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Shear Strength of Composite Beams with Dual Concrete Strengths

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Abstract. Currently, in precast concrete constructions, precast and cast-in-place concrete with different concrete strengths are used in a composite structural member. However, current design codes are not obvious for calculating the vertical shear strength of PC-CIP composite members using dual concrete strengths. In the present study, shear strength of composite beams using dual concrete compressive strengths (24MPa, 60MPa) was tested. The test variables were the section area ratio of two type concretes, flexural reinforcement ratio, and shear span-to-depth ratio.

Keywords: Shear strength, shear failure, dual concrete strengths, precast concrete, composite beam.

1. Introduction

Currently, the application of composite method using Precast Concrete (PC) and Cast-In-Place Concrete (CIP Concrete) increases to improve economic feasibility, constructability and structural integrity. As shown in Fig. 1, unfinished PC beams and slabs made in factories are assembled in fields, and then CIP concrete is placed to complete structural members. In this method, there are considerable differences between compressive strengths of PC and CIP concrete. According to the current design code for composite members (ACI 318-11, 17.2.3[1]), if the specified strength or other properties of the elements in composite members are different, properties of the individual elements or the most critical values shall be used in design. However, various ways of shear strength calculations are employed by structural engineers in the practical application because this design code is not obvious to calculate vertical shear strength of composite structural members.

Most previous researches [2]-[5] about the PC-CIP composite members have been focused on horizontal shear strength rather than vertical shear strength because monolithic behavior of composite members is the most critical factor to resist flexure and shear. The effect of surface smoothness, shear span-to-depth ratio, shear reinforcement, height of surfaces, and concrete strength on the horizontal shear strength of composite beams was investigated by Seamann et al. [2], Loov [3], Kahn [4] and Halicka [5]. However, due to aforementioned shear design problem, vertical shear strength of composite members should be researched in the case of using quite different concrete strengths. Furthermore, some test specimens in the previous studies [3], [5] failed in vertical shear failures such as diagonal shear cracking before interface cracking even though they were designed to expect horizontal shear failure. For this reason, experimental and theoretical evidences are required for composite members with dual concrete strengths.

2. Experimental Program

2.1. Major test parameters

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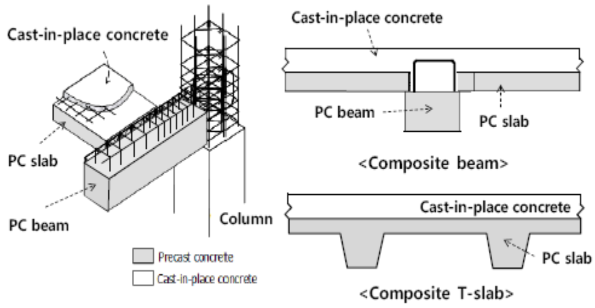

Fig. 1: Composite method using PC and CIP concrete

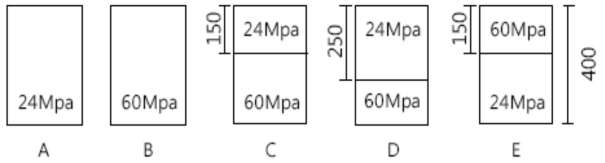

Fig. 2: Cross-section Type A ~ E

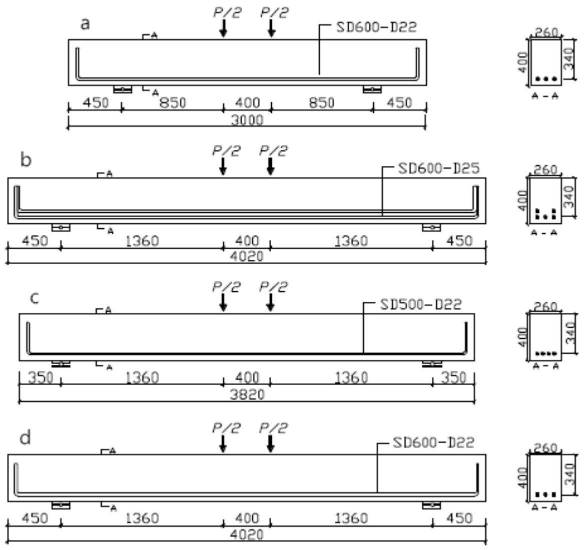

Fig. 3: Specimen and Test setup

The shear tests on 20 simply-supported beams were conducted to verify the shear resistance of composite beams using dual concretes with different compressive strengths. In the current design code (ACI 318-11 [1]), vertical shear strength of Reinforced Concrete beams is defined as below.

$$V_{c1} = 1/6\sqrt{f_{ck}}b_w d \quad \text{or} \tag{1}$$

$$V_{c2} = (0.16\sqrt{f_{ck}} + 17.6\rho_w V_u d/M_u)b_w d \tag{2}$$

where $V_{c2} \le 0.29\sqrt{f_{ck}}b_w d$ and $V_u d/M_u \le 1.0$.

The area ratio of high-strength to low-strength concrete, the flexural reinforcement ratio, and the shear span-to-depth ratio were considered as the main test parameters. As the first main test parameter, the area ratio of high-strength to low-strength concrete was classified into five types.(See Fig. 2) In the A and B-type sections, low-strength concrete(24MPa) and high-strength concrete(60MPa) was used for entire area, respectively. These specimens used for the control specimens to compare the shear strengths of the other composite sections of C, D and E-types. The C and D type section had low strength concrete (24MPa) in the upper 3/8 and 5/8 area, respectively, while high strength concrete (60MPa) was used for the lower part. In the E-type section, high strength concrete (60MPa) in the upper 3/8 area and low strength concrete (24MPa) was used for the lower area. The E-type section was tested to investigate the shear strength in the negative moment zone of continuous beams.

The second test parameter was shear span-to-depth ratio (*a/d*). In this test, shear span-to-depth ratio was planned to be 2.5 or 4.0 to investigate the effect of shear span-to-depth ratio on vertical shear strength of composite sections.(See Fig. 3) The flexural reinforcement ratio (ρ) was planned as the third test parameter. Fig. 3 shows the re-bar arrangement type a ~ d. Type 'a' has *a*/*d* = 2.5 and ρ = 1.31%. Types b ~ d have *a*/*d* = 4.0 and ρ = 2.87, 1.75, and 1.31 %, respectively.

2.2. Test specimens and setup

All the cross sections of specimens were 260 mm x 400 mm. The net length between the loading points was 2,100mm and 3,120mm when shear span to depth ratio was 2.5 and 4.0, respectively.(see Fig. 3) To secure the development length, specimens were extended over the loading point by the length 350mm or 450mm. In the case of specimen with the flexural reinforcement ratio, ρ = 2.87 %, 1.75 % and 1.31%, 5D25 bars were placed in two layers, 4D22 bars were placed in one layer, and 3D22 bars were placed in one layer at the bottom of the cross sections, respectively.

Two-point loading shear tests were conducted by using the UTM at the middle span and the beam specimens were supported by hinges at both ends.(See Fig. 3) The deflections of the beam specimens were measured by LVDTs in the middle span. Strain gages were attached to flexural re-bars to investigate that the yielding of flexural re-bars occurred before shear failure.

3. Test Results

3.1. Maximum shear strength and failure mechanism

The test results of specimens 1~5 which have 2.5 shear span-to-depth ratio and 1.31 % flexural reinforcement ratio are shown in Fig. 4 (a) and Table 1. After the diagonal shear crack occurred, specimens could resist more shear force without brittle failure. Finally the specimens failed when the diagonal shear cracks reached loading point from support hinges. The maximum shear strength of these specimens was defined when the diagonal shear crack started and it is marked as a round dot as shown in Fig. 4 (a). In case of specimens 2 and 5 where 60MPa concrete was used for the compression zone, the load-carrying capacity increased by 57% and 86% even after the initial diagonal cracking. On the other hand, in specimens 1, 3, and 4 where 24MPa concrete was used for the compression zone, the load increase after the initial diagonal cracking were only 15%, 10%, and 7%, respectively.

The test results of specimens 6~10 which have 4.0 shear span-to-depth ratio and 2.87 % flexural reinforcement ratio are shown in Fig. 4 (b) and Table 1. Unlike the test results of specimen 1~5, these specimens showed brittle failure with initial diagonal shear cracks at the maximum drift. The shear strengths of specimens 6~10 showed a similar tendency to those of specimens 1~5.

The test results of specimens 11~15 which have 4.0 shear span-to-depth ratio and 1.75 % flexural reinforcement ratio are shown in Fig. 4 (c) and Table 1. Similarly with the test results of specimen 6~10, these specimens showed brittle failure with initial diagonal shear cracks at the maximum drift. The test results of specimens 11~15 about the maximum shear strength showed a different tendency from those of previous specimens 1~10. According to the test results, the maximum shear strength was determined regardless of the area ratio of high-strength concrete, which is not consistent with general expectation. The maximum shear strength of the specimen 11 and 12 composed by 24Mpa and 60MPa is 185kN and 202kN, respectively. The specimen 11 and 12 did not show the distinct difference of the maximum shear strength in spite of the large difference of concrete compressive strength. The specimen 13 composed by 24MPa in the upper 3/8 and 60MPa in the lower 5/8 cross section showed the largest maximum shear strength. The maximum shear strength of the specimen 12 with only 60MPa is about 25% less than that of the specimen 13. This test result of specimens 11~15 are different from general expectation.

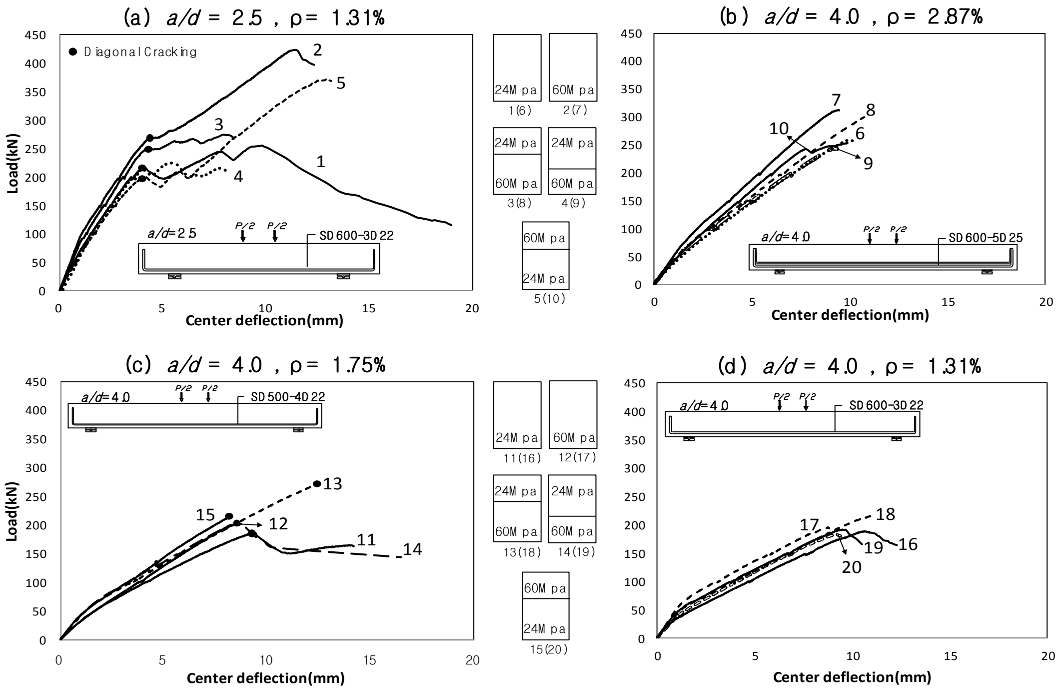

Fig. 4: Load - Center deflection relationship

The test results of specimens 16~20 which have 4.0 shear span-to-depth ratio and 1.31 % flexural reinforcement ratio are shown in Fig. 4 (d) and Table 1. Similar to specimens 6~15, these specimens showed brittle failure with initial diagonal shear cracks at the maximum drift. The maximum shear strength of these specimens, V_{test} was 183~215kN. It means that these specimens did not show large difference of the maximum shear strength in spite of the large difference of concrete compressive strength. Similar to the test result of specimens 11~15, the maximum shear strength of specimens 16~20 was determined regardless of the area ratio of high-strength concrete. The maximum shear strength of the specimen 16 and 17 composed by only 24MPa and 60MPa is 188kN and 195kN, respectively. The specimen 16 and 17 did not show the large difference of the maximum shear strength in spite of the large difference of concrete compressive strength. The specimen 18 composed by 24MPa in the upper 3/8 and 60MPa in the lower 5/8 cross section showed the largest maximum shear strength. The maximum shear strength of the specimen 17 with only 60MPa is about 10% less than that of the specimen 18. As mentioned above, this test result of specimen 16~20 are different from general expectation.

The failure mechanism was slightly dissimilar depending on the flexural reinforcement ratio. In the case of the specimens 11~20 with the ρ = 1.75 % and 1.31%, failure patterns were different according to concrete compressive strength in the web. When 24MPa concrete was used in the web (A-and D-type specimen), the expansion of diagonal crack occurred gradually. In the contrast, when 60MPa concrete was used in the web (B-and C-type specimen), the expansion of diagonal crack and final failure came out abruptly and simultaneously. In the case of the specimens 6~10 with the ρ = 2.87%, the expansion of diagonal crack and final failure occurred abruptly and simultaneously. Especially, horizontal shear crack as well as diagonal shear crack took place complexly in the specimen 9 and 10. Accordingly, when the shear span-to-depth ratio is large (*a/d*=4), the shear failure was resulted by the diagonal crack and the failure pattern was influenced by flexural reinforcement ratio.

Table 1: Test results of specimens 1~20

Specimen	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$f_{ck,24}$ (MPa)	27	-	27	27	27	25	-	25	25	25	21	-	22	23	23	25	-	25	25	25
$f_{ck,60}$ (MPa)	-	55	55	55	58	-	53	53	53	55	-	63	59	53	52	-	55	55	55	55
V_{test} (kN)	217	269	251	214	199	259	313	300	245	254	185	202	270	203	214	188	195	215	191	183
V_{c1} (Eq.1,kN)	152	219	197	180	182	147	215	192	176	177	134	234	198	172	170	146	218	194	177	177
V_{c2} (Eq.2,kN)	187	251	230	214	216	205	270	248	232	234	168	164	229	204	203	170	239	216	199	199
V_{test}/V_{c1}	1.4	1.2	1.3	1.2	1.1	1.8	1.5	1.6	1.4	1.4	1.4	0.9	1.4	1.2	1.3	1.3	0.9	1.1	1.1	1.0
V_{test}/V_{c2}	1.2	1.1	1.1	1.0	0.9	1.3	1.2	1.2	1.1	1.1	1.1	0.8	1.2	1	1.1	1.1	0.8	1.0	1.0	0.9

3.2. Effect of test parameter

The shear strength variation according to test parameter was shown in Fig. 5. First parameter is the effect of the area ratio of high-strength to low-strength concrete. In the case of specimens with low shear span-to-depth ratio(*a/d*=2.5) or high flexural reinforcement ratio(ρ = 2.87%), the maximum shear strength increased as the area ratio of high-strength concrete increased(See the line ① or ② in Fig. 5): B > C > A ≈ D ≈ E, which is consistent with general expectation. However, in the case of specimens with large shear span-to-depth ratio (*a/d*=4.0) and low flexural reinforcement ratio($\rho \leq$1.75%) (See line ③ or ④ in Fig. 5 and Table 1), the test results of section B were overestimated by the current codes. According to the research by Ashraf [6], the current design code overestimates vertical shear strength of RC beams whose flexural reinforcement ratio is 1.2%, shear span- to-depth ratio is 4.0 and concrete strength is larger than 35MPa.

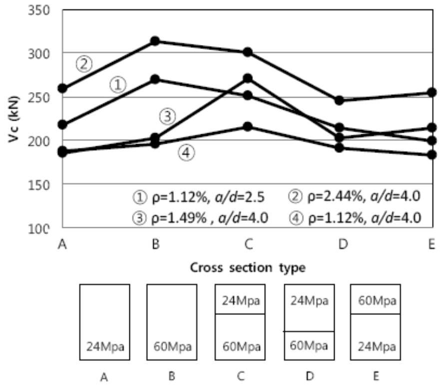

Fig. 5: Effect of test parameter

The line ④(ρ = 1.31 %, *a/d*=4), ③(ρ = 1.75 %, *a/d*=4) and ②(ρ = 2.81 % *a/d*=4,) were compared to analyze the effect of flexural reinforcement ratio on shear strength. As shown in line ④, ③ and ②, the vertical shear strength corresponding to each type specimen increased as flexural reinforcement ratio increased. The line ① (*a/d*=2.5, ρ = 1.31 %) and ④(*a/d*=4, ρ = 1.31 %) were compared to analyze the effect of shear span-to-depth ratio on shear strength. As shown in line ① and ④, the vertical shear strength corresponding to each type specimen increased as shear span-to-depth ratio decreased.

4. Conclusion

In the present study, through simple beam tests, the vertical shear strength of composite beams using dual concrete compressive strengths(24MPa, 60MPa) was tested. The area ratio of high-strength and low-strength concrete, the flexural reinforcement ratio and shear span-to-depth ratio were considered as the main test parameters. The major findings of the present study are as follows.

1) In the case of specimens whose flexural reinforcement ratio is high(ρ = 2.87%) or shear span-to-depth ratio is small(*a/d*=2.5), vertical shear strength increased as the area ratio of high-strength concrete increased: B (all section: 60MPa) > C (upper 3/8 section: 24MPa, lower 5/8 section : 60MPa) > A (all section: 24MPa) ≈ D (upper 5/8 section: 24MPa, lower 3/8 section: 60MPa) ≈ E (upper 3/8 section : 60MPa, lower 5/8 section : 24MPa). However, in the case of specimens whose flexural reinforcement ratio is low($\rho \leqslant$ 1.75%) and shear span-to depth ratio is large(*a/d*=4), there is small difference of the maximum shear strength between the A-type specimen with only 24MPa and the B-type specimen with only 60MPa. The C-type specimen(upper 3/8 section: 24MPa, lower 5/8 section: 60MPa) showed the largest vertical shear strength unlike general expectation.

2) In the early state of the test, flexural tensile cracks came out at the center and proceeded up to neutral axis and then diagonal shear cracks took place in the web. Finally, the diagonal shear cracks expanded from the supporting hinge to the loading point. In the case of specimens whose shear span-to-depth ratio is 4.0, the expansion of diagonal crack and final failure occurred abruptly and simultaneously. However, specimens whose shear span-to-depth ratio is 2.5 showed the increase of vertical shear strength after initial diagonal crack. In the case of the specimens whose shear span-to-depth ratio is 2.5, an initial diagonal crack was mainly affected by concrete strength in the web but final failure was mainly controlled by concrete strength in the compression zone.

3) The vertical shear strength of composite beams increased as the flexural reinforcement ratio increased and shear span-to-depth ratio decreased.

5. Acknowledgements

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