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Autor: Wästlund, Georg / Jonson, Per Olov

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Etude sur la fissuration des ouvrages en béton armé

Untersuchung über Rissbildung in Eisenbetonbauten

Investigation on formation of cracks in reinforced concrete structure

GEORG WÄSTLUND & PER OLOV JONSON, C. E.

Professor of Structural Engineering and Bridge Building, Royal Institue of Technology, Stockholm
Director, Swedish Cement and Concrete Research Institute at the Royal Institute of Technology, Stockholm

Swedish Cement and Concrete Research Institute, at the Royal Institute of Technology, Stockholm

Introduction

Formation of cracks in reinforced concrete structures has met with *increasing attention since high-grade reinforcement steels with higher allowable stresses came into use.* The width of cracks increases with increasing stress in reinforcement, irrespective of the steel grade.

In order to contribute to the elucidation of the crack formation problem, an investigation on this subject is being carried on by the Swedish Cement and Concrete Research Institute at the Royal Institute of Technology, Stockholm, in cooperation with the Institution of Structural Engineering and Bridge Building at the Royal Institute of Technology, Stockholm, and the Construction Department of the Royal Administration of Roads and Waterways. The main purpose of this investigation is to provide information regarding crack formation in reinforced concrete bridges. The investigation comprises laboratory tests as well as records and measurements of cracks in existing bridges. Moreover, the investigation will in the near future include a theoretical study of the problem in order to deduce formulae for the approximate calculation of the maximum width of cracks.

The object of the laboratory tests was to examine crack formation in T-beams submitted to positive and negative moments. In connection herewith a more detailed study of the strength of bond between concrete and reinforcement in progress.

The present paper deals in the first place with crack formation in

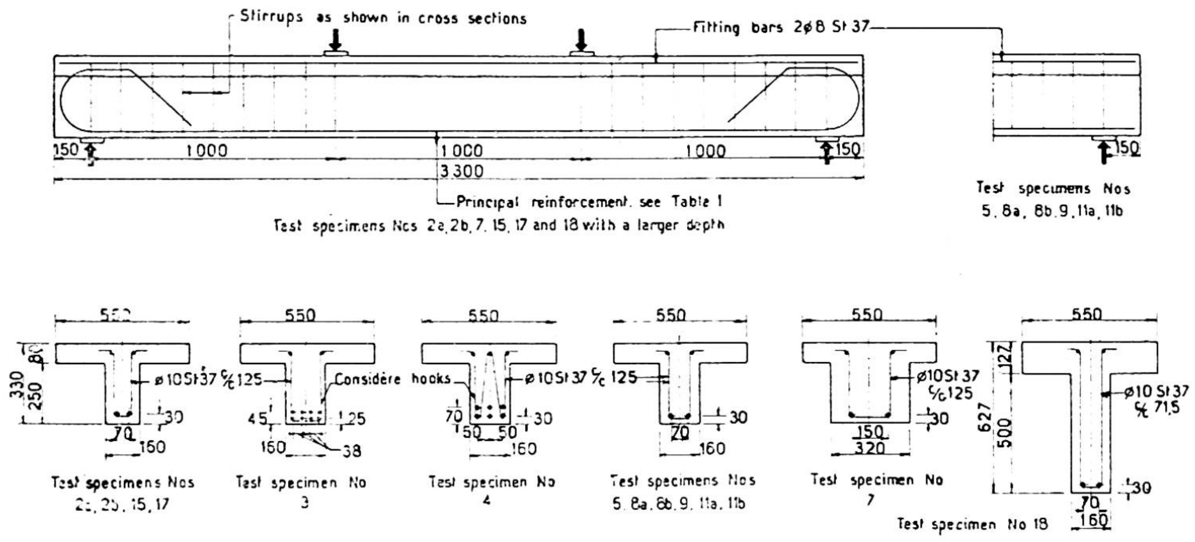

Fig. 1. Specimens used in tests regarding formation of cracks in T-beams subjected to positive moments. For test data, see Table 1.

beams subjected to positive moments, since it is only this part of the investigation that can be regarded as completed. Furthermore, a condensed account is given of some tests made on T-beams acted upon by negative moments, and some preliminary results of these tests are briefly stated.

Crack formation in T-beams submitted to *positive* moments has previously been dealt with more completely in *Proceedings of the Swedish Cement and Concrete Research Institute at the Royal Institute of Technology*, Stockholm, No. 10, 1947, reprinted from the review *Betong* (Concrete), No. 2, 1947 (49 pages, 12 tables, 52 figures, in Swedish).

1. Study of crack formation in T-beams subjected to positive moments

A. Laboratory tests

The laboratory tests were made in order to examine the effects on crack formation in T-beams by the following four factors, viz., 1) diameter of reinforcement bars, 2) ratio of reinforcement, 3) surface properties of reinforcement bars (plain bars and deformed bars), and 4) quality of concrete.

The test specimens are shown in fig. 1 and further test data are given in table 1. The test specimens differed in respect of the factors enumerated above. The tests were made as accurately as possible so as to curtail accidental errors. Thus, for instance, the concrete used for all test specimens was made of dried aggregate which was screened into separate fractions in advance. This was done in order to ensure uniform composition of the concrete used for making test specimens at different times. Accordingly, difference between the strength values was slight. The concrete was worked by hand in the forms, and had a slump of about 7 cm.

All cracks formed during the tests were successively studied, and their development was recorded. The widths of all cracks on both sides of the beam were measured on a level with the reinforcement by means of a microscope with an accuracy of about 1/100 mm.

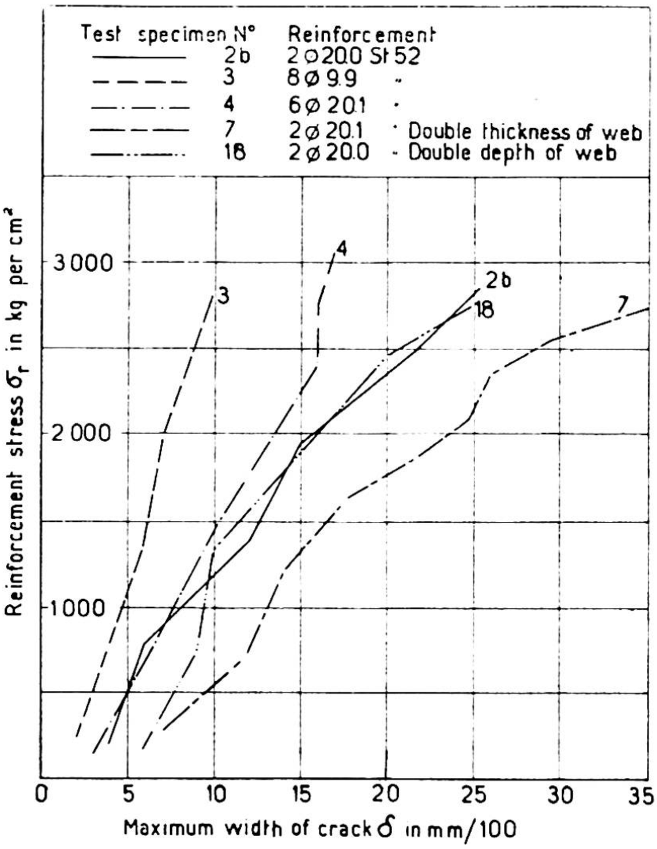

Fig. 2. Width of largest crack δ as a function of the reinforcement stress σ_r during the third application of load to five test beams differing in diameter of reinforcement bars (Nos. 2b and 3), ratio of reinforcement (Nos. 2b and 4), thickness of web (2b and 7), and depth of web (2b and 18).

In addition to the width of cracks, the total elongation of the beams was measured between the points of application of load. The deflections of the beams were measured at five points.

The reinforced concrete beams were tested in stages by repeated application and removal of load.

The results of the crack measurements are briefly summarised in fig. 2 to 4 and in table 1. They represent only the width of the *largest* crack observed during the *third* series of load application. The reason is that, in examining the test results, the greatest importance was attached to the behaviour of the beams during this load series, where the maximum load was equal to 3/4 of the ultimate load.

Diameter of reinforcement bars. The effect produced by the size of the diameter of reinforcement bars on the width of cracks is shown in fig. 2, vide test specimens Nos. 2*b* and 3 which were identical in every respect except for the diameter of the reinforcement bars. These curves show that *the width of cracks increases almost linearly with the diameter of the reinforcement bars.*

Ratio of reinforcement. The influence of the ratio of reinforcement on the width of cracks is illustrated by the results obtained from the tests made on specimens Nos. 2*b* and 4, in fig. 2. The curves show that the width of the largest crack observed on specimen No. 4, in which the area of reinforcement was three times as large as in specimen No. 2*b*, is slightly smaller with the same reinforcement stress. Under these circumstances *an increased ratio of reinforcement was favourable.*

Furthermore, the effect of the ratio of reinforcement can be exemplified

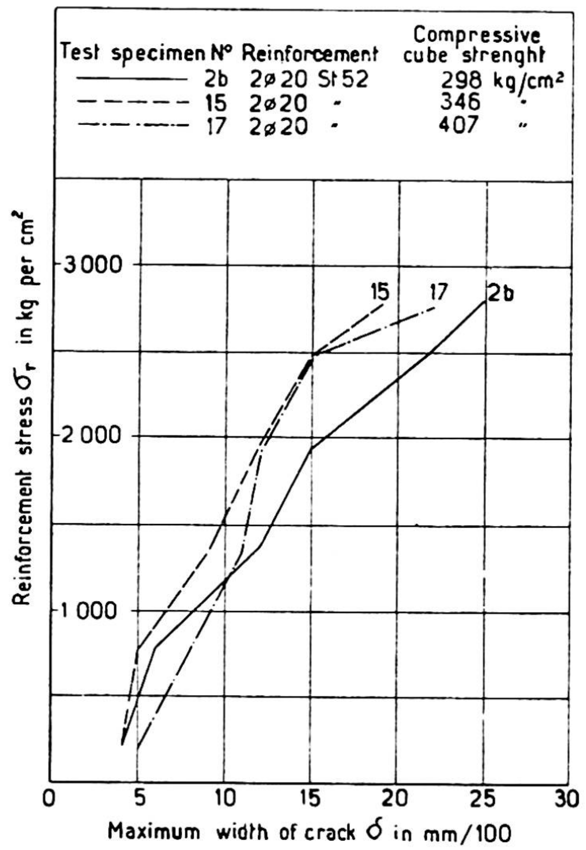

Fig. 3. Width of largest crack δ as a function of the reinforcement stress σ_r during the third application of load to three test beams differing in concrete strength.

by a comparison of test beams Nos. 2*b*, 7 and 18. These beams are provided with the same reinforcement, viz., 2 bars of 20 mm diameter, but the ratio of reinforcement of beam 2*b* is about twice as great as that of beams Nos. 7 and 18, because the latter two beams have twice the thickness and depth of web respectively. It will be seen from fig. 2 that *an increase in the thickness of web gives rise to a considerable increase in the width of cracks.* On the other hand, an increase in the depth of web is not likely to bring about an increase in the width of cracks. In all probability, it is the ratio of reinforcement in a relatively limited portion of the area under tension of the beam that influences the development of cracks. Consequently, the thickness of web should be only just large enough to ensure that the reinforcement is safely embedded in concrete.

Quality of concrete. The influence exerted by the quality of concrete on the width of cracks was investigated by tests made on three specimens. The results of these tests are reproduced in fig. 3. The compressive cube strength of the concrete (cube size $20 \times 20 \times 20$ cm) increases in the order : Nos. 2*b*, 15 and 17, but the curves in the diagram do not follow the same sequence. Therefore, these tests do not give any definite information as to the effect of the quality of concrete.

Surface properties of reinforcement. Fig. 4 shows the effect produced on the width of cracks by the surface properties of the reinforcement bars. All test specimens referred to in fig. 4 were identical in respect of cross-section and quality of concrete, and nearly equivalent as regards the ratio of reinforcement, but they differed as to type of reinforcement (see table 1). The greatest widths of cracks were observed on test beams Nos. 2*a* and 2*b*

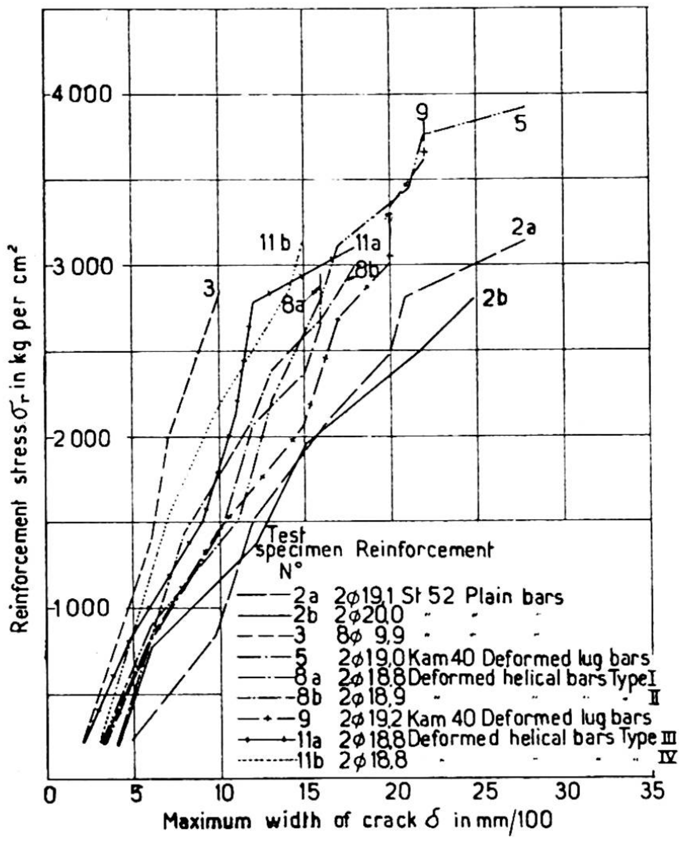

Fig. 4. Width of largest crack δ as a function of the reinforcement stress σ_r during the third application of load to ten test beams differing in diameter of reinforcement bars (Nos. 2b, 2a and 3) and in surface properties of reinforcement bars (Nos. 2a, 2b, 5, 9, 8a, 8b, 11a and 11b).

which were reinforced with 2 plain bars, 19.1 mm in diameter, and 2 plain bars, 20 mm in diameter, respectively, whereas the smallest width of cracks was observed on the test beam No. 3 which was reinforced with 8 plain bars, 9.9 mm in diameter. The widths of cracks which were obtained in tests made on beams reinforced with various types of deformed bars, 19 mm in diameter, were between these upper and lower limits. Test specimens Nos. 5 and 9 were identical in design. Both these beams were reinforced with deformed bars of the transverse lug type which is standardised in accordance with Swedish State Specifications for Cement and Concrete. Test specimens Nos. 8*a*, 8*b* and 11*a* were approximately equivalent to specimens Nos. 5 and 9, and were reinforced with deformed helical bars, types I, II and III. The results obtained in the case of test beam No. 11*b*, which was reinforced with deformed helical bars of type IV, were appreciably better. These four types of deformed helical bars were made for tests only, and will not be manufactured for sale. They differ in the pitch angle formed by the helical ridge and the longitudinal axis of the bar. The respective pitch angles of the four types of deformed helical bars were 27°, 36°, 45° and 52°. The larger the pitch angle, the greater the number of turns of the helix per unit length of bar.

Fig. 4 shows that the width of cracks observed on test beams reinforced with deformed lug and helical bars were smaller than those obtained in the case of the corresponding plain bars. However, the difference is not so great as might perhaps have been assumed.

Some test results which throw more light on the problems discussed above are given in table 1. The results of tests made on plain concrete beams are also reproduced in table 1.

Test specimen N°	Reinforcement and Remarks	Yield strength of reinforcement bars kg/cm²	Compressive cube strength (cube size 20×20×20 cm) $\sigma_{c\,28}$ kg/cm²	Computed (1) tensile stress in bending set up in concrete at first crack kg/cm²
1	Plain concrete.	—	280	30.4
2 a	2 ∅ 19,1 St 52, plain bars.	3 670	278	29 1
2 b	2 ∅ 20,0 St 52, plain bars.	3 810	298	32.7
3	8 ∅ 9,9 St 52, plain bars.	3 640	276	39.6
4	6 ∅ 20,1 St 52, plain bars.	3 680	271	31.8
5	2 ∅ 19,0 Kam 40, deformed lug bars (5).	4 240	283	36.9
7	2 ∅ 20,1 St 52, plain bars. Double thickness of web. Cf. Fig. 1.	3 680	283	21.7
8 a	2 ∅ 18,8 Deformed helical bars, type I (6).	4 290	281	32.6
8 b	2 ∅ 18,9 Deformed helical bars, type II.	4 300	290	32.0
9	2 ∅ 19,2 Kam 40, deformed lug bars.	4 420	321	28.2
11 a	2 ∅ 18,8 Deformed helical bars, type III.	4 950	319	28.2
11 b	2 ∅ 18,8 Deformed helical bars, type IV.	4 900	302	29.3
14	Plain concrete.	—	345	25.5
15	2 ∅ 20,0 St 52, plain bars.	3 810	346	23.2
16	Plain concrete.	—	355	23.7
17	2 ∅ 20,0 St 52, plain bars.	3 810	407	31.7
18	2 ∅ 20,0 St 52, plain bars. Double depth of web. Cf. Fig. 1.	»	314	31.5

B. Crack measurements on bridges

In addition to laboratory tests, crack measurements were made on seven bridges. The purpose of these measurements was to provide information as to development, distribution and width of cracks in actual structures.

Up to now, only results of measurements concerning crack formation in structural members submitted to *positive moments* have been worked out. Some characteristic data on the bridges subjected to the crack measurements are given in table 2.

In general, crack measurements covered half the length of each bridge. All concrete surfaces were closely examined, and the cracks were marked, recorded and mapped. The width of cracks was measured with an accuracy of about 2/100 mm by means of a microscope. During the measurements of the width of cracks, the bridges were mainly subjected to dead load stresses (due to the weight of the bridge and the earth pressure), and possibly also to temperature and shrinkage stresses. On the other hand, no live loads were applied to the bridges during the measurements.

All the seven bridges showed fairly regular formation of cracks. In the central portions of the spans the cracks were located in the lower parts of the girders, and the distance between the cracks varied from a few centimetres to about one metre. In general, the distance between cracks did not exceed 40 to 50 cm. On continuous bridges no cracks had formed in the vicinity of the zero moment points, but cracks were observed over supports in the upper parts of the girders and in the bridge deck.

No damage caused by crack formation in girders, due to positive moments, was detected on the bridges, just as could be expected, because most of the bridges were but a couple of years old. The oldest bridge,

TABLE 1. *Data on Reinforcement, Strength of Concretes at First Crack, Maximum Width of Crack, Maximum Distance Between Cracks, etc.*

mputed (2) nforcement stress at first crack kg/cm²	Width of largest crack in mm/100 during third loading at a computed reinforcement stress (2) σ_r=1600 (3) kg/cm²	σ_r=1900 (3) kg/cm²	(4) Maximum distance between cracks cm
—	—	—	—
1 020	13	—	23.0
1 062	13	- -	22.5
1 368	6	—	11.2
600	11	—	15.0
1 336	—	12	17.8
1 070	18	—	32.2
1 124	—	12	14.5
1 127	—	11	18.2
979	—	14	15.8
1 009	—	10	16.5
1 024	—	9	17.3
—	—	—	—
756	10	—	22.3
—	—	—	—
1 045	12	—	22.4
1 598	13	—	25.5

(1) These stresses are computed on the assumption that the concrete, in conjunction with the reinforcement (n = 15), is able to withstand both tensile and compressive stresses.
(2) These stresses are computed on the assumption that the concrete is not able to withstand any tensile stresses.
(3) Permissible stresses for the respective steel grades stipulated in present Swedish State Specifications for Cement and Concrete (Staten off. utredningar 1942 : 44).
(4) Maximum distance between two adjacent cracks measured after loading to yield strength of reinforcement.
(5) Distorted lug bars, Kam 40, with transverse lugs, are standardised according to the present Swedish State Specifications for Cement and Concrete and are manufactured for sale.
(6) Distorted helical bars were manufactured for tests only. These four types differ in the pitch angle between longitudinal axis of the bar and the helical ridge. The respective pitch angles of the types I to IV are 27°, 36°, 45° and 52°.

which is referred to as No. 6, was 10 years old at the time of examination.

On the other hand, lime bleeding was observed along many cracks in the bridge deck and in beams along the edges of the deck. This observation was made on one bridge, provided with a wearing top layer forming part of the load-bearing slab, without any special insulating layer, as well as on other bridges, which were provided with a waterproofing membrane between the load-bearing slab and the concrete pavement. On the first mentioned bridge it took rainwater only a few minutes to pass through cracks about 10 mm/100 in width. On the other hand, no similar water penetration phenomena were observed on the bridges provided with waterproofing membranes.

The widths of the largest tensile cracks formed in the lower parts of the girders on account of positive moments are given in table 2. In general, these cracks are so small that they do not expose the stability of the structure to any serious danger. It is to be noted, however, that all bridges subjected to examination, with the exception of bridge No. 7, were reinforced with bars made of standard steel St 44. If standard steel St 52 had been employed for reinforcement, and if use had been made of the higher allowable stresses specified for this grade of steel, then the width of cracks would certainly have been greater.

2. Study of crack formation in T-beams subjected to negative moments

LABORATORY TESTS

The investigation of crack formation in T-beams subjected to negative

Bridge (2) N°	Total number of spans	Examined spans N°	Length of span m	Depth of girder (slab) at centre of span cm	at supports cm	Width of girder (slab) at lower edge cm	(3) Tensile reinforcement at lower edge of girder (slab) at centre of span	Strength of concrete stipulated in specification (cube size 20×20×20 cm) kg/cm2
1	2	I	35.0	119.5	219.5	68	21 ⌀ 32	370
2	2	I	20.0	86.0	154.5	48	10 ⌀ 32+ 2 ⌀ 19	315
3	2	I	25.0	88.5	171.5	48	12 ⌀ 32	340
4	5	I and V	8.2	35.0	71.0	560	36 ⌀ 20	250
		II	11.2	»	»	»	54 ⌀ 20	»
5	5	I	46.3	255.2	507.0	70 (5)	34 ⌀ 32	340
		II	58.0	»	»	»	26 ⌀ 32	»
		III	»	»	»	»	30 ⌀ 32	»
6	5	Outer girder						
		I	10.0	105.0	105.0	70	11 ⌀ 32	330
		II	11·5	»	»	»	8 ⌀ 32	»
		III	11.5	»	»	»	9 ⌀ 32	»
		Inner girder						
		I	10.0	100.0	100,0	60	11 ⌀ 28	»
		II	11.5	»	»	»	8 ⌀ 28	»
		III	11.5	»	»	»	10 ⌀ 28	»
7	4	I	26.75	136.5	307.4	50	15 ⌀ 31	310
		II	31.50	»	326.3	»	9 ⌀ 31	»

moments is not yet completed. Accordingly, only some preliminary results are given below.

All test beams used in negative moment tests were identical in respect of the concrete area, see fig. 5, test specimen No. 102. The quality of concrete and total area of reinforcement were approximately equal in all test beams, whereas diameter and distribution of reinforcement bars varied. Reinforcement of four test specimens is shown in fig. 5. These test beams were reinforced with plain bars made of standard steel St 52. The theoretical span of the beams was 4.0 m. Each beam was subjected to two symmetrical concentrated loads, and the distance between loads was 1.28 m.

In these tests, the widths of transversal cracks were measured at the intersection of the cracks and four longitudinal gauge lines A, B, C and D. Positions of the gauge lines are indicated in fig. 5, see test specimen No. 107. Furthermore, reinforcement stresses in several bars of test beams Nos. 106, 107 and 111 were measured at the centre of a span. The deflections of the flange were measured along *three* longitudinal gauge lines on the test beams referred to above and along *one* gauge line on the other test specimens.

The following principal conclusions can be drawn from the preliminary test results.

1. It appears that distribution of reinforcement bars across the whole

Computed dead load ress in reinforcement at centre of span kg/cm²	(4) Width of largest cracks observed at lower edges of bridge girder mm/100
594	15,15,15,15,15,14,14,14
544	14,10,10,9,9,9,9,9
522	25,25,25,25,24,22,22,21
302	15,12,10,8,5 — — —
600	16,16,16,15,14,13,13,13
875	35,30,30,30,25,22,22,22
755	25,20,20,20,20,18,18,18
777	22,22,20,20,20,18,15,15
500	15,13,13,12,12,12,12,10
372	16,13,11,11,10,10,9,8
378	12,12,12,12,11,10,8,7
590	14,14,12,12,11,11,10,10
435	19,12,11,10,10,10,10,10
394	11,10,8,8,8,7,7,6
1 030	20,15,15,15,14,13,12,12
780	22,22,20,20,20,18,15,15

TABLE 2. *Characteristic Data on Bridges Subjected to Crack Measurements* (1).

(1) Cross-sections at centres of bridge spans and distribution of craks in some girders and bridge decks are shown in *Proceedings of the Swedish Cement and Concrete Research Institute at the Royal Institute of Technology, Stockholm*, No. 10, 1947.

(2) Bridges Nos. 1, 2 and 3 are girder frame bridges. Bridge No. 4 is a slab frame bridge. Bridges Nos. 5, 6 and 7 are continuous girder bridges.

(3) Bridges Nos. 1 to 6 are reinforced with plain bars made of standard steel, St 44. Bridge No. 7 is reinforced with deformed lug bars, Kam 40.

(4) It seems that these values have been exceeded at the construction joints where accurate measurements were rendered difficult by the vague contours of the cracks.

(5) The girders of this bridge are similar in shape to I-girders.

Gauge line	Observed width of cracks in mm/100			
	A	B	C	D
Test specimen N° 102 . . .	115	35	40	80
Test specimen N° 107 . . .	10	55	50	15
Test specimen N° 106 . . .	8	12	10	12
Test specimen N° 111 . . .	19	11	13	18

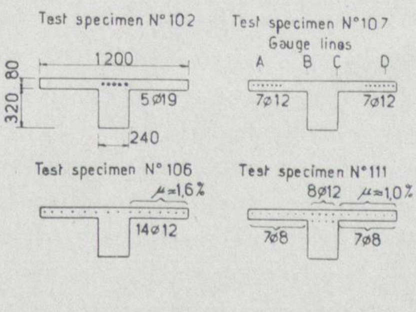

TABLE 3. *Maximum width of cracks observed on four test beams during the third application of load at a reinforcement stress of 1600 kg per cm². Cf. fig. 5.*

Fig. 5. Cross-section and reinforcement of four specimens used in tests regarding formation of cracks in beams subjected to negative moments.

flange, see test specimen No. 106, considerably reduces the width of cracks. This may be inferred from table 3 which gives a comparison of widths of cracks measured on the four test specimens shown in fig. 5. The greatest width of cracks was observed in the case of test specimen No. 102.

2. Reinforcement stresses observed in the tests were practically equal in all bars at the same height, irrespective of their position with reference to the web. All reinforcement bars can therefore be regarded as almost equally effective.

3. Ultimate loads of all specimens subjected to the tests were approximately equal. These loads were determined by the yield strength of the reinforcement.

Résumé

Le présent rapport décrit une étude qui porte sur la fissuration des ouvrages en béton armé. Cette étude comprend des essais de laboratoire effectués sur des poutres en T et des mesures des fissures produites dans les ponts existants. Les essais de labortoire ont pour but de déterminer l'influence exercée par divers facteurs sur la fissuration du béton. Une série de poutres d'essai a été soumise aux moments positifs. Les résultats de ces essais peuvent être résumés comme suit : 1° la largeur des fissures augmente en fonction presque linéaire du diamètre des barres d'armature; 2° la largeur des fissures est légèrement réduite par l'augmentation du rapport des sections de l'armature et du béton; 3° l'emploi des barres à entailles et des barres hélicoïdales, au lieu des barres lisses, réduit la largeur des fissures, dans la supposition que les diamètres des barres d'armature et les efforts dans l'armature soient égaux; 4° l'effet produit sur la largeur des fissures par la résistance du béton à la compression mesurée aux cubes d'épreuve est peu important.

Une autre série de poutres d'essai a été soumise aux moments négatifs. Les résultats préliminaires de ces essais montrent que la largeur des fissures diminue si les barres d'armature sont convenablement réparties sur toute la largeur de l'aile de la poutre.

Dans les mesures des fissures effectuées sur les ponts existants, les fissures ont été enregistrées et la largeur des fissures a été mesurée sur sept ponts. La fissuration était assez régulière sur tous les sept ponts. En général, un grand nombre de fissures a été observé sur chaque pont.

Zusammenfassung

Der Bericht behandelt eine Untersuchung über die Rissbildung in Eisenbetonbauten. Die Untersuchung zerfällt in Laboratoriumsversuche an T-Trägern und Rissmessungen an fertigen Brücken. Bei einer der Versuchsreihen wurden die Träger von positiven Momenten beansprucht. Die Ergebnisse dieser Versuche können in aller Kürze wie folgt zusammengefasst werden : 1. die Rissbreite nimmt ungefähr geradlinig mit dem Durchmesser der Bewehrungseisen zu; 2. die Rissbreite wird bei zunehmendem Bewehrungsverhältnis etwas verringert; 3. die Bewehrung aus Rippen- und Spiralstahl ergibt bei gleichem Durchmesser und gleicher Bewehrungsspannung kleinere Rissbreiten als glatte Rundstahlbewehrung; 4. die Würfelfestigkeit des Betons übt auf die Rissbreite keinen wesentlichen Einfluss aus.

Bei einer anderen Versuchsreihe wurden die Träger von negativen Momenten beansprucht. Die vorläufigen Ergebnisse dieser Versuche zeigen, dass die Rissbreite kleiner wird, wenn die Bewehrungseisen über die ganze Breite des Trägerflansches gleichmässig verteilt werden.

Bei den an sieben fertigen Brücken vorgenommenen Messungen wurden die Risse verzeichnet und die Rissbreite gemessen. Die Rissbildung war bei sämtlichen untersuchten Brücken ziemlich regelmässig, und die Risse waren bei jeder Brücke gewöhnlich in grosser Zahl vorhanden.

Summary

This paper deals with an investigation on crack formation in reinforced concrete structures. The investigation comprises laboratory tests on T-beams and crack measurements on seven bridges. The purpose of the laboratory tests was to determine the effects produced by various factors on crack formation. One series of test specimens was subjected to positive moments. The results of these tests can briefly be summarised as follows : 1° width of cracks increases almost linearly with the diameter of reinforcement bars; 2° width of cracks becomes slightly smaller as the ratio of reinforcement increases; 3° the use of deformed lug and helical bars, as compared with plain bars, reduces the width of cracks, assuming the diameters of reinforcement bars and the stresses set up in the reinforcement to be the same; 4° the compressive cube strength of concrete does not exert any notable influence on the width of cracks.

Another series of test specimens was submitted to negative moments. The preliminary results of these tests show that the width of cracks is reduced when reinforcement bars are properly distributed across the whole flange of the beam.

In the crack measurements made on seven bridges, cracks were recorded and the width of cracks was measured. All these bridges showed fairly regular formation of cracks, and the number of cracks observed on each bridge was usually large.

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