The Effect of Bedding Layer on the Strength of Shear Connection in Full-Depth Precast Deck

JONG-HEE KIM, CHANG-SU SHIM, SHIGEYUKI MATSUI and SUNG-PIL CHANG

ABSTRACT

Shear connection in a steel-concrete composite bridge with a full-depth precast deck is characterized by the material properties of the non-shrink mortar, which is the filler in the pockets for the shear connectors, and the existence of a bedding layer between the precast deck and the steel girder. As a consequence, the behavior of the shear connection is very different from that of the more widely used cast-in-place concrete deck. Experiments on push test specimens with several parameters varied, such as the cross-sectional area of the stud connectors, the compressive strength of the mortar, and the thickness of the bedding layer, were performed to evaluate the ultimate strength of the shear connection in the precast deck. The test results have shown that the effect of the compressive strength of the mortar on the ultimate strength of the shear connection is insignificant within the limit of these tests. The ultimate strength of the shear connection decreases considerably with an increase of the bedding layer thickness. An empirical equation for the ultimate strength of the shear connection considering the effect of the bedding layer thickness is presented in this paper. Based on the results, recommendations for the design of the stud shear connection in a full-depth precast deck are suggested.

INTRODUCTION

The maintenance and repair of bridge decks is becoming increasingly significant due to increased traffic loads. A precast concrete deck system is a very versatile system for the replacement of deteriorated bridge decks because this system can ensure the quality of concrete decks, reduce skilled labor demand and minimize traffic interference. Figure 1 shows the details of a typical shear connection in a full-depth precast concrete deck, which is covered in this paper. Most current design codes for stud shear connection are based on empirical equations obtained from tests of model composite beams with cast-in-place (CIP) concrete decks (EUROCODE, 1994; AASHTO, 1989). However, shear connection in a composite bridge with a full-depth precast deck is different from that of a CIP concrete deck. One of the differences resides in the material surrounding the stud connectors. In a composite bridge with precast concrete deck, the stud shear connector is embedded in the filler for the shear pocket, such as non-shrink mortar or epoxy mortar. Another difference lies in the fact that a bedding layer exists between the precast deck and the steel girder in a composite bridge with precast concrete decks. The thickness of the bedding layer varies along the bridge due to the change of girder section dimensions and the connection details at the upper flange of the girder at field splices. It is believed that these characteristics of a precast deck system can significantly affect the slip behavior and ultimate strength of the shear connectors.

This investigation was undertaken to assess the ultimate strength and load-slip characteristics of the shear connectors in a composite beam with a precast concrete deck. Among various possible types of shear connectors, only the headed stud shear connector was chosen for the current research. Tests were conducted on 24 push specimens with

Jong-Hee Kim is Ph.D., department of civil engineering, Seoul National University, Seoul, Korea.

Chang-Su Shim is Ph.D., department of civil engineering, Seoul National University, Seoul, Korea.

Shigeyuki Matsui is professor, civil engineering graduate school, Osaka University, Osaka, Japan.

Sung-Pil Chang is professor, department of civil engineering, Seoul National University, Seoul, Korea.

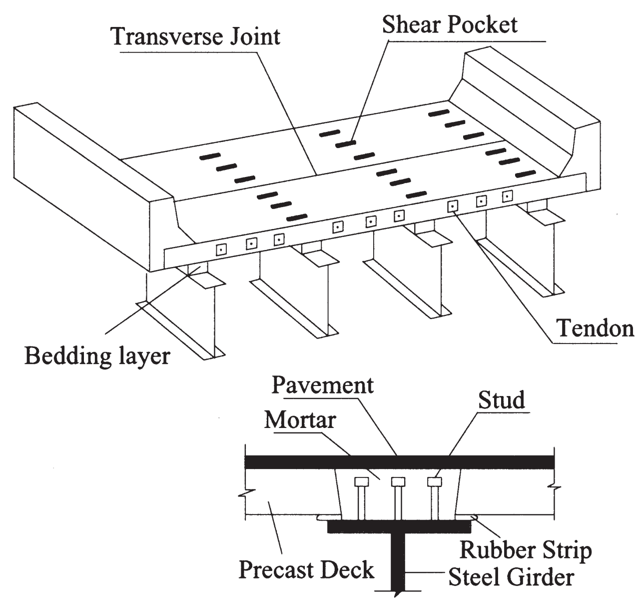


Fig. 1. Shear connection detail in full-depth precast deck.

Table 1. Push-out Specimens

Series	Specimen	Diameter of the stud (mm)	Compressive strength of the mortar (MPa)	Thickness of the bedding layer (mm)
DS	S613A	13	61.09	20
	S613B	13	61.09	20
	S616A	16	61.09	20
	S616B	16	61.09	20
	S619A	19	61.09	20
	S619B	19	61.09	20
	S619C	19	61.09	20
	S619D	19	61.09	20
	S622A	22	61.09	20
	S622B	22	61.09	20
CM	S419A	19	54.88	20
	S419B	19	54.88	20
	S419C	19	54.88	20
	S419D	19	54.88	20
	S819A	19	71.38	20
	S819B	19	71.38	20
	S819C	19	71.38	20
	S819D	19	71.38	20
TB	ST00A	19	55.48	0
	ST00B	19	55.48	0
	ST00C	19	55.48	0
	ST40A	19	55.48	40
	ST40B	19	55.48	40
	ST40C	19	55.48	40

various parameters. The parameters considered in these tests were the stud diameter, the compressive strength of the mortar and the thickness of the bedding layer.

EXPERIMENTAL WORK

Push-out Specimens

A push-out test specimen is presented in Figure 2. The width and length of the precast slab, which are similar to the dimensions of push specimens suggested by EUROCODE-4, were 600 mm and 700 mm, respectively. The thickness of the precast slab was chosen as 220 mm based on the typical size of the precast deck in a steel-concrete composite bridge. Shear pockets were placed in the precast slab for installation of the stud connectors. The dimensions of the shear pocket are shown in Figure 2. Two stud connectors were installed longitudinally in each concrete slab. The height of the studs was 150 mm. The dimension of the steel beam was 300 mm × 300 mm, and the thickness of the flange was 15 mm.

It has been shown that the casting directions of the concrete placed around the stud connectors can influence the static strength of shear connection due to the bleeding of the concrete (Maeda and Matsui, 1983). Therefore, in order to match the upright casting direction of concrete in real steel-concrete composite bridges, specimens were made as follows. First, the web of the H-shaped beam was cut into two

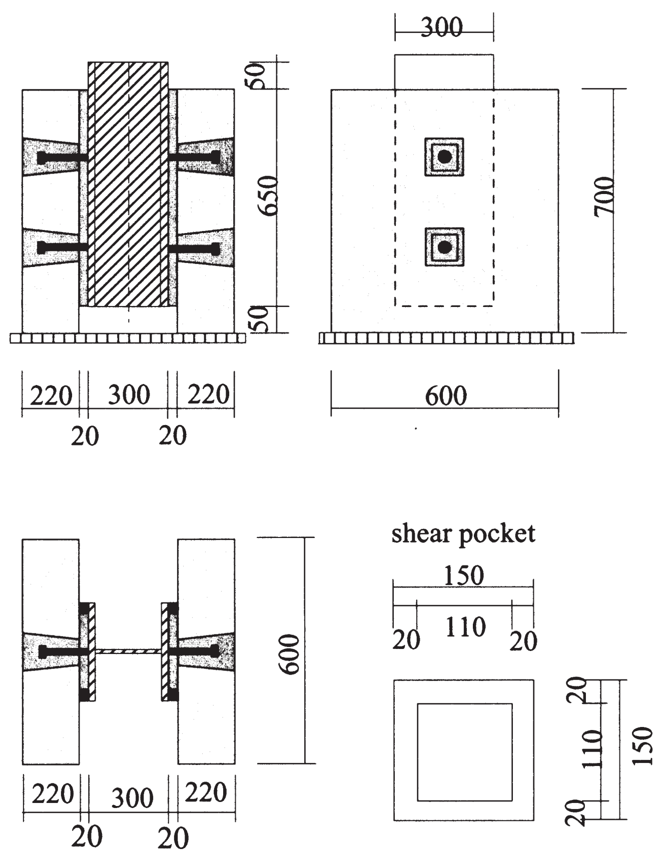


Fig. 2. Push specimen.

parts and both flanges of the beam were positioned upwards. The studs were then welded to the steel flanges and precast slabs were placed on rubber strips attached to the edges of the steel flanges. Shear pockets were then simultaneously filled with non-shrink mortar to ensure that each constituent had the same properties. Spacers having the specified thickness were put on the flange to ensure the proper thickness of the bedding layer. After curing, both flanges were connected into one I-section to form a push-out specimen, as shown in Figure 2. The flange surfaces of the steel beam were lubricated using oil to remove bond between the mortar and the steel beam.

Test variables

In this research, three variables were selected to investigate the ultimate strength of the shear connection in a precast deck: the diameter of the stud connector, the compressive strength of the mortar, and the thickness of bedding layer. Characteristics of all test specimens are presented in Table 1.

Tests of series DS specimens were performed to see the effect of stud shank diameter on the ultimate strength of the shear connection. Four different diameters were used in this test: 13 mm, 16 mm, 19 mm, and 22 mm. In this series, the compressive strength of mortar was 61.09 MPa, and the thickness of bedding layer was 20 mm.

Tests of series CM specimens were performed to evaluate the effect of the compressive strength of non-shrink mortar on the ultimate strength of shear connections. In a precast deck system, the mortar, having the same elastic modulus as the precast concrete, seems to be adequate for the filler in the shear pockets. The compressive strengths of the tested mortar were 54.88 MPa, 61.09 MPa, and 71.38 MPa. Four specimens were fabricated for each case. The diameter of the stud connectors in this series was 19 mm, and the thickness of the bedding layer was 20 mm.

Series TB specimens were tested in order to investigate the effect of the bedding layer on the behavior of the shear connection. Three different bedding thicknesses were selected as test variables considering the constructional conditions such as the change of the girder section along the span and connection details like bolts and splices. Three specimens for each bedding thickness of 0 mm, 20 mm and 40 mm were tested.

Test Procedures

All specimens were tested under static loading in a hydraulic testing machine with a capacity of 1000 kN. The load was applied to the upper end of the steel beam by the head of the machine through a steel distribution plate. The bottom of the concrete slab was not restrained to allow it to spread sideways freely when the load was applied. The test setup is shown in Figure 3.

The load was applied in increments varying from 19.6 kN to 39.2 kN, but was released at several load levels before failure. The applied load was measured with a load cell. Slip between the concrete slab and the steel beam was measured by four 1/100 mm dial gages at the level of the upper stud shear connectors (Figure 3). The dial gages were rigidly attached to the beam with a magnetic bar against brackets glued to the slabs. Residual slip was measured after each unloading step. An average value of the measured slips was used.

Material Properties

The compressive strength of the concrete was obtained by testing three 100 mm × 200 mm cylinders. After steam curing was performed for one day, the cylinders were stored in

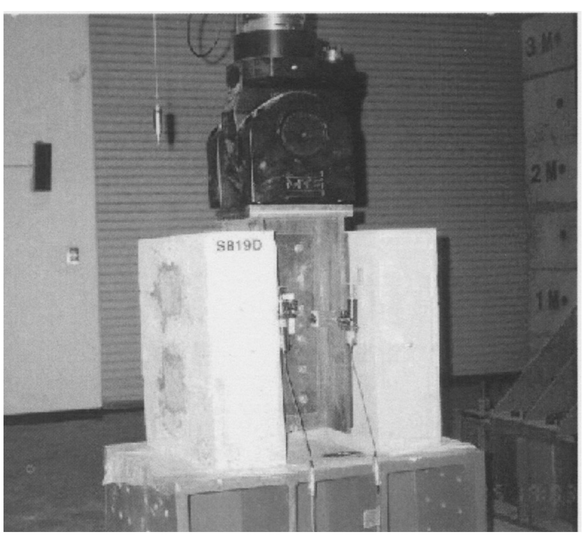


Fig. 3. Test setup.

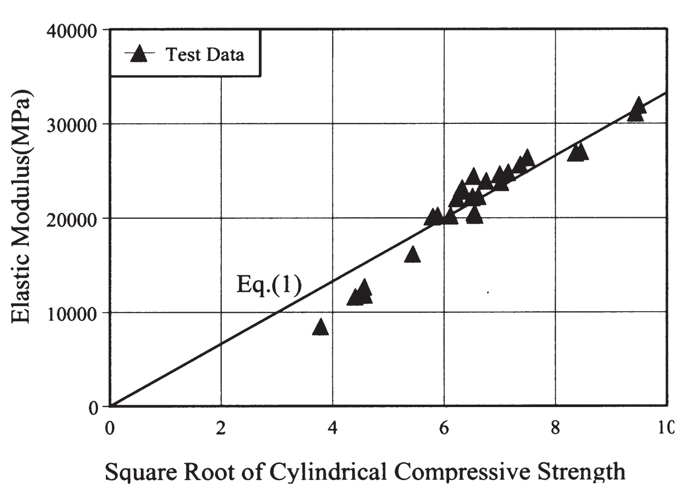


Fig. 4. Relationship between elastic modulus and compressive strength of mortar.

air until the time of testing to obtain the target strength. The mean 28-day compressive strength was 35.8 MPa.

The compressive strength of the injecting mortar was obtained through three 50 mm cube tests for three different types of mortar. The average compressive strength of each type of mortar was 54.88 MPa, 61.09 MPa, and 71.38 MPa, respectively. To obtain the relationship between the compressive strength and the elastic modulus of the mortar, several 100 mm × 200 mm cylinder tests were performed. Figure 4 shows that the elastic modulus of the mortar is nearly proportional to the square root of its compressive strength. For comparison with concrete, the following empirical equation is suggested, that was developed through a linear regression analysis:

$$E_m = 3280\sqrt{\sigma_m} \tag{1}$$

where

E_m = modulus of elasticity of the mortar, MPa

σ_{cm} = compressive strength of the mortar determined using a 100 mm × 200 mm cylinder, MPa

Material properties of the stud connectors were obtained from ASTM standard tension tests (ASTM, 1987). Three round tension test specimens were tested and the mean tensile strength was 503 MPa.

BEHAVIOR OF THE STUD SHEAR CONNECTION

The Effects of Bedding Height on the Behavior of Stud Shear Connector

The effects of bedding layer thickness on the behavior of the stud shear connectors are illustrated in Figure 5.

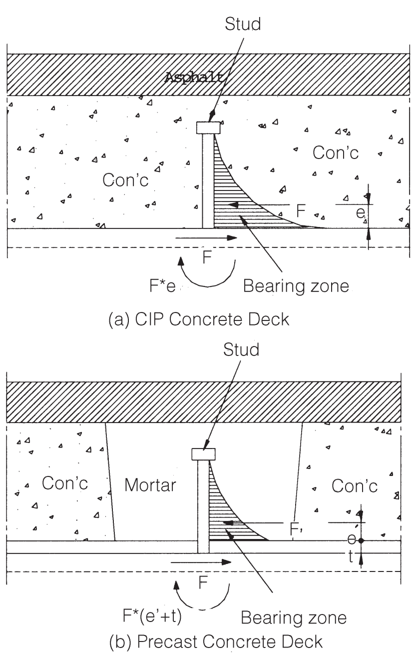


Fig. 5. Behavior of shear connection.

Because the bedding layer is thin (generally less than 40 mm) and has no reinforcement, cracking of the layer occurs at a relatively low level of the applied load. After cracking, the shear connector loses its bearing zone and shows a larger flexural deformation than for the case of a CIP deck. A weak bedding layer causes larger tensile stresses in the stud connector and decreases the ultimate strength of the shear connection.

Failure Patterns

All the failures occurred at the weld-collar/shank interface, and the failure plane was nearly parallel to the loading direction, as presented in Figure 6. From the figure, it can be seen that crushing occurred in the mortar in front of the stud connector, that is, in the bearing zone. A small gap appeared between the mortar and the upper part of the stud connector. The failure plane indicates that bending of the stud occurred due to crushing of the mortar.

Fig. 6. Faces of dowel failure section.

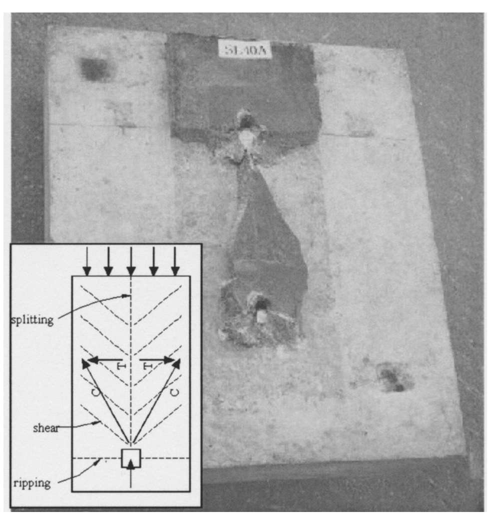


Fig. 7. Crack pattern in bedding layer.

Table 2. Summary of Results of Push-out Tests

Specimen	Ultimate Strength Q_u (kN)	$A_s f_{su}$ (kN)	$Q_u / A_s f_{su}$ (%)
S613A	71.18	66.8	107
S613B	62.36		93
S616A	92.59	101.1	92
S616B	71.28		70
S619A	122.14	142.6	85
S619B	119.88		84
S619C	144.31		101
S619D	134.26		94
S622A	141.64	191.2	74
S622B	154.67		81
S419A	117.06	142.6	82
S419B	123.46		87
S419C	105.67		74
S419D	114.12		80
S819A	105.01		73
S819B	115.57		81
S819C	124.44		87
S819D	128.72		90
ST00A	130.51		92
ST00B	149.77		105
ST00C	133.43		94
ST40A	98.22		69
ST40B	92.61		65
ST40C	96.53		68

During the static test, ripping cracks were observed in the bedding layer between the concrete slab and the steel flange. After failure occurred, three different crack patterns in the bedding layer were observed; ripping, splitting, and shear cracking, as shown in Figure 7.

Figure 8 shows a stud connector that was extracted from the failed specimen. In this figure, it can be seen that considerable flexure occurred at the stud shank, especially at the lower part of the stud.

Load-Slip Characteristics

A typical load-slip curve is shown in Figure 9. The load-slip path can be assumed to be linear at low loads, up to about 50 percent of the ultimate load. It is believed that at these loads, inelastic action was confined to the mortar. At higher loads, however, slip increased greatly with small increments of load, indicating the presence of large inelastic deformations; plastic deformation of the mortar accompanied by cracking in the bedding layer and yielding of the stud steel probably occurred at this load level. In Figure 9, the slope of the load-slip path after the initial loading remained nearly constant during the tests. This indicates that the tangent stiffness at loading was nearly the same as the stiffness at unloading.

Figure 10(a), (b) and (c) represent the load-slip and the load-residual slip curves for different values of the diameter of the stud, compressive strength of the mortar, and thickness of the bedding mortar, respectively.

Figure 10(a) shows that slip and residual slip of the shear connection at the same load were greater as the diameter of the stud decreased. S613, S616, S619 and S622 in the figure represent the average slip value for stud shanks 13, 16, 19 and 22 mm-diameter, respectively.

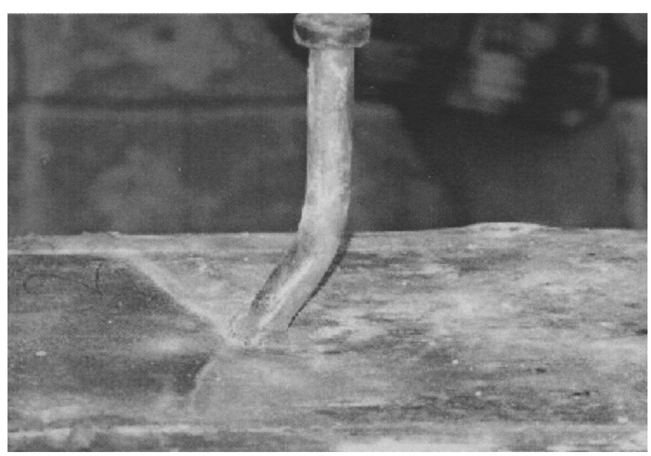


Fig. 8. Deformed shape of the stud connector.

In Figure 10(b), S419, S619, and S819 represent three types of mortar, that is, 54.88 MPa, 61.09 MPa, and 71.38 MPa, respectively. It can be seen that there was little observed difference in the slip and the residual slip between mortars having different compressive strengths.

Figure 10(c) shows that the thickness of the bedding mortar had a considerable effect on the slip behavior of the shear connection. The amount of slip and residual slip of specimens with thicker bedding layers was larger than those with thinner bedding thickness.

A larger slip at failure was observed in specimens having thicker bedding layers as shown in Figure 11. Since the bedding layer is weak and produces less constraint, the bearing zone of the shear connection plays no important role in resisting the shear load. The shear load, therefore, acts on the stud connector at the height of the bedding layer thickness, and a greater flexural moment on the stud can occur in a specimen having a thicker bedding layer.

Ultimate Strength of the Shear Connection

The results for the 24 specimens are given in Table 2. The ultimate strength of each specimen obtained from the tests, the calculated tensile strength of the stud, and the ratios of the test results to the calculated tensile strength of the stud are listed in this table.

The results of the CM series tests, investigating the effect of various compressive strengths of the mortar, are presented in Figure 12. Test results showed that the varying compressive strength of the mortar had no significant effect on the ultimate strength of the shear connection. The calculated tensile strengths of the stud are also compared with test results in the figure. Many design codes, including EUROCODE-4 and AASHTO, recommend the use of the tensile strength of the shear connector, $A_{sh}f_{su}$, as an upper bound on the ultimate strength of shear connections with high-strength concrete. The mortar used in these tests is considered to be in the high-strength range. The ultimate strengths of the shear connections in these tests, with a bedding layer thickness of 20 mm, ranged from 75 to 101 percent of the tensile strength of the stud. This is because cracks occur in the bedding layer at low loads, thus causing the bending moment on the stud connector to increase significantly. Therefore, if the ultimate strength of the shear connection is evaluated from the current design codes, it could be unconservative.

The most significant factor influencing the ultimate strength of the shear connection is the diameter of the stud shank. Figure 13 shows the measured ultimate strength of the shear connection versus the cross-sectional area of the studs. It can be seen from this figure that the ultimate strength is proportional to the cross-sectional area of the studs. An empirical equation to evaluate the ultimate strength of the shear connection according to the cross-sectional area of the studs is suggested from a linear regression analysis of the test results, as presented in Equation 2. The correlation coefficient of the equation is 0.94.

$$Q_u = 0.36 A_{sh} + 18.71 \tag{2}$$

where

Q_u = ultimate strength of shear connection, kN
A_{sh} = cross-sectional area of stud, mm^2

In addition, the ratios of the measured ultimate strength of the shear connections to the calculated tensile strength of the stud connectors are plotted versus the diameter of the studs in Figure 14. In general, the ratio decreased as the diameter of the stud increased.

Figure 15 indicates that the thickness of the bedding layer has a significant effect on the ultimate strength of the shear connection in precast decks. In the figure, it can be seen that the ultimate strength decreases with an increase of the bedding layer thickness. The ultimate strength of shear connections, with a bedding layer thickness of 0 mm, ranged from 92 to 105 percent of the tensile strength of the stud connectors. However, the ultimate strength of shear connections, with a bedding layer thickness of 40 mm, ranged from 65 to 69 percent of the tensile strength of the stud connectors. This is due to the increased bending of the stud connector due to the presence of the bedding layer, which does not provide enough constraint to the bearing zone at the level of the weld collar.

Since a bedding layer is inevitable in steel-concrete composite bridges with a full-depth precast deck, it is necessary to suggest an empirical equation that considers the effect of the bedding layer thickness. Therefore, a modification factor accounting for the effect of the bedding layer on the ultimate strength of the shear connection is suggested from a linear regression analysis of the test results, as presented in

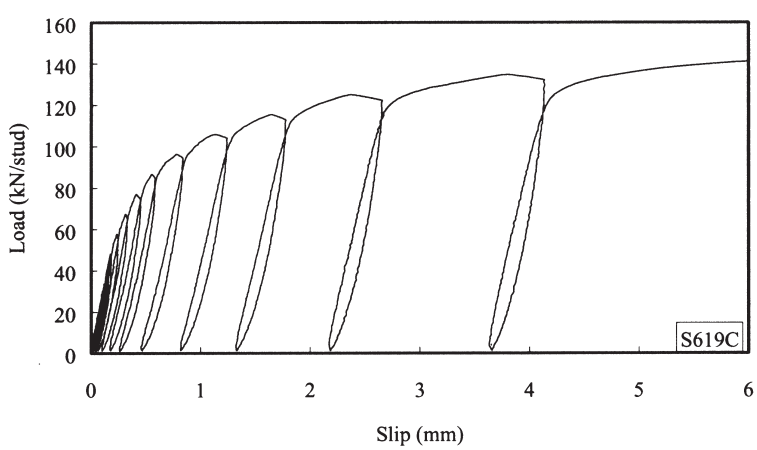
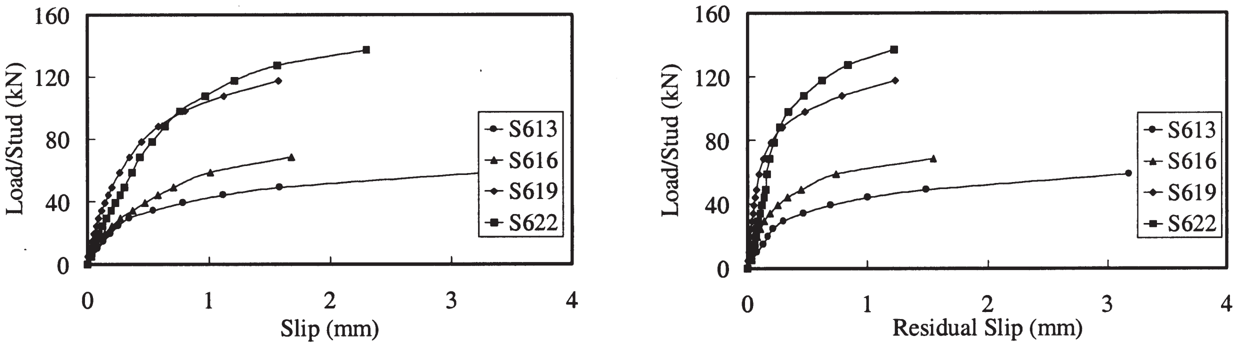
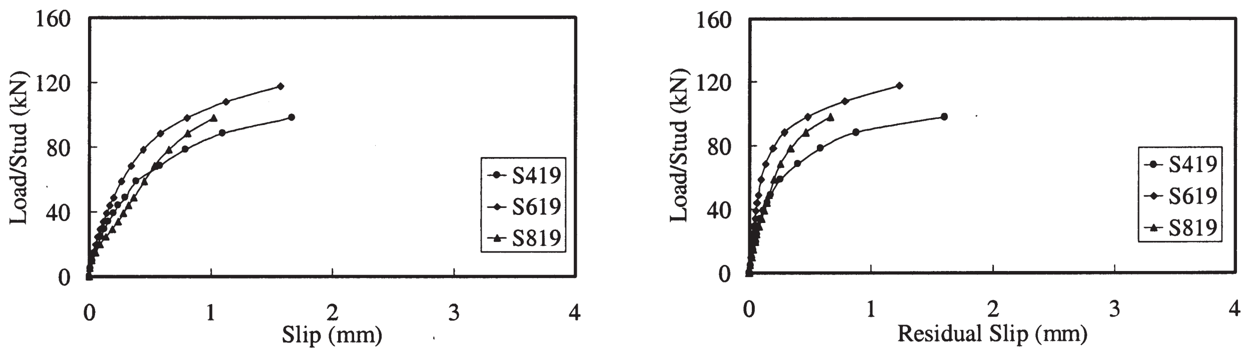


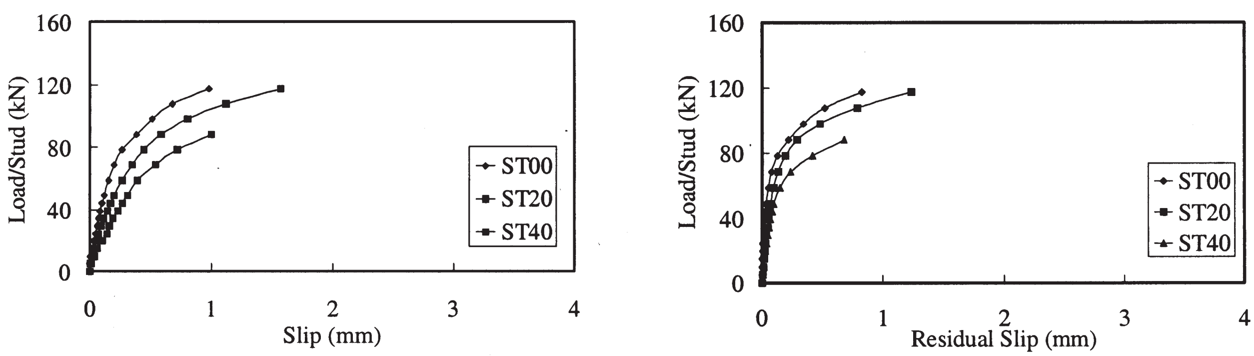
Fig. 9. Load-slip curve of the stud.



(a) diameter of the stud



(b) compressive strength of mortar



(c) thickness of the bedding mortar

Fig. 10. Slip and residual slip.
(a) Diameter of the stud
(b) Compressive strength of mortar
(c) Thickness of the bedding mortar

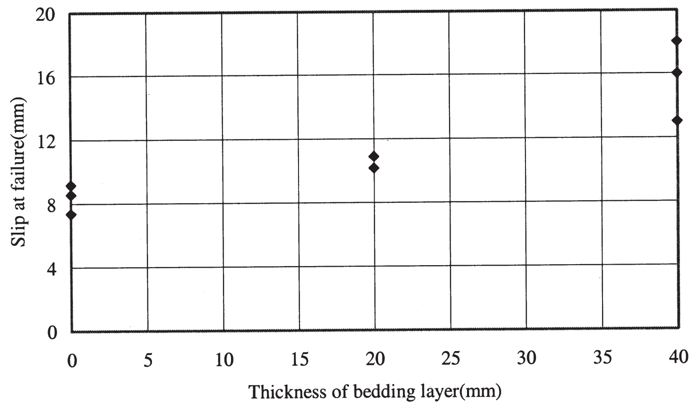


Fig. 11. Slip capacity of the shear connection versus thickness of bedding layer.

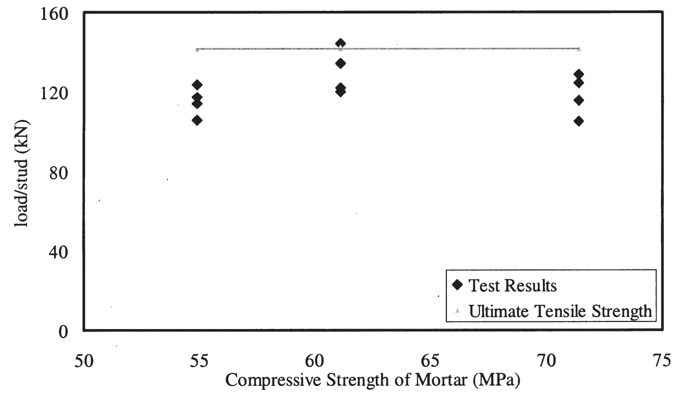


Fig. 12. Ultimate strength of the shear connection versus compressive strength of mortar.

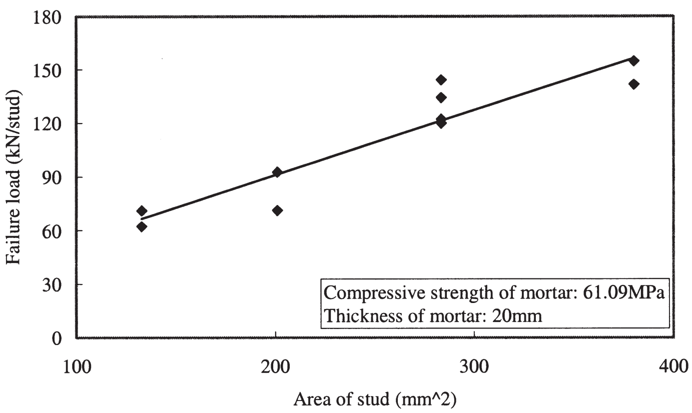


Fig. 13. Ultimate strength of the shear connection versus stud area.

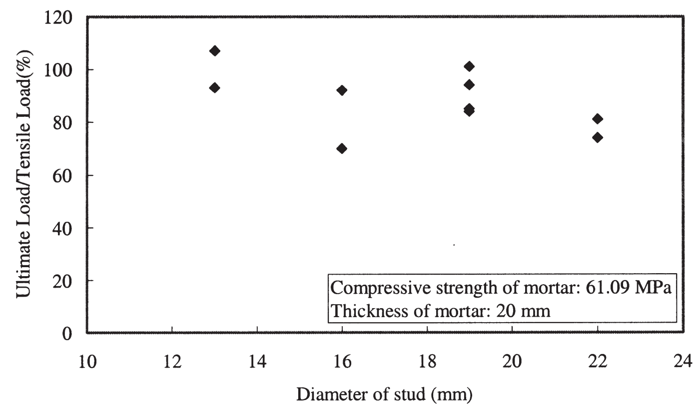


Fig. 14. Ratios of shear connection ultimate strength to tensile strength versus stud diameter.

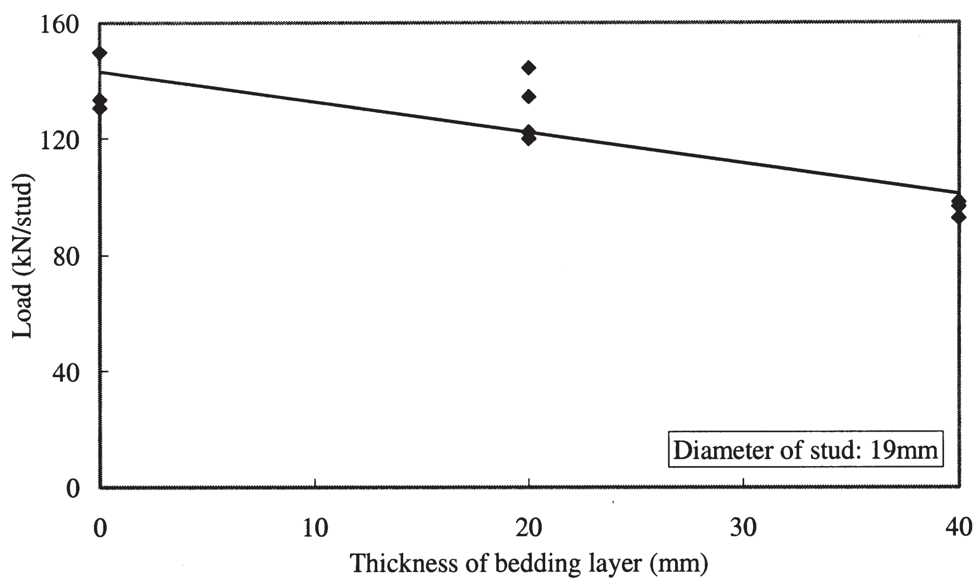


Fig. 15. Ultimate strength of the shear connection versus thickness of the bedding layer.

Equation 3. The average value of the results for the specimens with a bedding layer thickness of 20 mm is used as the standard value in the equation. The correlation coefficient is 0.93.

$$\alpha = 1 - 0.0086(b_h - 20) \tag{3}$$

where

b_h = thickness of bedding layer, mm

α = modification factor considering the bedding layer

DESIGN RECOMMENDATIONS

It is recommended that a mortar be selected with the same elastic modulus as the concrete used for the precast deck to ensure not only an adequate transformed section, but also adequate stiffness of the shear connection. When a mortar with a high compressive strength is used, the ultimate strength of the shear connection is proportional to the cross-sectional area of the stud shank and should be modified to account for the thickness of the bedding layer, as shown in Equation 4.

$$Q_u = \alpha(0.36 A_{sh} + 18.71)$$
$$\alpha = 1 - 0.086(b_h - 20) \tag{4}$$

where

Q_u = ultimate strength of the shear connection, kN

A_{sh} = cross-sectional area of the stud, mm^2

b_h = thickness of bedding layer, mm

α = modification factor considering the bedding layer

The thickness of the bedding layer generally varies along the span because of the change of girder section, connection details on the upper flange of the steel girder, and field adjustment of the profile of the riding surface. Therefore, it is conservative to use the thickest bedding layer in evaluating the ultimate strength for the design.

CONCLUSIONS

Experiments were performed in order to investigate the effects of three parameters: area of the stud, compressive strength of the mortar, and thickness of the bedding layer, on the ultimate strength of the shear connection of a typical full-depth precast concrete deck system. The results of previous studies on the shear connection of CIP slabs cannot be considered applicable to the precast deck system using constant thickness decks. Therefore, a new empirical equation is suggested considering the characteristics of a precast deck system where non-shrink mortar is used as filler.

The following three conclusions can be drawn from this study:

1. In the range of the current tests, the compressive strength of the mortar had little effect on the observed ultimate strength of the shear connection because the compressive strength of the mortar was high enough and the bearing capacity of the bedding layer became the weak point.
2. The ultimate strength of the shear connection is proportional to the cross-sectional area of the stud shank, similar to the results of previous research on shear connection in CIP slabs. Therefore, the ultimate strength can be expressed as a function of the stud area.
3. In the design of composite bridges with full-depth precast decks having constant thickness, the bedding layer is unavoidable. The ultimate strength of the shear connection decreases with an increase of the bedding layer thickness due to increased bending of the connectors, which should be recognized in the design.

Finally, design recommendations considering construction conditions are presented.

ACKNOWLEDGMENTS

This research was conducted as a cooperative project of the Seoul National University Civil Engineering Department, DAEWOO Institute of Construction Technology, and the Ministry of Construction and Transportation of Korea.

REFERENCES

EUROCODE 4 (1994), "Design of Composite Steel and Concrete Structures," DD ENV 1994-1-1:1994, Draft for Development.

AASHTO (1989), *Standard Specifications for Highway Bridges*, American Association of State Highways and Transportation Officials, Washington, DC, 14th Ed.

Maeda, Y. and Matsui, S. (1983), "Effects of Concrete Placing Direction on Static and Fatigue Strengths of Stud Shear Connectors," Technical Report, Osaka University, Vol. 33, No. 1733, October, pp. 397-406.

ASTM (1987), *Standard Testing Methods*, American Society for Testing and Materials, Philadelphia, PA.

NOTATION

E_m Modulus of elasticity of mortar, MPa

σ_{cm} Compressive strength of mortar using 100 mm × 200 mm cylinder, MPa

Q_u Ultimate strength of the shear connection, kN

A_{sh} Area of the stud, mm^2

f_{su} Tensile strength of the stud, MPa

b_h Thickness of bedding layer, mm

α Modification factor considering the bedding layer