reviews the state of the art for structural performance and design of steel reinforced concrete (SRC) coupling beam in the coupled wall systems. SRC coupling beam can be recognized as an alternative to reinforced concrete coupling beam and provide potential merits of improved ductility and reinforcement simplification. Concrete encasement in the SRC coupling beams is effective to prevent web buckling and flange instability and hence web stiffeners can be removed. Behavior of SRC coupling beam is depended on both embedment length and reinforcement details of boundary in the RC wall. The SRC coupling beam designed by AISC Seismic Provisions and empirical equations exhibited stable behavior.

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