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Experimental Study on Shear Connector for Precast Concrete Decks

Chul-Hun Chung* Chang-Su Shim** Un-Yong Jeong***

* Senior Researcher, Ph.D, Daewoo Institute of Construction Technology, Korea
** Ph.D, Department of Civil Engineering, Seoul National University, Korea
*** Chief Researcher, Ph.D, Highway Research Institute, Korea Highway Corporation, Korea

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Abstract

For the design of shear connection for the composite precast concrete slabs, it is necessary to investigate its strength, stiffness, slip capacity and fatigue endurance. For these purposes, push-out tests were performed with variations of the stud shank diameter and the compressive strength of the mortar. From the experimental studies, it could be observed that the deformation of the shear studs in a full-depth precast concrete slabs were greater than those in a cast-in-place slabs. The static strength of the shear connections obtained agree approximately with those evaluated from the tensile strength of the stud shear connectors owing to the effect of the bedding layer between the slabs and the beams. An empirical equation for the initial shear stiffness of a shear connection was also proposed. On the basis of the push-out tests, a full-scale composite beams with 8.0 m span was designed and fatigue tests were carried out to study the behaviour of the stud shear connection and its effects on the flexural behaviour of the beam. The bonding and friction between the concrete slab and the steel beam considerably increased the fatigue endurance of the shear connection.

***keywords** : bridge, precast concrete slab, fatigue, composite beam, shear connector*

1. Introduction

With the expansion of urban boundaries, the traffic burden on most bridges has increased dramatically, so that rehabilitation of the deck system is required more frequently than before. A view of a composite bridge with a full-depth precast concrete slab is shown in Fig. 1. As shown in the figure, shear pockets are distributed in the precast concrete slab for installation of stud shear connectors, and non-shrinkable mortar fills the pockets to achieve the composite action. For levelling the steel girders, bedding layers of 15~40mm thick are used. Owing to the structural system with bedding layer and the properties for material surrounding the shear connectors, the behaviour of the stud shear connection is very different from that of the widely used cast-in-place (CIP) concrete slabs.

The strength, stiffness, and ultimate slip capacity of the shear connection has been known to be influenced by many parameters: cross sectioned area of the stud shank,[1] height of the stud,[2] tensile strength of the stud,[3] compressive strength and elastic modulus of the concrete[1,3,4] and direction of concrete placing.[5] But there has not been enough research on the shear connection with a full-depth precast concrete slab considering the characteristics of the filling material, non-shrinkable mortar and bedding layer. Therefore, it is necessary to investigate the strength, stiffness and fatigue characteristics of shear connection through experiments.

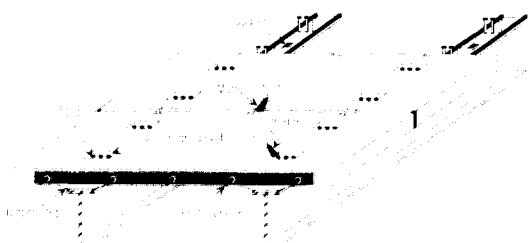


Fig. 1 Composite bridge with full-depth precast slab

For these purposes, push-out speci-mens were fabricated and then static and fatigue tests were carried out. On the basis of the results of these push-out tests, a composite simply supported beam of 8.0m long with seven precast slabs was designed. Each panel contains pocket holes to allow room for shear studs and a groove on each transverse side so that two adjacent panels formed a shear key. The pocket holes and the shear key joints were filled with non-shrinkable mortar. The effects of the material properties of the mortar and the bedding height on the strength and stiffness were examined through experiments and finite element analyses. The strength and initial shear stiffness of the shear connection were evaluated. The static and fatigue behaviour of the composite beam, including the effects of bond and friction, were estimated.

2. Push-out Tests

2.1 Experimental Work

The design of specimens for static and fatigue push-out tests was similar to that suggested by BS 5400,[6] but it has shear pockets for stud shear connectors and a 20mm thick bedding mortar layer between the precast slab and steel beam . Studs were welded on the flange using a stud- welding gun. As shown in Fig. 2, two studs were arranged in the longitudinal direction in each slab. The precast concrete slab, shear pockets and bedding were cast at the same time, with concrete and mortar, respectively to make sure that each constituent has the same properties.

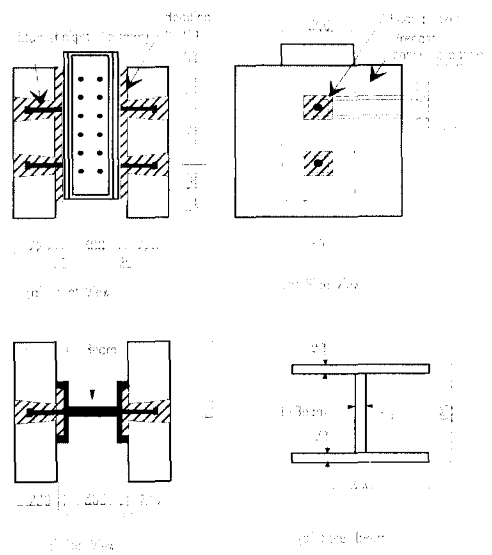


Fig. 2 Specimen for push-out test (dimensions in mm)

The cylindrical compressive strength of the concrete for the precast slab was 35.8 N/mm^2, and the material properties of each mortar type are summarized in Table 1. Three types of mortar were used and were classified as series A, B, and C. The yield strength and tensile strength of the stud shear connector, which were obtained from direct tensile tests, were 343 N/mm^2 and 450 N/mm^2, respectively. For analytical studies, the relation of the elastic modulus of mortar to the cylindrical compressive strength of mortar was evaluated through several tests, and is plotted in Fig. 3. Equation (1) presents the relation.

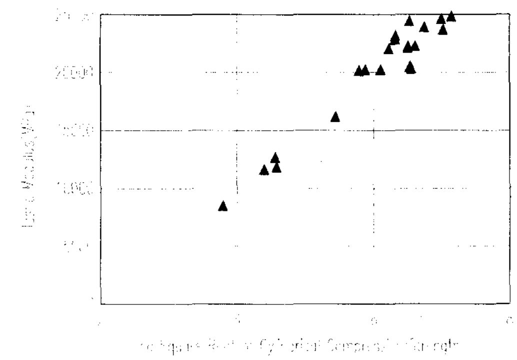


Fig. 3 Relationship between elastic modulus and compressive strength of mortar

$$E_m = 3.26 \times 10^3 \sqrt{\sigma_{cm}} \qquad (1)$$

where, E_m is the modulus of elasticity of mortar(in MPa), and σ_{cm} is the compressive strength of mortar using 100x200mm cylinder(in MPa). From the compression tests, it is observed that the compressive strength of mortar using a 50mm cubic mould is 1.25 times greater than that using 100x200mm cylinder.

2.2 Static Behaviour

Four displacement transducers were installed at the level of the upper stud for measuring slip. The average value from the four transducers was used for evaluating the shear stiffness of the shear connection. The static strength of the shear connection was obtained by dividing the failure load by the number of connectors. Characteristics of the static test specimens and their static strength are given in Table 2. All the failures occurred at the weld collar/shank interface and splitting crack were

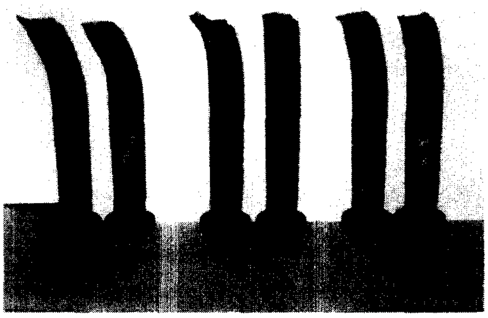
observed in the bedding layer. The observed failure mode of the stud shear connectors and bedding mortar are shown in Fig. 4. As shown in the figure, the failure mode induced a relatively large deformation of the studs larger than that in the case of CIP slab.

Table 1 Material properties of mortar

Type	Compressive strength using cubic mould (N/mm^2)	Compressive strength using cylinder mould (N/mm^2)	Elastic modulus(MPa)
Series A	54.88	43.9	2.16
Series B	61.09	48.9	2.28
Series C	71.38	57.1	2.46

Table 2 Static strength of push-out specimens

Specimen	Diameter of stud (mm)	Comp. strength of mortar (N/mm^2)	Ultimate strength (kN/stud)
S13B-1 S13B-2	13	61.09	71.18 62.36
S16B-1 S16B-2	16	61.09	92.59 71.28
S19A-1 S19A-2 S19A-3 S19A-4	19	54.88	117.06 123.46 105.67 114.12
S19B-1 S19B-2 S19B-3 S19B-4		61.09	122.14 119.88 144.31 134.26
S19C-1 S19C-2 S19C-3 S19C-4		71.38	105.01 115.57 124.44 128.72
S22B-1 S22B-2	22	61.09	141.64 154.67



(a) Static failure of stud

(b) Crack in bedding mortar

Fig. 4 Failure patterns

The static strengths of the shear connection obtained from the specimens of series B correlate approximately with those evaluated from the tensile strength of shear connectors, that is, $A_{sh}\sigma_u$, as shown in Fig. 5, since the bearing zone, where the shear force is concentrated, is weak and cannot give enough constraint. The weld collar, about 5mm high, cannot play an effective role in resisting the shear force because the bedding layer cracked at a relatively low level of shear force. In Fig. 5, the curve for the empirical equation suggested by Ollgaard et al.[1] is given for the case where the compressive strength and elastic modulus of mortar are the same as for the present push-out specimens. Also, we can expect that the static strength of the shear connection decreases as the thickness of the bedding layer increases.

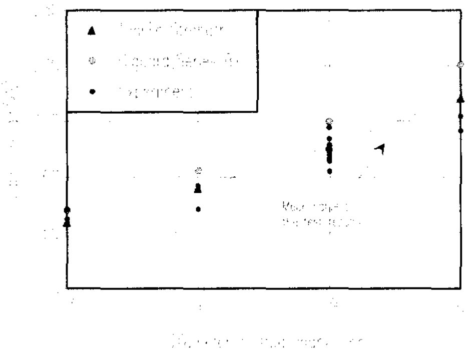
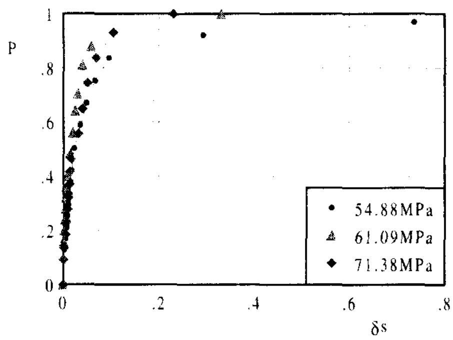
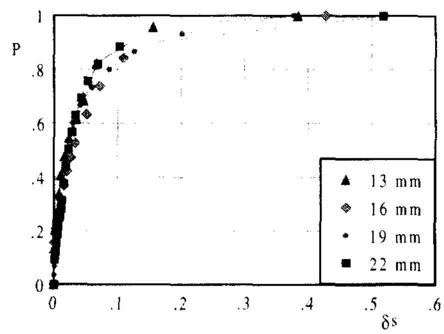


Fig. 5 Static strength of shear connection

Load-slip curves were obtained from the static tests, as shown in Fig. 6. The initial shear stiffness of shear connections with a full-depth precast concrete slab was evaluated as equation (2) suggested by Oehlers and Coughlan .[7,8] In this equation, the mean value of static strength obtained from static tests was used for D_{max}. This equation could be used for the evaluation of the shear stiffness of stud shear connection in the case of precast slab systems. Of course, this equation should be modified through further experiments with variations in bedding height. This equation is



(a) For various compressive strength of mortar



(b) For various shank diameters of the studs

Fig. 6 Static load-slip curves

$$K_{si} = \frac{D_{max}}{d_{sh}(104 \times 10^{-3} - 96 \times 10^{-5}\ \sigma_{ck})} \quad (2)$$

where K_{si} is the initial shear stiffness of shear connector(in N/mm), D_{max} is the mean static strength of shear connection(in N), d_{sh} is the diameter of stud shank(in mm) and σ_{ck} is the compressive strength of the mortar using a 50 mm cubic mold(in MPa).

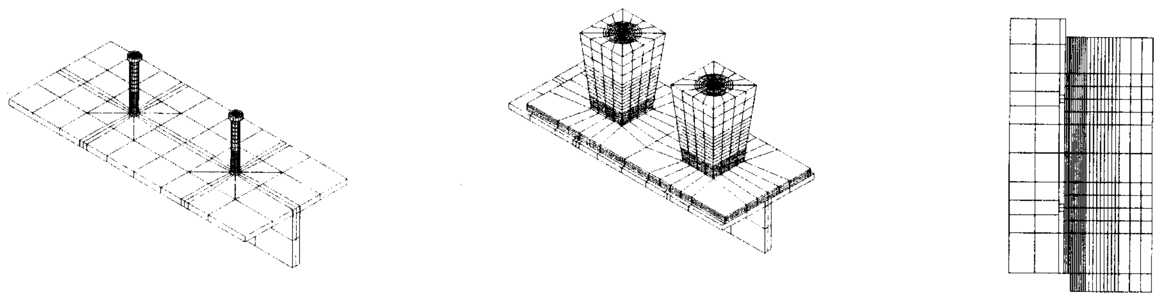
The ultimate slip capacity of the shear connection, which is the slip when the load has reduced by 1% from its peak,[8] can be evaluated through the linear regression analysis of test results, as given in equation (3).

$$S_{ult} = (1.8368 - 0.0228\ \sigma_{ck})d_{sh} \quad (3)$$

where S_{ult} is the ultimate slip capacity of the stud shear connection(in mm).

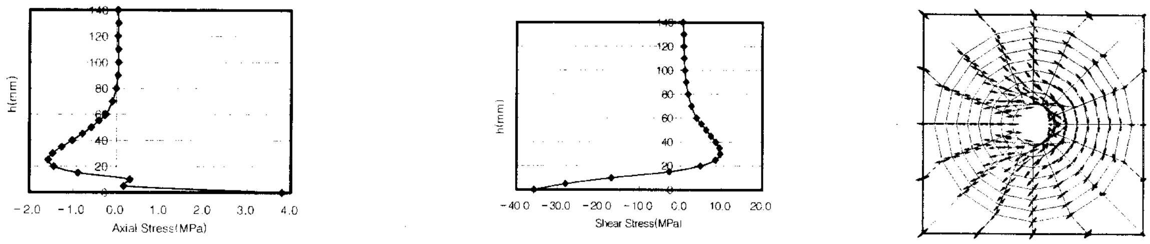
The correlation coefficient is 0.75. The slip capacity is probably greater than that of CIP slab, owing to the effect of bedding layer.[8]

A Finite element model of the push-out specimens was constructed using the finite-elemnt package ABAQUS[9] in order to investigate the initial stress distribution of the stud shear connectors and bedding layer, as shown in Fig. 7. Three-dimensional brick elements are used for steel beam, stud, and concrete. The distributions of flexural and shear stresses along the stud shank are shown in Fig. 8(a) and (b) when the shear load per stud is 9.8kN. The stresses are concentrated around the root of the stud shank below a height of 20mm. On the basis of the maximum principal tensile stress at the bedding layer ahead of the stud shank as shown in Fig. 8(c), which was obtained from the linear elastic analysis, a crack occurs at about 3.0 % of the static strength of the stud shear connection for each specimen.



(a) Steel beam and stud (b) Shear pocket and bedding mortar (c) Side view of model

Fig. 7 Finite element model of push-out specimen



(a) Flexural stress (b) Shear stress (c) Max. principal stress in bedding layer

Fig. 8 Stress distributions

Table 3 Fatigue tests

Specimen	Compressive strength of mortar (N/mm^2)	Maximum load (N/mm^2)	Minimum load (kN)	Stress range (MPa)
F150A	54.88	36.75	1.255	125.2
F170A	54.88	41.65	1.255	142.5
F130B	61.09	31.85	1.255	107.9
F150B	61.09	36.75	1.255	125.2
F180B	61.09	44.10	1.255	151.1
F130C	71.38	31.85	1.255	107.9
F150C	71.38	36.75	1.255	125.2
F180C	71.38	44.10	1.255	151.1
F180C	71.38	44.10	1.255	151.1

Therefore, the flexural deformation of the stud shear connector is greater than that in the case of CIP slabs, which can resist the splitting force batter through adequate reinforcement.

2.3 Fatigue Endurance

The specimens used for fatigue tests are listed in Table 3. The relation between the ratio of the shear force range to the static strength(R/D_{max}) and the number of the load cycle at failure is presented in Fig. 9. The relation is described in Equation (4) and the correlation coefficient is 0.87.

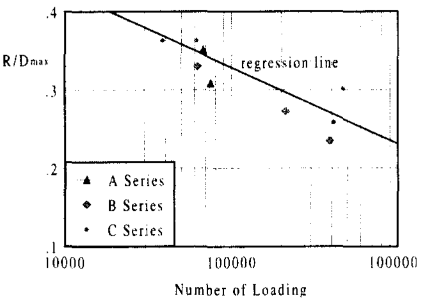


Fig. 9 Results of fatigue tests

$$R/D_{max} = 1.5117N^{-0.1355} \qquad (4)$$

where R is the shear force range (in N), D_{max} is the mean static strength of the stud shear connection·(in N) and N is the number of loadings at failure.

Residual-slip curves obtained from fatigue tests are shown in Fig. 10. The equations of residual slip for each range of shear load are given in Equation (5). As the range of shear load increases, the residual slip increases. After some certain number of cycles of fatigue loading, the residual slip increased abruptly, as shown in Fig. 10. Owing to the residual slip, the secant stiffness of shear connection increased during the fatigue tests. The equation are

$$\delta_r = 3.0 \times 10^{-6} N + 7.53 \times 10^{-2}, \ r=0.79 \quad \text{(F130 series)} \qquad (5a)$$

$$\delta_r = 3.0 \times 10^{-6} N + 16.6 \times 10^{-2}, \ r=0.74 \quad \text{(F150 series)} \qquad (5b)$$

$$\delta_r = 14.0 \times 10^{-6} N + 12.7 \times 10^{-2}, \ r=0.89 \quad \text{(F170 series)} \qquad (5c)$$

$$\delta_r = 20.0 \times 10\text{-}6 N + 25.5 \times 10\text{-}2, \ r=0.93 \quad \text{(F180 series)} \qquad (5d)$$

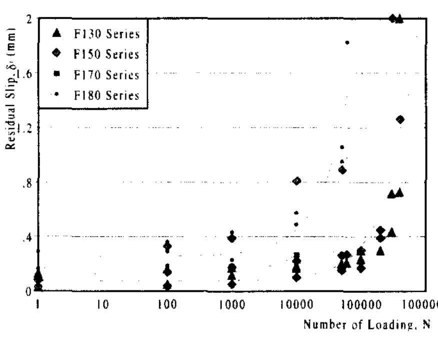


Fig. 10 Residual-slip curves

where δ_r is the residual slip (in mm), N is the number of loading and r is the correlation coefficient.

3. Composite Beam Test

3.1 Experimental Work

On the based of the results of the push-out tests, a simply supported composite beam with seven precast slabs was designed as shown in Fig. 11. Studs of 19mm diameter were arranged uniformly at 400mm pitch and three studs were used in each pocket. The degree of shear connection, defined as the strength of the shear connection in a shear span as a proportion of the strength required for full shear connection, was anticipated to be 1.11. In order to eliminate the effect of compression in the precast slab on the steel beam, composite action was achieved by filling the shear pocket for the stud connectors with mortar after introducing the longitudinal prestress.

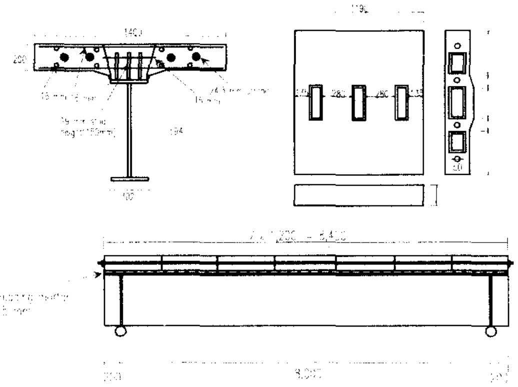


Fig. 11 Composite beam (dimensions in mm)

As shown in Fig. 12, slips was measured using 1/1000mm linear variable differential transducer, and longitudinal strains in the studs at 20mm above the root of the stud were measured to estimate the relative connector loads. Material properties of the stud are the same as those for the push-out specimen. The cylindrical compressive strengths of concrete for the precast slab and the mortar are 35.5MPa and 53.3MPa, respectively.

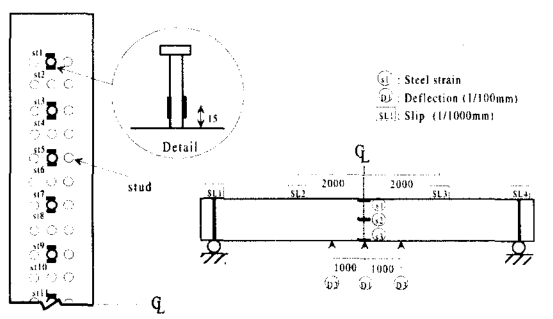


Fig. 12 Measurement positions (dimensions in mm)

Table 4 Test procedure for composite beam

Loading step	Maximum load (kN)	Minimum load (kN)	Range of longitudinal shear force (kN)	Number of loadings
Step 1	241.1	34.3	206.8	100,000
Step 2	346.9	34.3	312.6	100,000
Step 3	392.0	34.3	357.7	300,000

The test procedures are presented in Table 4. A single concentrated load was applied at midspan of the composite beam by a 490kN hydraulic actuator. After each step of fatigue loading, in logarithmic scale, static tests are carried out to examine the deterioration of the shear connections.

3.2 Fatigue Behaviour

The results of static tests and measurements of deflections and slip indicate that the shear connection behaviour of the specimen can be considered as a full interaction. The slip between the precast slab and steel beam was nearly zero until 1000 cycles of second step fatigue loading. The loadslip curves after bonding was broken are presented in Fig. 13. The residual slip is also presented in the figure and does not change significantly in magnitude for a given range. The loadslip response in Fig. 13 shows that the shear stud started to take shear loads at a load of about 73kN. Thus, the slip of the shear stud should show a sudden change.

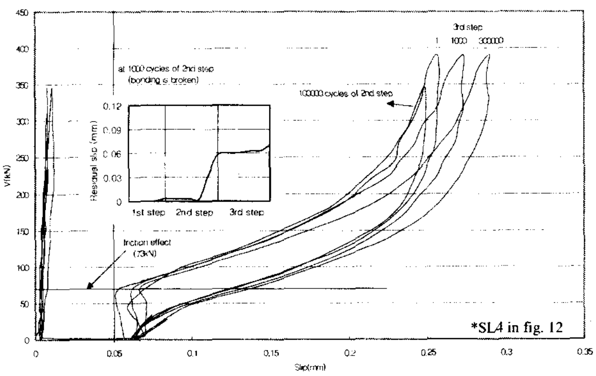


Fig. 13 Slip curves

The load redistribution from weaker connectors to stronger connectors can be seen from Fig. 14. In the figure, the strain in the stud at the support, that is, ST2, increases and becomes nearly the same as the other strains in the stud. Residual slip causes a redistribution between the stud shear connections in the shear span. Therefore, connectors can be assumed to fail at their mean endurance. These phenomena allow the uniform distribution of shear connectors in a shear span for fatigue loadings.

The flexural stiffness of the composite beam, the tangent stiffness evaluated from measured deflections as shown in Fig. 15, decreases by about 13% of the initial value after all the fatigue loadings were applied. The residual deflection after completing the fatigue tests was 0.74mm.

3.3 Bonding and Friction Effects

As shown in Fig. 14, the shear load carried by the shear connectors is negligible until the bonding and frictional resistance is overcome. Therefore, the bonding and friction between the precast slab and the steel beam increase the endurance of the shear connectors. After bonding was broken, the deflection of the composite beam increased by 12 % of the initial value not considering the residual value.

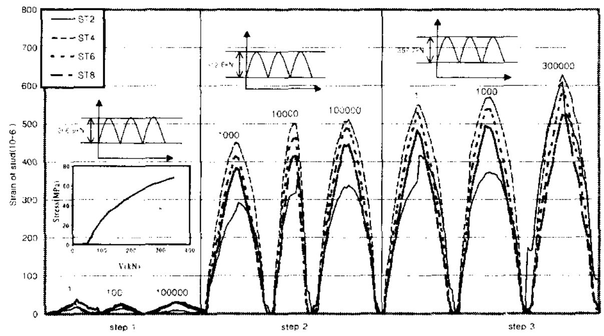


Fig. 14 Behaviour Studs during fatigue tests

The secant stiffness of a shear connection considering frictional resistance, K_{secnew}, suggested by Seracino et al.[10] can be evaluated from Fig. 13. The shear stiffness of a shear connection (K_{secnew}) from the measured slip value at the end of the second step of fatigue tests, without residual slip, evaluated by iterative analysis using partial interaction theory,[8,11] is 183.0 kN/mm. The tangent stiffness of a shear connection without the frictional effect is 155.0 kN/mm, which is 15% smaller than K_{secnew}. The initial shear stiffness of a shear connection(K_{si}) evaluated by means of Equation (2), is 171 kN/mm. Fig. 13 indicates that interfacial slip is prevented by friction when the shear force is less than the frictional resistance. This phenomenon could be observed from the fact that the strain in the stud was nearly zero and was not changed as the load increased up to a certain value. Therefore, the shear load on the connector was nearly zero as shown in the figure. After bonding was broken, the tangent stiffness of the shear connection was nearly constant during fatigue tests. The flexural behaviour of the composite beam is changed from full interaction to partial interaction, as shown in Fig. 15, when the shear load on the interface between the slab and the steel beam exceed the friction.

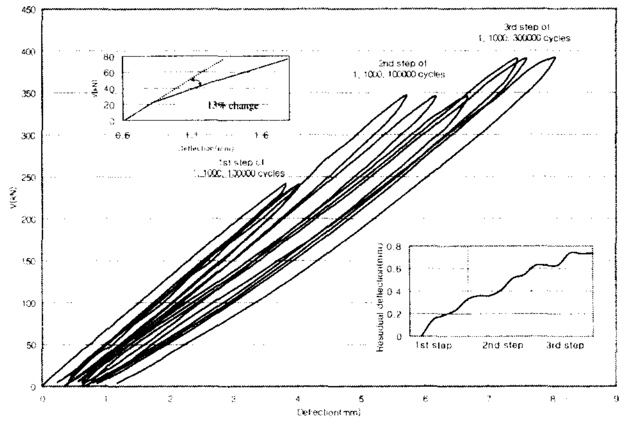


Fig. 15 Midspan deflection

4. Conclusions

In this paper the behaviour of shear connection in a full-depth precast concrete slab is investigated through push-out tests and finite element analyses. The static strength of the shear connection in the full-depth precast concrete slab agrees approximately with that evaluated from the tensile strength of the shear connectors since the bearing zone is relatively weak and cannot give enough constraint. The ultimate slip capacity of the shear connection in the full-depth precast slab is greater than in the case of CIP slabs owing to the effect of the bedding layer. On the basis of the mean value of the static strengths, an empirical equation for the relationship between the shear force range and the number of fatigue loadings at failure is suggested.

Before bonding and friction are broken, the behaviour of the specimen can be considered as full interaction. In evaluating an existing shear connection, the effects of bonding and friction on the fatigue endurance of the shear connection should be considered. The redistribution of connector loads from weaker connectors to stronger connectors can be seen from the results for slip and strain in stud shear connectors.

Parameter studies on the thickness of the bedding layer need to be carried out through further experiments in order to evaluate the effects of the bedding layer's thickness on the behaviour of shear connections with respect to strength, stiffness and ultimate slip capacity.

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