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The Influence of Bond Slip in Post-tensioned Prestressed Concrete Beams

Influence du glissement de l'armature des poutres en béton précontraint

Einfluß der Stahlgleitung in Spannbetonbalken

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Introduction

At the ultimate design of a prestressed concrete beam it is generally assumed that sections remain plane during bending. This implies that the following formula shall hold good

$$\frac{x}{h} = \frac{\epsilon_b}{\epsilon_b + \epsilon_{ba}}.$$

In this formula x means the depth of the compression zone, h the effective depth of the beam, ϵ_b the ultimate concrete strain at the top of the compression zone and ϵ_{ba} the concrete strain at the level of the reinforcement.

Now both the values ϵ_b and ϵ_{ba} are affected by the efficiency of the bond. If the bond is good, the value of ϵ_b will be about $4\,^0/_{00}$ — the European concrete committee recommends $3{,}5\,^0/_{00}$ — and ϵ_{ba} will be equal to $\Delta\,\epsilon_a$, i. e. the increase in steel strain counted from the moment when the surrounding concrete has zero strain. If the bond is bad that will not be the case — ϵ_b will decrease and ϵ_{ba} will be greater than $\Delta\,\epsilon_a$.

Pull-out Tests

To study the character of the bond around a Freyssinet prestressing cable, pull-out tests were performed with 18 concrete prisms with square section 25×25 cm and a length of 80 cm. The Freyssinet-cable consisted of 12×5 mm wires (ultimate strength 150 kg/mm^2) enclosed in a corrugated sheetiron tube 0,2 mm thick. Several grout mixes were used. Further details may be found in [1], where these tests — with the authors permission — were first presented by FRITZELL. The mix that showed the best properties as to fluidity and slip consisted of cement + water + intrusion aid. The wct ratio was 0,4 and the intrusion aid amounted to 1 per cent of the cement weight. A typical result of the pull-out tests is shown in Fig. 1. The charge was effected by an ordinary

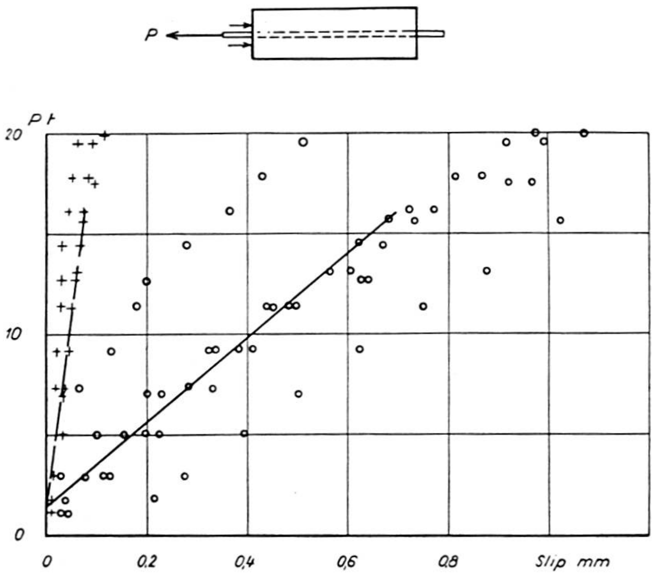

Fig. 1. Typical Result of the Pull-out Tests.

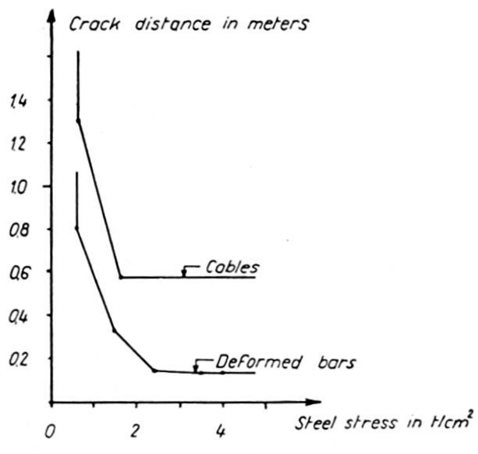

Fig. 2. Crack Distances

Freyssinet jack. The slips were measured in both ends of the test specimen, u_0 designating the slip in the pulled end and u_l the slip in the free end. As can be seen from the straight lines, the test result can be fairly well described by the simple theory that the bond stress is proportional to the slip. The slip "modulus" e.g. the relation between bond stress and slip, as calculated from the tests amounts to about 600 kg/cm³, which is only about one tenth of the value attained with deformed bars (as measured by K. G. BERNANDER [2]. Rupture was obtained at a slip of about 1 mm, and was accompanied by splitting of the concrete whereupon the whole cable — including the tube — could be pulled out of the concrete. The bond must therefore be characterized as rather loose, which means that a prestressing cable of this type is not well suited to distribute cracks in comparison with ordinary mild steel. To give an impression of this, Fig. 2 shows crack distances as measured in two of the beam tests described below, one being reinforced with Freyssinet cables only and the other supplemented with deformed bars. To make the results comparable the crack distance in the latter beam have been corrected so as to give the same ratio of circumference to steel area in both cases. The crack formula used for this correction is due to WÄSTLUND, JOHNSSON and OSTERMAN (cf. [3]). The steel stress in the diagram is the increment above the prestress.

In this case the cable diameter was 32 mm. With larger cables the crack distribution would be more unfavorable.

Model Test

As mentioned, the concrete strain ϵ_b will decrease if the bond is bad, and that is due to the bad crack distribution caused by the bond slip. See Fig. 3.

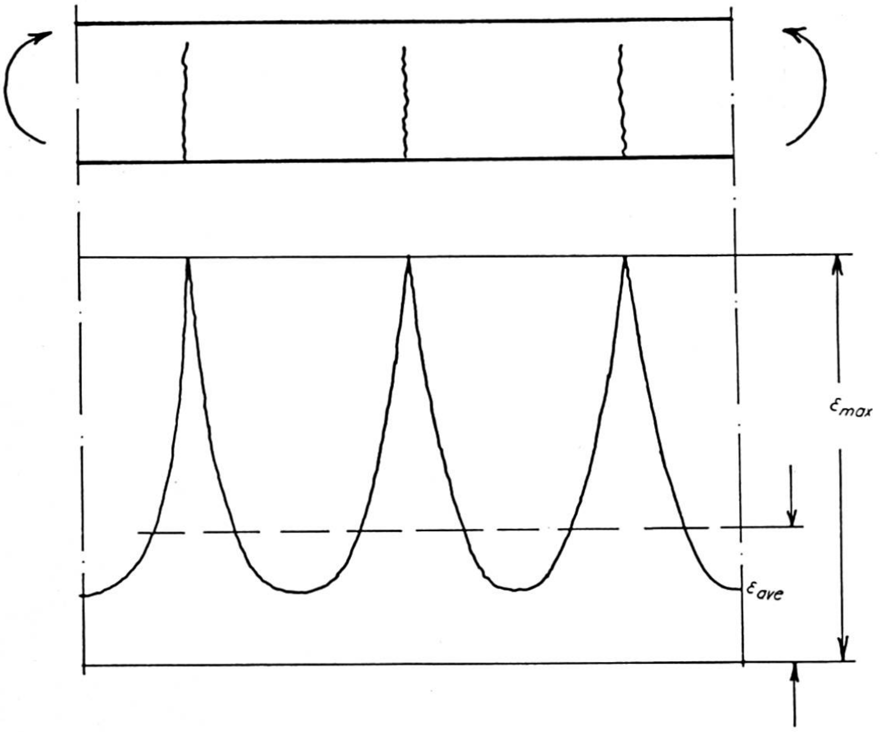

Fig. 3. Strain Distribution Along the Compression Side of a Beam Subject to Bending Only.

If the crack distances are large and the compression zone is small the average value of the concrete strain will be much smaller than the peak values. To study this effect tests were performed with a plexiglass model that was to represent the concrete lamella between two consecutive cracks, Fig. 4. The model was 16 mm thick, 100 mm wide and 250 mm long. The load was applied by means of steel prisms of different lengths, and the strain was measured with seven strain gages along the upper side of the lamella. The diagram shows the strain distribution at different ratios between the depth of the compression zone and the crack width. In Fig. 5 the ratio of the average strain to the maximum strain is reproduced versus the ratio x/s. Of course the results from this model test cannot be directly applied to concrete — for several reasons — but it shows the tendency.

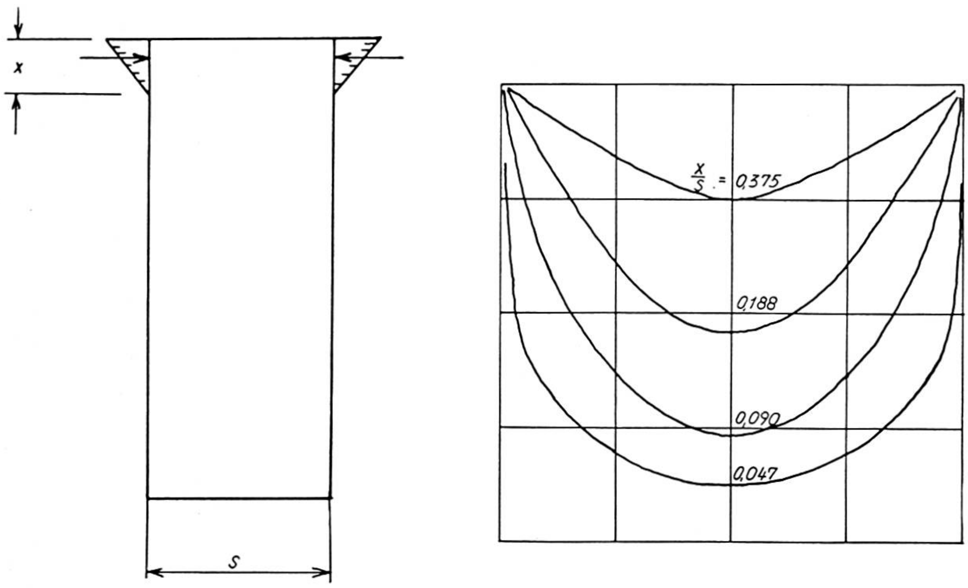

Fig. 4. Plexiglass Model and Strain Distribution Along the Compression Side.

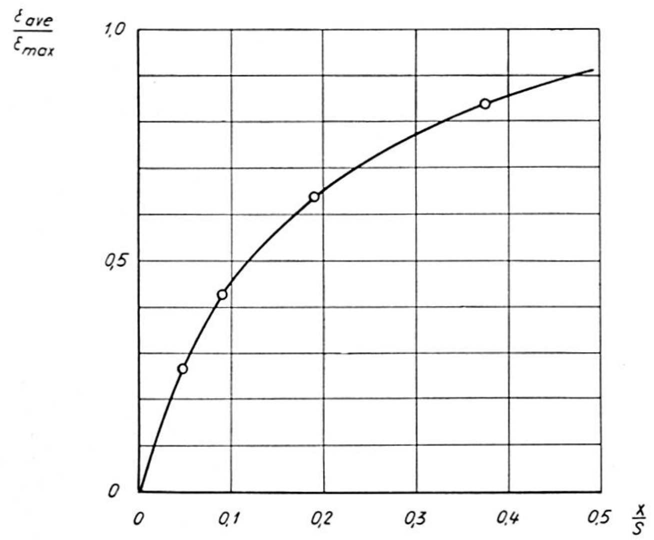

Fig. 5. Ratio of Average Strain to Maximum Strain in the Model Test.

Beam Tests

Beside the above mentioned effect concerning crack distribution the bond slip causes a detachement of the reinforcement towards the ends of a beam. In the extreme case that there is no bond at all, the strain distribution will have the form shown in Fig. 6. The beam is in this example assumed to be loaded by two symmetrically placed concentrated loads. The steel strain $\Delta\,\epsilon_a$

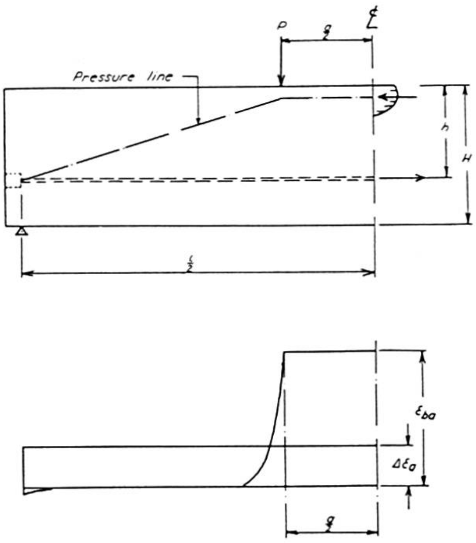

Fig. 6. Approximate Strain Distribution in the Tendon ($\Delta\,\epsilon_a$) and in the Surrounding Concrete (ϵ_{ba}). Two Concentrated Loads.

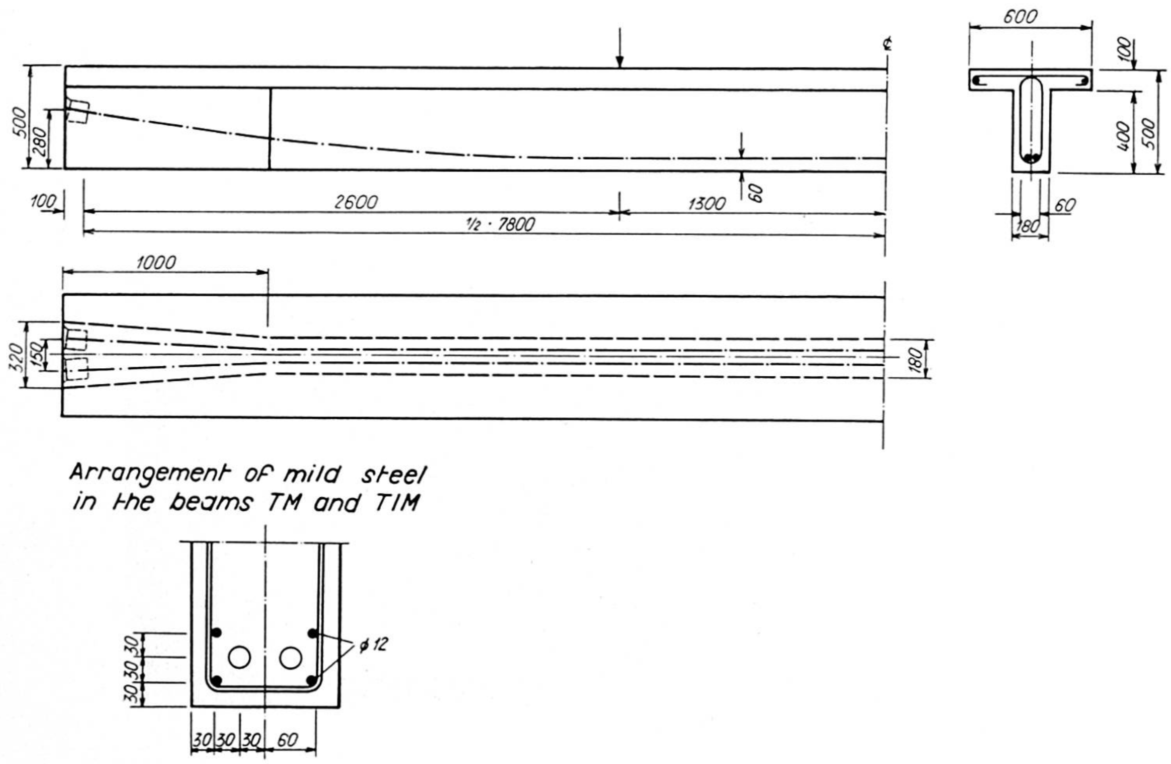

Fig. 7. Test Beams of T-Section.

is constant from anchorage to anchorage. The concrete strain at the level of the reinforcement is principally concentrated to the part between the loads and is practically zero outside this part. Since the total extension must be the same for the reinforcement as for the concrete, the areas under the diagrams must be equal, which means that the steel strain must be smaller than the concrete strain. In this case the ratio of steel strain to concrete strain, a ratio that may be called bond coefficient, since it expresses the efficiency of the bond, will be approximately a/l.

In this way the bond slip problem can be divided into two partial problems, one concerning the influence of the crack distribution on the compressive concrete strain and another concerning the bond coefficient. This way to attack the problem seemed to be appropriate in the beam tests shown in Fig. 7 and 8. The beams were of two kinds i.e. T-beams and rectangular beams. They were 8 m long and 0,5 m deep. The tendons were of the Freyssinet type and consisted of 12×5 mm wires each. (Ultimate strength 150—184 kg/mm^2.) Each beam was furnished with two tendons. Two of the T-beams were supplemented with ordinary reinforcement consisting of 4×12 mm

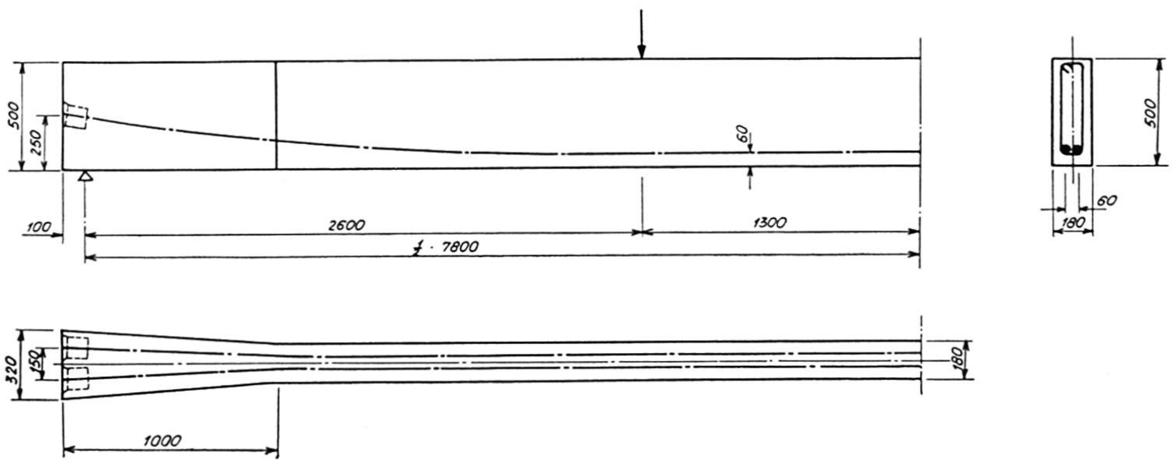

Fig. 8. Test Beams of Rectangular Section.

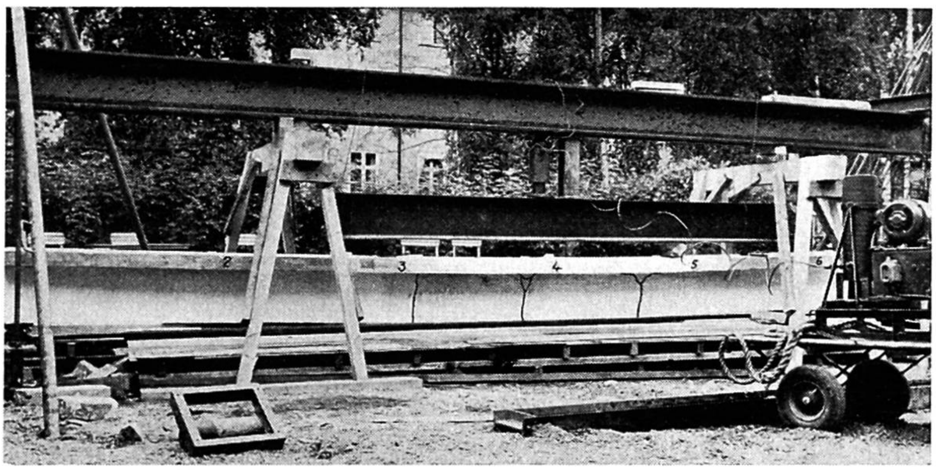

Fig. 9. Crack Distribution in the Non-Grouted T-Beam (T).

deformed bars (yield limit 40 kg/mm^2). The concrete strength was about 400 kg/cm^2. Half the number of beams were injected with the kind of grout mentioned above, and half the number were left ungrouted. Beam characteristics are given in Table 1.

The load was applied in the thirdpoints. Fig. 9, 10 and 11 show the crack distribution in the non-grouted beams; T-beam, rectangular beam and T-beam supplemented with deformed bars. Fig. 12, 13 and 14 show the crack distribution in the grouted beams; T-beam, rectangular beam and T-beam with deformed bars. Table 2 gives the test results in a concentrated form. The ratios x/s were obtained from the test beams by measuring the depth of the compres-

Table 1

Beam	Cube strength of concrete kg/cm^2	Steel percentage		Steel qual. kg/mm^2 $\sigma_{0,2}/\sigma_{rupt.}$	Prestress kg/mm^2	
		Tendon	Suppl. Reinf.			
T	394	0,186	—	128/152	70	ungrouted
R	406	0,615	—	124/150	69	
TM	450	0,184	0,168	128/152	75	
TI	374	0,178	—	164/184	77	grouted
RI	402	0,625	—	134/150	71	
TIM	428	0,183	0,168	128/152	72	

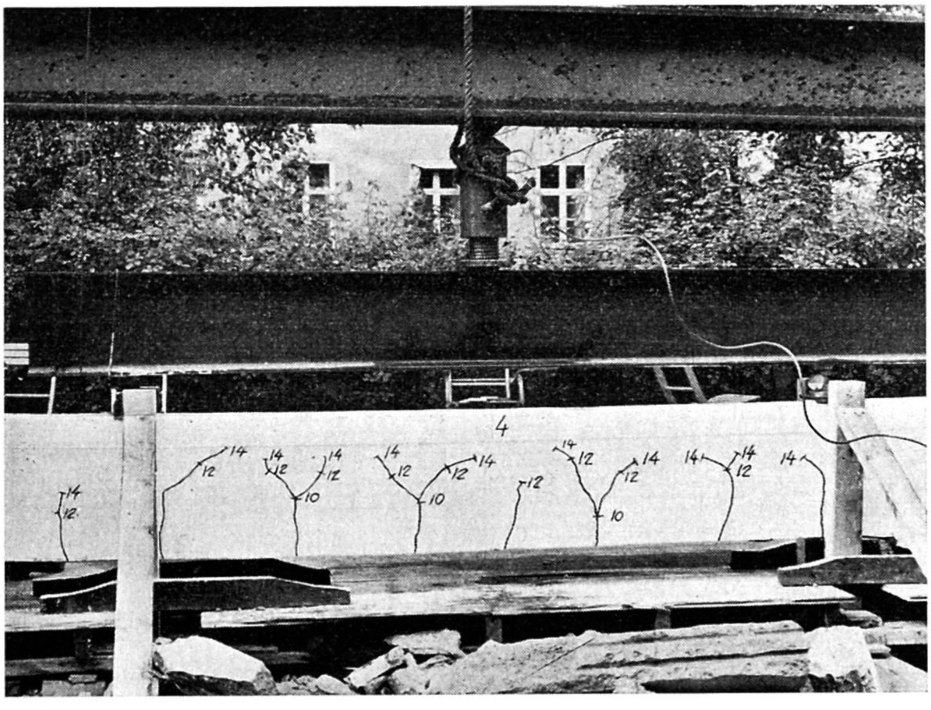

Fig. 10. Crack Distribution in the Non-Grouted R-Beam (R).

Table 2. Moments Are Given in mt

Beam	T	TI	TM	TIM	R	RI
x/s	0,04	0,18	0,25	0,26	0,26	0,35
F	$\frac{1}{3}$	1	$\frac{1}{3}$	1	$\frac{1}{3}$	1
$F\,\epsilon_{ave}$	0,2	2,2	0,8	2,5	0,8	2,8
calc. $M_{rupt.}$	23,5	36,4	36,7	40,0	21,5	25,3
obs. $M_{rupt.}$	23,6	37,0	37,0	36,6	21,5	24,6
$\frac{\text{obs.}}{\text{calc.}}$	1,00	1,02	1,00	0,92	1,00	0,97

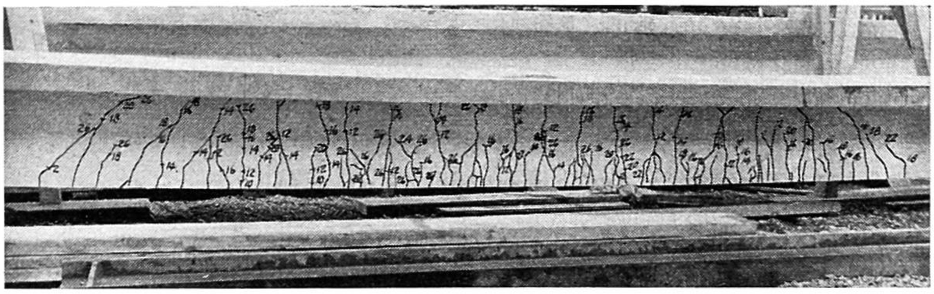

Fig. 11. Crack Distribution in the Non-Grouted T-Beam with Supplementary Mild Steel (TM).

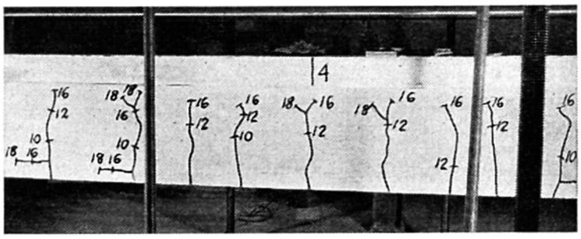

Fig. 12. Crack-Distribution in the Grouted T-Beam (TJ).

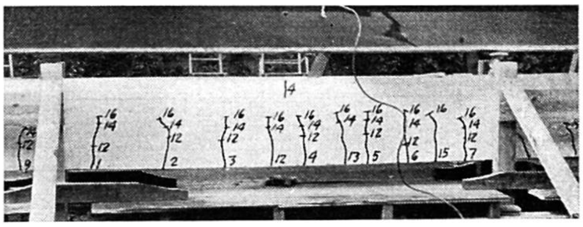

Fig. 13. Crack Distribution in the Grouted R-Beam (RI).

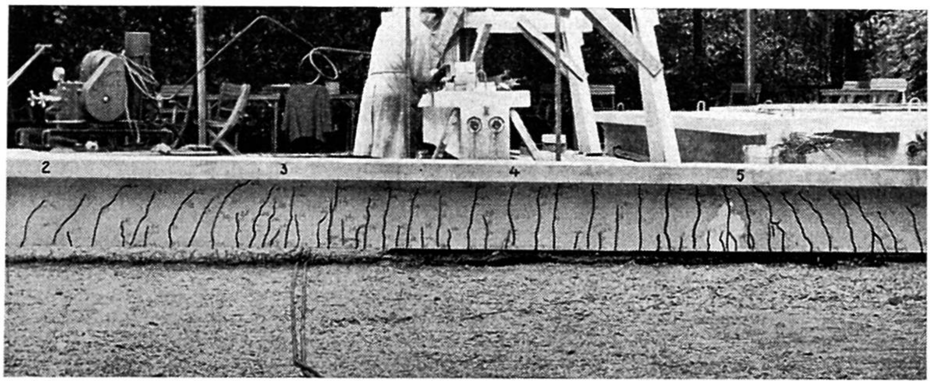

Fig. 14. Crack Distribution in the Grouted T-Beam with Supplementary Mild Steel (TIM).

sion zone at rupture, and by taking the average crack distance between the loads.

The bond coefficient F was chosen to $^1/_3$ in the non-grouted beams and to 1 in the grouted beams. The next row shows that instead of using the ultimate strain value of the order of $3{,}5\,^0/_{00}$ it is necessary to use smaller values, expecially in beam T, which is ungrouted and has a very unfavourable crack distribution. The values of ϵ_{ave} were taken from the curve in Fig. 5 that resulted from the model test with $\epsilon_{max} = 3{,}5\,^0/_{00}$. The ultimate bending moments were calculated according to a Stüssi stress distribution with $\alpha = 0{,}72$ and $\beta = 0{,}42$. Cf. [4]. As can be seen the test results conform quite well with the theory. TIM is an exception which is due to the fact that the test set-up used for that beam did not allow it to be ruptured completely.

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Summary

The contribution describes tests that have been carried out at the institution of structural engineering and bridge building at the Royal Institute of Technology, Stockholm, Sweden. The tests comprise pull-out tests, plexiglass model tests and beam tests. The Freyssinet post-tensioning system with cables of 12×5 mm wires was used. It is shown that the cable as a crack distributor is inferior to ordinary reinforcement, and that the crack distribution may have a marked influence on the rupture load of a prestressed beam.

Résumé

La contribution décrit des recherches effectuées à l'Ecole Royale Polytechnique Supérieure de Stockholm (section des ponts et charpentes). Il s'agit d'essais d'arrachement (pull-out tests), d'essais sur modèles en plexiglas et d'essais d'adhérence par effort tranchant (beam tests). On utilisa des câbles Freyssinet comprenant 12 fils de ∅ 5 mm.

Ces essais ont montré que les câbles de précontrainte répartissent moins bien les fissures que les armatures ordinaires et que cette répartition peut exercer une influence marquée sur la charge de rupture d'une poutre précontrainte.

Zusammenfassung

Der Aufsatz beschreibt Versuche, die in der Abteilung für Brücken- und Hochbau der Kgl. Technischen Hochschule Stockholms durchgeführt worden sind. Die Versuche umfassen Ausziehversuche, Plexiglas-Modellversuche und Balkenversuche. Das Freyssinet-Spannbetonsystem mit Kabeln aus 12×5-mm-Drähten wurde benutzt. Es wird gezeigt, daß das Kabel als Risseverteiler der gewöhnlichen schlaffen Bewehrung unterlegen ist, und daß die Risseverteilung einen deutlichen Einfluß auf die Bruchlast eines Spannbetonbalkens haben kann.