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Numerical study of stress states near construction joint in two-plate-girder bridge with cast-in-place PC slab

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Abstract. For reducing construction cost, two-plate-girder bridges are getting popular in Japan. This type of bridge employs a PC slab, which is often cast-in-place. In such a case, concrete is not usually cast over the whole slab at one time: some portions are constructed earlier than the rest. Therefore, a construction joint is inevitably created. Due to the drying shrinkage of concrete, tension stress may occur in concrete slab. High tensile stress can be expected near the construction joint where concretes with different ages meet. Moreover, prestressing is not applied over the whole length of slab at one time. This may also serve as a source of tensile stress in the slab. Thus there is a chance that cast-in-place PC slab, especially near the construction joint, may be subjected to tensile cracking. In the present study, stress states near the construction joint in the cast-in-place PC slab of a two-plate-girder bridge are investigated numerically. The finite element method is employed and the three-dimensional analysis is conducted to see the influence of dry shrinkage and prestressing. The stress states in the PC slab thus obtained are discussed. The simplified model of a plate girder for this class of analysis is also proposed.

Key words: two-plate-girder bridge; cast-in-place PC slab; stress state; construction joint; finite element analysis.

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1. Introduction

For reducing construction cost, two-plate-girder bridges are employed in recent years in Japan (Nakazono 2002, Ohgaki *et al.* 1998, Sakai *et al.* 1997, Takahashi *et al.* 1996). This type of bridge typically comes with a PC slab prestressed in the transverse direction. Concrete of the slab is often cast-in-place. In this case, since concrete is not cast over the whole slab at one time and some parts are constructed earlier than the rest, a construction joint is inevitably created in the slab.

Due to the dry shrinkage of concrete, tensile stress is expected near the construction joint where concretes with different ages are connected. Moreover, prestressing is not applied over the whole range of the slab at one time. Prestressing near the construction joints is not applied until the later stage when the slabs at both sides of the construction joint are ready for prestressing. This construction procedure may also serve as a source of tensile stress. Thus there is a chance that a cast-in-place PC slab, especially near the construction joint, is subjected to unexpected tensile cracking during construction.

In the present study, stress states near the construction joint in a two-plate-girder bridge with a cast-in-place PC slab are studied by three-dimensional finite element analysis. The influence of dry shrinkage and prestressing are focused on. The simplified model of a plate girder for this class of analysis is also discussed.

2. Bridge model

A bridge model for the present study, which is shown in Fig. 1, is constructed based on an existing three-span continuous two-plate-girder bridge with a cast-in-place PC slab. The span lengths are 27.4 m, 44.9 m and 27.4 m. The left and the right halves of the bridge model are identical to each other. The model is of a typical size for this type of bridge: the distance between the two plate girders is 5.6 m and the overhang part is 2.45 m.

The prestressing force by a PC cable is 390.89 kN and each end of the PC cable is fixed on a square plate with the side of 135 mm long at the slab edge. The square plate is placed at the mid-height of the side of the PC slab. Fig. 2 illustrates the layout of PC cables. The distance between two adjacent PC cables is 0.5 m except in the vicinity of the bridge ends.

Young's modulus and Poisson's ratio of concrete are 2.6×10^4 N/mm^2 and 0.17, respectively, while those of steel are 2.1×10^5 N/mm^2 and 0.3. The dry shrinkage is evaluated by the formula given in Japanese specifications for highway bridges (Japan Road Association 2002) and is given in Table 1.

The construction of this bridge is assumed to take the following steps:

Step 1: Concrete is cast in a part of a center span. This portion is 27.3 m long and is called the central slab hereafter.

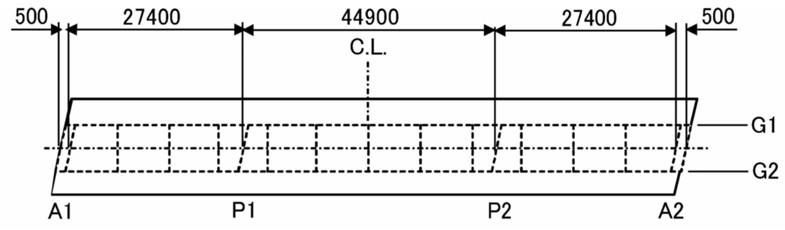
Step 2: Three days later, prestressing is applied to the PC cables. However, two PC cables at each end of the central slab remain unprestressed.

Step 3: On the same day as Step 2, concrete is cast in the remaining slab portions, which are called the end slabs.

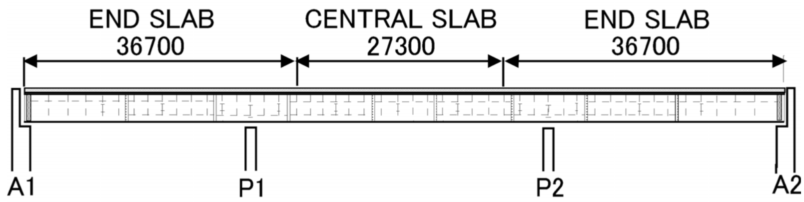
Step 4: Ten days after Step 1, i.e., seven days after Step 3, prestressing is applied to the PC cables. Two PC cables near each construction joint remain unprestressed.

Step 5: Thirteen days after Step 1, i.e., ten days after Step 3, all the remaining PC cables are prestressed.

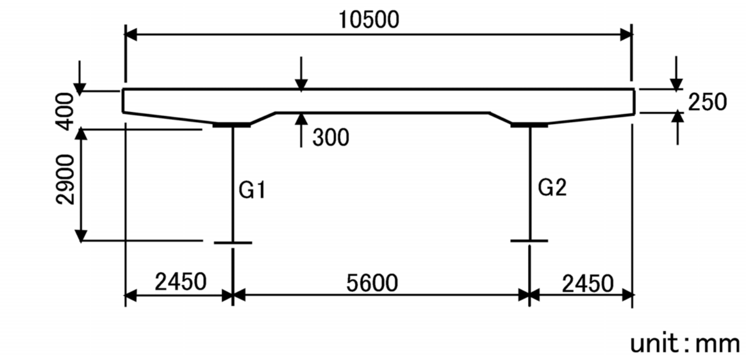
These construction steps are illustrated in Fig. 3.



(a) Top View



(b) Side View



(c) Cross Section

Fig. 1 Bridge model

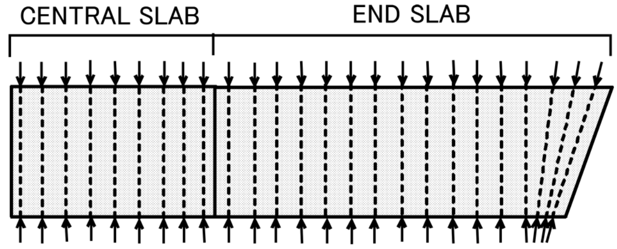


Fig. 2 Layout of PC cables (half of the bridge model)

Table 1 Strain due to Dry Shrinkage

Age	Strain due to Dry Shrinkage
3 days	2.83×10^{-6}
6 days	5.59×10^{-6}
7 days	6.71×10^{-6}
10 days	9.16×10^{-6}
13 days	1.043×10^{-5}

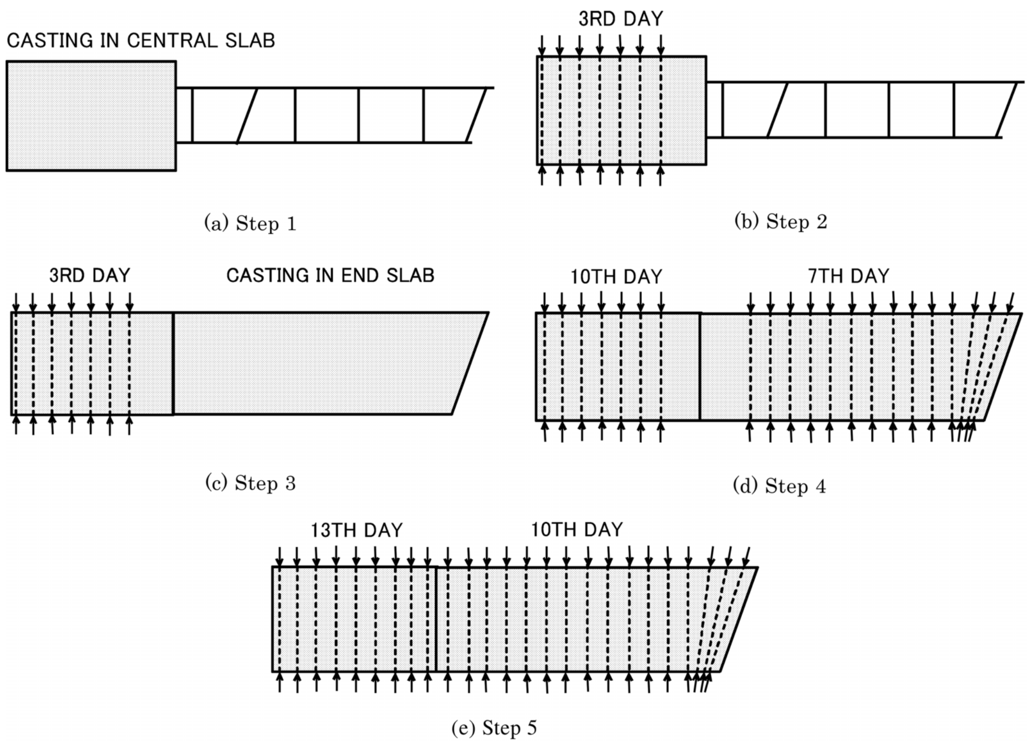


Fig. 3 Construction steps

3. Analysis method

The present model is a skew bridge. It is not symmetric with respect to the mid-span of the bridge. However, the consideration of symmetry does not appear to influence the stress state near a construction joint much due to its position. Considering also computational cost, only half of the slab is to be analyzed. The finite element mesh for the slab is presented in Fig. 4. The number of solid elements used in this mesh is 16,240 and that of shell elements is 144. The shell elements are employed to simulate the square plates on which the prestress cables are fixed. All the analyses in the present study are carried out using ABAQUS (Hibbitt, Karlsson and Sorensen, Inc. 1995).

The webs of the plate girders have cross beams, horizontal stiffeners and vertical stiffeners. In addition to the thickness change of the web, these secondary members further impose restrictions on the finite element modeling of the bridge. The girders are thus complicated structures and it takes a

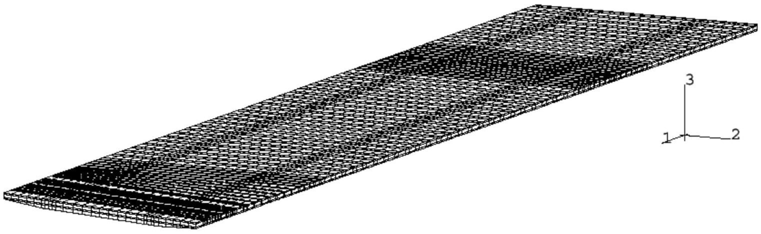


Fig. 4 Finite element mesh for slab

lot of time to construct their three-dimensional finite element meshes. The number of elements becomes quite large inevitably.

Considering that the present study is focused on stress states near the construction joint and stress states in the plate girders are outside its scope, the present research proposes a simplification of the plate girder in its modeling. Since the torsional rigidity of an I-girder is small and the distance between the two plate girders at the location of a cross beam changes little, a vertical stiffener at the location of a cross beam is treated as a cantilever whose rigidity represents the mechanical behavior of the plate girder. In the present analysis, the cantilever is further simplified as a simple horizontal spring that acts in the transverse direction with the spring constant equivalent to the bending stiffness of the cantilever. The values of those spring constants are evaluated as 34,563 N/mm at the intermediate cross beam and 114,293 N/mm at the cross beam located at the intermediate support.

The effectiveness of this spring model is explored by comparing the results due to the complete three-dimensional finite element analysis. In this three-dimensional finite element model, 2345 shell elements and 212 beam elements are required for each plate girder. The slab and the plate girders are perfectly bonded.

The dry shrinkage is a three-dimensional phenomenon: all the three normal strain components decrease equally. In finite element analysis, it is often more convenient to deal with this behavior by making an appropriate conversion into temperature effect. The dry shrinkage is therefore transformed into temperature change, for which the constant of thermal expansion is adjusted so that the effect of the dry shrinkage is represented. Prestressing force is applied as distributed loads over the square rigid plate (135 mm × 135 mm). The end-of-girder cross beam is imbedded in the concrete. Therefore, this portion of the bridge is assumed to be restrained; all the degrees-of-freedom at this portion of the girder are assumed to be completely restricted.

Since the casting of concrete is carried out in the central slab and the end slabs separately, the structure under consideration changes at Step 3. This structural change is dealt with by assuming Step 2 to give the initial state for the analysis at Step 3 and later stages.

4. Numerical results

4.1 Phases

In the present study, stress states in the slab at the following phases are computed:

Phase 1: Three days after the casting of concrete in the central slab
(before the prestressing of PC cables in the central slab)

Phase 2: Three days after the casting of concrete in the central slab
(after the prestressing of PC cables in the central slab, which corresponds to Step 2)
Phase 3: Six days after the casting of concrete in the central slab
Phase 4: Ten days after the casting of concrete in the central slab
(before the prestressing of PC cables in the side slabs)
Phase 5: Ten days after the casting of concrete in the central slab
(after the prestressing of PC cables in the end slabs, which corresponds to Step 4)
Phase 6: Thirteen days after the casting of concrete in the central slab
(before the complete prestressing of PC cables)
Phase 7: Thirteen days after the casting of concrete in the central slab
(after the complete prestressing of PC cables, which corresponds to Step 5)

4.2 Validity of spring model

Two numerical results using the three-dimensional finite element model and the spring model are compared with each other. To this end, the numerical results at Phase 7 in terms of the normal stresses in the slab along α–, β–, γ– lines are considered. As shown in Fig. 5, α–line is on the

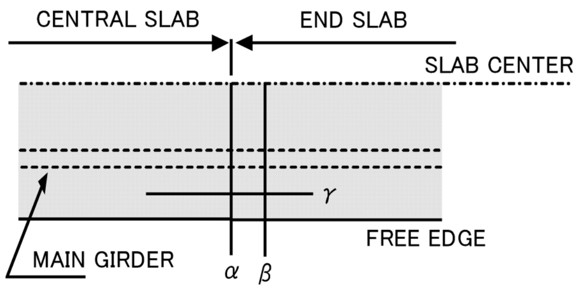
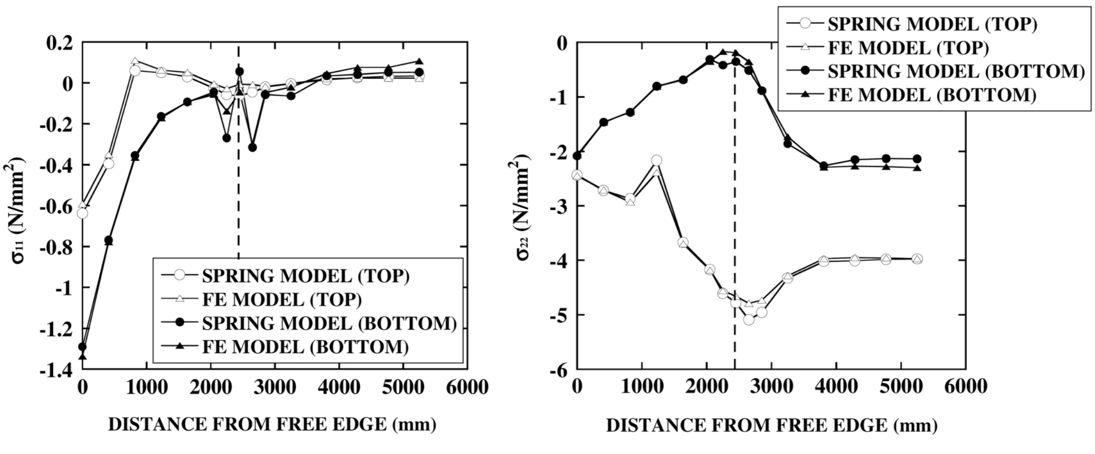
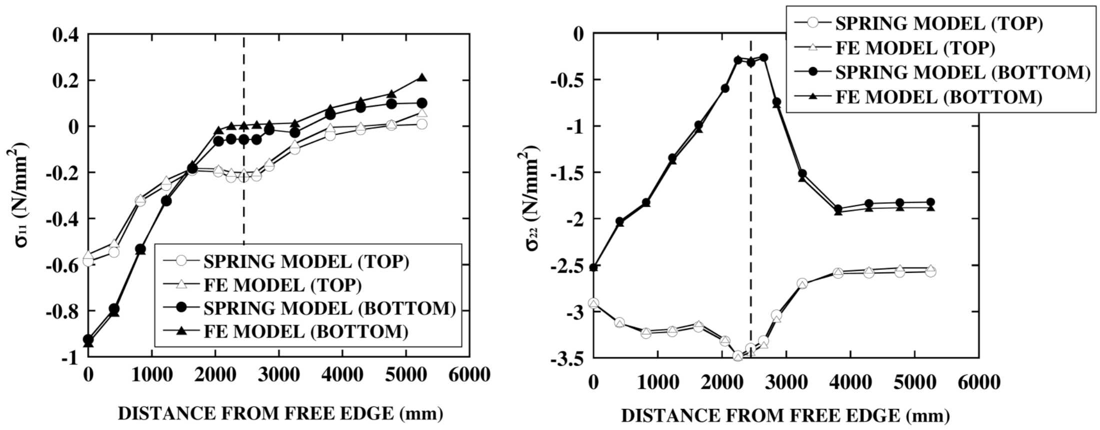


Fig. 5 Lines for stress evaluation



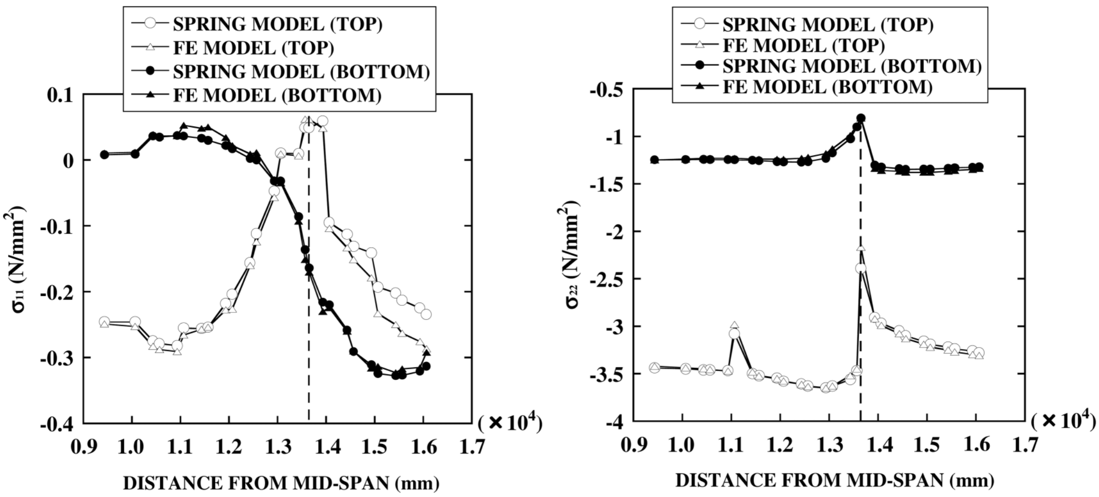
(a) Normal Stress in Longitudinal Direction σ_{11} (b) Normal Stress in Transverse Direction σ_{22}

Fig. 6 Normal stresses along α–line



(a) Normal Stress in Longitudinal Direction σ_{11} (b) Normal Stress in Transverse Direction σ_{22}

Fig. 7 Normal stresses along β–line



(a) Normal Stress in Longitudinal Direction σ_{11} (b) Normal Stress in Transverse Direction σ_{22}

Fig. 8 Normal stresses along γ–line

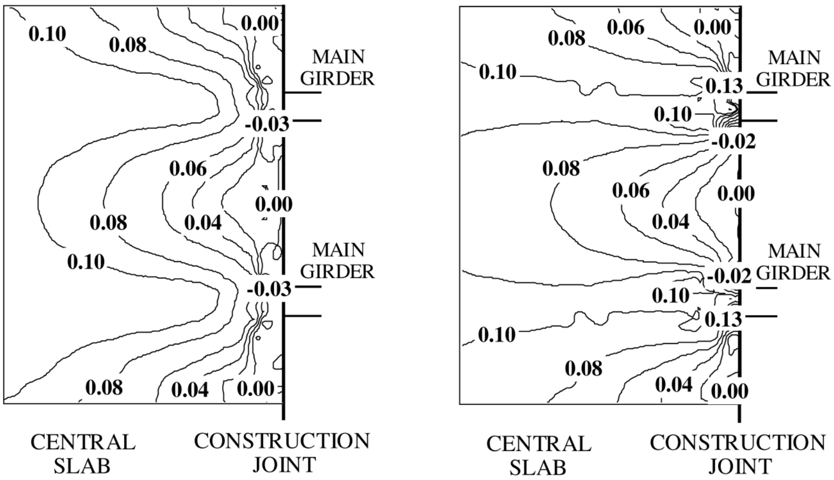
construction joint, β–line is parallel to α–line with the distance of 1.5 m, and γ–line is the centerline of the overhang part. Stresses along these lines are relatively large.

The results are summarized in Figs. 6 to 8. The dashed lines in Figs. 6 and 7 correspond to the center of the top flange of the plate girder, while the dashed line in Fig. 8 is the position of the construction joint. “TOP” and “BOTTOM” in these figures indicate which slab surface, top or bottom, the stress acts in. These figures confirm the validity of the spring model since the difference between the two sets of the numerical results is so small. Only the spring model is therefore utilized in the following analyses.

4.3 Stress states near construction joint

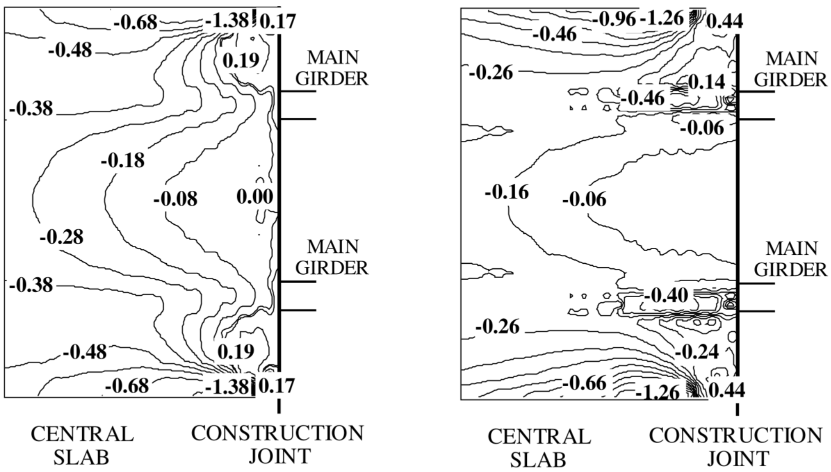
Figs. 9 to 15 present the numerical results at Phases 1 to 7 in the form of maximum-principal-stress distribution near the construction joint in the slab. The central and end slabs shown in these figures are about 7.6 m long.

The stress state at Phase 1 is caused by the dry shrinkage of concrete. Due to the constraint provided by the plate girders, tensile stress is induced, but it is small. The stress in the bottom



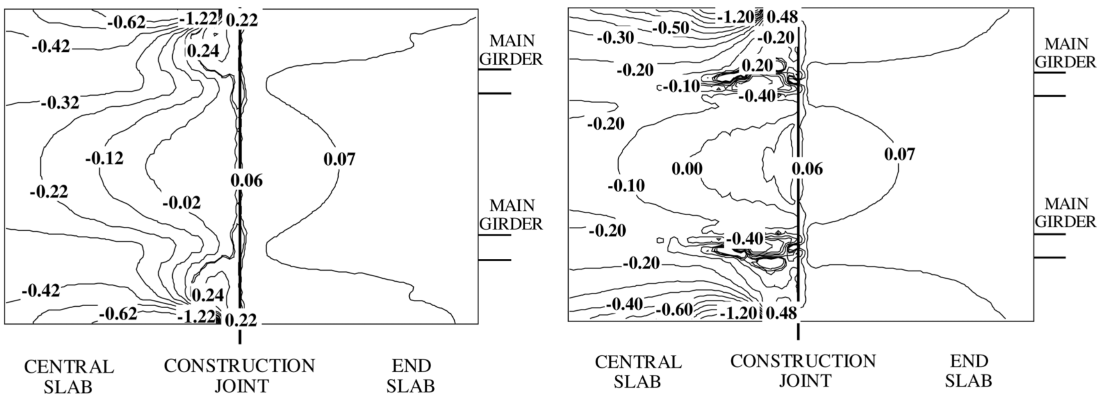
(a) Top Surface (b) Bottom Surface

Fig. 9 Distribution of maximum principal stress in slab at Phase 1 (N/mm^2)



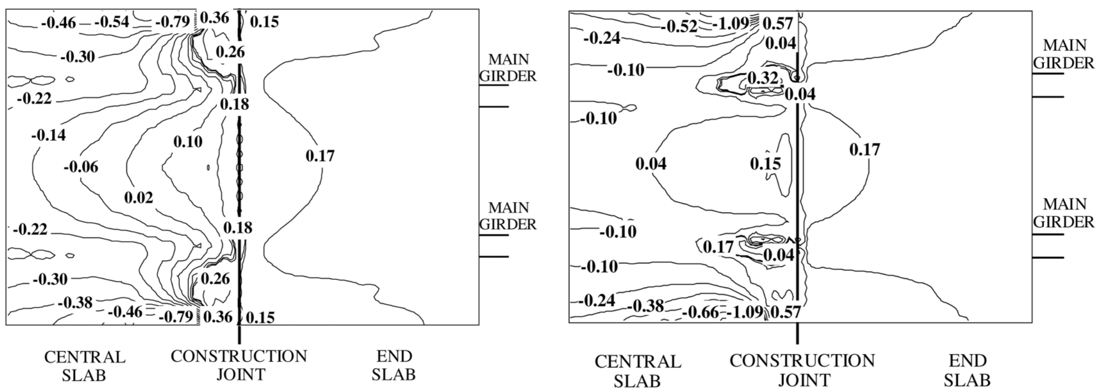
(a) Top Surface (b) Bottom Surface

Fig. 10 Distribution of maximum principal stress in slab at Phase 2 (N/mm^2)



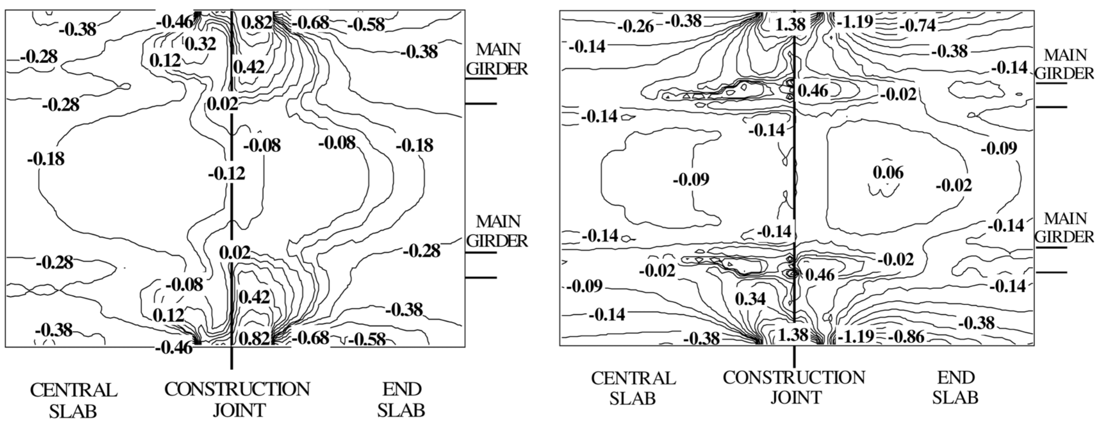
(a) Top Surface (b) Bottom Surface

Fig. 11 Distribution of maximum principal stress in slab at Phase 3 (N/mm^2)



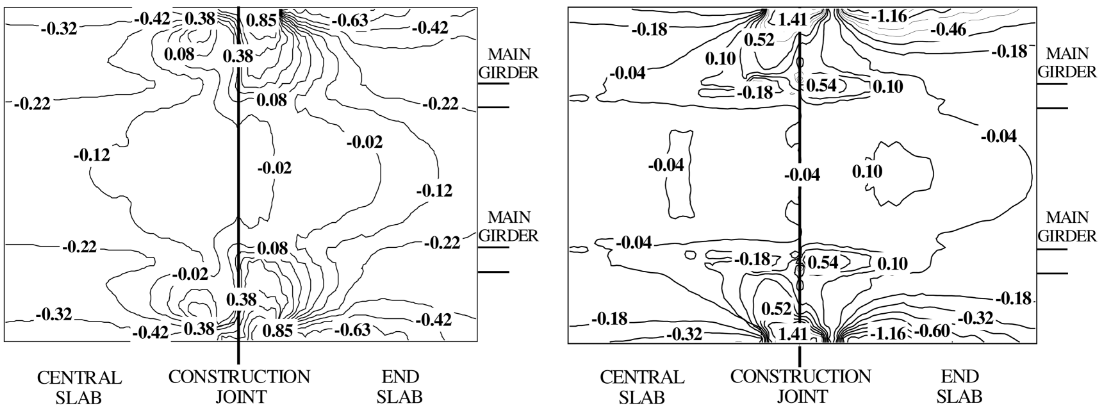
(a) Top Surface (b) Bottom Surface

Fig. 12 Distribution of maximum principal stress in slab at Phase 4 (N/mm^2)



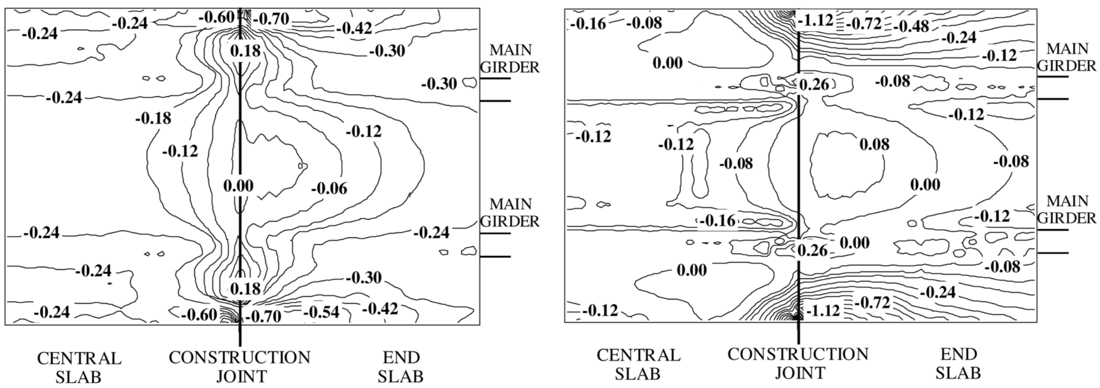
(a) Top Surface (b) Bottom Surface

Fig. 13 Distribution of maximum principal stress in slab at Phase 5 (N/mm^2)



(a) Top Surface (b) Bottom Surface

Fig. 14 Distribution of maximum principal stress in slab at Phase 6 (N/mm^2)



(a) Top Surface (b) Bottom Surface

Fig. 15 Distribution of maximum principal stress in slab at Phase 7 (N/mm^2)

surface is larger than that in the top surface since the constraint due to the plate girders is imposed on the bottom surface.

At Phase 2, most part of the concrete slab is found to be in a state of compressive stress due to the application of prestressing. The prestressing appears to be less effective in the portion between the two plate girders. This is attributable to the constraint that the plate girders provide. Relatively large tensile stress is observed near the end of the central slab. This is because two PC cables in this region are not stressed at this stage of construction.

Phase 3 is associated with the stress state three days after the casting of concrete in the end slabs. The dry shrinkage of the end slab increases tensile stress and decreases compressive stress in the central slab. This stress change is more or less 0.05 N/mm^2. The end slab is subjected to small tensile stress.

At Phase 4, which is four days after Phase 3, the dry shrinkage of concrete advances and the stress change about 0.1 N/mm^2 from Phase 3 is recognized. Larger stress change than that between Phases 2 and 3 can be attributed to larger dry shrinkage, as realized in Table 1.

At Phase 5, the prestressing is applied to the above stress state except for two cables near each construction joint. Most of the slab is in a state of compressive stress. However, the neighborhood of the construction joint in the overhang portion is subjected to large tensile stress. This is the region of no prestressing. This implies the importance of the construction procedure with respect to the prestressing.

The dry shrinkage makes a difference in stress state at Phase 6. Compared with Phase 5, tensile stress increases and compressive stress decreases. The stress change is about the same as that between Phases 2 and 3.

Phase 7 is the state where all the PC cables are prestressed. Tensile stress near the construction joint in the overhang portion disappears. However, tensile stress still remains in some regions near the construction joint. By comparing the stress states at Phases 6 and 7, it is observed that compressive stress in some parts of the overhang portion decreases due to the application of the prestressing.

5. Conclusions

Stress states near the construction joint in a two-plate-girder bridge with a cast-in-place PC slab have been investigated. The following can be stated based on this study:

(1) The spring model that simplifies a plate girder is effective for the stress analysis of a concrete slab.

(2) The dry shrinkage of concrete indeed causes tensile stress in a slab, because of the constraints due to plate girders and the variation of age along the construction joint. Tensile stress in the bottom surface is larger than that in the top surface in general.

(3) Prestressing of PC cables reduces tensile stress. The stress change is larger where the influence of the constraints due to plate girders is small. Namely, the stress change is larger in the overhang portion of the slab than between the two plate girders and in the bottom surface than in the top surface.

(4) Large tensile stress is observed in the region left unprestressed. The tensile stress is especially large when the region of no prestressing is constrained by the adjacent slab.

(5) Even after prestressing is complete, a tensile stress state still remains in some regions near the construction joint.

(6) The prestressing may decrease stress value in the region of compressive stress state.

(7) The largest tensile stress is observed when partial prestressing is applied. The order of PC cables into which prestressing is introduced is therefore quite important and must be determined carefully.

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