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Crack Widths and Deformation Behavior of Reinforced Concrete Structures

Largeur de fissures et comportement en déformation de structures en béton armé

Rissbreiten und Verformungsverhalten von Stahlbetontragwerken

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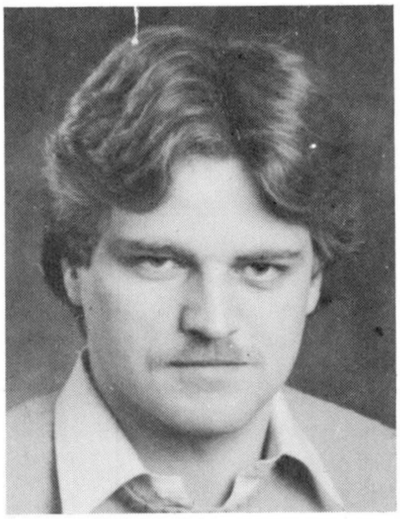

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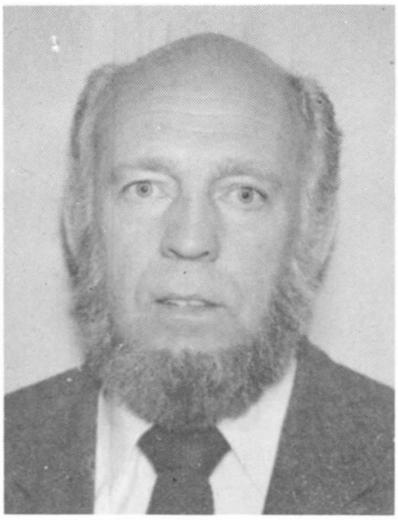

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SUMMARY

In this contribution the results of tests are shown. With the tests the increase of crack widths and deformations in dependence on load duration and number of load cycles was investigated. Especially considered are the consequences of the initial stress state caused by shrinkage on the crack width development. Besides simple tension and bending tests biaxial compression-tension tests were also carried out on reinforced concrete panels.

RÉSUMÉ

Gracê à des essais, l'augmentation des largeurs de fissures et des déformations dépendant de la durée et de la valeur de la charge devait être clarifiée. Les conséquences de l'état d'auto-contraintes créé par le retrait sur l'évolution des largeurs de fissures sont prises en considération. Outre les essais de traction et de flexion, des essais biaxiaux compression-traction on été réalisés.

ZUSAMMENFASSUNG

Mit Versuchen sollte geklärt werden, wie gross die Verformungs- und Rissbreitenzunahmen in Abhängigkeit von der Belastungsdauer und der Anzahl der Lastwiederholungen sind. Die Auswirkungen des durch Schwinden verursachten Eigenspannungszustandes auf die Rissbreitenentwicklung wurden besonders berücksichtigt. Neben den reinen Zug- und Biegeversuchen wurden auch biaxiale Druck-Zugversuche an Stahlbetonscheiben durchgeführt.

1. INTRODUCTION

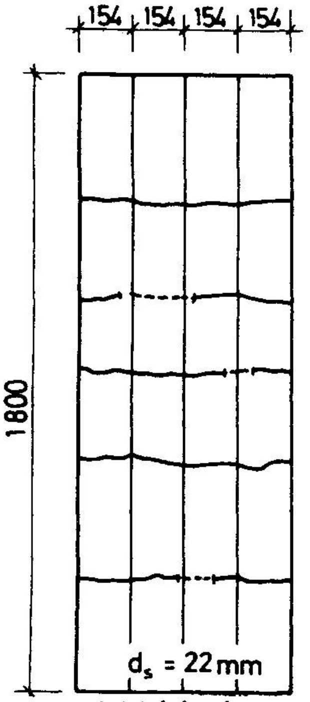
The durability of reinforced concrete structures mainly depends on crack widths and deformations. The protection against corrosion of the reinforcement is lost when crack widths are large and the stability is endangered. With too large deformation increases owing to long-term loads considerable usage restrictions of the building may result. In this contribution the results of about 120 tests on crack spacing, crack widths, and deformation behavior of reinforced concrete structures under monotonically increasing, cyclic, and long-term loads are presented.

2. CRACK SPACINGS

The average and maximum crack spacings of the reinforced concrete panels [1, 2], the centrically and eccentrically reinforced tension specimens [3, 4, 5], and the reinforced concrete beams [6] are presented in table 1. A dependence of the crack spacing on the concrete compressive strength and on the related rib area was not observed.

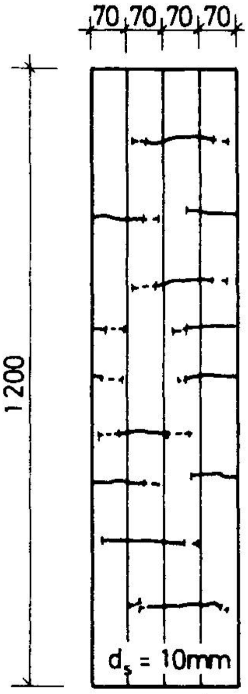
Owing to repeated loads and permanent loads no new cracks occured (not considering a few exceptions) with constant top load. As a result of unintentional eccentricities with the regularly and centrically reinforced tension specimens the cracks separated the concrete only partially at initial loading. Thus, the cracks still developed with repeated and permanent loads.

The crack development which occured with the eccentrically reinforced tension specimens (see Fig. 3) and the reinforced concrete beams are to be traced back to the decrease of concrete tensile strength owing to repeated loads.



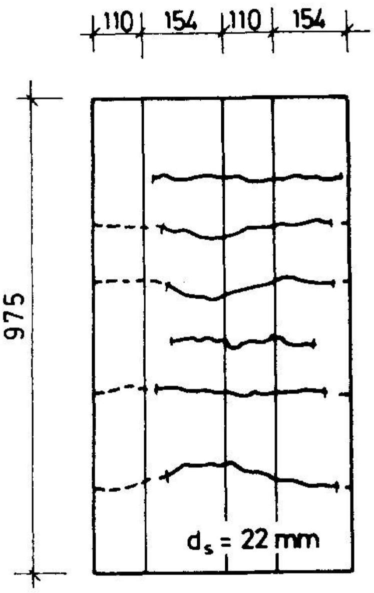
—— initial loading
----- as a result of repeated loads

Fig. 1 Crack pattern of intended centrically reinforced specimen S 22



—— initial loading
----- after permanent load of 144 days

Fig. 2 Crack pattern of intended centrically reinforced specimen DAUER 4



—— initial loading
----- as a result of repeated loads

Fig. 3 Crack pattern of eccentrically reinforced specimen E 11

In the crack patterns of the reinforced concrete panels [2] without transverse compression (see Fig. 4) and with 0,6 β_c transverse compression (see Fig. 5) no dependence of the amount of cracks on transverse compression can be seen.

Specimen	d_s (mm)	ü (mm)	s (mm)	reinforcement	number of specimens	crack spacing (mm) a_m	crack spacing (mm) a_{max}	calculated average crack spacing (mm) $a_m = 2\,(ü + 0{,}1 \cdot s) + 0{,}1\,\frac{d_s}{\mu}$	calculated average crack spacing (mm) $1{,}7 \cdot a_m$
reinforced concrete panels	10x8,5	10	50	ribbed bars with transverse reinforcement	2	134	185	105	178
				ribbed bars	5	136	200		
				ribbed mats	2	107	150		
	10x5,5	11	50	ribbed bars with transverse reinforcement	2	126	200	147	249
				ribbed bars	2	103	200		
				ribbed mats	1	102	125		
	5x16,0	42	100	ribbed bars	2	140	250	183	311
centrically reinforced tension specimens	1x10,0	30	70	ribbed bars	10	128	210	135	230
	1x10,0	40	90		2	127	220	200	340
	1x16,0	32	80		3	115	160	131	223
	1x16,0	48	112		2	183	240	219	372
	1x16,0	64	144		2	333	390	322	547
	1x22,0	44	110		20	174	310	180	306
	1x22,0	66	154		27	290	450	300	511
	1x22,0	88	198		16	359	630	442	752
	1x28,0	56	140		2	200	300	229	390
	1x28,0	84	196		2	333	450	382	650
	1x28,0	112	252		2	417	530	563	957
excentrically reinforced tension specimens	1x22,0	44	110	ribbed bars	8	156	280	180	306
	1x22,0	66	154		4	285	425	300	511
reinforced concrete beams	1x22,0	44	150	ribbed bars	3	244	300	214	363
	2x22,0	44	75	ribbed bars	2	162	250	151	256
	3x22,0	44	54	ribbed bars	2	113	185	131	223

Tab. 1 Crack Spacings

In accordance with the approach in the CEB/FIP requirements [7] for the calculation of the average crack spacing a_m the following equation resulted for ribbed bars and mats:

$$a_m = 2\,(ü + k \cdot s) + 0{,}1\,\frac{d_s}{\mu}\,; \qquad k = 0{,}1 \text{ for ribbed bars}$$

This yields a satisfactory agreement with the experimentally determined crack spacings (see table 1) for design of buildings. The effective zone of the reinforcement was established as in Fig. 6 according to Gergely and Lutz [8] as with the eccentrically reinforced tension specimens no dependence of the crack spacing on the height of the specimen was stated.

Furthermore a differentiation between tensile and flexural load could be neglected with respect to the CEB/FIP requirements so that it can generally be calculated with k = 0,1 for ribbed bars. The average crack spacings multiplied by 1.7 are in approximate accordance with the largest crack spacings of the experiment (see table 1).

With smooth mats the bond strength is generally transferred by the transverse reinforcement only. Cracks always form at the transverse reinforcement because of the smaller concrete cross section in this area. Forces can be transferred into the concrete until only two transverse reinforcement bars are left between two cracks. Thus the maximum crack spacing corresponds to the double spacing of transverse reinforcement. With this spacing only one transverse reinforcement bar is left between two cracks and no more forces can be introduced into the concrete.

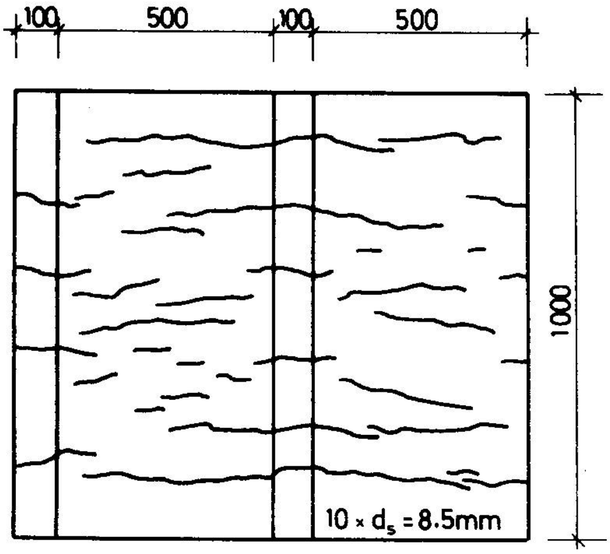


Fig. 4 Crack pattern of reinforced concrete panel B 19 (Q = 0)

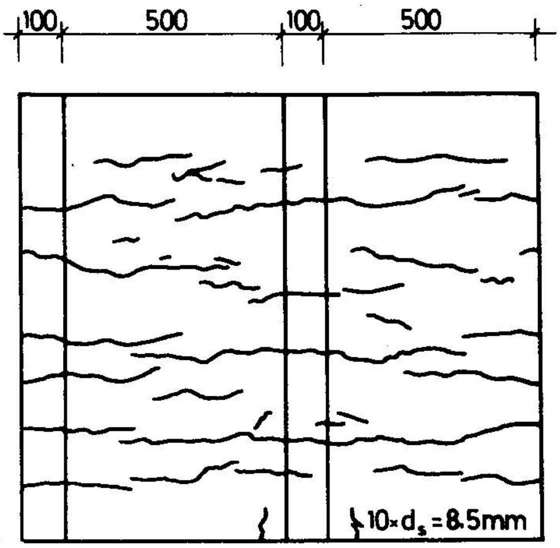


Fig. 5 Crack pattern of reinforced concrete panel B 11 (Q = 0,6 β_c)

3. CRACK SPACINGS

It was shown in [4] that the deformations of a reinforced concrete specimen mainly occur in the cracks and that the average crack w_m widths can be calculated with the equation stated in [7]:

$$w_m = \varepsilon_m \cdot a_m. \tag{2}$$

The maximum crack width results in approximately:

$$w_{max} = 1{,}7 \cdot w_m. \tag{3}$$

4. DEFORMATION BEHAVIOR OF CENTRICALLY AND ECCENTRICALLY REINFORCED TENSION SPECIMENS

The principal correlations between average strain over the cracks and external load related to the steel cross sectional area resulting from monotonically increasing and cyclic loading are shown in Fig. 7.

In order to describe the stress-strain behavior of centrically reinforced concrete specimens loaded in tension neglecting shrinkage of concrete the following idealization for initial loading.

$$\varepsilon_m = \frac{\sigma_s}{E_s} \sqrt{1 - \left(\frac{\sigma_s^1}{\sigma_s}\right)^2} \tag{4}$$

yielded a good agreement. This idealization is also valid for reinforced concrete panels under transverse load and for eccentrically reinforced tension specimens, if the effective concrete cross section according to Fig. 6 and the centrical concrete tensile strength are taken as a basis for the determination of the steel stress σ^1_s. The largest average strain at top load which stabilizes after a certain number of repeated lods can be approximately recorded with:

$$\varepsilon^o_{m,max} = \frac{\sigma^o_s}{E_s}\sqrt{1-\left(\frac{\sigma^1_s}{\sigma^o_s}\right)^5} \quad . \qquad (5)$$

At complete unloading a residual strain of about

$$\varepsilon_r = 0{,}2 \cdot 10^{-3} \qquad (6)$$

remains in the specimen. This is independent of the number of load cycles.

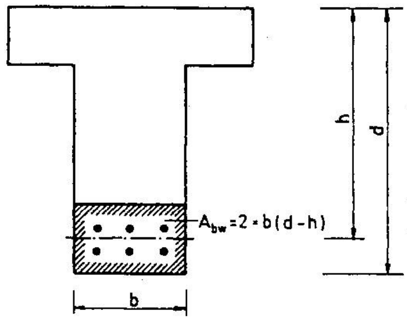


Fig. 6 Effective zone of reinforcement (acc. to [8])

It was stated with all tests that after approximately 5000 load cycles or after a 6-months permanent load no considerable deformation increases occured.

The initial stress state caused by shrinkage results, related to the load beginning, in larger average strains compared with the specimens without shrinkage. The stress-strain behavior of specimen S07 shown in Fig. 8 makes clear that the average strains can exceed those of the pure steel.

In case the shrinkage influence is considered for the determination of the steel stress in the cracked cross section directly after the first crack, the average strain related to the initial load can also be calculated according to Eq. (4) using $\sigma^1_{s,schw}$

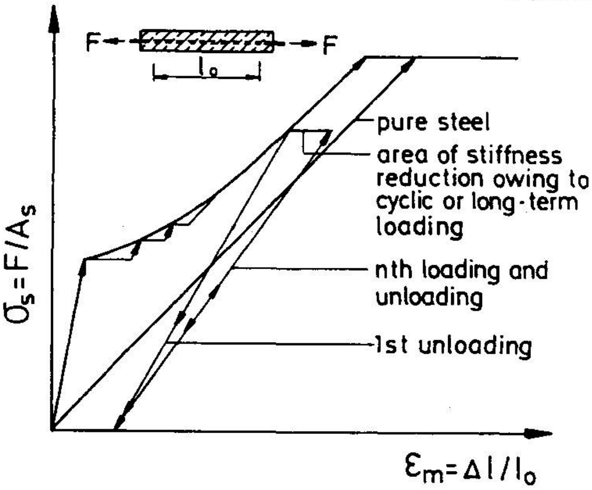


Fig. 7 Stress-strain relationships for axially loaded reinforced concrete

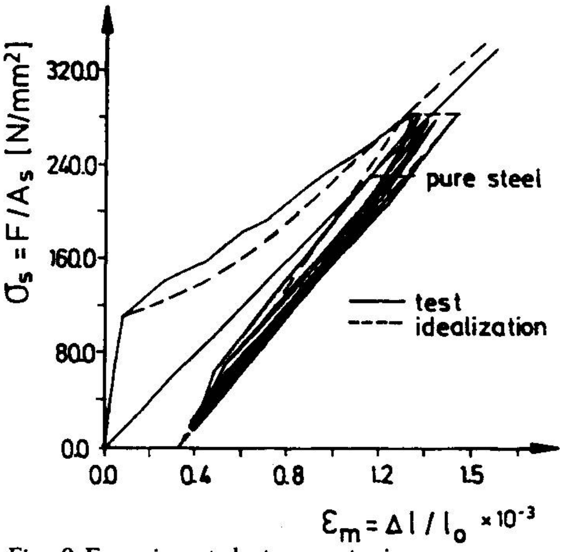


Fig. 8 Experimental stress-strain relationships of specimen S07 under shrinkage and idealization

$$\varepsilon_m = \frac{\sigma_s}{E_s}\sqrt{1-\left(\frac{\sigma^1_{s,schw}}{\sigma_s}\right)^2} \qquad (7)$$

The largest average strain increase at top load which stabilizes after a certain number of load cycles results to approximately

$$\Delta\varepsilon^o_{m,schw} = \frac{\sigma^o_s}{E_s}\left[\sqrt{1-\left(\frac{\sigma^1_s}{\sigma^o_s}\right)^5} - \sqrt{1-\left(\frac{\sigma^1_s}{\sigma^o_s}\right)^2}\right] \qquad (8)$$

as with specimens without shrinkage.

At complete unloading of the specimens a residual strain of

$$\varepsilon_r = 0{,}2 \cdot 10^{-3} + \varepsilon_m^o + \Delta\varepsilon_{m,schw}^o - \varepsilon_s^o \tag{9}$$

is left.

5. NOTATIONS

b	= width
d	= total height
h	= height from center of gravity of tension reinforcement to compression edge
d_s	= diameter of reinforcement bar
$ü$	= smallest concrete cover of reinforcement at pure tension = distance between bottom side of reinforcement bar and tension edge at eccentric tension and flexion
s	= distance of reinforcement bar (see table 1)
A_s	= steel cross sectional area
A_{bw}	= effective concrete cross section (see Fig. 6)
$A_{b,n}$	= area of concrete (net)
μ	$= \frac{A_s}{A_{bw}}$
F	= force
E_s	= modulus of elasticity of steel
β_c	= cylinder crushing strength
σ_s	= steel stress
Q	= lateral pressure
σ_s^1	= steel stress in concrete cross sectional area directly after first crack
σ_s^o	= maximum steel stress at cyclic or long-term loading
$\sigma_{s,schw}^1$	= steel stress in crack cross sectional area directly after the first crack considering shrinkage influence
ε_s^o	= steel strains at top load
ε_m	= average strain
ε_m^o	= average strain at top load
$\varepsilon_{m,max}^o$	= largest average strain owing to cyclic or long-term loading
ε_r	= residual strain in specimen after unloading
$\Delta\varepsilon_{m,schw}^o$	= strain increase owing to repeated loads at top load considering shrinkage influence
a	= average crack spacing
a_{max}	= maximum crack spacing
w_m	= average crack width
w_{max}	= maximum crack width

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* Summary, notations, and legends to pictures both in German and in English.