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Analytical Study on a Longitudinal Joints of the Slab-Type Modular Bridges

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***Abstract*—**In this study, a longitudinal joint connection was proposed for the short-span slab-type modular bridges with rapid construction. The slab-type modular bridge consists of a number of precast slab modules and has the joint connection between the modules in the longitudinal direction of the bridge. A finite element based parameter analysis was conducted to design the shape and the dimensions of the longitudinal joint connection. Numbers of shear keys within the joint, height and depth of the shear key, tooth angle, and the spacing were considered as the design parameters. Using the local cracking load at the corner of the shear key and the cross-sectional area of the joint, an efficiency factor was proposed to evaluate the effectiveness of the longitudinal joint connection. The dimensions of shear key were determined by comparing the cracking loads and the efficiency factors obtained from the finite element analysis.

***Keywords*—**precast, slab bridge, modular bridge, shear key

I. Introduction

PRECAST slab bridge is a suitable bridge type for the replacement of a short-span bridge which needs a rapid construction especially in urban area, where a severe traffic jam may occur during the construction. The national bridge inventory in Korea indicates that, among the bridges over 30 years in service, 87% of them are the short-span bridges. Their span length is less than 20 m [1]. It is expected that the demand for the replacement of the short-span bridge will be dramatically increased in the near future. A slab-type modular bridge has been proposed in this study in order to prepare the demand for the replacements of the short-span bridges.

The slab-type modular bridge proposed in this study consists of a number of precast slab modules segmented in the transverse direction. The modules are connected by filling the longitudinal joints between the modules with high strength mortar and prestressing tendons in the transverse direction. The nominal compressive strengths of the concrete used for the precast modules and joints are 50 MPa and 80 MPa, respectively. The curing time of the filling concrete required to develop 80% of the nominal compressive strength is about 7 days. The construction time of the precast slab modular bridge is dominated by the curing time of the filling concrete, because the slab-type modular bridge is completed by the prestressing work after curing the filling concrete. Accordingly, the short curing time of the filling concrete can reduce the construction time of the bridge.

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Fig. 1 Concept of a slab type of modular bridge

The longitudinal joint of the slab-type modular bridge has to transfer the shear force induced by the service load. Usually, the shear key is formed to increase the shear stiffness and shear capacity. The longitudinal joints have the shear keys to transfer the shear force. The joints with shear keys transfer the shear force by the direct diagonal compression force, friction force, and dowel action mobilized due to shear displacements at the interface between the prefabricated concrete slab and the insitu

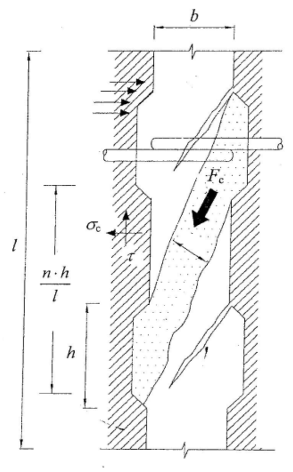

Fig. 2 Model for the shear transfer [2]

joint concrete. The shear keys work as mechanical locks preventing any significant slip along the joint. The maximum shear capacity of the joints is governed by the failure of shear keys. Significant shear slip may occur when the shear key effect is reduced by shearing cracks along the joint or by local cracking or crushing of the shear key corners [3].

Since the shear stress and the local stress of joints are influenced by the shape of the joint, the shear capacity of the joint having the shear key is influenced by the dimension of joint including the shear key. Meanwhile, the material cost of the joint concrete used for the precast slab modular bridge is over three times the cost of the normal concrete. Increasing the cross-sectional area of the joint increases the material cost as well as the construction cost. Therefore, the dimensions of the joint have to be decided in consideration of the shear capacity and the material cost.

In this study, a longitudinal joint connection was proposed for the short-span slab-type modular bridges with rapid construction. The slab-type modular bridge consists of a number of precast slab modules and has the joint connection between the modules in the longitudinal direction of the bridge. A finite element based parameter analysis was conducted to design the shape and the dimensions of the longitudinal joint connection. Numbers of shear keys within the joint, height and depth of the shear key, tooth angle, and spacing were considered as the design parameters. Using the local cracking load (P_{cr}) at the corner of the shear key and the cross-sectional area of the joint, an efficiency factor was proposed to evaluate the effectiveness of the longitudinal joint connection. The dimensions of shear key were determined by comparing the cracking loads and the efficiency factors obtained from the finite element analysis.

II. Finite Element Analysis

A. Parameters and Cases of Analysis

The slab-type modular bridge designed with 10 m span length has been used for the parameter analysis. The thickness of the designed slab-type modular bridge is 450 mm. Fig. 3 shows the shapes of the longitudinal joints with single shear key and double shear keys. The parameters related to the dimensions of joint are numbers of shear keys (N), tooth angle (β), depth (D) and height (H) of shear key, and spacing (S) between precast slabs. To verify the effect of the number of shear keys on the shear capacity, the number of shear keys is considered as the design parameter. Usually, the single shear key is formed in the typical joints of precast bridge deck. The ranges of the parameters are decided by considering the references [3] and [4]. Table 1 shows the analysis cases and the parameters for each case.

B. Finite Element Model

The finite element analysis is conducted using the ABAQUS [5]. Fig. 4 shows the 2-dimensional finite element model with double shear keys as an example. The plain strain element with

TABLE I
ANALYSIS CASES AND PARAMETERS

Analysis Case	N	D (mm)	H (mm)	β(°)	S (mm)
S1_D20_H40_@30	1	20	40	30	20
S1_D20_H60_@30	1	20	60	30	20
S1_D20_H80_@20	1	20	80	20	20
S1_D20_H80_@30	1	20	80	30	20
S1_D20_H80_@40	1	20	80	40	20
S1_D20_H100_@20	1	20	100	20	20
S1_D20_H100_@30	1	20	100	30	20
S1_D20_H100_@40	1	20	100	40	20
S1_D20_H120_@30	1	20	120	30	20
S1_D30_H60_@30	1	30	60	30	20
S1_D30_H90_@30	1	30	90	30	20
S1_D30_H120_@20	1	30	120	20	20
S1_D30_H120_@30	1	30	120	30	20
S1_D30_H120_@40	1	30	120	40	20
S1_D30_H150_@20	1	30	150	20	20
S1_D30_H150_@30	1	30	150	30	20
S1_D30_H150_@40	1	30	150	40	20
S1_D30_H180_@30	1	30	180	30	20
S1_D40_H80_@30	1	40	80	30	20
S1_D40_H120_@30	1	40	120	30	20
S1_D40_H160_@30	1	40	160	30	20
S1_D40_H200_@30	1	40	200	30	20
S1_D40_H240_@30	1	40	240	30	20
S2_D10_H30_@30	2	10	30	30	20
S2_D10_H40_@20	2	10	40	20	20
S2_D10_H40_@30	2	10	40	30	20
S2_D10_H40_@40	2	10	40	40	20
S2_D10_H50_@20	2	10	50	20	20
S2_D10_H50_@30	2	10	50	30	20
S2_D10_H50_@40	2	10	50	40	20
S2_D10_H60_@30	2	10	60	30	20
S2_D20_H60_@30	2	20	60	30	20
S2_D20_H80_@20	2	20	80	20	20
S2_D20_H80_@30_t10	2	20	80	30	10
S2_D20_H80_@30	2	20	80	30	20
S2_D20_H80_@30_t30	2	20	80	30	30
S2_D20_H80_@40	2	20	80	40	20
S2_D20_H100_@20	2	20	100	20	20
S2_D20_H100_@30	2	20	100	30	20
S2_D20_H100_@40	2	20	100	40	20
S2_D20_H120_@30	2	20	120	30	20
S2_D30_H90_@30	2	30	90	30	20
S2_D30_H120_@30	2	30	120	30	20

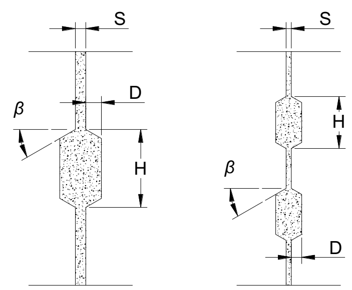

Fig. 3 Shape of longitudinal joint – single shear key & double shear keys

250 mm thickness was used for the model. The frictional coefficient (0.65) is applied on the interface between precast concrete (blocks on both sides) and joint. The lateral displacement is restrained on both sides (left side and right side) and the vertical displacement of the left side is restrained. The vertical load (shear force) is applied on the reference point coupled with the vertical displacement of the right side. The applied vertical load is 100 kN.

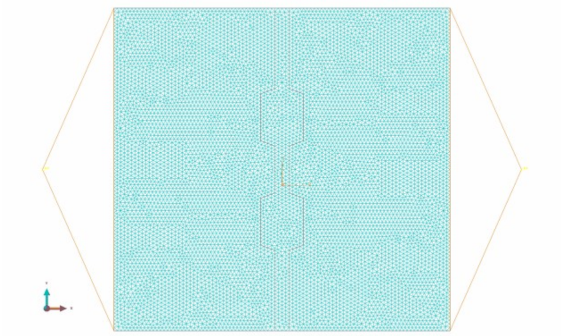

Fig. 4 Finite element model for shear key

III. Result of Analysis

A. Cracking Load, P_{cr} with height of shear key

Fig. 5 shows the distribution of the maximum principal stress σ_{11}. The peaks of σ_{11} are appeared at the shear key corners. It means that the crack is initiated at the shear key corner, and the cracking load P_{cr} inducing σ_{11} as much as the modulus of rupture $0.63\sqrt{f_{ck}}$ can be considered as the elastic limit. P_{cr} can be calculated from the peak of σ_{11} using the equation expressed in (1).

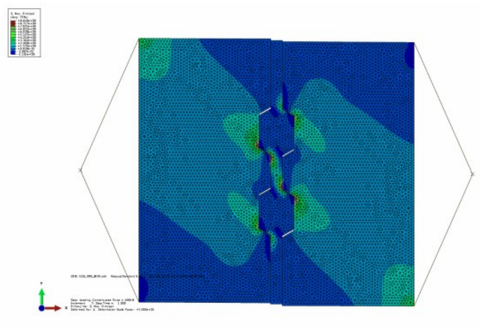

Fig. 5 Contour of maximum principal stress

$$P_{cr} = (\sigma_{11} / 0.63\sqrt{f_{ck}})P_{applied} \tag{1}$$

Where f_{ck} is the nominal compressive strength of the concrete in MPa; $P_{applied}$ is the applied vertical load on the finite element model (100 kN).

Fig. 6 shows the cracking load calculated from the peak of σ_{11} at shear key corner of the slab concrete with height of the shear key. Fig. 7 shows the cracking load calculated from the peak of σ_{11} at shear key corner of the joint concrete with height of the shear key. Since the compressive strength of the joint concrete (80 MPa) is higher than the compressive strength of the slab concrete (50 MPa), the cracking load of the slab concrete is much less than the cracking load of the joint concrete. For this reason, as shown in Fig. 8, the cracking load of the joint with shear key is dominated by the cracking load of the slab concrete in most of the analysis cases.

In Fig. 8, except the case of S2-D10, the cracking loads of analysis cases having double shear keys are greater than that of analysis cases having single shear key. The cracking load of the joint having double shear keys decreases as the depth of the shear key decreases. In cases of the joint having single shear key, the cracking load of joint decreases in the same manner.

According to the cracking loads of analysis cases, the longitudinal joint having double shear key, depth of shear key more than 20 mm, and height of shear key around 100 mm is considered to be appropriate.

B. Efficiency Factor, C_{eff} with height of shear key

The dimensions of the joint have to be decided in consideration of the shear capacity and the material cost. The efficiency factor C_{eff}, which represents the cracking load in unit cross-sectional area of the joint, is proposed to verify the effectiveness of the joint. The efficiency factor C_{eff} can be calculated from the cracking load and the cross-sectional area of the joint using the equation expressed in (2).

$$C_{eff} = 1{,}000(P_{cr} / A_{joint}) \tag{2}$$

Where P_{cr} is the cracking load of the joint in kN; A_{joint} is the cross-sectional area of the joint in mm^2.

Fig. 9 shows the comparison of the efficiency factors of the analysis cases with height of the shear key. The efficiency factor decreases as the height of shear key increases in similar manner of the P_{cr}. The efficiency factors of joints having double shear keys are maintained around the value of 3 in range of their heights of shear key, while the efficiency factors of joints with single shear key decrease extremely as height of shear key increases. This result indicates that the joint with double shear keys may increase the shear capacity without great increase of the cross-sectional area of the joint. That is, the joint with double shear key is more efficient.

Fig. 10 shows the efficiency factors of the joints with double shear keys. The highest efficiency factor is appeared in case of S2-D20 (20 mm depth of shear key) with 80 mm height of the shear key. The maximum efficiency factor of S2-D10 (depth of shear key is 10 mm) shows similar value in case of S2-D20. However, as shown in Fig. 8, the cracking load is much lower than the cracking load of S2-D20. Therefore, the longitudinal joint having double shear keys, 20 mm depth, and 80 mm height of shear key may be considered to be the most efficient.

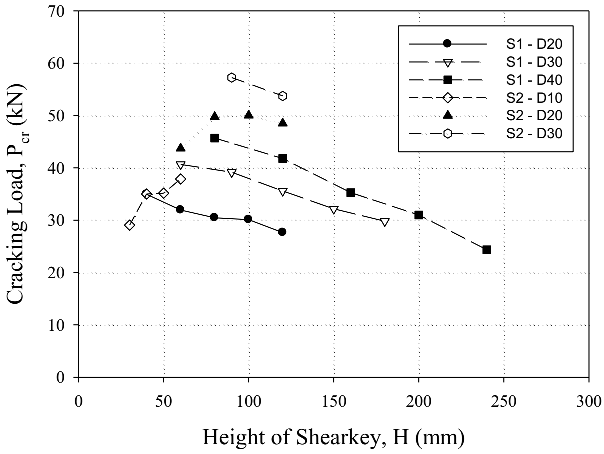

Fig. 6 Cracking load based on the slab concrete (β = 30˚, S = 20 mm)

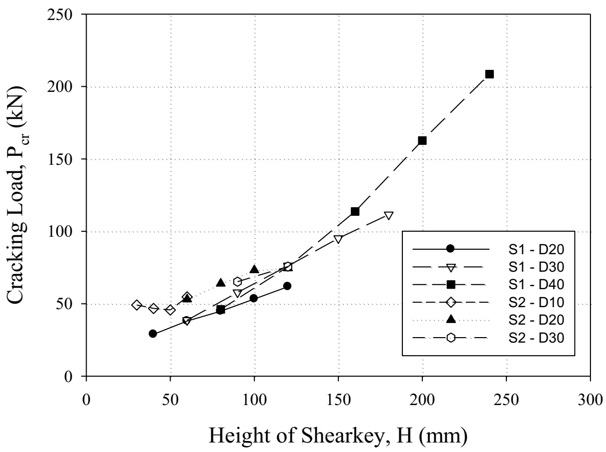

Fig. 7 Cracking load based on the joint concrete (β = 30˚, S = 20 mm)

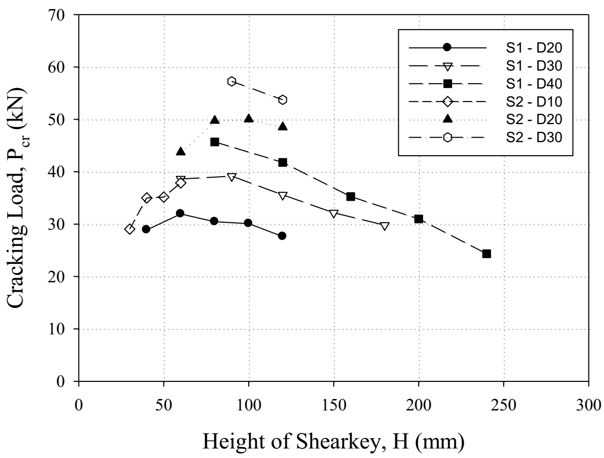

Fig. 8 Minimum cracking load (β = 30˚, S = 20 mm)

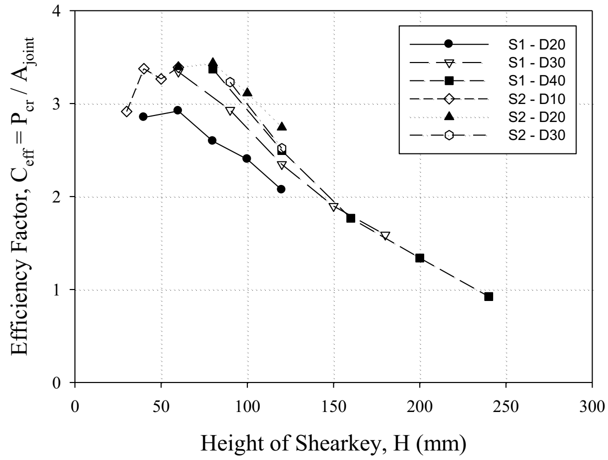

Fig. 9 Efficiency factor with height of shear key (β = 30˚, S = 20 mm)

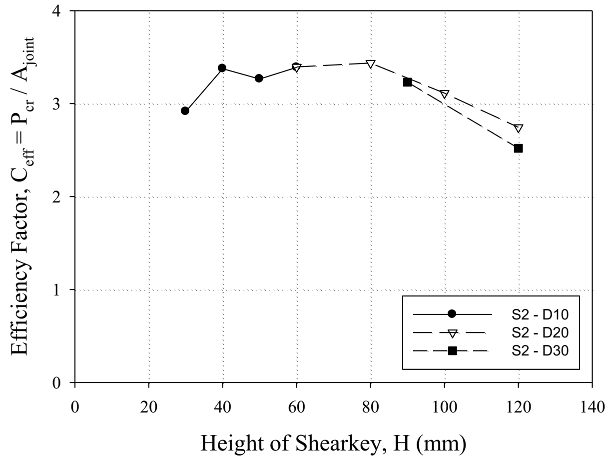

Fig. 10 Efficiency factor with height of shear key : double shear keys (β = 30˚, S = 20 mm)

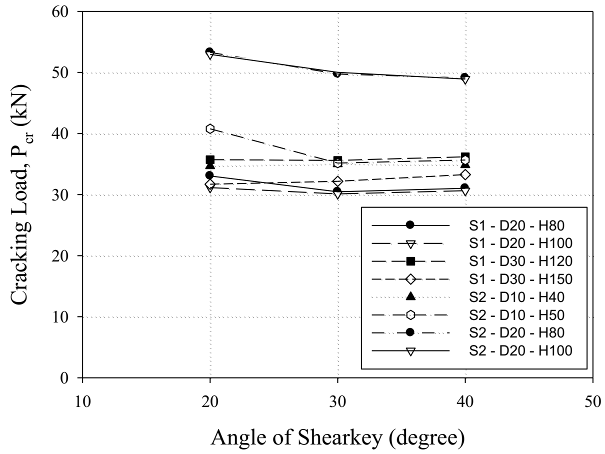

Fig. 11 Cracking load with tooth angle (S = 20 mm)

C. Effect of tooth angel (angle of shear key)

Fig. 11 shows the cracking load with the tooth angle of shear key. The cracking load does not vary significantly with the tooth angle of shear key, and the variation of the tooth angle may change the area of joint little. The recommended value of the tooth angle is about 25˚ in reference [3]. According to Eurocode 2, the tooth angle should be less than or equal to 30˚ [6]. In this study, the tooth angle of shear key is decided as 30˚.

D. Effect of spacing

Fig. 12 and Fig. 13 show the cracking loads and the efficiency factors with the variation of the spacing between the precast slabs. The change of spacing does not affect the cracking load, while efficiency factor increase significantly as the spacing is reduced. This is because the much of the cross-sectional area of the joint is reduced as the spacing decreases. Therefore, it is favorable to reduce the spacing between the precast slabs when the workability is guaranteed.

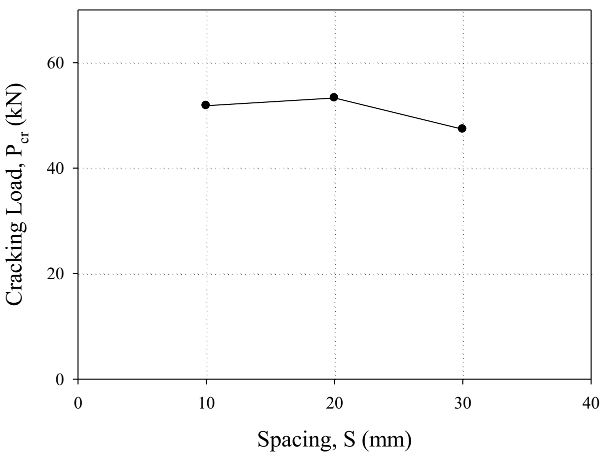

Fig. 12 Cracking load with spacing
(N = 2, D = 20 mm, H = 80 mm, β = 30˚)

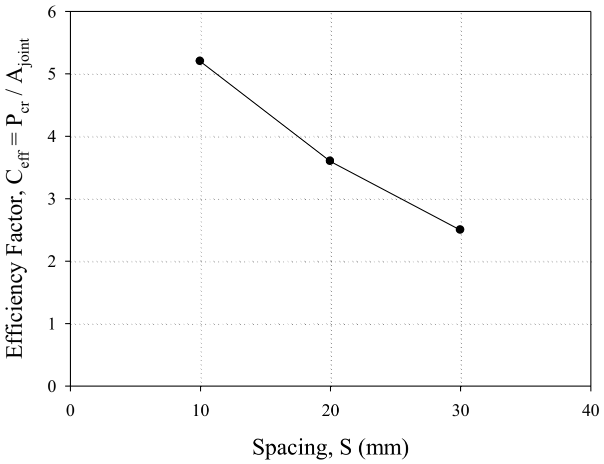

Fig. 13 Efficiency factor with spacing
(N = 2, D = 20 mm, H = 80 mm, β = 30˚)

E. Appropriate dimension of shear key

From the results of the parameter analysis using finite element model, the most efficient shape of the longitudinal joint connection and the dimensions for the precast slab modular bridge (span length is 10 m) are decided as shown in Fig. 14.

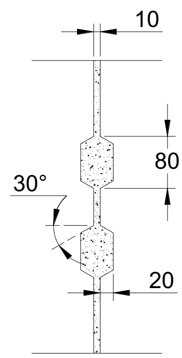

Fig. 14 Dimensions of longitudinal joint for the precast slab modular bridge (span length is 10 m)

IV. Conclusion

In this study, a finite element based parameter analysis was conducted to design the shape and the dimensions of the longitudinal joint connection in the slab-type modular bridge. From the results of the parameter analysis, the following conclusions can be made about the shape of the longitudinal joint connection.

1. The minimum local cracking load at the corner of the shear key is dominated by the local crack of the precast slab.
2. Generally, increase of the height and decrease of the depth of the shear key may decrease the local cracking load and the efficiency of the joint connection.
3. The usage of the double shear keys in the joint connection may increase the local cracking load and improve the efficiency of the joint connection.
4. The change of the spacing between the precast slabs does not affect the cracking load, while efficiency factor increases significantly as the spacing is reduced.
5. It may be favorable to use a number shear keys and reduce the spacing of the joint in order to improve the shear capacity and the efficiency of the joint connection with shear key

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