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Structural Behavior of Partially Filled Steel Grid Composite Deck

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Abstract**—**In order to apply partially filled steel grid composite deck as the horizontal supporting structure of various kinds of infrastructures, the variation of its flexural strength according to design parameters such as cross and longitudinal bars constituting the steel grid and the type of shear connection is evaluated and compared experimentally.The result shows that the design sensitivity of the deck to the spacing of the cross bars is insignificant in the case of structure withlow risk of punching failure or without load distribution problem.By means of shear connection composed by transverse rebarand longitudinal bar without additional shear stud bolts, the complete interaction between steel grid and concrete slab is able to be achieved and the composite deck can develop its bending resistance capacity.

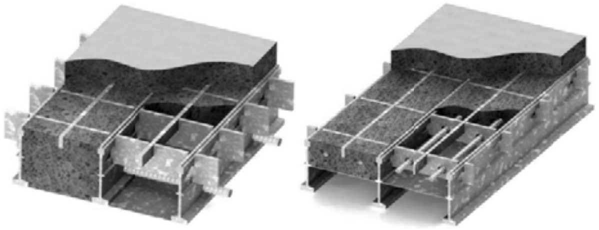
Keywords**—**bending strength,composite action, shear connection,steel grid composite deck

I. INTRODUCTION

STEEL grid composite deck as shown in Fig. 1 has large influence on the constructability and economic efficiency of bridges by reducing the weight of the slab and enabling fast construction in sites with large volume of traffic. This deck has been firstly introduced in 1930's and is still today the subject of continuous research and development to derive diversified sectional details[6]-[8].According to those researches partially filled steel grid composite decks permit a relative long-distance transportation and construction under unfavorable condition due to its comparatively light-weighter structural section property than fully filled grid decks. The structure of the deck considered in this study pertains to this class of partially filled steel grid composite deck. The steel grid is composed by T-beams to take charge of the flexural tension, cross bars connecting perpendicularly to the T-beams, andlongitudinal bars connected perpendicularly to the cross bars and parallel to the T-beams. The connection of the T-beam to the concrete slab is achieved by means of shear connection installed at the top of the T-beams.

In order to apply partially filled steel grid composite deck as the horizontal supporting structure of various kinds of infrastructures, the variation of its flexural strength according to various design parameters is evaluated and compared experimentally. The test variables chosen for the evaluation of the change of strength with respect to the sectional details are the cross and longitudinal bars constituting the grid and the type of shear connection.

The comparative evaluation of the bending and interface shear behavior is conducted through the analysis of the deflection and strain, and the slip between the concrete slab and steel grid. The force equilibrium method[1] based on partial shear connection method[5] is applied to evaluate the interface shear behavior by calculating the horizontal shear force at the composite interface.



(a) fully filled (b) partially filled

Fig. 1 Steel grid composite deck [7]

II. EVALUATION METHOD OF INTERFACE SHEAR FORCE

The performance of steel-concrete composite structures depends on the effective transfer of shear force at the interface between steel member and concrete slab by the shear connectors. The structural behavior of shear connector, for example load-slip relationship, is indirectly obtained by push-out test. However, several researchers [2]-[4][9] reported the impossibility to predict accurately the behavior of the real composite deck by using the load-slip behavior provided by the push-out test since the constraints existing between the steel member and concrete slab caused by external loads is different from that of the push-out test.Eurocode 4 [5]proposesthe partial shear connection(PSC) method to predict the structural behavior of the composite deck.However, Abdullah[1] reported that the PSC method cannot consider the effects of the shear span length and sectional condition on the moment resistance capacity, and proposed a method deriving the horizontal shear force and other sectional forces of structural members as expressed in (1).The assumptions for the derivation of the Equation are the uniformly distribution of the slip along the

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length of shear span, andthat steel deck remains fully effective up to the considered load.

$$\mathrm{F} = \mathrm{T} = \frac{\left(\frac{P}{2}L_s - M_r\right)}{z} \tag{1}$$

$$M_r = \frac{\delta_{L/4} - \delta_{3L/4}}{L_s(L - 2L_s)} E_s I_s \tag{2}$$

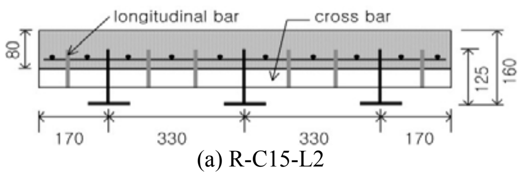
$$\mathrm{z} = \frac{1}{3}(2d + \frac{sL_s}{(\delta_{L/4} + \delta_{3L/4})}) \tag{3}$$

where F is the horizontal shear force at the composite interface; T is the tensile force in the steel deck;P is the applied load; $L_s$is the shear span length; M_r is the bending momentof the steel deck; z is the moment arm between tensile and compressive force; d is the distance from the top of the slab to the centroid of the steel member; s is measured end slip; $\delta_{L/4}$ and $\delta_{3L/4}$ are deflection at the position of applied loads.

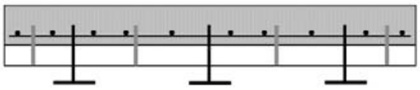
The force equilibrium method assumes that the distribution of slip is uniform along the shear span for the calculation of the member force. However, the actual slip distribution is just close to uniform but is not uniform. For verification and assessment of its applicability to the calculation of the horizontal shear force of steel grid composite deck, the moment arm, z, is determined from the strain distribution measured by strain gauges installed in the section and, this value is used for the calculation of the horizontal shear force. This shear force is then compared with the results obtained from the deflection and end slip.

III. EXPERIMENTAL PROGRAM

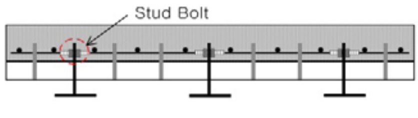
For the bending tests performed to evaluate the bending strength of the partially filled steel grid composite deck, a total of 5 specimens were fabricated by distinguishing 3 types of decks. The 3 types of slabs differentiate the method transferring the applied load to the main supporting structure that is the T-Beam, and type of shear connection.The types of the specimens are summarized in Table I. Fig.2 illustrates the sectional details of the major specimens. The design compressive strength of concrete is 30 MPa and the adopted steel for T-beam and supporting bars is SM400 [10].



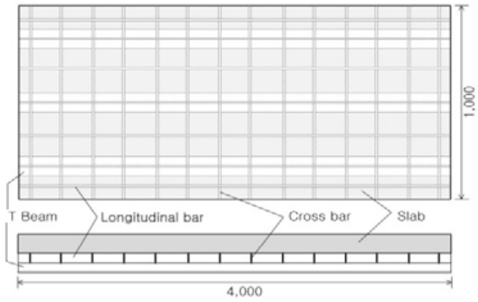
(a) R-C15-L2



(b) R-C30-L1



(c) SB-C15-L2



(d) composition of steel grid

Fig. 2 Details of steel grid composite deck

TABLE I
SPECIMENS FOR THE BENDING TEST

specimen	shear connection type	cross bar spacing (cm)	number of longit. bar	test parameter
R[a]-C15[b]-L2[c]	rebar +longit. bar (Type *R*)	15	2	standard specimen
R-C30-L1		30	1	cross and longit. bar
R-C30-L2		30	2	
R-C45-L2		45	2	cross bar
SB[a]-C15-L2	rebar +longit. bar + stud bolt (Type *SB*)	15	2	stud bolts

[a]R: rebar shear connection;[a]SB: additional stud bolt;[b]C15/C30/C45: cross bar spacing;[c]L1/L2: number of longitudinal bar

In the test, loading was applied through displacement control using an actuator with capacity of 1,000kN. Two-point linear loading with shear span of $L/4$ was realized using a loading beam to approximate the moment distribution under uniform loading condition. Three 200 mm-LVDTs were installed to measure the deflection and, two 50 mm-LVDTs were disposed at each end to measure the slip occurring between the steel grid and the concrete slab. Moreover, apart from the strain gauges bonded on the reinforcement during the fabrication of the specimens, strain gauges were installed at 5 spots in the flange and web of the T-beam and at 5 spots at the top and sides of the concrete slab.

IV. TEST RESULTS AND ANALYSIS

A. *Load-Deflection Relationship*

Fig.3 illustrates the deflected shape of the specimens at the end of loading.Table II arranges the measured test data of the load and displacement. The load-deflection curves for each type of test variables plotted in Fig.4are used for the comparative analysis of the bending behavior according to the test variables.

1.*Strength According to the Spacing of Cross Bar*

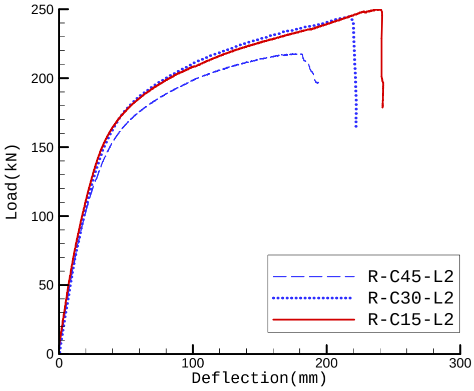
Fig. 4(a) compares the bending strength according to the change of the spacing of the cross bars as 15, 30 and 45 cm fulfilling the transfer of the applied load to the T-beam.

Fig. 3 Deflection under maximum loading condition

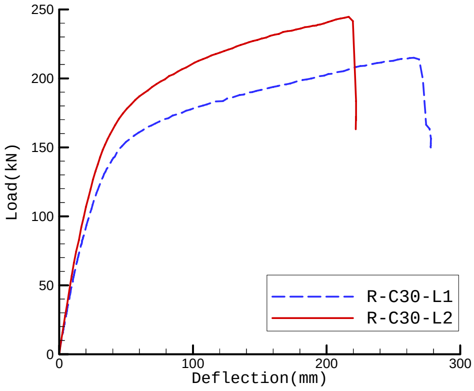
TABLE II
BENDING TEST RESULTS

specimen	P_{slip} (kN)	$\delta_{slip,max}$ (mm)	P_y (kN)	δ_y (mm)	P_{max} (kN)	δ_{max} (mm)	P_{max}/P_y
R-C15-L2	107.8	0.43	165.5	40.8	249.6	239.3	1.51
R-C30-L1	89.0	0.42	134.9	35.9	214.8	266.6	1.59
R-C30-L2	67.5	0.37	167.4	42.7	244.4	216.1	1.46
R-C45-L2	118.2	0.27	153.4	40.1	217.4	181.7	1.42
SB-C15-L2	151.1	0.19	178.2	43.1	241.0	200.2	1.35

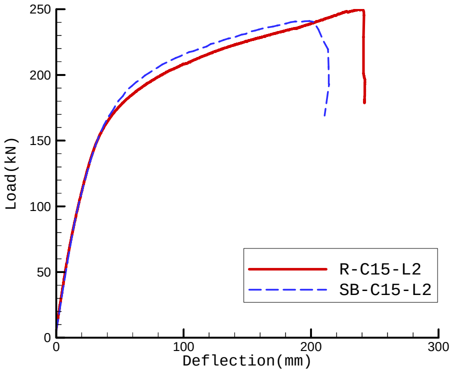
P_{slip}, P_y, P_{max}: applied load at initial slip, yielding and end of test; $\delta_{slip,max}$, δ_y, δ_{max}: maximum slip at the interface, deflection at yielding and maximum deflection



(a) spacing of cross bar

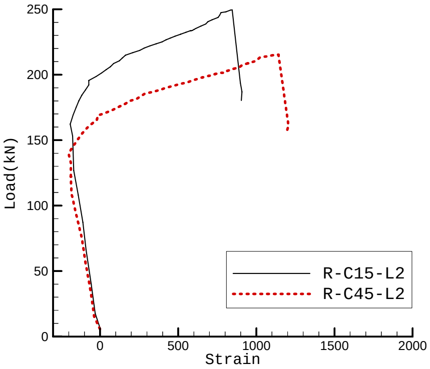


(b)number of longitudinal bar

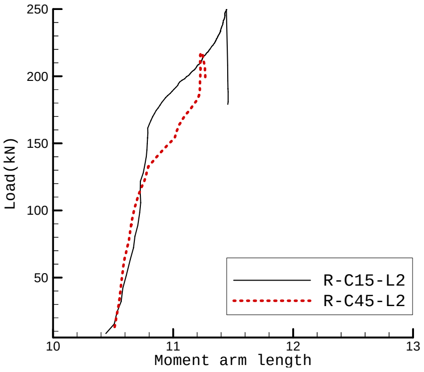


(c) shear connection type

Fig. 4 Load-deflection curve



(a) strain of rebar



(b) moment arm length

Fig. 5 Comparison of strain and moment arm length

(a) R-C15-L2

(b) R-C45-L2

Fig. 6 Comparison of crack pattern

It can be observed that there is practically no difference in the bending strength for spacing of 15 cm and 30 cm and, that the corresponding load-deflection curves are nearly identical. But, the bending strength reduces by about 15% when the spacing between the cross bars is 45 cm.

The crack pattern of the concrete slab observed during the test was analyzed to find out the cause of such reduction of the bending strength. As shown in Fig.6, the spacing of 45 cm between the cross bars allowed the propagation of inclined cracks due to flexural shear apart from the cracks initiated between the cross bars and at the top of the cross bars, which is a crack pattern fundamentally different from those exhibited by the other specimens. In relation with this result, the comparison of the strain of the main rebar in Fig.5(a) reveals that large spacing between the cross bars reduces the load at the point turning onto tensile state leading to the occurrence of larger strain for the same load. In addition, the comparison of the change of the moment arm of the sectional force obtained from the strain measured at the center of span in Fig.5(b) shows that the change of the neutral axis of the specimen with large spacing between the cross bars is larger for the same load, which means that the spread of plasticity through the section depth has made larger progress.

2.*Strength According to the Number of Longitudinal Bar*

The comparison of the bending behavior according to the change of the number of longitudinal bars in Fig. 4(b) indicates that the increase of the number of longitudinal bar from 1 unit to 2 units between the T-beams increases the bending strength by approximately 14%.

The improvement of the bending strength through the increase of the number of longitudinal bars can be explained by the subsequent increase of the bending stiffness and strength of the steel grid and, the improvement of the interface composite action following the enlargement of the contact area with concrete and the increase of the shear connection stiffness due to the shorter shear span of the transverse rebar supported by the longitudinal bars. Among these factors, the improvement of the bending strength caused by the increase of the interface composite action will be confirmed by the results of the evaluation of the composite action presented later in this paper.

3.*Strength According to Shear Connection Type*

Fig.4(c) compares the load-deflection curves according to the change of the shear connection type that are rebar and rebar+stud bolt. It was expected that the installation of stud bolts additionally to the rebar would increase the bending stiffness and strength, but the test results showed that the effect on the bending strength was insignificant.

B. *Evaluation of Interface Shear Force*

For the comparison of the behavioral characteristics of the specimens according to the shear connection type, the force equilibrium method calculating the horizontal shear force from the displacement(deflection and slip) or strain measured during the bending tests was applied. The corresponding results are arranged in Table III and Fig.7.In the Table, $K_{slip}$is the initial slip stiffness obtained from the horizontal shear force-slip curve after the first occurrence of slip, $F_{slip}$and F_y stand for the interface shear force obtained from measured strain ($F_{slip,s}$,$F_{y,s}$) or displacement ($F_{slip,d}$,$F_{y,d}$) at occurrence of initial slip and yielding of the specimen.

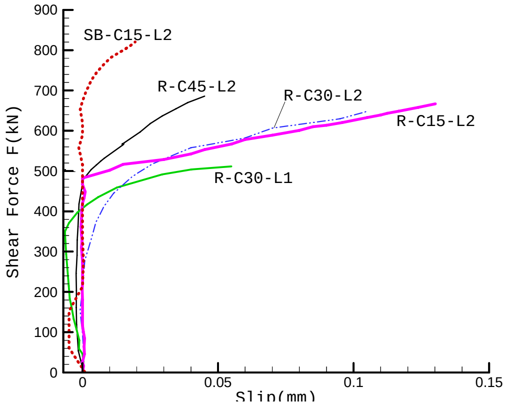


Fig. 7 Shear force-Slip curve

TABLE III
COMPARISON OF INTERFACE SHEAR STIFFNESS AND SHEAR FORCE

Shear connec. type	specimen	K_{slip} (kN/mm)	F_{slip} (kN)		F_y(kN)		(1)/(2)
			$F_{slip,s}$	$F_{slip,d}$	$F_{y,s}$ (1)	$F_{y,d}$ (2)	
R	R-C15-L2	1552	472.2	501.9	666.9	711.7	0.94
	R-C30-L2	2004	291.4	318.1	647.6	710.9	0.91
	R-C45-L2	3798	480.0	534.2	686.2	760.8	0.90
	R-C30-L1	934	351.4	378.1	511.5	545.9	0.94
SB	SB-C15-L2	4401	678.3	710.5	819.7	864.7	0.95

The comparison of specimens R-C30-L1 and R-C30-L2 differing by the number of longitudinal bars reveals the difference in the slip stiffness according to the reduction of the number of longitudinal bars. Considering that both specimens do not exhibit significant difference in their horizontal shear force at occurrence of initial slip, it can be assessed that the longitudinal bar has poor effect on the improvement of the bonding strength. The increase of the slip stiffness by the addition of longitudinal bars could be explained partially by the shortening of shear span of the transverse rebar supported by the longitudinal bars.

The comparison of the specimens of series R with those of series SB in which stud bolts are additionally installed shows large difference in the horizontal shear force at occurrence of initial slip and at yielding.In addition, the slip stiffness is larger by about 80% on the mean in the case of additional stud bolts, which indicates the improvement of the composite action through the addition of stud bolts.

The comparison of the horizontal shear force obtained from the measured strain distribution and displacements(deflection, end slip) shows that the horizontal shear force calculated using the displacement is larger by about 6 to 10%. This result can be explained by the possible introduction of error in the measurement of the strain and displacement, and the actual non-uniformity of the slip distribution along the shear span length contrarily to the assumption of the force equilibrium method. Further tests and finite element analysis should be conducted in the future to clarify the causes of such discrepancy. Within the scope set in this study, it is founded out that the horizontal shear force can be calculated using the measured strain or displacement within an error of about 10%.

C. *Comparison of Results from Test and Theory*

Table IV compares the bending strength, $M_{\max}$ obtained from the test with the theoretical bending strength, M_n calculated by means of the theory of plasticity assuming the complete interaction at the interface [5]. Moreover, considering that the horizontal shear force developed at the interface is equal to the compressive force acting on the concrete slab or to the tensile force acting on the steel member with respect to the equilibrium conditions, the horizontal shear force, $F_{\max}$, calculated from the measured strain is also compared to the horizontal shear force, F_n, derived from the theory of plasticity.

TABLE IV
COMPARISON OF BENDING STRENGTH AND SHEAR FORCE BY TEST AND THEORY

Shear connec. type	specimen	$F_{\max}$ (kN)	F_n (kN)	$F_{\max}/F_n$	$M_{\max}$ (kNm)	M_n (kNm)	$M_{\max}/M_n$
R	R-C15-L2	864	740	1.17	124.8	89.0	1.40
	R-C30-L2	825		1.11	122.2		1.37
	R-C45-L2	870		1.18	108.7		1.22
	R-C30-L1	765		1.03	107.4		1.21
SB	SB-C15-L2	911		1.23	120.5		1.35

The results reveal that most of the specimens develop bending strength larger by more than 15% than the theoretical values. In addition, it is also verified that the specimens can sustain horizontal shear force corresponding to theoretical complete interaction; a maximum slip of 0.43 mm occurred according to the degree of shear connection. Despite of some difference in the bending strength, the maximum slip occurring until the maximum load was very small and, the corresponding horizontal shear force was seen to exceed the shear resistance capacity provided by complete interaction. Therefore, the evaluation of the resistance capacity of the steel grid composite deck in this study can be conducted based on the theory of plasticity assuming complete interaction.Furthermore, the bending strength developed by the specimens with cross bar spacing of 45 cm appeared to be smaller than that of the specimens with cross bar spacing of 15 cm due to the stiffness of the steel grid, load distribution and occurrence of flexural shear cracks in the slab. However, since the actual bending strength of the specimens with cross bar spacing of 45 cm was larger by 22% than the theoretical value, the design sensitivity of the deck to the spacing of the cross bars is insignificant in the design in the case where the steel grid composite deck is used in structure with low risk of punching failure or without load distribution problem caused by the application of concentrated load.

V. CONCLUSION

The following conclusions could be drawn from the corresponding results.

- In the case where the steel grid composite deck is used in structure with low risk of punching failure or without load distribution problem caused by the application of concentrated load, it is founded out that the design sensitivity of the deck to the spacing of the cross bars is insignificant in the design.
- The improvement of the composite action owing to the increase of longitudinal bars in the steel grid is attributable to the increase of the shear stiffness brought by the shortening of shear span of the transverse rebar supported by the longitudinal bars rather than to the increase of the bonding strength at contact area. Further tests and analyses are required to clarify this feature.
- By means of shear connection composed by longitudinal bar and transverse rebar at spacing of 150mm without additional stud bolts, the composite deck can develop bending resistance capacity close to the case of theoretical complete interaction.
- The results obtained from assessment of applicability of force equilibrium method to the calculation of the horizontal shear force of steel grid composite deck shows that the horizontal shear force can be calculated using the measured strain or displacement within an error of about 10%.

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