ANALYSIS OF AND PROPOSAL FOR DEALING WITH EARLY CRACKS IN 13 M PRECAST REINFORCED CONCRETE HOLLOW-SLAB MEMBERS

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ABSTRACT

Because of the influence of the depth-span ratio, early structural cracks caused by self-weight loading are common in simply supported beams of 13 m precast reinforced concrete hollow slabs. However, such cracks seldom occur in prestressed concrete members. Although there are few research publications available on the method involving the use of moulds incorporating an internal air bag in precast hollow-slab members, this kind of slab is widely used in bridge projects for its convenience in construction and its cost advantage. To determine the main reasons for the early cracks in a batch of 13 m precast reinforced concrete hollow-slab members being used in four bridges under construction, along whose midspans transverse cracks have appeared, a wide-ranging investigation covering the method of construction to the distribution of the cracks was conducted on site. Theoretical calculations, combined with detailed numerical analysis, revealed that the main reason for the induction of early cracks in members is self-weight loading. It is shown that the theoretical values correlate well with the results of the numerical analysis. In order to evaluate the performance of the bridge deck system in which the cracks appear and to judge the effect of these early cracks on structural behaviour, numerical analysis was used and it was concluded that the bridge deck is able to fulfil the serviceability requirements and to provide adequate bearing capacity. Effective and economical anti-cracking measures and a technical proposal are recommended with regard to the design, construction and amendment of the design specifications.

Keywords: Precast reinforced concrete; hollow-slab members; early cracks; numerical analysis

1. INTRODUCTION

Four reinforced concrete bridges that span rivers were recently constructed in Inner Mongolia. Each span of the bridge superstructure consists of 12 pieces of simply supported precast hollow slabs with a 13 m long reinforced concrete pavement, 10 cm thick, and a bituminous concrete layer, 7 cm thick. The bridge substructure consists of columnar piers and a ribbed abutment.

Early cracks in slab members during precasting have led to construction being interrupted for a time. Few research publications are available on the method involving the use of moulds incorporating an internal air bag in normal precast hollow-slab members, although a considerable volume of research has been conducted on the cracking of prestressed concrete members (Jin, Tay Choon, 1987; Yang, Lin, 1995; Li et al. 2004). Moreover, normal precast hollow slabs are widely used in bridge projects for their convenience in construction and cost advantage, as described in *World Construction* (1986). Consequently, there is a need to conduct research to provide guidelines for the design and construction of normal precast bridge slab members. This paper combines theoretical calculations with detailed numerical analysis from which it is concluded that self-weight loading is the main reason for the induction of early cracks in precast members. In order to evaluate the performance of the bridge deck system in which the cracks appear and to judge the effect of the early cracks on structural behaviour, numerical analysis was used and it was concluded that the bridge deck is able to provide adequate bearing capacity. However, main load-carrying members are required not to crack under the action of self-weight loading, even though the structural system composed by the members may fulfil normal serviceability requirements. This work has solved the problems in engineering practice, leading to a proposal for effective and economical anti-cracking measures. The technical proposal covers design, construction and the amendment of the design specifications.

2. CRACKING INVESTIGATION

The bridge slabs, as the main load-carrying members of the superstructure, are normally 13 m precast reinforced concrete hollow slabs designed according to the standard drawings. The sectional dimensions of the middle and side slab members are shown in Fig. 1. The

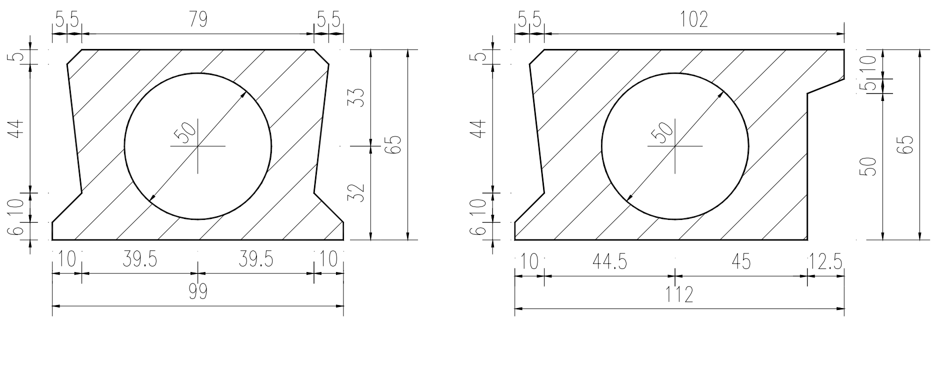


Figure 1. Sectional dimensions of 13 m middle and side slabs (cm).

hollow slab is 12.96 m in length, with a theoretical span of 12.60 m. The concrete grade of the slab members is C30. The tensile zones of every middle and side slab are reinforced with main bars of 14Φ22 near the midspan, with a 3 cm concrete layer over them to protect the main bar. The compressive zones at the midspan section are reinforced as follows: middle slab 5Φ10 and side slab 7Φ10. The bridge deck system is made up of 12 pieces of simply supported hollow slabs, hinged side by side. The bridge superstructure is a composite-type pavement structure as there are two additional layers over the bridge deck system: one is C30 reinforced concrete pavement 10 cm thick, and the other is a bitumen concrete coating 7 cm thick. The concrete grade of the joints is C30, and the joint dimensions are shown in Fig. 2. The precamber for the 13 m precast hollow slabs is 1.5 cm.

The hollow slabs were initially precast on summer days at the casting yard. The precast members stayed on the casting bed of the internal air bag mould for about 10 days, after which they were removed from the bed and placed on sleepers (temporary supports) positioned along the lines of the theoretical supports of the 13 m slab. The theoretical span is 12.60 m. No cracks were found in the 13 m members at this stage. However, transverse cracks, 0.01 – 0.02 mm in width, occurred in the vicinity of the tensile zone near the midspan after the slab members had lain on the sleepers for one or two days. The cracks extended from the bottom of the slab to a certain height and then became stable. Field observations show that cracking is more serious in side slabs than middle slabs, which indicates that side slabs crack more easily than middle slabs.

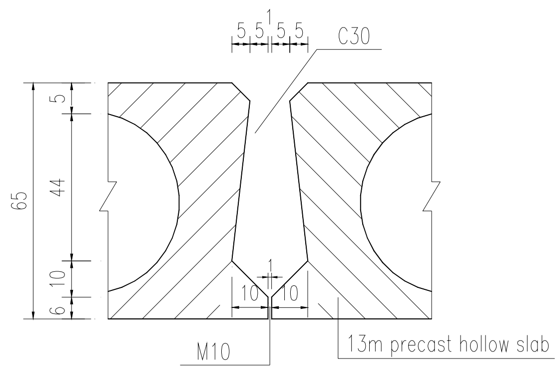


Figure 2. Joint dimensions (cm).

Investigations were conducted on site to demonstrate that the forming of cracks has little, if anything, to do with the method of construction and the properties of the materials, which all comply with the appropriate norms and requirements. However, further investigations and observations showed that the distribution of cracks was concentrated on the tensile face near the midspan and there were no cracks near the supports. At first sight, it was assumed that the cracks had appeared due to insufficient design strength (80%) of the concrete while the hollow slabs were stored on the sleepers. To test this assumption, full-scale samples consisting of 8 pieces of middle slab and 8 pieces of side slab were precast in situ. The samples were not removed from the casting bed until 100% concrete strength had been reached. Unfortunately, similar tensile cracks appeared in the side slab samples, although the cracks in the middle slab samples were slight. Evidently, it was the tensile stress caused by the weight of the slab beam itself exceeding the tensile strength of the concrete that led to the appearance of this kind of crack.

The four bridges' slab members were designed according to the standard drawing, JTG D62-2004 (Code for Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts, 2004), in which there is no requirement for checking the cracking resistance of normal reinforced concrete members under self-weight loading. In engineering practice, the usual simply supported beam is indeed seldom likely to crack on self-weight loading because of the generally favourable depth-span ratio. However, the 13 m reinforced concrete member, with a depth-span ratio of up to 1/20, is a quite different case. As the span length increases, the bending moment near the midspan causing by self-weight loading becomes the controlling factor of 13 m members. Early vertical cracks would have occurred in zones of large moment when the tensile stress causing by the self-weight loading exceeded the tensile strength of the concrete.

3. CALCULATIONS FOR CHECKING THE CRACKING RESISTANCE

Given the section dimensions, the reinforcement of the member and the stress-strain relationships between reinforcing bar and concrete, calculation theory on homogeneous elastic materials can be applied to check the deformation of reinforced concrete members.

On condition that the position of the centroid, the magnitude of the area and the moment of inertia to the centroid axis remain unchanged, the cross-section of the middle or side slab can be regarded as equivalent to an L-shape section, as shown in Fig. 3.

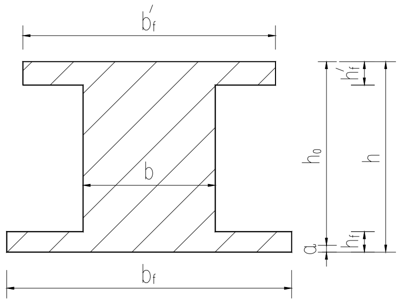


Figure 3. Equivalent section of the slab.

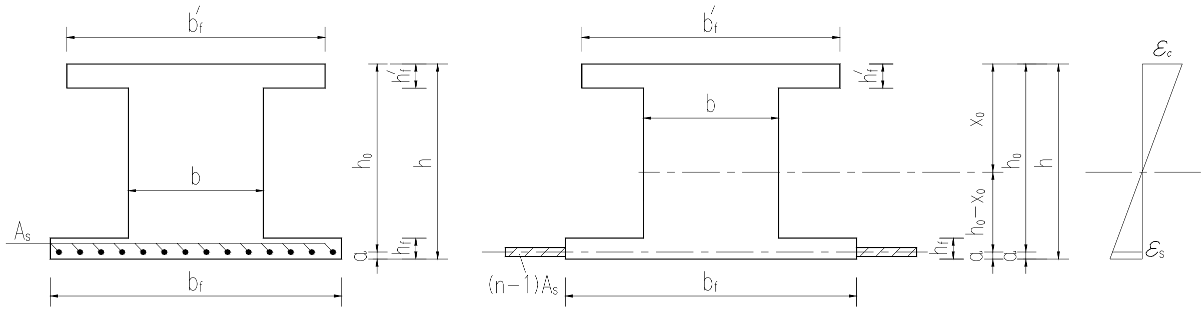
The area of reinforcement in the tensile zone, A_5, can be transformed into an equivalent concrete area, nA_5. Compression reinforcement is ignored in the calculations because it has little influence on the checking of the cracking resistance. Fig. 4 shows the transformation section for the cracking check calculations. With the equivalent transformation of two materials between concrete and reinforcement, Fig. 4(a) and Fig. 4(b) show the same mechanical behaviour in cracking resistance calculations.

$$n = E_s / E_0 \qquad (1)$$

Where n = ratio of modulus of elasticity

E_5 = elastic modulus of reinforcement

E_0 = initial elastic modulus of concrete.



(a) **(b)**

Figure 4. Transformation section for cracking check calculations.

The total area of the transformed section, A_0, is:

$$A_0 = A + (n-1)A_s = b'_f h'_f + b(h - h'_f - h_f) + b_f h_f + (n-1)A_s \tag{2}$$

The height of the tensile region, x_0, is:

$$\begin{aligned} & b'_f h'_f (x_0 - \frac{h'_f}{2}) + \frac{1}{2} b(x_0 - h'_f)^2 = b_f h_f (h - x_0 - \frac{h_f}{2}) \\ & + \frac{1}{2} b(h - h_f - x_0)^2 + (n-1)A_s (h_0 - x_0) \end{aligned} \tag{3}$$

The moment of inertia to the neutral axis of the transformed section, I_0, is:

$$\begin{aligned} I_0 = & \frac{1}{12} b'_f {h'_f}^3 + b'_f h'_f (x_0 - \frac{h'_f}{2})^2 + \frac{1}{3} b(x_0 - h'_f)^3 + \frac{1}{3} b(h - h_f - x_0)^3 \\ & + \frac{1}{12} b_f h_f^3 + b_f h_f (h - x_0 - \frac{h_f}{2})^2 + (n-1)A_s (h_0 - x_0)^2 \end{aligned}$$

(4)

The bending stiffness, W_0, can be written as:

$$W_0 = \frac{I_0}{h - x_0} \tag{5}$$

For reinforced concrete hollow slabs, let the unit weight $\rho = 25 \times 10^{-6} N/mm^3$, the tensile strength of concrete C30 $R_f = 2MPa$, and thus the critical cracking moment M_{cr} is:

$$M_{cr} = \gamma_m W_0 R_f \tag{6}$$

Where γ_m is the plastic coefficient; 1.45 is recommended.

The bending moment at the midspan on self-weight loading, M , is:

$$M = \frac{1}{8} q l_0^2 = \frac{1}{8} A \rho l_0^2 \quad (7)$$

The cracking resistance coefficient, K_f , can be written as:

$$K_f = \frac{M_{cr}}{M} \quad (8)$$

The calculation results of the cracking check for the 13 m precast reinforced concrete hollow slabs on self-weight loading in Inner Mongolia are presented in Table 1. The results show that the critical cracking moment (191.85 kN.m) of the middle slab is larger than its midspan bending moment (180.42 kN.m), which is caused by self-weight loading. The results also show that the critical cracking moment (205.82 kN.m) of the side slab is smaller than its midspan bending moment (210.50 kN.m). It is apparent that the middle and side slabs do not conform to the standard for cracking resistance on self-weight loading. When the precast members are being moved and stored, although 80% of the concrete strength for the 13 m slab does satisfy the design requirement, they do not have the ability to resist cracking on self-weight loading. Consequently, transverse cracks near the midspan are foreseeable. Table 1 indicates that the cracking resistance coefficient of the middle slab is much larger than that of side slab, which coincides with the field observation that cracking is more serious in side slabs than in middle slabs.

Table 1. Calculation results of cracking check for 13 m precast hollow slab members.

Position	$A(mm^2)$	$A_0(mm^2)$	$x_0(mm)$	$I_0(10^{10}mm^4)$	$W_0(mm^3)$	$M_{cr}(10^6N.mm)$	$M(10^6N.mm)$	K_f
Middle slab	363 660	393 814.6	350.95	1.978 399 4	661 561 42.49	191.852 8	180.420 8	1.063
Side slab	424 285	454 439.6	335.97	2.228 743 9	709 723 27.09	205.819 7	210.498 4	0.978

As the critical cracking moment is proportional to the tensile strength of concrete, 80% of the concrete strength of precast members is much easier to crack than 100% strength of the concrete. The middle slab members, which are moved after reaching 100% of the concrete strength, would not crack by and large, although there is no adequate margin of resistance cracking. Side slab members can obviously not resist cracking either in this case, which is in agreement with the results from the in situ investigation of the samples.

If the concrete grade increases to C40, then $E_0 = 33$ *GPa,* $R_f = 2.4$ *MPa.* Let us repeat the cracking check calculations listed in Table 1. The middle and side slabs, with adequate margins to resist cracking, are all unlikely to crack on self-weight loading. It is indicated that the use of a higher concrete grade would be an efficient method of preventing such cracking.

4. NUMERICAL ANALYSIS

4.1 Finite element modelling

Finite element modelling was used to examine the behaviour of the 13 m slabs subjected to self-weight loading. Based on the mechanically symmetrical properties of the structure, a half-span was considered in the analysis. Although there are a variety of finite elements available in ANSYS, only solid 45 and pipe 20 were used to represent the concrete and reinforcement because of the simple, yet numerically stable, performance. The finite element mesh of the concrete model and the reinforcement cage model are shown in Fig. 5 and Fig. 6 respectively.

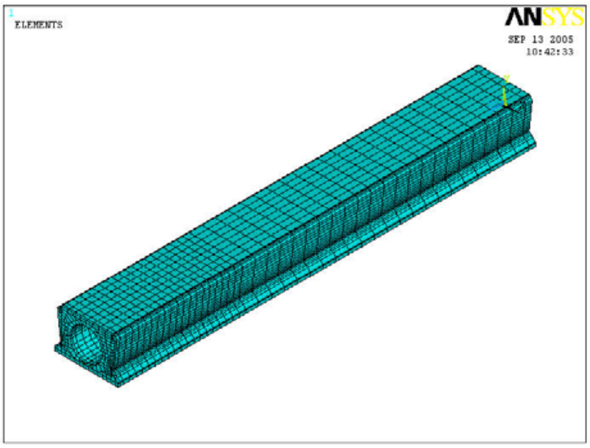


Figure 5. The concrete finite element model for half-span of slab.

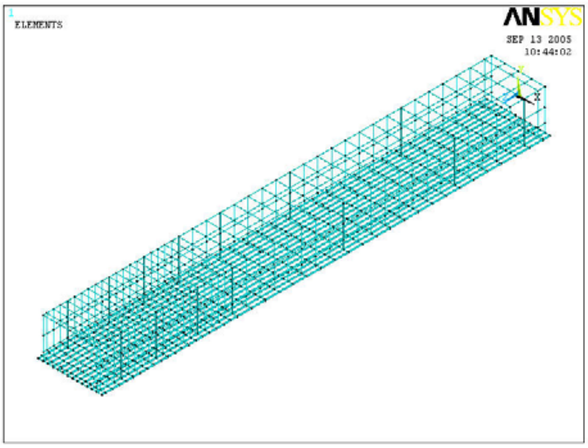


Figure 6. The reinforcement cage finite element model for half-span of slab.

4.2 Results of analysis

According to the analysis results, the cross-section at midspan is the controlling section where the most adverse stress occurred. Fig. 7 shows the stress distribution in the vertical direction at midspan. It can be seen from Fig. 7 that the maximum tensile stress (3.024 MPa) caused by self-weight loading exceeds the tensile strength of the concrete (2.01 MPa). The numerical analysis results are in excellent agreement with the cracking check calculations.

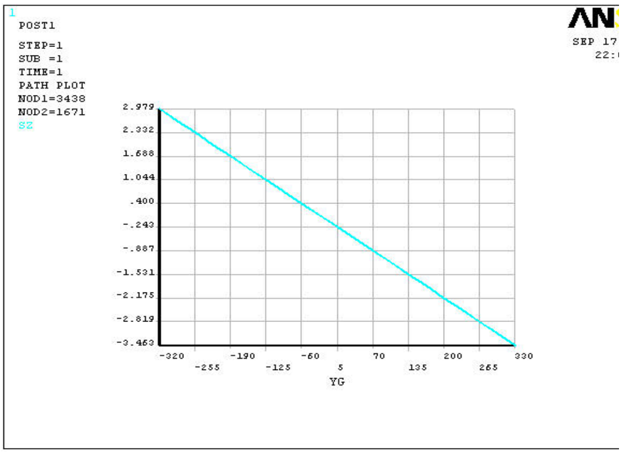


Figure 7. Stress distribution along the vertical direction at midspan.

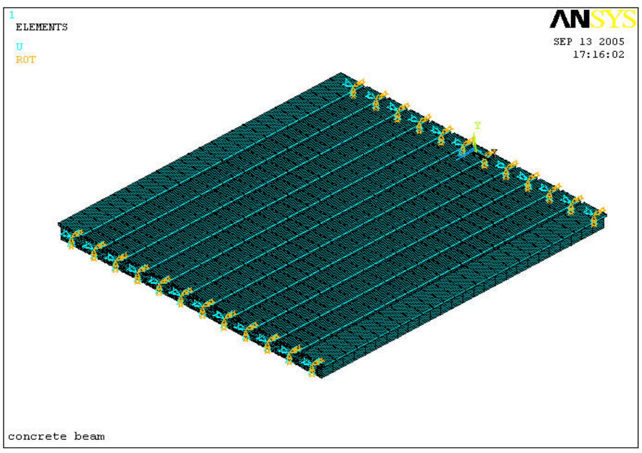


Figure 8. Model of the bridge deck system.

5. EVALUATION OF BRIDGE DECK SYSTEM

In order to evaluate the performance of the bridge deck on which the cracks appear and to judge the effect of these early cracks on the structural behaviour, numerical analysis was used to check the ultimate carrying capacity of the bridge slab system.

5.1 Transverse distribution factor

A finite element model for the bridge slab system, as shown in Fig. 8, was constructed to examine the effect on the bridge deck subjected to service loading. The bridge deck system is made up of 12 pieces of simply supported hollow slabs, hinged side by side. The transverse distribution factors of vehicle wheel loads for every slab are listed in Table 2. It can be seen from Table 2 that the maximum transverse distribution factors of vehicle wheel loads for the side and middle slabs are, respectively, 0.284 and 0.248. These factors are significant in the following check of the ultimate carrying capacity of the side and middle slabs.

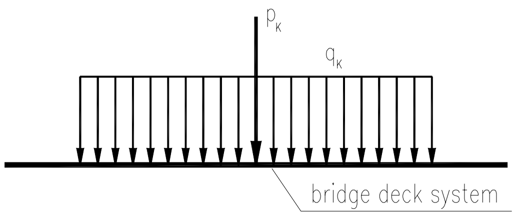


Figure 9. Load arrangement.

5.2 Check of ultimate carrying capacity

According to drawing JTG D62-2004 (Code, 2004), the bridge slab system is subjected to the following loading, as shown in Fig. 9: uniform load $q_k = 10.51KN/m$ and concentrated load $P_k = 212KN$. Tables 2 and 3 show the checking results on bending resistance and shear capacity for the slab beam. It is obvious from Tables 2 and 3 that the slab beam can satisfy the equation $\gamma_0 S \le R$ with an adequate margin of safety. Since the slabs considered in the check of ultimate carrying capacity are the most adverse condition for the bridge deck system, we can conclude that the bridge slab system is able to fulfil the serviceability requirements and to provide adequate bearing capacity.

Table 2. Checking results of bending resistance.

Member	Live load moment (KN.m)	Dead load moment (KN.m)	Load combination S (KN.m)	Structural capacity R (KN.m)	Important factor of structure γ_0
Middle slab	280.15	341.8	802.37	895.52	0.9
Side slab	320.82	373.9	897.80	915.85	0.9

Table 3. Checking results of shear capacity.

Member	Live load shear (KN)	Dead load shear (KN)	Load combination S (KN)	Structural capacity R (KN)	Important factor of structure γ_0
Middle slab	53.60	105.17	201.24	279.22	0.9
Side slab	61.38	115.05	223.99	309.03	0.9

6. CONCLUSIONS AND RECOMMENDATIONS

In bridge engineering, with regard to mainly load-carrying members, it is required that members do not crack under the action of self-weight loading, even though the structural system composed by the members is able to provide normal serviceability. However, there is no corresponding requirement in the present design code. In order to meet the requirement, it is necessary to amend the crack checking calculations for normal precast reinforced concrete members in design specifications.

When reinforced concrete members are about to crack, the tensile stress of the reinforcement is around 20 MPa. So there are two main ways of improving the members' cracking resistance: one is to enlarge the section size of the members and the other is to enhance the concrete strength grade. For 13 m precast reinforced concrete hollow slabs, if the section size is not enlarged, it is suggested that the concrete strength grade be increased to C40. With the cement grade and the effectiveness improved, it is possible to improve the concrete strength without increasing the cost.

For rapid construction, precast members are usually removed from the casting bed with 80% concrete strength. In this case, an efficient approach to preventing members from cracking would be to shorten the distance between the temporary supports (sleepers) for the 13 m precast slabs. This should be applied within proper limits, otherwise new cracks close to the supports would appear in the top surface of the slab beams.

With highway bridge overloading increasing, for bridge engineers there is no better choice but to substitute 13 m precast slab members with prestressed concrete hollow slabs to control the cracks caused by self-weight loading. However, 13 m precast slab members have been widely used in current bridge projects because of their convenience in construction and their lower cost. It would seem that the proposed methods presented in this paper may result in a new approach to controlling cracks in 13 m precast reinforced concrete hollow-slab members.

7. REFERENCES

[1] Code for Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts, 2004. JTG D62-2004.

[2] Jin, Tay Choon, 1987. Jurnal Institusi Jurutera Malaysia, 40, pp. 41-50.

[3] Li, T, Yan, Y and Yan, W, 2004. Progress in safety science and technology. Proc. 2004 International Symposium on Safety Science and Technology, Part A, Vol. 4, pp. 693-698.

[4] World Construction, 1986. 39(10), pp. 38, 40-41.

[5] Yang, Lin, 1995. Structural Engineering Review, 7(4), pp. 277-288.