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Design Basics of a Continuous Composite Slab with Unbonded Tendons

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Summary

Theoretical and experimental research on steel-concrete composite slabs with unbonded tendons shows that a composite slab with horizontal shear resistance high enough to withstand the shear induced during the post-tensioning work can be analyzed using the principles developed for post-tensioned concrete slabs in addition that horizontal shear should be checked as a possible failure state. The steel sheet can be fully utilised in the calculations of the effective stiffness and the flexural resistance of the composite slab.

1 Background

At the VTT Building Technology, Finland, a theoretical and experimental research project was undertaken on post-tensioned composite slabs during the years 1994-1996. The purpose of the project was to present the principles of design with respect to resistances at the failure states and performance at the service state.

Prestressing is a powerful method to improve the performance of a composite slab at the service state. Cracking and deflections decreases and flexural stiffness increases by prestressing. These benefits can be utilized in different ways depending on the requirements of an actual building: span lengths can be substantially longer, slab depths can be smaller and a slab can be built in a more severe athmosphere. The benefits from a steel sheet are that it is used as a formwork and it can be used as a substitution of reinforcement necessary as minimum reinforcement and a means to reduce the weight of the floor. It also increases the stiffness of a cracked section.

As a in-situ construction method itself, composite contruction can benefits most from prestressing techniques suitable for building site. For this reason, the research project focused on the post-tensioning methods, especially with unbonded tendons which have small measures in anchorages and sheatings and are finished without grouting (Fig.1).

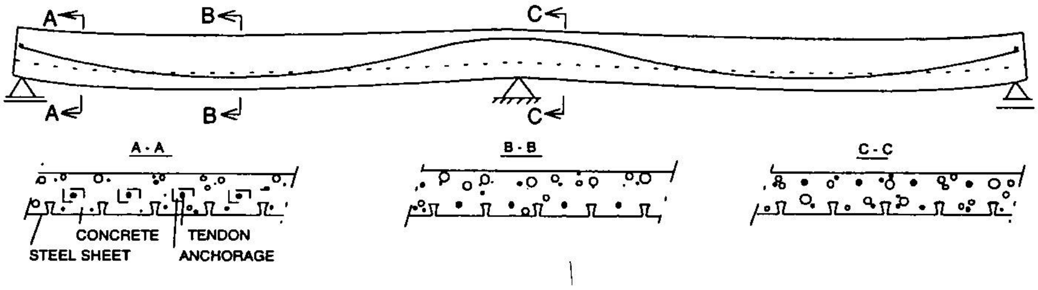

Fig.1. A composite slab with parabolic unbonded tendons.

2 Load balancing approach

The load-balancing approach has been presented by T.Y. Lin and N.H. Burns [3]. It gives a quick and reliable method to calculate the stresses caused by prestressing in any type of structure.

A curved prestressing tendon induces both horizontal and vertical components of the tendon force. The vertical components of a parabolic tendon can be supposed to be uniformly distributed along the length of the slab with the magnitude of

$$w = \frac{8Ph_f}{L^2}$$

where w is the uniformly distributed vertical components of the tendon force
P the tendon force
h_f sag (drape) of the tendon
L the horizontal length of the parabola.

This simple equation is based on a close similarity of a parabola with a circle and small angles between the parabola and the line connecting the ends of the parabola. In a continuous composite slab, the vertical components along the whole length of the slab can be calculated separately for each different parts of parabolas by the aid of the same formula. When the vertical components upwards are as great as the acting loads, the slab is load-balanced. Such a composite slab is purely compressed due to the horizontal component of the tendon force which roughly equals to that.

Prestressing induces support reactions in a continuous slab which in turn induces secondary effects. The bending moment $M_w(x)$ caused by the vertical component of the tendon force is the total internal moment due to the prestressing, and the common methods for continuous beams can be used in calculation of the diagram. The prestressing force causes a primary bending moment $M_1(x)$ in each section. The secondary bending moment $M_2(x)$ is the difference between the total and primary internal bending moments. The secondary moment is needed for the assesment of the secondary support reactions caused by the prestressing.

3 Flexural stresses in a continuous composite slab

The cross-sectional values of a composite slab with unbonded tendon can be calculated by transforming all bonded reinforcement to concrete by the relation of the elastic modules.

$$A_m = \sum n_k A_k$$
$$I_m = \sum \left(n_k I_k + n_k A_k e_k^2\right)$$

where k the structural part (c refers to concrete, s to rebars and a to steel sheet)
A_k the area of a structural part
I_k the second moment of area of a part with respect to its own centroid
e_k the distance between the centroidal axes of the part and the composite slab
$n_k = E_k/E_c$

In a cracked section, only the compressed concrete is taken into account. The stiffnesses of the uncracked and cracked sections are calculated by multiplying the second moment areas of transformed sections by the elastic modulus of concrete.

The flexural stresses of a continuous slab can be calculated as a sum of the stresses due to the tendon force P, the total bending moment M_w caused by the prestressing and the bending moment caused by the self-weight and other gravity loads, M_p.

$$\sigma = -\frac{P}{A_m} - \frac{M_w}{I_m} y + \frac{M_p}{I_m} y$$

where y the distance from the cetroidal axis of the composite slab to the level of calculation
and the other symbols are given in the formulae above.

4 Shear stresses in the joint

The composite action between the concrete and the steel sheeting was investigated by column tests simulating a balanced composite slab and by push-out tests simulating a joint in a bent slab. A full-scale loading test on a continuous post-tensioned composite slab was also carried out in order to verify the calculation model developed on the basis of balanced load approach and small-scale tests.

Shear stresses are induced in a load-balanced composite slab in the joint due to the transfer of the tendon force in the steel sheeting. This happens in a short anchorage zone where also the tendon force acting locally transfers to a uniform compression of the concrete (Fig. 2a). The composite action in compression was studied by the aid of loading tests on short columns with steel sheetings on two opposite edges. No stirrups were placed in specimens because the calculated failure load of the concrete part was higher than the force needed to cause a compressive stress of 7 N/mm^2, when usually the sustained compressive stresses vary from 1 to 2.5 N/mm^2 in prestressed slabs (Figs. 2b and 2c).

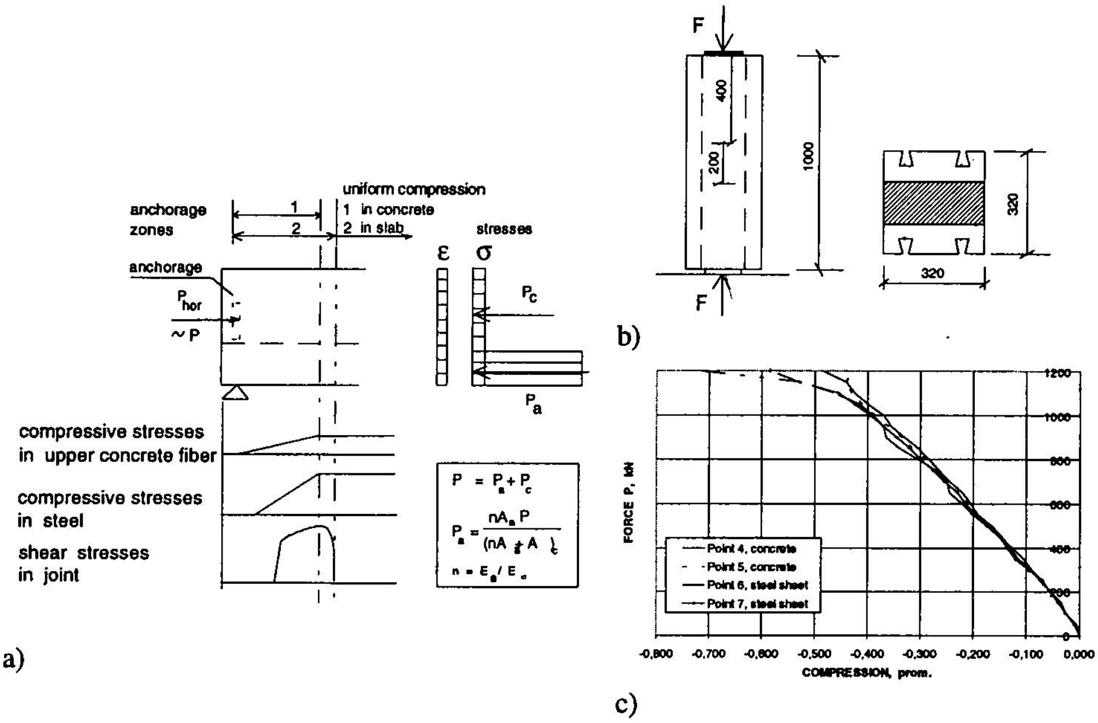

Fig. 2. a) Schematical presentation of transfer of tendon force in the concrete and steel sheeting. b) Compressive tests on short columns c) Results from a compressive test on a short column.

The capability of the joint to transfer the compression force from anchorage to the steel sheeting should be experimentally verified for each type of composite slab. This is due to the short transfer length and relatively high shear stresses which increase with time.

5 Effect of time on a prestressed composite slab

The distribution of stresses varies during the lifetime of a composite slab due to the time-dependence of the stress-strain relations of concrete and prestressing steel, shrinkage of the concrete and composite action between the concrete and steel sheeting. In a composite slab, the continuous change of stresses and strains cause a continuous change in the location of the centroidal axis and stiffnesses, too. For this reason, the cross-sectional values are calculated for all the different times of consideration.

The estimation of the creep of a composite slab happens usually according to the methods generated for concrete structures. The creep is dependent on the measures and surrounding of the slab as well as the time of loading. The relaxation properties of a tendon are defined experimentally.

The shrinkage and creep are restricted by the steel sheeting. This induces additional bending moments and normal forces in the composite slab. However, in a post-tensioned composite slab these additional effects are small. At first, the distance between the centroidal axis of the totally or nearly uncracked concrete part and that one of the composite slab is small and secondly, the permanent load causing creep is usually balanced.

The shear stresses at the ends of the slab gradually increases due to the increase of the share of the tendon force carried by the sheeting, but decreases at the same time due to the losses of the tendon force. The unbalanced loads induces the shear stresses opposite to the stresses induced by the tendon force.

A calculation model was developed for the analysis of the long-term deformations of a composite slab withunbonded tendons in the project at VTT Building Technology. The work was undertaken by modifying the composite slab program CompCal of the Technical University of Lausanne, Switzerland. The performance of the programme has been verified for the ordinary slabs in Lausanne and for the short-term behaviour of a prestressed composite slab at VTT. The creep and shrinkage properties of concrete were programmed according to the widely used expressions presented in CEB-FIP Model Code for concrete structures [1]. The calculated examples show that the long-term deflections will be substantially reduced by post-tensioning [3].

6 Results from a full-scale loading test

A full-scale loading test was undertaken on a continuous composite slab with unbonded tendon with eight line loads (Fig. 3). The width of the slab was 920 mm. The steel sheeting was manufactured from four pieces: two pieces were connected along the longitudinal centre line and these were laid on the supports. The sheet was not continuous over the middle support. The measures and tendons of the specimen were planned to meet the requirement of balanced load by the aid of hand-calculations and computer programme. The slab type used in the experiment was tested beforehand by the small-scale column and push-out tests. Compressive stresses of concrete of about 3.3 N/mm^2 were caused by four tendons and their anchorages of the type BBR-Cona-Single when the average compressive strength of concrete was measured as 32 N/mm^2.

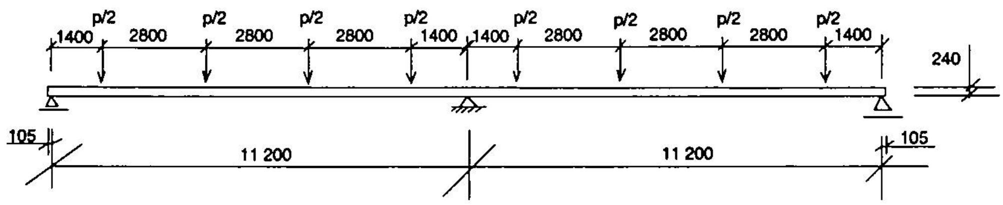

Fig.3. The flexural loading test on a continuous composite slab with unbonded tendons.

The deformations of the specimen were recorded during the tensioning work and the interval between tensioning and loading. There was a cambering of about 2 mm during tensioning which increased 0.2 mm during the first 18 hours. The slip values between the the steel sheet and concrete was recorded during tensioning as 0.07 - 0.11 mm at different points and the slip increased only at one measurement point during the following 18 hours. The measurements were stopped as the changes became neglicible.

The specimen was loaded after a week when the average compressive strength of concrete was 42.7 N/mm^2. The load was increased five times in a range of working loads and then increased to failure. The first crack appeared at the middle support at the load which was lightly greater than the calculated value of the load causing the cracking moment. Only one visible crack formed at the middle support because there was no additional reinforcement. This lead to an redistribution of the support moment so that the support reactions at the ends of the specimen were greater than calculated for a continuous slab. The deflections of the specimen increased inlinearly especially after the cracking had began in the spans. The cracking was strongly distributed along the spans with distances about 150 - 200 mm from each other in the middle.

The failure of the specimen took place in the middle of the other span as the concrete crushed due to compression. The deflections were about 250 mm in each span at failure state. The slips due to loading between the steel sheet and concrete were recorded at the ends of the specimen and they were between 0 and 0,007 mm at the failure state. The sagging moment caused by the line loads and self-weight was greater than the calculated flexural resistance of the specimen taking the steel sheet into account.

7 Design of a composite slab with unbonded tendons

Design principles were developed based on the theoretical and experimental research on steel-concrete composite slabs with unbonded tendons. A composite slab with horizontal shear resistance of the joint high enough to withstand the shear induced during the post-tensioning work can be analyzed using the principles developed for post-tensioned concrete slabs in addition that horizontal shear should be checked as a possible failure state. The effect of the anchorage force on the joint should be studied experimentally for each type of composite slab. The steel sheet can be fully utilised in the calculations of the effective stiffness and the flexural resistance of the composite slab.

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