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Shear Strength of Prestressed Precast Concrete and Cast-in-Place Concrete Composite Beams

[Chul-Goo Kim, Hong-Gun Park, Su-Min Kang, Geon-Ho Hong]

***Abstract*—Composite construction of prestressed precast concrete and cast-in-place concrete having different concrete strengths are frequently adapted in the modular construction. However, current ACI318-11 design codes do not clearly define shear design methods for such composite beams. In this present study, simply supported prestressed composite beams without vertical shear reinforcement or only with horizontal shear reinforcement were tested to evaluate the effect of prestressed concrete on shear strength and shear design method for such composite members. The test variables were the area ratio of two concretes, prestress force, shear span-to-depth ratio, and shear reinforcement ratio. The results showed that shear strength was increased by increase of the prestress force and the prestressed concrete area, and decrease of shear span-to-depth ratio.**

Keywords—Shear Strength, Prestressed Concrete, Precast concrete, Composite Beam

I. Introduction

In precast concrete construction, precast concrete (PC) members such as columns, beams, and slabs are integrated with cast-in-place concrete (CIP) to enhance integrity of structure members and reduce construction period. Generally, PC beams and slabs are pre-tensioned to decrease member size and increase flexural cracking strength and shear strength.

In composite members, different concrete strengths are used. The concrete strength of PC members prestressed by high compressive force is over 35MPa and that of CIP is 24MPa. According to ACI 318-11$^{1)}$, for the design of this composite member, if the specified strength, unit weight, or other properties of the various elements are different, properties of the individual elements or the most critical values can be used. However, it is not clear that the sum of the shear strengths of individual elements can assure safety of composite members because prestressed and nonprestressed members are placed together in one section.

The majority of previous studies$^{2)\sim5)}$ with respect to composite members mainly focused on horizontal shear strength in the interface of PC and CIP. This is because shear slip of two concretes is significant factor in terms of integrity of composite members. On the other hand, the studies about vertical shear strength of composite members are insufficient. Kim et al.$^{6),7)}$ studied vertical shear strength of nonprestressed PC and CIP composite members. In these studies, the sum of individual elements and effective concrete strength calculating with area ratio of two concretes can predict composite members conservatively except several specimens having high strength concrete (60MPa) in compression zones.

In this study, composite members(prestressed PC and nonprestressed CIP) are tested to evaluate the effect of prestressed concrete on the vertical shear strength. Design considerations for prestressed PC and CIP composite members are provided.

II. Test Program

A. *ACI318 design code*

In ACI318-11$^{1)}$, the vertical shear strength of prestressed concrete beams is defined as follows,

$$V_{c1} = \left(0.05\sqrt{f_{ck}} + 4.9\frac{V_u d_p}{M_u} \right) b_w d \qquad (1)$$

$$V_{c2} = \min(V_{ci}, V_{cw}) \qquad (2)$$

$$V_{ci} = 0.05\sqrt{f_{ck}}\, b_w d_p + V_d + \frac{V_i M_{cre}}{M_{\max}} \qquad (3)$$

$$M_{cre} = \left(\frac{I}{y_t} \right)(0.5\sqrt{f_{ck}} + f_{pcc} - f_d) \qquad (4)$$

$$V_{cw} = (0.29\sqrt{f_{ck}} + 0.3 f_{pc}) b_w d_p + V_p \qquad (5)$$

Equation (1) and (2) are simple and detailed equations, respectively. The detailed equation is composed of flexure-shear cracking and web-shear cracking strength and calculated by the lesser of V_{ci} and V_{cw} (See Fig. 1). The terms V_u and M_u represent factored shear force and moment. V_d is shear force at section due to unfactored dead load. V_i is factored shear force at section due to externally applied loads occurring simultaneously with $M_{\max}$. M_{cre} is moment causing flexural

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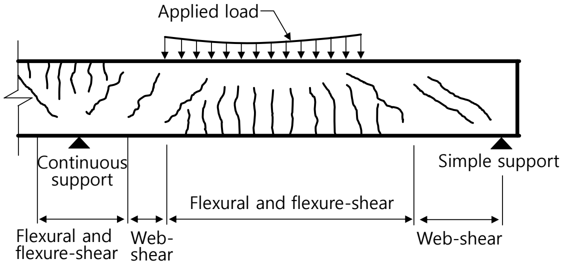

Figure 1. Types of cracking in prestressed concrete beams

cracking at section due to externally applied loads. $M_{\max}$ is maximum factored moment at section due to externally applied loads. f_{pcc} is compressive stress in tension zone. f_{pc} is compressive stress in concrete at centroid of cross section resisting externally applied loads. V_p is vertical component of effective prestress force at section.

B. *Test parameters*

Sixteen simply supported beams were tested to investigate shear strength of prestressed PC and CIP composite members. The area ratio of PC and CIP, prestressing force, shear span to depth ratio, and shear reinforcement ratio were used for main test parameters. As the first main test parameter, the area ratio of PC (60MPa) and CIP(24MPa) was classified into four types (See Fig. 2). In A and B monolithic sections, 24MPa and 60MPa concretes were used for the entire area, respectively. These specimens were used for the control specimens to compare C and D composite sections.

The second test parameter was prestress force. Prestress(pre-tension) is only used in PC members(60MPa), so CIP members(24MPa) were not affected by prestress. To investigate the effect of prestress force on shear strength, two different jacking forces were applied at six strands ($f_j = 0.55 f_{pu}, 0.7 f_{pu}$). The third test parameter was shear span-to-depth ratio(*a/d*=3.0, 4.0). The shear reinforcement ratio was planned as the fourth test parameter. Minimum shear reinforcement for resisting horizontal shear was used to minimize horizontal shear cracking.

C. *Test specimens and setup*

All the cross sections of specimens were 260mm x 400mm. The net lengths between the loading points were 975mm and 1,300mm for *a/d*=3.0 and 4.0, respectively. The six prestressing strands were arranged with two layers in the lower section.

Two-point loading shear tests were conducted at the middle span and the beam specimens were supported by hinges at both ends.(See Fig. 2) The deflections of the beam specimens were measured by LVDTs in the middle span. Strain gauges were attached to flexural re-bars to investigate that the yielding of flexural re-bars occurred before shear failure.

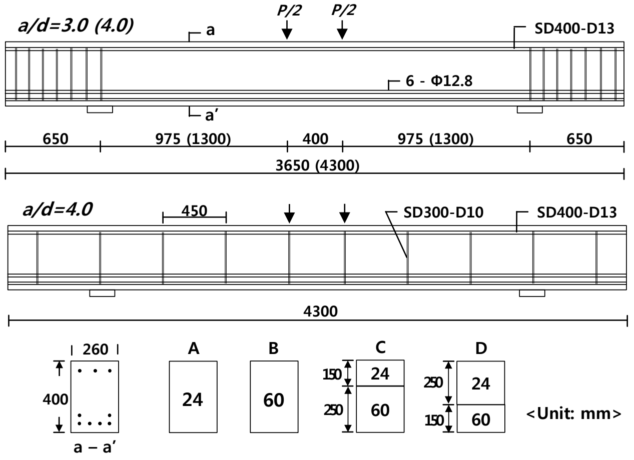

Figure 2. Specimens and test setup

D. *Material*

Table 1 presents the mix design for 24MPa and 60MPa concretes. Concrete cylinders were tested on the day of beam tests. The actual compressive strengths of 24MPa and 60MPa concretes were 23~27MPa and 52~57MPa. Table 2 presents the actual yield strengths of the strand and flexural bars. The yield strengths were f_y =1,854MPa for 12.7mm strand, f_y =340MPa for D10 bars, and f_y =480MPa for D13 bars. The yield strength of the strand was estimated by the 0.2% offset method. (See Fig. 3)

Table 1. Mixture proportions of concrete

Nominal strength	W/C	Unit weight (kg/m^3)				
		W	*C*	*S*	*G*	*SP*
24	49.4	162	328	869	979	3.5
60	29	180	620	625	935	8.06

Table 2. Mechanical properties of reinforcement

Type	f_y (MPa)	ε_y ($\mu\varepsilon$)	E_s (MPa)
12.7mm SWPC 7BL	1,854	8,829	210
SD300 D10	340	1,847	184
SD400 D13	480	2,400	200

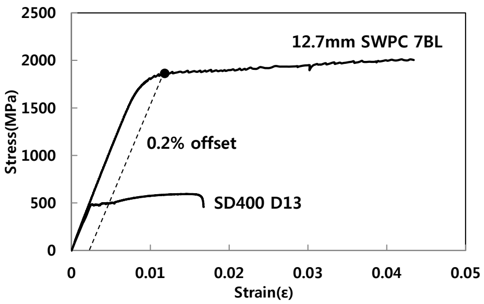

Figure 3. Stress-strain relationship of strand and re-bar

III. Test results

The test results are shown in Fig. 4, Fig.5, and Table 3. Simple and detailed equations (Eq. (1) and (2)) for prestressed members are used to predict PC members (60MPa) and Eq. (6) and (7) for nonprestressed members are used to predict CIP members (24MPa).

$$V_{c1} = 0.167\sqrt{f_{ck}}\,b_w d \qquad (6)$$

$$V_{c2} = (0.16\sqrt{f_{ck}} + 17\rho\frac{V_u d}{M_u})b_w d \qquad (7)$$

A. *Specimens 1-A ~ 1-D*

The shear strength of 1-A ~ 1-D having *a/d*=3.0 and $f_j = 0.55 f_{pu}$ is proportional to the are ratio of prestressed sections (1-B (544kN) > 1-C (392kN) > 1-D (358kN) > 1-A (200kN)). Flexural cracking strength of 1-B~1-D which are prestressed in tension zone is five times higher than nonprestressed 1-A. The flexural cracking strength affects shear strength because prestressed members having higher flexural stiffness show higher shear strength.

Diagonal tension failure occurred in all the specimens. The 1-D composite member shows horizontal shear cracking at the interface of PC and CIP. Crack patterns of diagonal shear are different from typical reinforced concrete(RC) beams. RC beams were failed with diagonal shear cracks at the middle of shear span and bond slip of flexural reinforcement. However, in prestressed members, diagonal shear cracks occurred near the loading points without bond slip of flexural reinforcement.

B. *Specimens 2-A ~ 2-D*

The shear strength of 2-A ~ 2-D having *a/d*=3.0 and $f_j = 0.70 f_{pu}$ is also proportional to the are ratio of prestressed sections (2-B (632kN) > 2-C (456kN) > 2-D (358kN) > 2-A (154kN)). The strengths of flexural cracking and diagonal shear cracking are increased as jacking forces are increased from $0.55 f_{pu}$ to $0.70 f_{pu}$.

The failure mode of 2-A ~ 2-D is similar to 1-A ~ 1-D. All the specimens experienced diagonal shear cracking and only 2-D shows horizontal shear cracking at the interface. The shear strength of 2-A is 23% lower than 1-A despite of using same test parameter conditions.

Failure mechanism of specimens having *a/d*=3.0 is different according to web concrete strength. In the section B and C having 60MPa in the web, a flexural crack propagated toward the loading point was transformed to a diagonal shear crack and then shear failure occurred. On the other hand, in the section A and D having 24MPa in the web, a diagonal shear crack developed in the web was propagated to the loading and support points and then specimens failed.

C. *Specimens 3-A ~ 3-D*

The shear strength of 3-A ~ 3-D having *a/d*=4.0 and $f_j = 0.70 f_{pu}$ increases as the prestressed areas increase(3-B (428kN) > 3-C (284kN) > 3-D (278kN) > 3-A (144kN)). The strengths of flexural cracking and diagonal shear cracking are decreased due to higher shear span to depth ratio. The shear strength of 3-B drops 32% than 2-B.

Compared failure mechanism of 3-A and 3-B, final shear failure of prestressed 3-B was delayed by prestress force even severe diagonal shear cracking happened. On the other hand, nonprestressed 3-A failed right after diagonal shear crack occurred in the web. Prestress force applied between diagonal shear cracking surfaces was contributed to increase shear strength. According to increase shear span to depth ratio, specimens are subjected to flexural action so failure modes of composite sections C and D were changed. Diagonal shear cracks initiated in CIP members (24MPa) were propagated to the interface having lower friction resistance, and then diagonal and horizontal shear failure occurred.

D. *Specimens 4-A ~ 4-D*

In specimens 4-A ~ 4-D, minimum shear reinforcements for horizontal shear strength are used to minimize the effect of horizontal shear cracking. The shear strength of 4-A ~ 4-D having *a/d*=4.0, $f_j = 0.70 f_{pu}$, and s=450mm is increased 20~39% rather than 3-A ~ 3-D. Flexural stiffness and flexural cracking strength are same as 3-A ~ 3-D, but shear strength is increased because minimum shear reinforcements simultaneously resist vertical and horizontal shear after diagonal shear cracking.

In Fig. 5, the location of shear reinforcement is indicated with dashed lines. All the specimens experienced diagonal shear cracks with shear compression failure. As horizontal shear crack was constrained by shear reinforcement, composite sections C and D showed different crack patterns from 3-C and 3-D. Diagonal shear crack lines were penetrated to shear reinforcement, so shear strength of all the specimens was increased in spite of same test parameter conditions with 3-A and 3-D.

IV. Experimental analysis

A. *Effects of design parameters*

To investigate effects of prestress force, shear span to depth ratio, and shear reinforcement ratio, parametric studies are conducted to show variations of shear strength of prestressed specimens B~D in Fig. 6. The shear strength increased as prestress force except for D specimens because D specimens failed with horizontal shear cracking at the interface, which are not related to prestress. The increased flexural cracking strength by higher prestress affects shear strength.

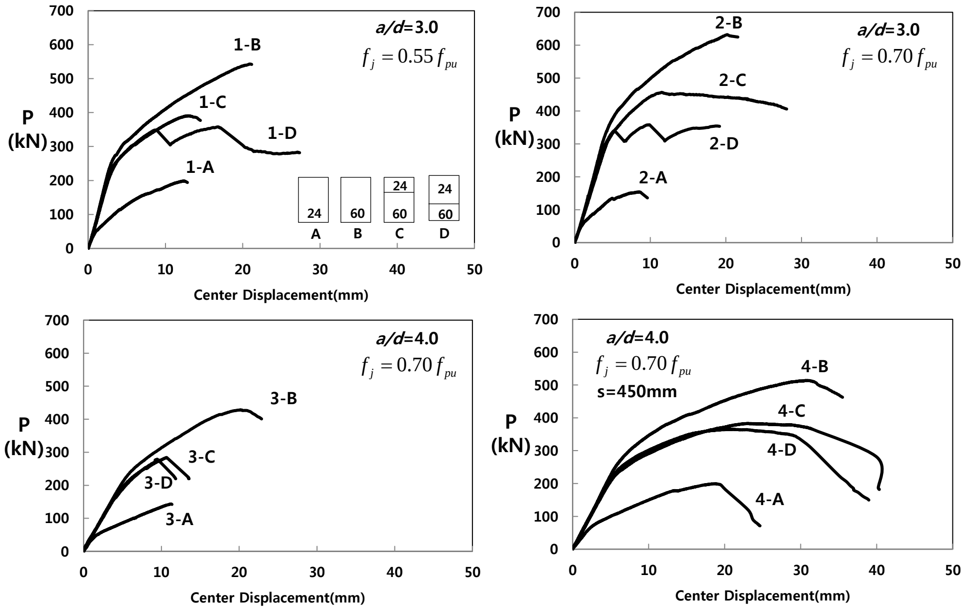

Figure 4. Vertical load – center displacement relationships of 1-A ~ 4-D

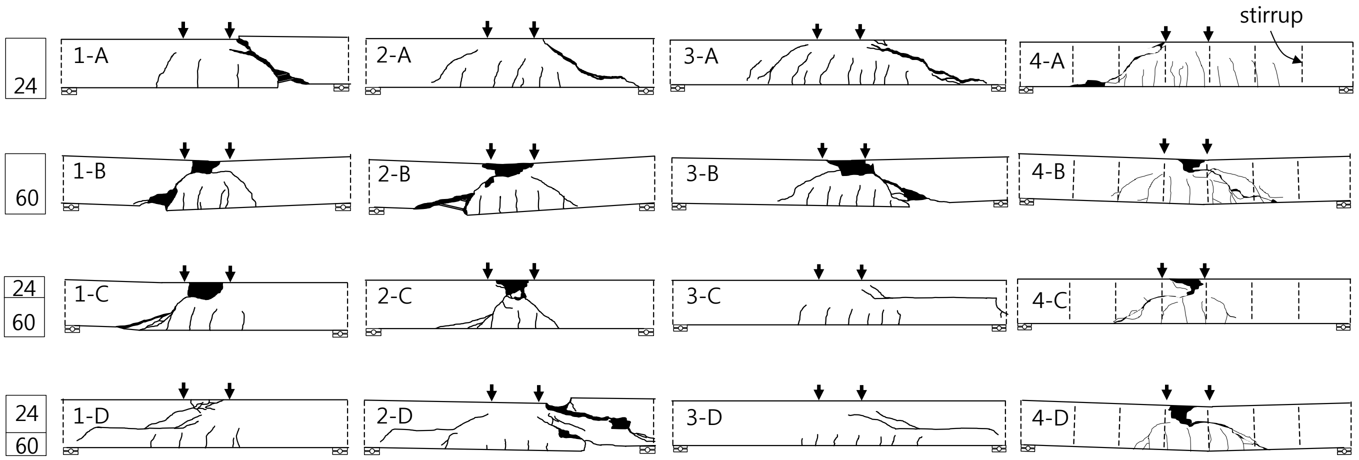

Figure 5. Crack patterns of 1-A ~4-D at the end of tests

Table 3. Test results of 1-A ~ 4-D

Specimen	**1-A**	**1-B**	**1-C**	**1-D**	**2-A**	**2-B**	**2-C**	**2-D**	**3-A**	**3-B**	**3-C**	**3-D**	**4-A**	**4-B**	**4-C**	**4-D**
$f_{ck,24}$ **(MPa)**	23	-	23	23	23	-	23	23	23	-	23	23	27	-	27	27
$f_{ck,60}$ **(MPa)**	-	57	57	57	-	57	57	57	-	57	57	57	-	52	52	52
V_{test} **(kN)**	100	272	196	179	77	316	228	179	72	214	142	139	100	257	191	183
V_{c1} **(kN)**	68	262	172	113	68	262	172	113	68	204	141	99	73	203	143	103
V_{c2} **(kN)**	70	257	269	219	71	315	339	277	69	248	254	219	75	232	245	194
V_{test} / V_{c1}	1.47	1.04	1.14	1.58	1.13	1.21	1.33	1.58	1.06	1.05	1.01	1.40	1.37	1.27	1.34	1.78
V_{test} / V_{c2}	1.43	1.06	0.73	0.82	1.08	1.00	0.67	0.65	1.04	0.86	0.56	0.63	1.33	1.11	0.78	0.94

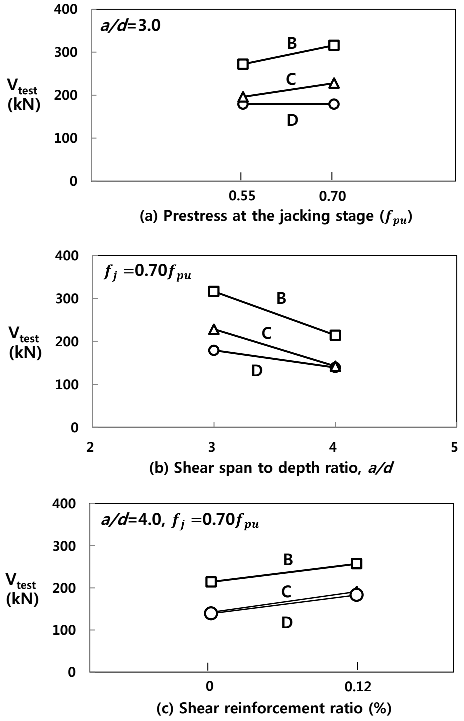

Figure 6. Effects of test parameters

The variation of shear strength according to *a/d* showed that shear strength decreased as *a/d* increased. According to minimum shear reinforcement, the shear strength was increased even though the spacing of stirrup was not satisfied with spacing limits($s \leqq 0.75h$). The shear strength of composite sections C and D was respectively increased 35% and 32% because the horizontal shear crack was constrained by stirrups. Maximum strain of stirrups at the failure was very small. The shear strength of monolithic section B was increased 20% due to stirrups penetrated to diagonal shear crack. Maximum strain of stirrups at the maximum load is 1,143 $\mu\varepsilon$ which does not reach yield strain of stirrups.

B. Contribution of prestress

To investigate the contribution of prestress on shear strength, test results of prestressed composite specimens(PSC) and nonprestressed composite specimens(RC) are compared in Fig. 7. In RC specimens, flexural reinforcing bars exhibiting similar flexural capacity with PSC specimens ($A_{ps} f_{ps} \approx A_s f_y$) were used instead of strands to compare in same conditions. The nonprestressed section (A specimen) was excluded.

Fig. 7 show load - center displacement curves of PSC and RC specimens according to section types. The flexural cracking strength of nonprestressed PSC specimens is 3.3~3.8 times higher than that of prestressed RC specimens. Accordingly, the shear strength of section B, C, and D in PSC is 2.2, 1.3, and 1.5 times higher than that of RC, respectively

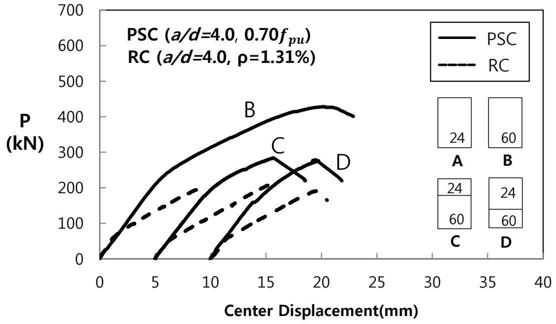

Figure 7. Comparisons between PSC and RC specimens

Sectional prestressed specimens C and D exhibit just 1.3 and 1.5 times higher shear strength, while full prestressed specimen B of PSC shows 2.2 times higher shear strength than RC. This is because specimens C and D were failed by diagonal shear cracking developed in the nonprestressed CIP and horizontal shear cracking at the interface, even though flexural cracking strength was increased due to prestress force.

C. Predictions of composite beams

To predict vertical shear strength of PC and CIP composite beams, measured test results and current design codes are compared. In this study, since composite beams are composed of two different elements, prestressed PC and nonprestressed CIP, the shear strength are individually estimated by (1),(2) for PSC and (6),(7) for RC.

The estimations by summation of two elements are shown in Fig. 8. Solid lines indicate estimation with simple equations ((1) and (6)) and dashed lines indicate prediction with detailed equations ((2) and (7)). The simple equations safely estimated the shear strength of the composite beams. However, the ratio (V_{test} / V_{pred}) of test shear strength to prediction of section D is 1.40~1.78. It means that the area ratio of prestressed sections is not critical factor to increase shear strength. The prestressed area is not proportional to shear strength.

On the other hand, the detailed equations do not safely predict the shear strength of the composite beams. The C and

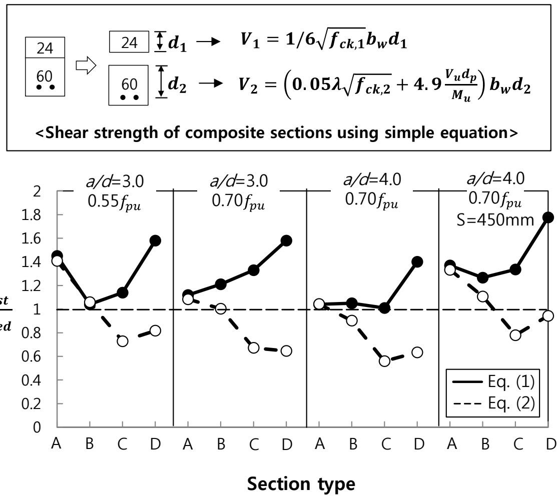

Figure 8. Shear strength predictions of composite sections

D composite sections by summation of individual elements is not accurately estimated, while the B monolithic section is well predicted by detailed equations. It is noted that the sum of shear strength of individual elements by detailed equations cannot assure the safety of the overall structure. Prediction with individual summation by the simple equations is recommended to estimate prestressed PC and CIP composite beams.

V. Summary and conclusion

In this present research, simply supported beams were tested to investigate the shear strength of prestressed PC and CIP composite beams. Test variables are the area ratio of PC and CIP, prestress force, shear span to depth ratio, and shear reinforcement ratio. According to test results, shear behavior and design consideration of composite beams are studied.

1. Sectional prestressed PC and CIP composite beams (C and D) show similar shear behavior to full prestressed PC beams(B). Initial flexural cracking strength and flexural stiffness of prestressed composite beams are increased by prestress force in the tension zone. The shear strength is increased as the prestressed areas and prestress force increase and shear span to depth ratio decreases.
2. Failure mechanism of prestressed composite beams is different depending on the web concrete strength. When web concrete strength is high(60MPa in this test), a diagonal shear crack is transformed from flexural cracks, and then shear failure occurred. On the other hand, when web concrete strength is low(24MPa), a diagonal shear crack is abruptly developed in the web, and then brittle shear failure occurred.
3. The design recommendation of prestressed PC and CIP composite beams is estimating by summation of two individual elements using simple equations of PC and RC. In the contrast, safety of structures cannot be assured when prestressed composite beams are predicted by detailed equations.

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