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Experiments on Shear Connections of PSC Girders with Prefabricated Slabs

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Abstract

For the fast construction and replacement of bridges in urban area, a prefabricated bridge system can be an excellent alternative. Details of prefabricated slabs for PSC girders were developed and static tests on shear connections were conducted to propose design equations of the shear connection. Stirrups and stud connectors were used as shear connectors and non-shrink mortar was used for the filling material in shear pockets for shear connectors. Stirrups and studs were fabricated to insert embedded nut-type devices in PSC girders. Shear strength of the shear connection considering chemical bond, friction and mechanical connectors was evaluated and empirical equations were suggested. Due to the mechanical connectors, ultimate slip capacity of the shear connection was sufficient for shear load redistribution, and suggested details of the shear connection showed good performance in terms of strength and ductility.

Keywords: prefabricated slab, shear connection, shear strength, bond, ductility

1. Introduction

A full-depth precast panel system for PSC girder bridges is very attractive design alternative for the rehabilitation of deteriorated concrete slabs as well as for a newly constructed bridge, which is shown in Fig. 1. A new shear connection detail for the efficient application of precast decks to PSC girders is suggested as presented in Fig. 2. The horizontal shear strength at the interface between the two interconnected elements is of primary importance in order to achieve sufficient composite action. Generally, shear stirrups are used for shear connectors in PSC girder bridges having CIP concrete slabs. In this system, stirrups and studs can be used for the shear connectors, and a detail for easy installation of precast decks is proposed.

Several researchers did experiments on the shear connection between CIP slabs and PSC girders. Mattock[1)], Loov[2)], Walraven[3)], Patnaik[4)] suggested empirical equations for the evaluation of the shear connection. A summary of the previous research is shown in Table 1. Fig. 3 shows the test results of the previous research and it can be said that there was large variation in shear strength of the shear connection in PSC beam bridges. The line shown in Fig. 3 are based on a coefficient of friction μ of 1.0 and a concrete strength of at least 27.5 MPa by the ACI code for a rough surface[2)]. The term $\rho_v f_y$ is referred to as the clamping stress. Recently, Menkulasi[5)] did experiments on the shear connection for precast decks and suggested empirical equations. A typical equation for the horizontal shear strength is as Equation (1)[6)].

$$V_n = cA_{cv} + \mu(A_{vf} f_y + P_c) \quad (1)$$

where, c =cohesion factor, A_{cv} =area of concrete engaged in shear transfer, μ =friction factor, A_{vf} =area of shear reinforcement crossing the shear plane, f_y =yield strength of reinforcement, and P_c =permanent net compressive force normal to the shear plane.

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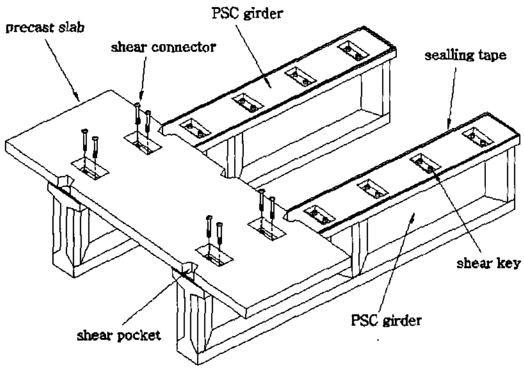


Fig. 1 Precast deck system for PSC girder bridges

2. Experiments

2.1 Test specimen

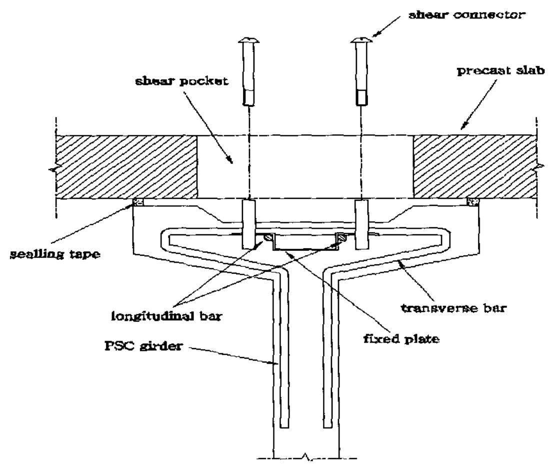
Push-off specimens having parameters of connector type, surface condition, normal force, and bedding thickness were fabricated and static tests were performed to evaluate the horizontal shear strength of the shear connection. Fig. 4 shows the detail of the test specimen and Table 2 summarizes the test specimens.

In earlier research, the shear strength of the connection was assumed to vary directly with the amount of reinforcing steel crossing it. Many shear-friction equations have been proposed by various researchers.

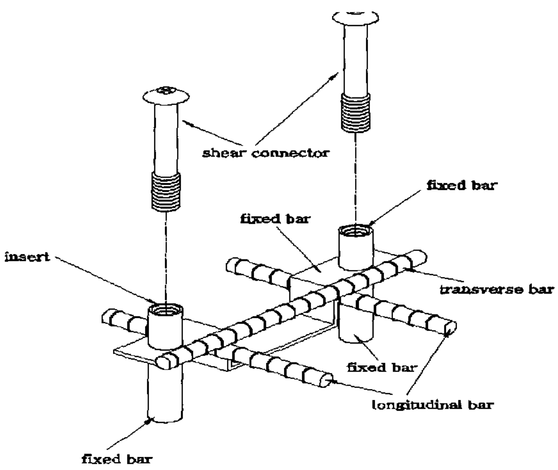
Stirrups and studs were used for shear connectors. In table 2, ST and SD indicate stirrup and stud, respectively. As denoted, C, S, R mean the surface conditions of the interface are smooth, shear key, and rough. Shear key has 200mmx200mm surface and 10mm depth. Bedding layer is essential for precast decks and has effects on the shear strength. The interface of the push-off specimen is 560mm x 660mm. The normal stress is categorized into three steps, minimum, average, and maximum. In Table 2, B, M, U indicate minimum, average, and maximum normal stress. In the case of B-series specimens, there is no additional normal force except for the self-weight of the specimen.

For M-series and U-series specimen, normal forces represent dead load before and after shear connection, respectively. Average normal force considers the dead load of the concrete slab and maximum normal force means additional dead loads including pavement, barriers. In terms of bedding height, practical situations for PSC girders were considered for the determination of test variables.

Mean values of compressive strength of concrete and mortar were obtained from cylinder tests as summarized in Table 3. Yield strength of stirrup and stud is 412MPa and 441MPa, respectively.



(a) Shear connection



(b) Connector detail

Fig. 2 Shear connection details

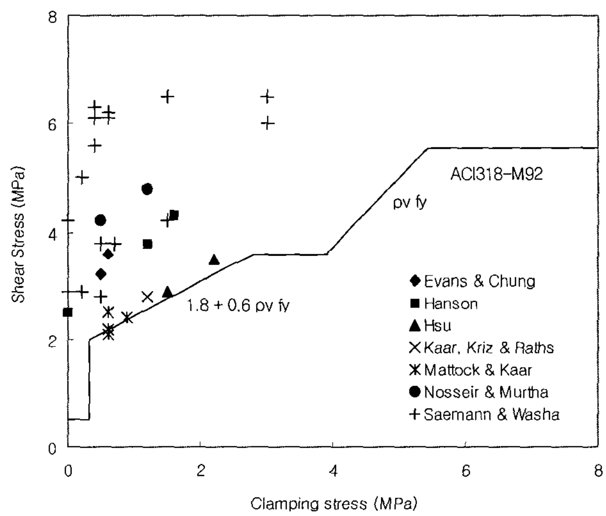


Fig. 3 Shear stress according to clamping stress from previous tests

2.2 Loading and measurements

In order to evaluate horizontal shear strength of the shear connection, push-off tests were done using the test setup in Fig. 5. Load was introduced by displacement control with 1mm/150sec. speed. During the tests, relative displacements at the interface were measured at both sides of the specimen.

3. Results

3.1 Bond strength of the interface

The critical interface for the determination of bond strength is not clear because of the bedding layer.

According to the relative strength of the shear connectors, load-slip curves can be categorized into two types, as

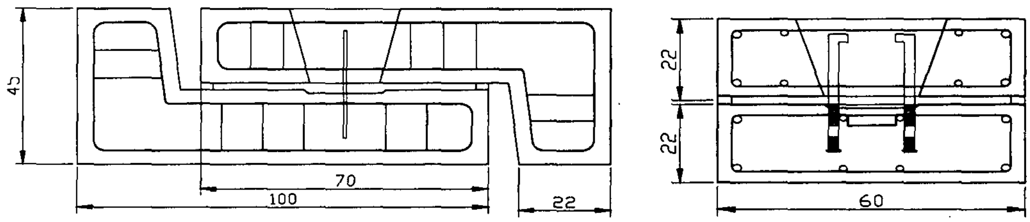
Table 1 Previous research on horizontal shear strength

Researcher	Empirical equations	Characteristics
Mast (1958)[7]	$v_n = \rho f_y \mu$	Linear shear firction
Birkeland (1966)[8]	$v_n = 2.78\sqrt{\rho_v f_y}$	Parabolic function
Hsu (1976)[9]	$v_n = 0.66\sqrt{\rho_v f_y f_c}$	Initially cracked and uncracked
Mattock (1976)[1]	$v_n = 0.467 f_c'^{0.545} + 0.8(\rho_v f_y + \sigma_n)$	Reinforcement
Shaikh (1978)[10]	$v_u = \lambda\sqrt{6.9\phi\rho_v f_y}$	Effect of concrete density
Walraven (1987)[3]	$v_n = C_1(\rho_v f_y)^{C_1}$	Precracked shear interface
Loov&Patnaik (1994)[11]	$v_{n0} = 0.6\sqrt{0.1 f_c'}$ $v_n = k\sqrt{\rho_v f_y f_c'}$ $v_n = k\sqrt{(0.1+\rho_v f_y) f_c'}$	Without stirrup concrete strength smooth interface & rough interface

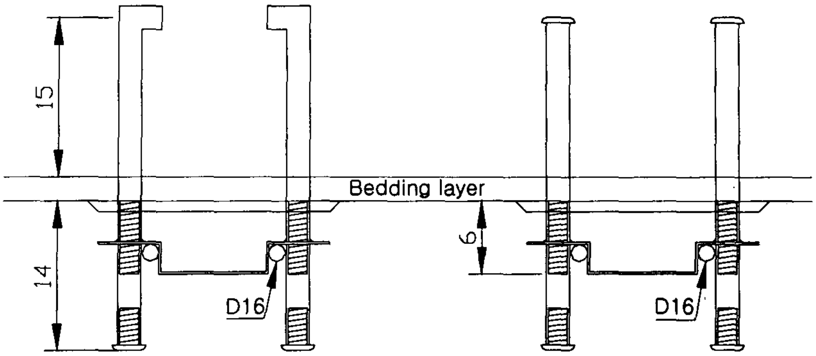
v_n : shear strength, ρ_v : ratio of the area of steel to the area of concrete, f_y : yield stress of the shear reinforcement f_c : compressive strength of concrete, μ : coefficient of friction, σ_n : direct stress acting across the shear plane

Table 2 Details of test specimens

Specimen	Shear connector	Diameter	# of Shear connectors	Interface	Vertical load	Bedding thickness	Quantity
N0-0CM				Smooth	Average	10mm	2
N0-0SM				Shear key			4
N0-0RM				Rough			2
ST13-1SM	Stirrup	13mm	1 pair	Shear key	Average	10mm	2
ST13-2SM			2 pair				2
ST16-1CM		16 mm	1 pair	Smooth			1
ST16-1SU				Shear key	Max.		1
ST16-1SM					Average		4
ST16-1SB					Min.		2
ST16-1RM				Rough	Average		1
ST16-2SM			2 pair	Shear key			2
ST19-1SM		19 mm	1 pair				2
SD16-2CM	Stud	16 mm	1 pair	Smooth	Average	10mm	2
SD16-2SU				Shear key	Max.		2
SD16-2SM1					Average		2
SD16-2SM2						20mm	2
SD16-2SM3						30mm	2
SD16-2SB					Min.	10mm	2
SD16-2RM				Rough	Average		1
SD16-4SM			2 pair	Shear key			2
SD19-2SM		19 mm	1 pair				2
SD22-2SM		22 mm					1
Total							43



(a) Details



(b) Stirrup (c) Stud

Fig. 4 Push-off test specimen

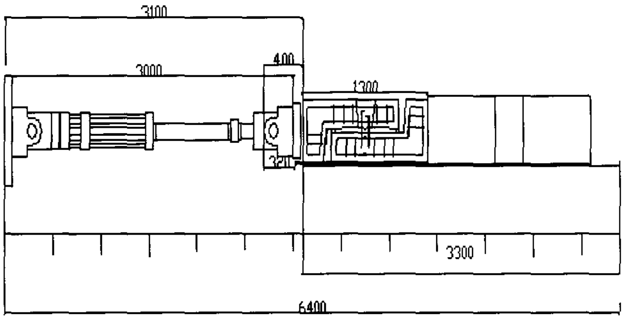


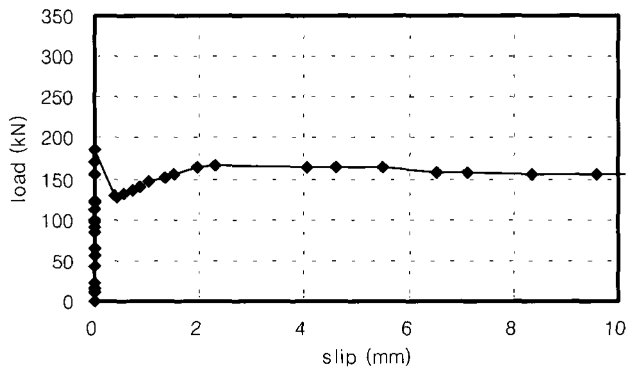
Fig. 5 Test setup

Table 3 Compressive strength of concrete & mortar

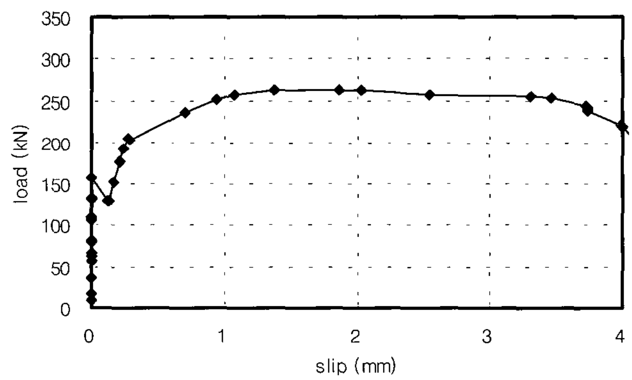
	Stirrup specimen	Stud specimen	Standard curing(28days)
Concrete	31.2 MPa	21.8 MPa	30.1 Mpa
Mortar	55.4 MPa	53.6 MPa	61.8 Mpa

shown in Fig. 6. Bond strength can be obtained from the tests easily because the slip means the bonding failure.

Table 4 summarizes the test results in terms of strength and slip capacity. Even though test results showed relatively high variation of the strength, three parameters showed main effects on the bond strength. Interface conditions affected the bond strength considerably. The specimen with shear key showed the highest bond strength.

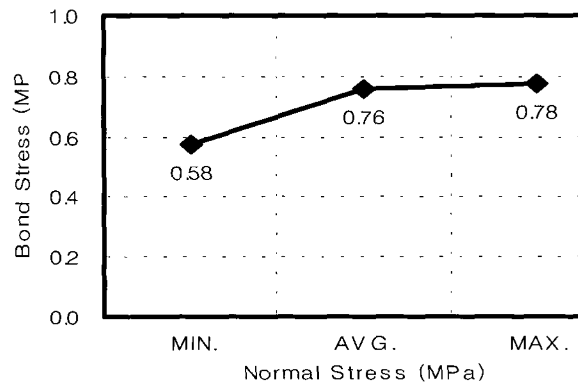


(a) Bond strength dominant

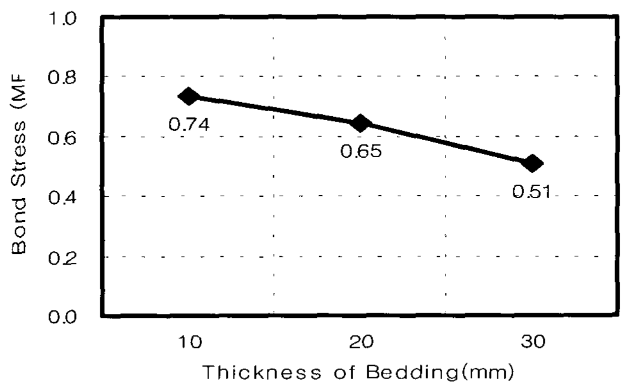


(b) Connector strength dominant

Fig. 6 Load-slip curves



(a) Effect of normal stress



(b) Effect of bedding thickness

Fig. 7 Bond strength of the interface

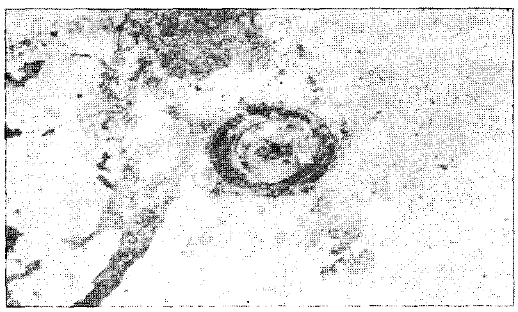


Fig. 8 Failure of the shear connection

Table 4 Test results

Specimen	Bond failure (MPa)	Yield failure (kN)	Ultimate slip (mm)
N0-0CM	0.54	*	0
N0-0SM	0.69	*	0
N0-0RM	0.61	*	0
ST13-1SM	0.52	195	6.2
ST13-2SM	0.59	263	5.8
ST16-1CM	0.55	128	9.5
ST16-1SU	0.78	263	10.0
ST16-1SM	0.85	288	10.0
ST16-1SB	0.68	192	10.0
ST16-1RM	0.65	211	7.9
ST16-2SM	0.63	338	9.9
ST19-1SM	0.46	352	8.0
SD16-2CM	0.55	215	6.5
SD16-2SU	0.75	314	10.0
SD16-2SM1	0.74	350	8.4
SD16-2SM2	0.65	303	10.0
SD16-2SM3	0.51	262	10.0
SD16-2SB	0.58	198	8.1
SD16-2RM	0.66	292	7.8
SD16-4SM	0.69	387	10.0
SD19-2SM	0.73	314	8.2
SD22-2SM	0.32	303	10.0

Whereas the bond strength increases as the normal stress increases, the bond stress decreases as the bedding thickness increases. The other parameters showed negligible effects. From the test results, the following empirical equation for the mean bond strength of the interface was proposed[12].

$$f_{bond} = -0.11 t_b + A \tag{2}$$

where, f_{bond} =bond strengh of the interface (MPa), t_b = bedding thickness (mm), and A is the constant for interface conditions, 0.67 for smooth, 0.75 for rough, and 0.82 for shear key interface.

3.2 Shear strength of the connectors

For the evaluation of the horizontal shear strength of the shear connection, it is necessary to estimate the shear strength of the connectors. As can be seen in Equation (1), three main parameters can be included in the shear strength, which are yield strength of the connector, normal force, and surface conditions. Judging from the previous research re-

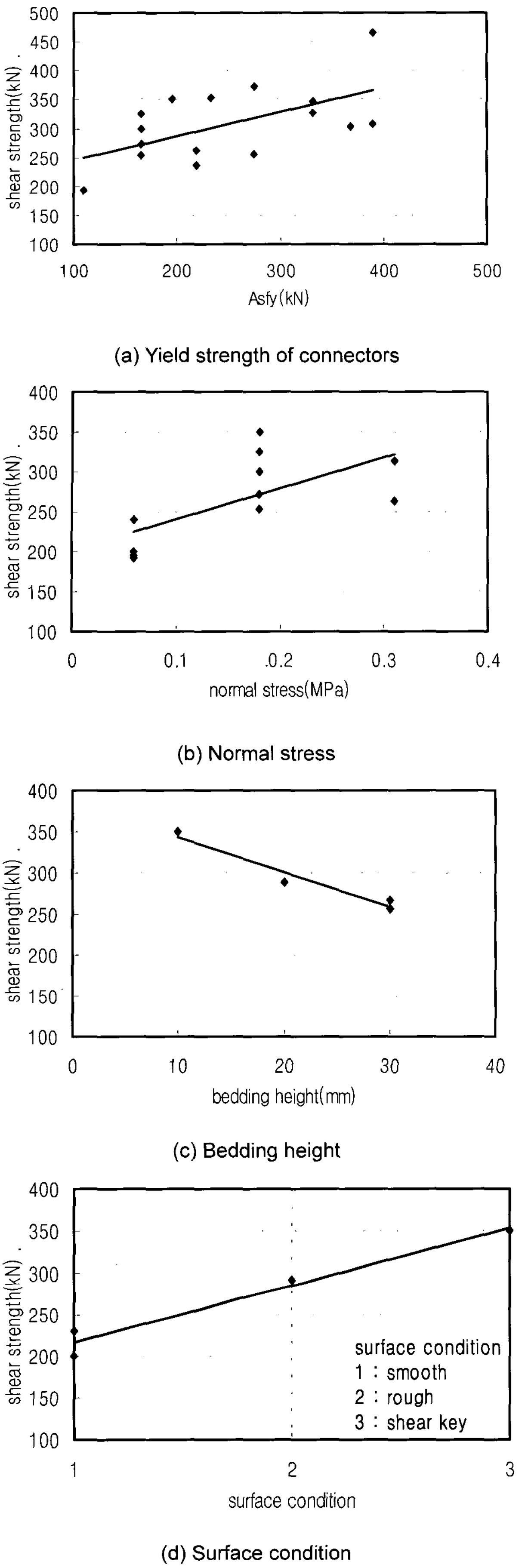


Fig. 9 Shear strength of the connectors

sults[13], the bedding thickness can affect on the shear strength considerably. Fig. 8 showed the failure modes of the specimens. Shear failure occurred at the shank of connectors. Bedding layer showed failure before connector failure because of low bearing capacity.

Fig. 9 presents the effects of each parameter including the bedding thickness. It is obvious that shear strength of the connectors increases as the yield strength of the connectors, $A_s f_y$, increases as in Fig. 9(a). In terms of normal stress acting on the interface, normal force is constant in push-off tests. However, in composite beams the normal force increases as the applied load increases. Push-off tests therefore give conservative values for the design. Inevitably it is necessary to have bedding layer when precast decks are installed over the girders. As in Fig. 9(c), the bedding layer decreases the shear strength directly, which is similar with the other tests[13]. Specimens with shear key showed the highest strength. It is recommendable to use shear key on the top surface of the girders.

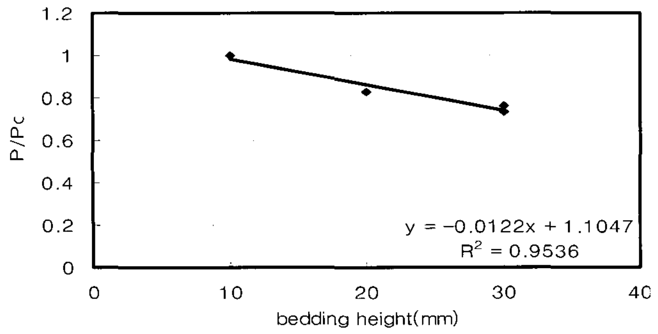
Based on the test results, an empirical equation was suggested as Equation (3). In the equation bedding height, yield strength of the connectors, and normal force are considered. In terms of the surface conditions, it is assumed to have shear key. Fig. 10 shows the evaluation of the shear strength of the shear connectors. The empirical equation shows the good agreement with the test results.

$$V_s = 1.01(A_s f_y + P_c)(1.1 - 0.012 t_b) \qquad (3)$$

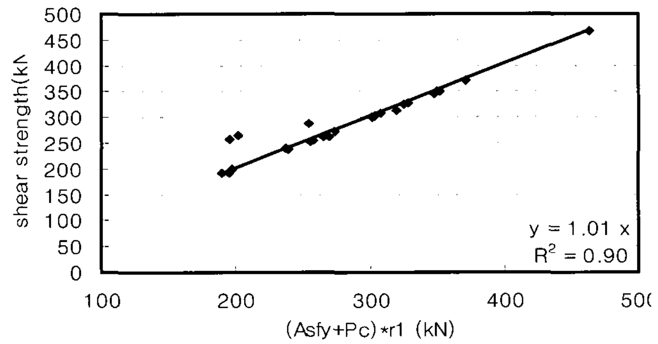
where, V_s =shear strength of the connectors (kN),
A_s =shank area of the connectors (mm^2),
f_y =yield strength of the connectors (kN/mm^2),
P_c =normal force(kN), t_b =bedding height (mm).

In the design of shear connectors for prestressed concrete composite beams, the shear strength is mainly dependent on the bond and frictional resistance of the interface. Comparing the test results with current design codes[6], shear strength of the suggested connection is slightly lower than the design values because of bedding layer and surface conditions. However, this difference does not cause any problem in design because full shear connection can be obtained easily using the suggested shear connection.

Maximum slip capacity of the suggested shear connection showed around 10 mm at the time of connector fracture and the slip at the maximum yield load of the connectors was about 2 mm. Form the previous tests for cast-in-place decks[(2)], slips at failure ranged from 2 to 7mm. Although bond and friction mainly resist the horizontal shear in actual bridges, it is important to assure good ductility of the shear connection. The shear connection in this system showed sufficient ductility for shear load redistribution.



(a) Reduction factor for bedding height



(d) Empirical equation

Fig. 10 Empirical equation of shear strength

4. Conclusions

For the application of full-depth precast decks to PSC girder bridges, a new shear connection was proposed. Details of prefabricated slabs for PSC girders were developed and static tests on shear connections were conducted to propose design equations of the shear connection. Stirrups and studs were fabricated to insert embedded nut-type devices in PSC girders. Shear strength of the shear connection considering chemical bond, friction and mechanical connectors was evaluated, and empirical equations for bond strength and shear strength of the shear connectors were suggested. Due to the mechanical connectors, ultimate slip capacity of the shear connection was sufficient and suggested details of the shear connection can accomplish the design requirements in terms of strength and ductility. For the suggestion of the design equation of shear strength of the shear connection, the shear strength must be evaluated through additional experiments on composite beams.

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