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Flexural Behavior of Continuous Composite Bridges with Precast Concrete Decks

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Abstract

For the construction of open-topped steel box girder bridges, prefabricated concrete slab could offer several advantages over cast-in-situ deck including good quality control, fast construction, and elimination of the formwork for concrete slab casting. However, precast decks without reinforcements at transverse joints between precast slabs should be designed to prevent the initiation of cracking at the joints, because the performance of the joint is especially crucial for the integrity of a structural system. Several prestressing methods are available to introduce proper compression at the joints, such as internal tendons, external tendons and support lowering after shear connection. In this paper, experimental results from a continuous composite bridge model with precast decks are presented. Internal tendons and external tendons were used to prevent cracking at the joints. Judging from the tests, precast decks in negative moment regions have the whole contribution to the flexural stiffness of composite section under service loads if appropriate prestressing is introduced. The validity of the calculation of a cracking load for serviceability was presented by comparing an observed cracking load and the calculated value. Flexural behavior of the continuous composite beam with external prestressing before and after cracking was discussed by using the deflection and strain data.

Keywords:continuous composite brodge, precast concrete deck, cracking, external prestressing

1. Introduction

For medium span bridges, composite box girders can be an attractive form of construction. Two different types of box girders may be considered – those where complete closed steel boxes are fabricated, and those where an open 'U' section is fabricated. For either class, the box section may be either rectangular or trapezoidal. Prefabricated slab could be effectively applied to the open-topped steel box girder bridges because formwork for concrete slab can be avoided. There are many kinds of precast slab and they are characterized into two groups; prefabricated slabs with reinforced joint or nonreinforced joint. Fig. 1 shows an overview of a precast deck bridge which is dealt with in this paper. It is necessary to introduce longitudinal prestress because there is no reinforcements in the joints.

Although there would be considerable prestress losses in prestressed steel bridges, it is necessary to introduce prestress by internal or external tendons for the crack prevention at the joints of prefabricated concrete slabs. Especially for continuous open-topped steel box girder bridges, the combination of two prestressing methods, internal tendons before shear connection and external tendons after shear connection, is recommendable from the previous research results[2,3,7)]. Experimental and theoretical studies have been undertaken to develop the design guides for composite bridges with prefabricated slabs. From this studies, the most significant consideration in design of steel-concrete composite bridges with full-depth prefabricated slabs is the serviceability such as cracking and leakage at the joints[2,3,7)]. A precast slab bridge has two types of connections; shear connection between the steel box girder and the precast deck and transverse joints between precast panels. The transverse joint in this prefabricated slab is a female-to-female type.

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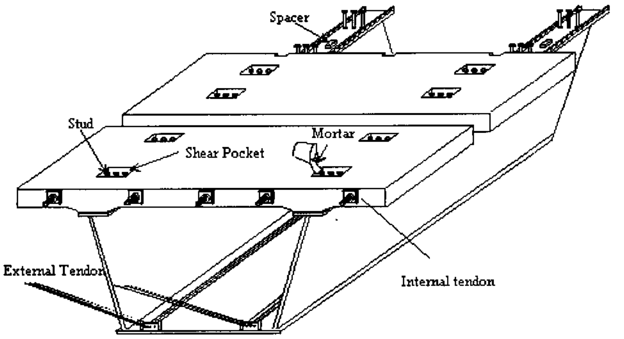


Fig. 1 Overview of a precast deck bridge

A continuous steel box gider bridge with precast decks was fabricated and static tests were performed. Internal tendons and external tendons were used together for the crack control at the joints. The experimental results from the model are presented and discussed in this paper.

For the full-depth prefabricated slab of this research, there is no reinforcement in the transverse joints except longitudinal prestressing tendons as shown in Fig. 1. Therefore, it is necessary to prevent the initiation of cracks in transverse joints. It means that the joints should be in compression under service loadings. Proper prestress should be introduced to the joints in negative moment regions as well as in positive moment regions. It is more complicated to control cracking for continuous composite bridges with precast slabs.

Bending of the main beams results in compressive stresses in mid-span regions of the deck slab and these are normally well within the compressive resistance of the concrete. However, local tensile stresses due to wheel loads should be calculated, especially for concrete slab with wider girder spacing. In positive moment regions, relatively small amount of prestress is required to make sure service ability. For negative moment regions, tensile stresses over intermediate supports due to global effects also should be evaluated to determine the magnitude of the longitudinal prestress. Fig. 2 shows the basic concept of longitudinal prestress. From the previous research[8)], it is worth noting that it is necessary to introduce prestress after shear connection, which can be obtained by lowering an intermediate support or external prestressing, for ensuring enough compressive stress behind shear pockets. Especially for continuous composite bridges, prestressing by internal tendons, which is done before shear connection, cannot make sure to introduce enough compression at the concrete slab and joints in the negative moment regions. Therefore, it is necessary to use two kinds of prestressing method for economical construction of precast decks in continuous composite bridges[8)]. There could be alternatives such as shear connection detail without shear pockets or reinforced joints in negative regions.

For the design of prestressed steel bridges, it is very important to estimate the prestressing losses because the losses are considerably high[1,5)]. Therefore, advantages of precast decks should be considered in the design of precast deck bridges for economical constructions. For example, prefabrication of the precast panels can reduce the losses by shrinkage and creep of concrete.

For ensuring serviceability limit state, the tensile stresses at the transverse joints should be prevented so that the flexural stiffness of a composite section in a negative region can be evaluated including uncracked concrete slab. After cracking, the behavior of composite bridges at ultimate limit state needs to be investigated through experiments.

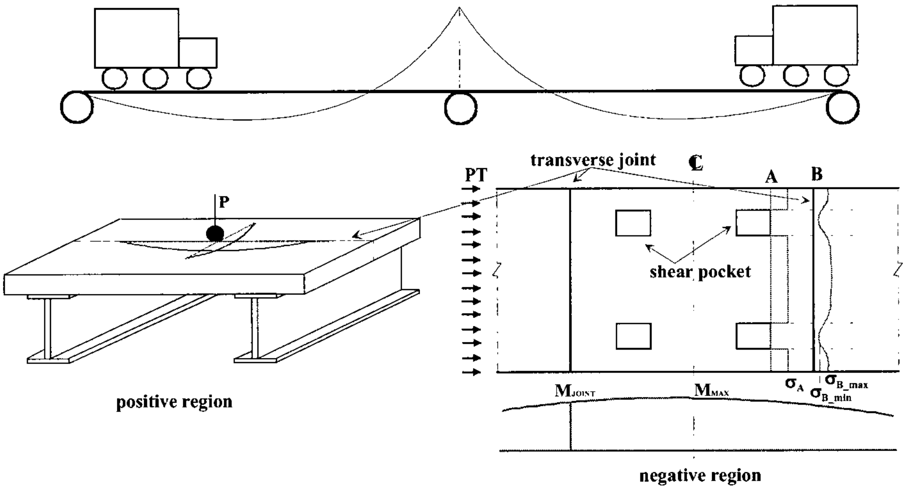


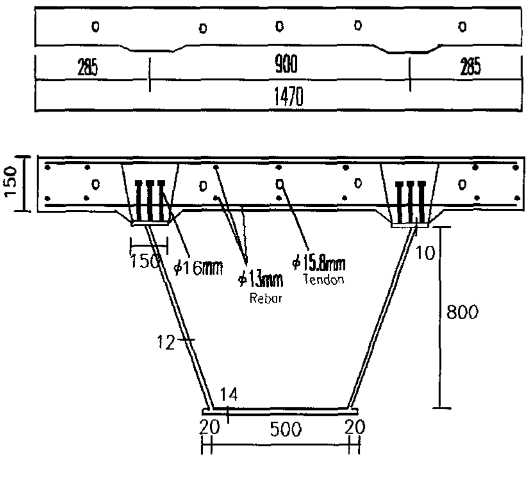
Fig. 2 Design concept for continuous composite bridges

2. Experimental work

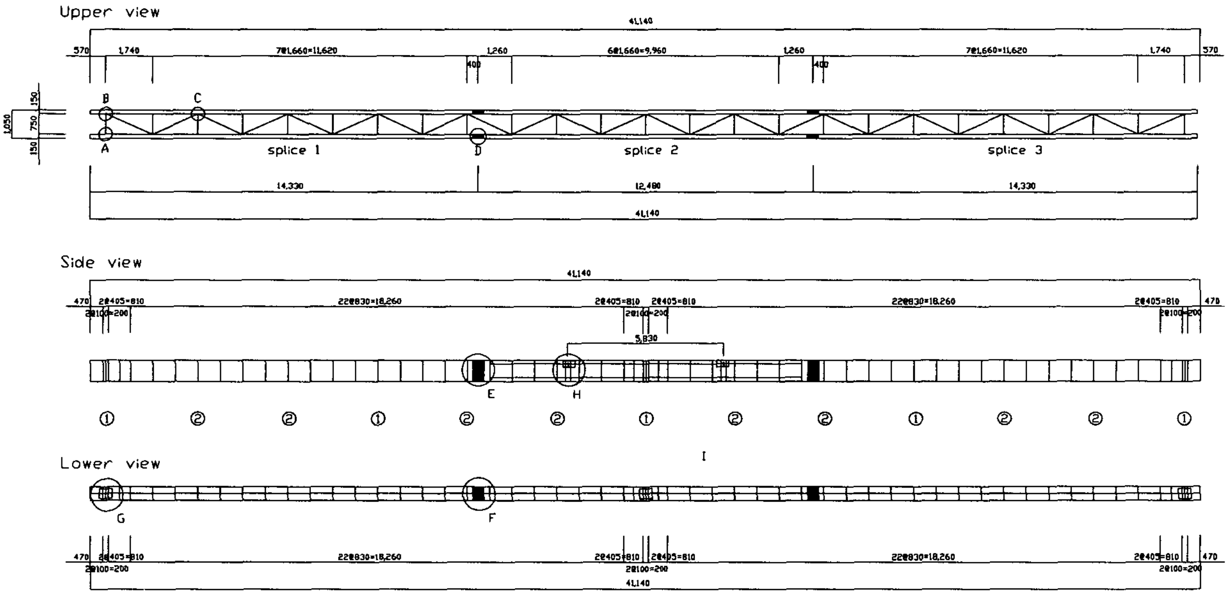
2.1 Test specimens

A continuous composite box section of open-topped steel trapezoidal box with prefabricated slabs, CBG2, were fabricated. The model has 20m-20m span length and external prestress was introduced to the composite section in the negative moment region. Fig. 3 illustrates the composite section and details.

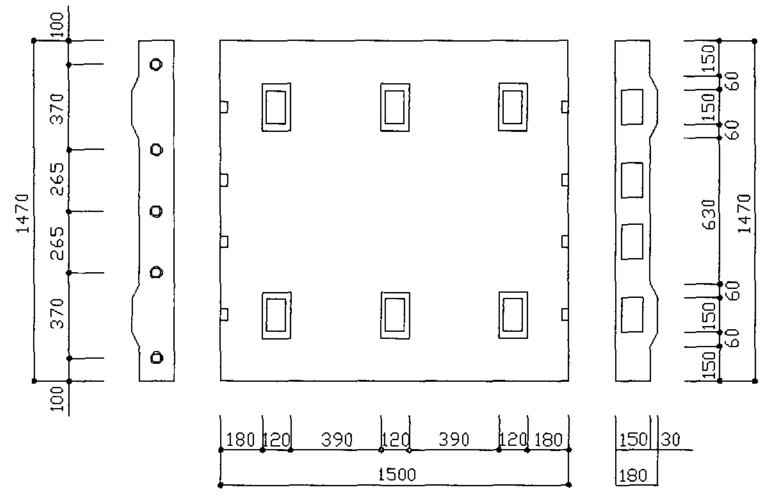
Three pieces of the girder were connected at the inflection points by high tension bolts as shown in the plan view of Fig. 3(b). The precast panel was 150 mm thick and had three shear pockets for stud connectors as presented in Fig. 3(c). Stud shear connectors of 16mm were welded with 510 mm spacing for full shear connection. Five internal tendons



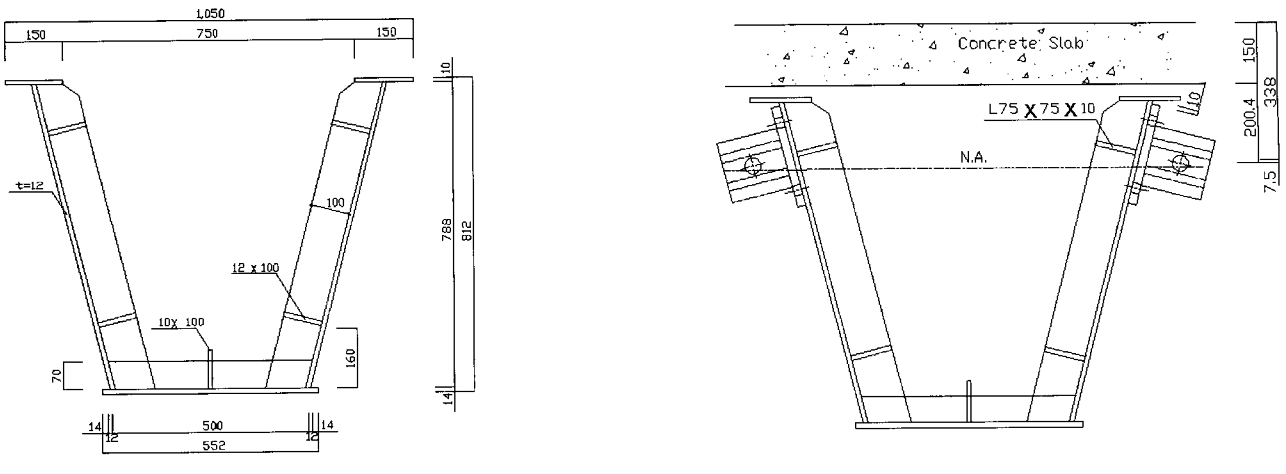
(a) Cross section



(b) Plan view



(c) Precast deck (continued)



(d) Steel section

(e) Anchorage for external cable

Fig. 3 Test specimen

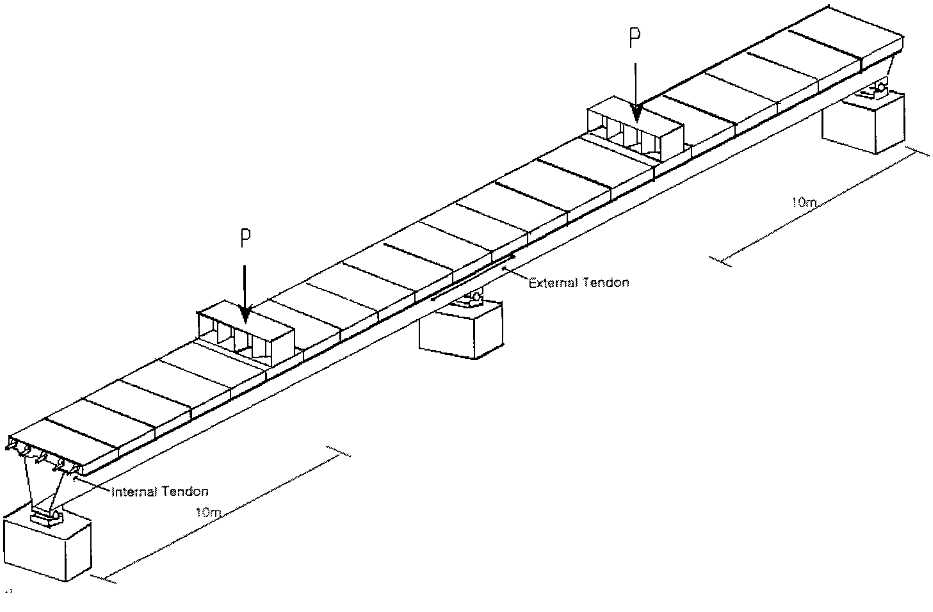


Fig. 4 Test setup

of 15.8 mm diameter were used for the longitudinal prestress before shear connection. Vertical and longitudinal stiffeners were welded to prevent buckling failure before flexural failure as shown in Fig. 3(d). Two external tendons were tensioned after shear connection as presented in Fig. 3(e).

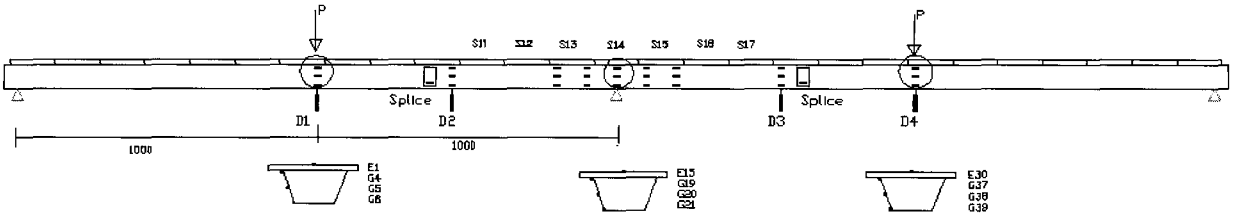
2.2 Loading and measurements

Two concentrated loads were applied at both mid-spans of the bridge models by a closed loop electro-hydraulic testing system as shown in Fig. 4. Static tests were done to investigate the elastic and inelastic behavior of the prefabricated deck bridge.

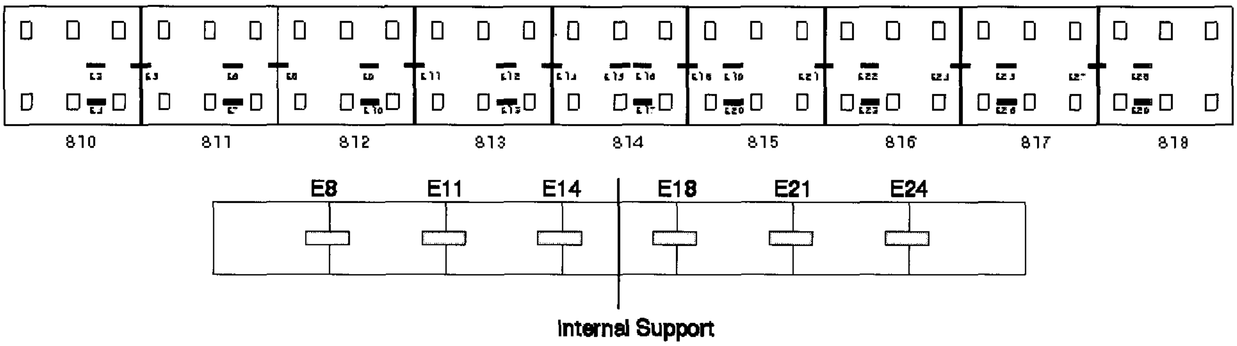
Displacements of the continuous bridge were measured at each mid-span with LVDT, and relative displacements (slips) between the steel girder and the concrete slab were also measured as in Fig. 5(a). Several strain gages were installed on composite sections. After cracking, crack widths were evaluated by Omega gages. In order to find out the prestressing force change, two load cells were installed at the anchorage of external tendons

2.3 Material properties

Material properties of steel sections and precast concrete and mortar are listed in Table 1 and Table 2, respectively. Judging from the previous research[6)], the compressive strength of filling material should be higher than that of precast concrete to obtain the same elastic modulus and to



(a) Displacement and strain



G : steel strain gage, E : concrete strain gage

D : displacement transducer

(b) Strain of concrete slabs and joints

Fig. 5 Measurement

assure quality of the mortar in actual construction sites. It is very important to control the quality of the filling material as specified in a design guideline of precast deck bridge. In this experiment, compressive strength of the mortar was much higher than the required strength.

3. Results

3.1 Elastic and fatigue behavior

Finite element analysis was performed to verify the test results using DIANA[4]. Shell elements were used for the concrete slab and the steel box girder. Full interaction was assumed and elastic analysis was performed for the comparison. During the static tests in the elastic range, the flexural stiffness of composite bridge showed good agreement with that of finite element analysis assuming no cracking, which is presented in Fig. 6. Strain distribution of composite sections in positive and negative regions of Fig. 7 showed full interaction behavior of the sections and good agreement with analysis results. This is because the magnitude of longitudinal prestress was determined to prevent tensile stresses at the joints under the applied service load. Therefore, the stiffness of the concrete slab in the negative moment region can be included in the flexural stiffness of a composite section if the longitudinal prestress is introduced properly to prevent cracking under service loadings.

Table 1 Material properties of steel

	Yield stress (MPa)	Tensile strength (in spec.)
Box section	240	0.141
Stiffeners, Diaphragm	240	0.092
Bracing	240	0.264
Tendon	Yield load = 196 kN, Tensile load = 231 kN, Area = 138.7 mm^2, Ep = 190 GPa	

Table 2 Compressive strength of concrete and mortar (MPa)

CBG2	28 days	Prestressing time	Loading time
Precast concrete*	47.6	47.6	47.6
Transverse joint	60.9	47.5	47.5
Shear connection	61.6	46.3	46.3

* : average value of all the precast concrete panels

3.2 Cracking

In order to explain the effects of external prestressing, brief results of the previous test on a 10m-10m continuous bridge model(CBG1) need to be referred. CBG1 has the same section as CBG2. In the tests of CBG1 and CBG2, the first cracking were detected at the transverse joint, while the first cracking was detected in the concrete slab for the

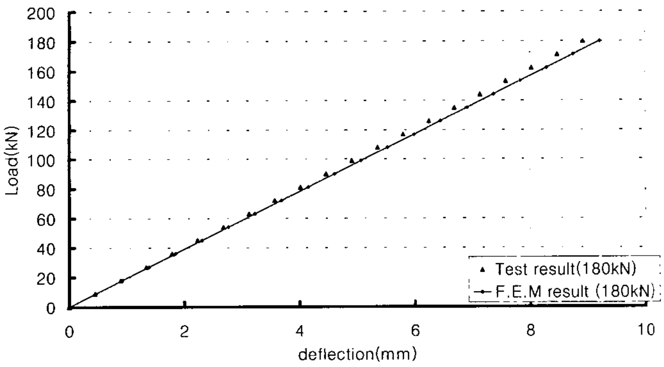


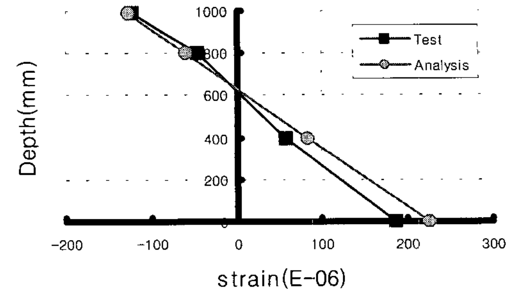
Fig. 6 Load-deflection curve

test results on composite beams having shorter span[2,3,7].

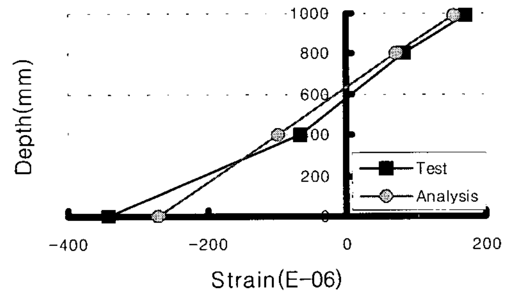
This is because of difference in tensile stresses at the joints and concrete slab at the maximum negative moment by the applied load. In actual bridges, the first cracking will occur at the transverse joints of intermediate support and therefore the longitudinal prestress should be determined by considering the joint cracking.

As can be seen in Fig. 8, there was noticeable difference in crack patterns of two bridge models with and without prestressing after shear connection. Because of the external prestressing after shear connection, we could have good distribution of cracks. For CBG2, cracking between shear pockets in CBG1 model where there is not enough compressive stress due to internal tendons, was not observed. Therefore, it should be carefully considered that the interface of a shear pocket is weak area for cracking unless the prestress after shear connection is introduced.

Table 3 shows the summary of the cracking loads from calculation and observation during tests. Observed cracking loads in Fig. 8 and measured strain data in Fig. 9 and Fig. 10 were nearly the same. Test results showed that it is proper to evaluate cracking load by neglecting bonding strength at interface of the joint and shear pocket area. Two results of cracking load had similar safety level and can be

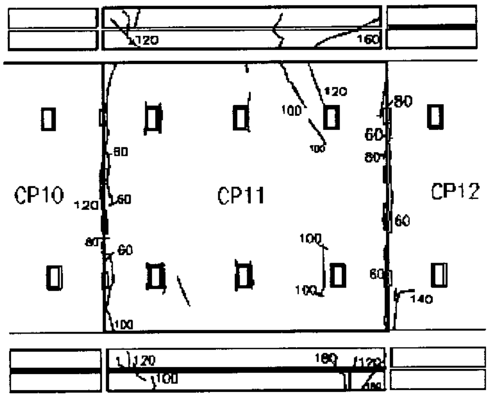


(a) Maximum positive mement section

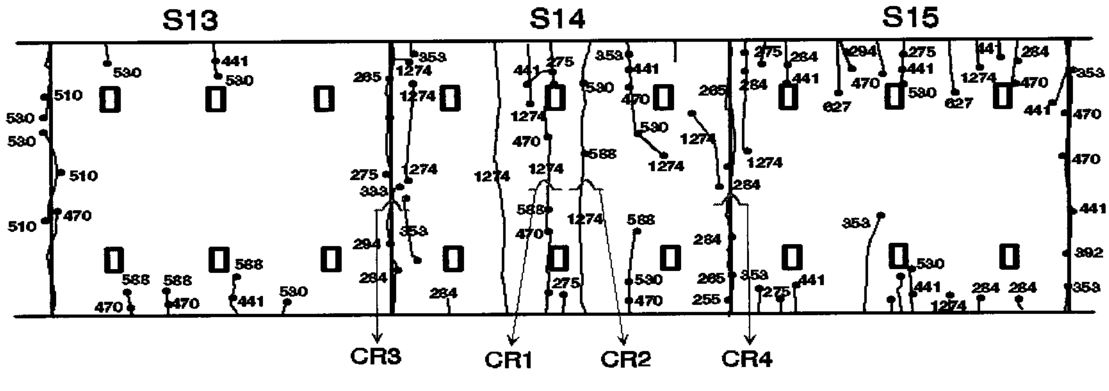


(b) Maximum negative moment section

Fig. 7 Strain distribution (Load : 180 kN)



(b) CBG 1 (10m-10m model without external tendons)



(a) CBG 2

Fig. 8 Crack pattern

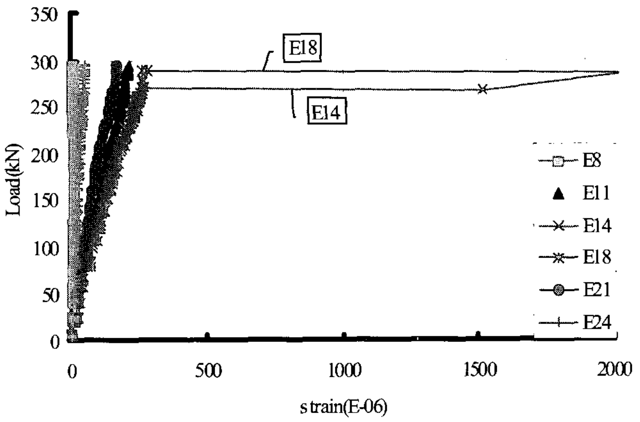


Fig. 9 Load-strain curves at transverse joints (cracking phase)

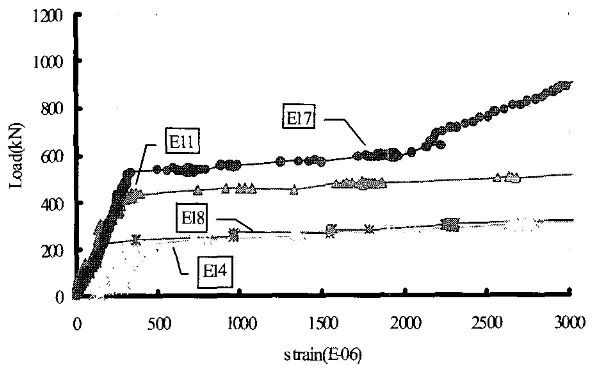


Fig. 10 Load-strain curves at transverse joints (after cracking)

Table 3 Cracking load

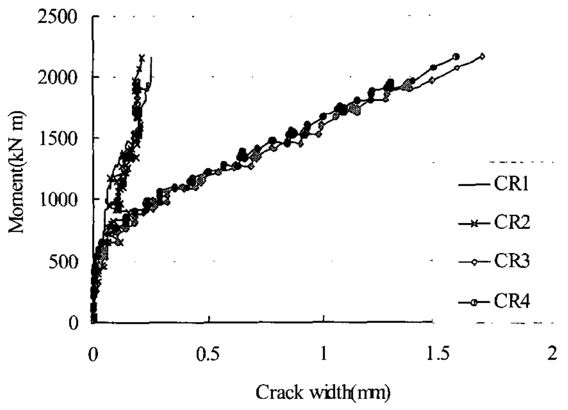
	CBG 1	CBG 2
Calculation	419 (633*) kN	193 (290*) kN
Experimental results	600 kN	274 kN
Ratio	1.43 (0.95*)	1.42 (0.95*)

* : if considering bond strength 2.0MPa of the joint

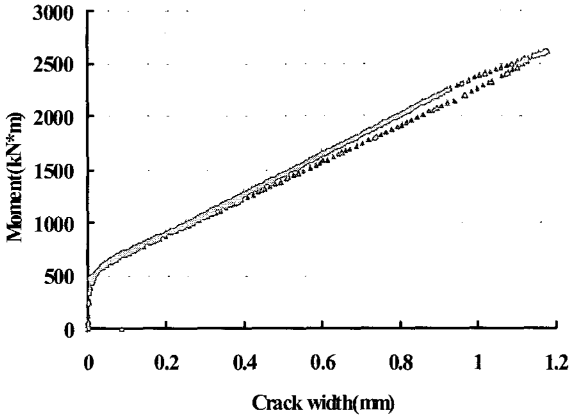
used for statistical evaluation of proper safety level for design when there are enough test results. In order to assume the serviceability for cracking, the design section should be the transverse joints and the bonding strength of the joint should be ignored for the evaluation of the prestress.

3.3 Inelastic behavior

After cracking, four gages were attached at cracks to measure crack widths as presented in Fig. 8. Due to the longitudinal prestress, cracks were closed when the applied load was removed. As the load was applied, crack width at



(a) CBG 2



(b) CBG 1

Fig. 11 Load-crack width curves

the joint was much more than that measure at the crack on precast decks as shown in Fig. 11. Fig. 11(b) shows the measured crack width of the joint crack of CBG1 model without external prestressing. Judging from the crack patterns, the bonded internal tendons do some role as reinforcements. It means that there was tension stiffening effect by the internal tendons.

Cracking in the negative moment region resulted in lowering the neutral axis of the composite section over the internal support, which is shown in Fig. 12. When the applied load was lower than the cracking load, the neutral axis was nearly the same as that of uncracked section. Strain distribution, which was measured over after cracking load, showed that the neutral axis was higher than the calculated value neglecting concrete section as ordinary design. This is because of the prestressing by internal and external tendons. The neutral axis of the composite section at maximum positive moment was not changed as presented in Fig. 13. Moment redistribution of a continuous composite bridge results from cracking of the concrete slab and yielding of the steel box girder. For this specimen with external and internal tendons for prestressing, it is more complex to evaluate the amount of moment redistribution by cracking.

For the CBG2 model with external tendons, prestressed forces were measured using load cells. The location of the tendons was at the neutral axis of the composite section assuming uncracked section. Tendon forces were not changed before cracking load as the load was applied, as shown in Fig. 14. However, after cracking load, the forces were increased because the neutral axis of the composite section became lower than the location of the tendons. This made the cracking pattern of CBG2 more favorable than CBG1 model. For the ultimate design of external tendons, it would be conservative to calculate the increment of tendon forces due to cracking by assuming cracked section. Fig. 12 shows that the eccentricity of external tendons after cracking is smaller than that of cracked section

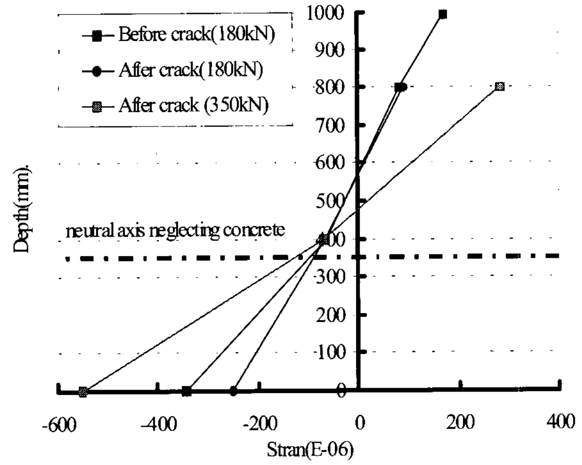


Fig. 12 Strain distribution of a composite section over an internal support

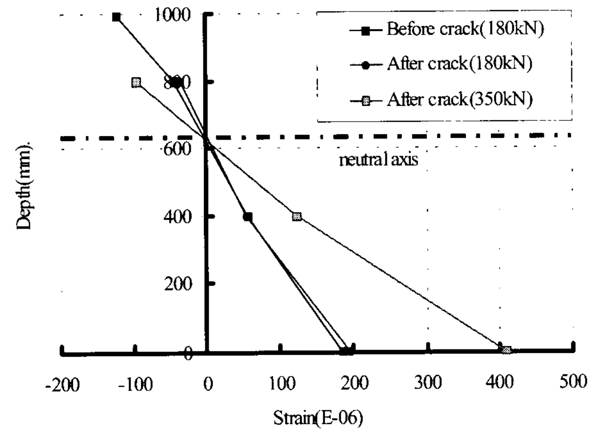


Fig. 13 Strain distribution of a mid-span composite section

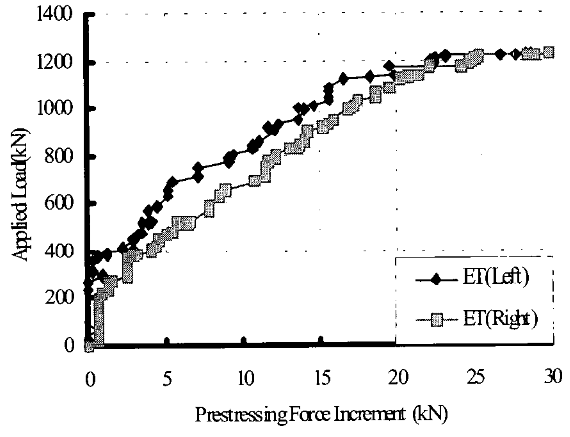


Fig. 14 External cable force curves after cracking

4. Conclusions

Analytical and experimental studies were performed to suggest a design basis for continuous composite bridges with full-depth precast decks. A combination of two kinds of prestress should be used to introduce the compression at the joints in negative moment regions, especially the joint area between shear pockets. A continuous composite box girder bridges with precast decks was tested and their results are presented and compared with the previous model without external prestressing. If the prestress is properly introduced in precast deck bridges, the stiffness of the precast concrete slab in the negative moment region can be included in the calculation of the stiffness of the continuous beam and adequate safety for cracking can be obtained. Test results showed that it is proper to evaluate cracking load by neglecting bonding strength of the joint and shear pocket area. Judging from the crack patterns, the bonded internal tendons do some role as reinforcement. External tendons resist the applied moment after cracking and make the crack distribution more favorable. For the ultimate design of external tendons, it would be conservative to calculate the increment of prestressed forces due to cracking by assuming cracked section.

Acknowledgements

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