The strength of concrete and reinforced concrete under sustained and frequently repeated loading

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The Strength of Concrete and Reinforced Concrete under Sustained and Frequently Repeated Loading.

Festigkeit des Betons und des Eisenbetons bei dauernder und bei oftmals wiederholter Belastung.

La résistance du béton et du béton armé soumis à des efforts permanents et répétés.

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Investigation of the fatigue strength of concrete is a matter which, for the following reasons, involves lengthy and extensive research: the strength of the concrete depends on its age; it depends also on the treatment which the concrete has undergone (for instance on its water content, its temperature and its previous condition with or without shrinkage). Again, the development of strength of the concrete is influenced by the properties of the cement. The strength of the concrete depends also on the size of the concrete test blocks, and the action of the steel reinforcing bars in carrying the load is governed by the variable resistance of the concrete to deformations. This last factor can vary within very wide limits, being in turn dependent on the duration of loading, on the magnitude of the load, and the degree of moisture of the concrete.

In reference to fatigue effects, account has further to be taken of all those many influences which play a part in ordinary experiments on concrete and reinforced concrete — such as the amount of cement, the water-cement ratio, the grading, and the nature of the aggregate, the manner of preparation, etc. For each of these factors it has to be ascertained whether its effect on the fatigue strength is in any way different from that on the ordinary strength.

Here the expression "fatigue strength" is used in a general sense, but for technical application it becomes necessary to define the exact form in which the term is used — whether in the sense of resistance to tension, compression, alternations between tension and compression, bending, shear, buckling etc. — and also to define the method of loading whether this be stationary, frequently repeated, or in part stationary and in part frequently repeated. All these factors require to be ascertained and to be taken into account.

In the following pages a brief summary will be given of what is already known regarding the fatigue strength of concrete and reinforced concrete, and it shows — as the author has frequently mentioned elsewhere — that many questions still remain open for systematic research.

1) *Fatigue compression strength of concrete.*

The figures quoted below refer to concrete which was more than six months old at the time of testing and which after being at first treated wet had been put in storage.

a) *Fatigue compression strength under stationary loading (stationary fatigue strength).*

No results of experiments on the strength of concrete under long sustained loading are yet available, but a few observations have been made which may serve as a basis for further experiments. These are the results of the experiments described under b) and c) below, from which it may be anticipated that the stationary fatigue strength of the concrete will work out at something over 4/5ths of the strength ascertained in ordinary compression tests[1].

b) *Fatigue compressive strength under frequently repeated loading (surge load strength).*

In completion of the exploratory experiments by *Joly, Hatt, Ornum*[2] and from *Mehmel*[2], extensive researches have lately been carried out by *Graf* and *Brenner*[3] for the German Committee on Reinforced Concrete.

According to these experiments, the fatigue compressive strength of concrete columns of varying compositions — containing, in particular, varying amounts of cement and varying grading of aggregates — was found to be about 0.6 times the prism strength as determined by the ordinary breaking test. The composition of the concrete was of smaller significance, but as the strength increased the ratio generally decreased a little.

The number of loading repetition for such tests was of about 260 per minute, the total number of loading repetitions applied for obtaining the value of fatigue strength was two millions.

The number of repetitions required to cause fracture increased with increasing frequency of loading repetitions per minute (the frequencies used for the tests varied from 10 to 450 per minute). The fatigue strength was a little higher in value for increased frequencies.

c) *Fatigue compressive strength under the simultaneous effect of stationary loads and frequently repeated loads.*

When stationary loads were added to the frequently repeated loads, the amplitude of stresses due to moving loads (imposed two million times) decreased as the stationary loads increased. This is exemplified in Fig. 1 which shows the

[1] If it is a question of increasing the permissible compressive stress of concrete in this proportion it must be remembered that the magnitude of the deformation of the concrete under long duration of loading come into account also (compare, for instance, *Graf:* "Beton und Eisen" 1934, pages 167 and following. Also *Hummel* in "Zement", 1935, pages 799 and following.

[2] Compare also *Graf:* Die Dauerfestigkeit der Werkstoffe und der Konstruktionselemente. (Julius Springer, Berlin), pages 116 foll.; also *Hatt* and *Mills,* Bulletin 34 of the Purdue University, 1928.

[3] Compare also Publication N° 76 of the German Committée for Reinforced Concrete. A later report will appear in 1936.

following values for the amplitude S in the case of concrete for which the prism strength was 180 kg per sq. cm:

for stationary load $\sigma_u = 6$ kg per sq. cm; S = 109 kg per sq. cm
" " " $\sigma_u = 118$ kg " S = 39 kg "
" " " $\sigma_u = 157$ kg " S = 8 kg "

Here each experiment lasted for at least five days. The figures just quoted also show that with a duration of about five days the resistance to stationary loads approximates to the prism strength as determined by the ordinary breaking test (165 kg per sq. cm being the total load in the fatigue experiment as against 180 kg per sq. cm in the breaking test).

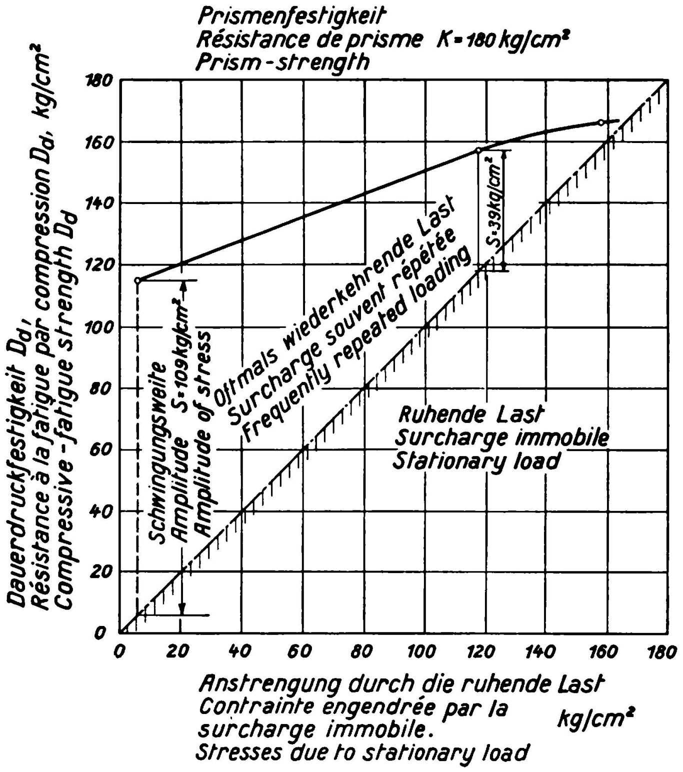


Fig. 1.

Compression fatigue tests with prisms of plain concrete.

d) *General remarks on fatigue strength.*

According to the regulations for concrete and reinforced concrete, the permissible compressive stress in concentrically loaded columns is at most one third of the strength of a concrete test cube 28 days old. If, then, the prism strength is assumed to be at least two-thirds the strength of a cube, the permissible stress in the concrete amounts to one half the prism strength.

This amount of stress is not much less than the resistance of prisms to frequently repeated compressive loading if the increase in strength with age is left out of account. If an appreciable increase in strength with age is assumed to take place, then the assumptions currently made in Germany as to the usual stressing of concrete in columns concentrically loaded are suitable even from the point of view of frequently repeated loadings.

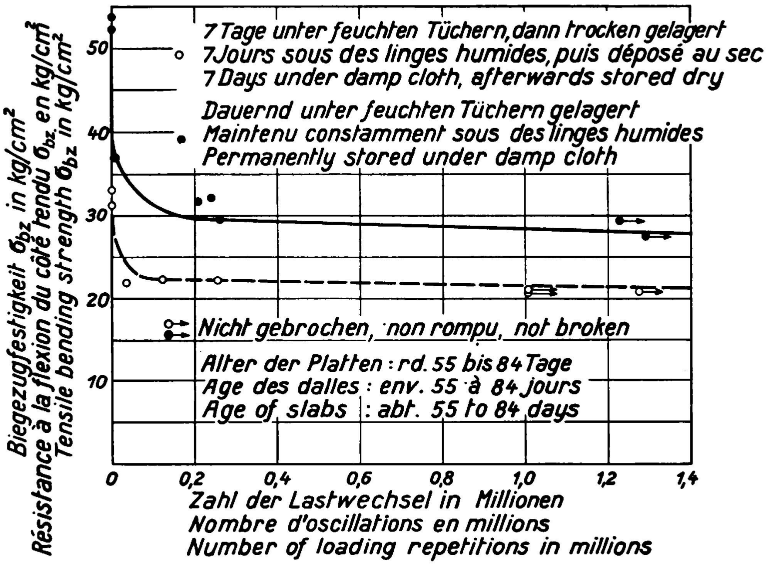
At some future time it may be determined under what conditions an increase in the permissible compressive stress in the concrete may be allowed in cases where stationary loads predominate or are alone decisive.

2) *Fatigue tensile strength of concrete.*

Experiments relating to this matter have been carried out in Karlsruhe, and these showed similar ratios in the case of tensile loading as those given under 1a) and 1b) for compressive loading[4]. These results have not yet been published.

3) *Fatigue bending strength of concrete.*

Clemmer[5] and later *Olden*[5] have investigated the fatigue bending strength of road concrete. The frequency of the load was 40 per minute. The results



Abmessungen 20×40×170 cm, Auflagerentfernung 150 cm
2 Lasten im Abstand von 50 cm, σ_u beim Dauerversuch 4,9-5,2 kg/cm²
Dimensions 20×40×170 cm, distance des appuis 150 cm
2 charges à la distance de 50 cm, σ_u pour l'essai à la fatigue 4,9-5,2 kg/cm²
Dimensions 20×40×170 cm, distance of supports 150 cm
2 loads 50 cm apart, σ_u for fatigue test 4,9-5,2 kg/cm²

Fig. 2.

Bending fatigue tests with slabs of plain concrete.

show that the fatigue bending strength under repeated non-alternating loads (surge loads) may be taken at approximately one half the bending strength as determined under the usual conditions.

The author's own experiments carried out in 1935 and reproduced in Fig. 2 yielded the following results. Beams which were maintained constantly wet showed fatigue bending strength under repeated non-alterning loads (surge loads) up to 28 kg per sq. cm, the ordinary bending strength being 53 kg per sq. cm, so that the ratio was 0.53 to 1. Beams which after being originally treated wet were subsequently stored dry showed a fatigue bending strength under repeated

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[4] As reported by Prof. Dr. Ing. *Kammüller*.

[5] In the report by *Graf:* Die Dauerfestigkeit der Werkstoffe und der Konstruktionselemente, page 117.

non-alternating loads (surge loads) up to 21 kg per sq. cm only, the ordinary bending strength being 32 kg per sq. cm, so that the ratio was 0.66 to 1.

Further experiments are in hand.

4) *Fatigue compressive strength of reinforced concrete columns.*

The following points call for notice in investigating the fatigue strength of reinforced concrete columns.

a) The elasticity of the steel, and therefore the resistance of the reinforcement to buckling, is not influenced, or, only to an inappreciable extent, by long duration of loading, or by frequently repeated loading.
b) Under loading of long duration the crushing limit is reduced[6].
c) The deformations of concrete are largely dependent on the duration and the magnitude of the load. Hence the participation of the concrete in transmitting the forces that occur in reinforced concrete columns changes according to the duration and magnitude of the loading, and apart from this is dependent on the composition and humidity of the concrete.

No test results have come to the knowledge of the author regarding any experiments about the carrying capacity of reinforced concrete columns under long duration of loading, under frequently repeated loading, or under the simultaneous influences of stationary and frequently repeated loading.

5) *Fatigue bending strength of reinforced concrete slabs.*

The carrying capacity of reinforced concrete slabs constructed in the usual way is determined by the resistance of the steel in the tensile zone.

Under loads which increase gradually and slowly, the yield point of the steel is exceeded in the tensile zone, and the deformations which then occur in the slab under ordinary conditions are so great as to make the latter appear practically unusable. The carrying capacity of slabs under a stationary load is therefore directly dependent on the yield point of the tensile reinforcement. The yield point is found to be somewhat smaller under long duration loading than it appears in the ordinary tensile test (see under 4).

The resistance of the tensile reinforcement when subjected to frequently repeated (non-alternating) loading may be as high as the elastic limit of ordinary round bars, provided the surface remains in good condition[7]. In steels having a high yield point the fatigue tensile strength is lower than the yield point, and in such steels the dependence of the fatigue strength on the surface conditions of the rods is much more marked than is the case in ordinary commercial rods. In simple slabs, for instance, the tensile reinforcement broke down when:

σ_s max. was in excess of .	2900	3100	3300	2830	kg per sq. cm
(amplitude of stress . .	2570	2640	2830	2565	kg ,,)
for an yield point of . .	2970	4280	4500	6150	kg ,,
using a grade of steel . .	St 37	St 60	"Isteg"	common Steel[7]	

[6] See: among others *Siebel* and *Pomp:* Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, Band X, Publication N° 100.

[7] See, for instance, in "Beton und Eisen", 1934, page 169.

According to this and other experiments carried out at Stuttgart it is advisable to assume, for the present, that the resistance of the tensile reinforcement when subject to frequently repeated loading is limited by an amplitude of 2600 kg per sq. cm, presuming in this connection that the surface conditions are sound, is adequate and will remain undisturbed.

It follows, as in the case of steel construction, that those steels which possess a high yield point under stationary loading may be subjected to higher permissible stresses under stationary loads than under moving loads: such steels should, therefore, be used for those structural members which are mainly subject to stationary loads.

The permissible loading on slabs should be governed not only by the carrying capacity, but also by the consideration that cracks in the concrete in the tensile zone may reduce the protection afforded to the reinforcement if the width of these cracks exceeds a limit depending on the prevailing conditions — as for instance, in the case of structures in the open[8]. What width of cracks may be tolerated as a means of reconciling experimental results with experience on old structures has not yet been determined.

6) *Fatigue bending strength of reinforced concrete beams.*

It has been assumed, in the explanation of the conditions governing the fatigue strength of slabs in Section 5, provided that ordinarily the reinforcement possesses adequate anchorage, and that this being so the properties of the concrete do not come into account in other words that the current regulations are fulfilled and that this prescribed minimum strength of the concrete is overstepped. In the case of beams, however, this assumption is in general not valid, because thicker steel bars have to be used in beams than in slabs, with the consequence that the pressure on the concrete from the hooks and so forth is greater. Moreover, the bent bars have to resist appreciably higher radial compressions at the places of bending, which, where the bars are of large diameter and the concrete is of moderate strength, may lead to the concrete being damaged before the tensile forces in the steel bars cause these to reach the yield point[9].

The strength of the concrete should, therefore, be governed by the dimensions of the reinforcement, or at any rate the required strength of concrete should be in relation to the reinforcement, dependent on limits which however have yet to be determined. These conditions become more obvious for frequently repeated loadings than for stationary loads[10].

Most of the fatigue bending experiments on reinforced concrete beams which have hitherto been published have investigated the effect of frequently repeated loading below the value of fatigue strength in relation to the ultimate load, determined in the usual way after completion of fatigue tests.

It was to be expected, from numerous results of other kinds of fatigue tests, that frequently repeated loads, considerably in excess of the permissible load but below the fatigue strength, should have little or no effect on the ordinary

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8 See "Beton und Eisen", 1935, page 148.

9 See "Beton und Eisen", 1935, page 147.

10 The German regulations for reinforced concrete, in their present form, tend to operate in this direction.

breaking load[11]. Hence the fatigue bending strength of reinforced concrete beams can be found only by determining those frequently repeated loadings which do not cause breakage but if increased slightly will cause failure.

It has been suggested, to make the permissible *load* dependent on a maximum permissible width of cracks. If this principle is to be applied to the case

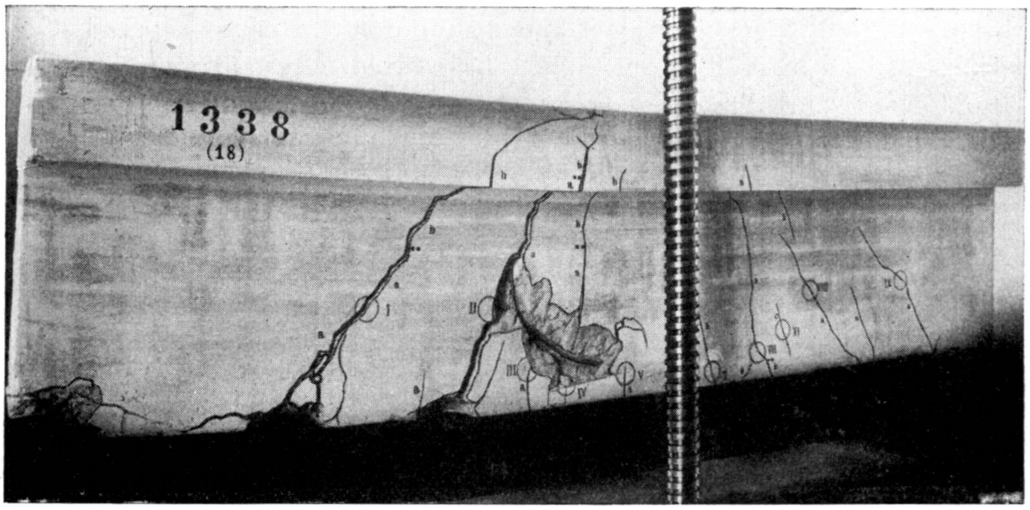

Fig. 3.

Reinforced concrete beam after frequently repeated bending.

of beams it must be specially noted that the width of the cracks is maximum in those regions where the sectional area of the reinforcement undergoes a change, particularly at places of bent up bars, but otherwise under normal conditions, the permissible loads would be dependent on the distance between the cracks. In this connection attention should also be paid to what was said at the end of Section 5.

Summary.

Investigations as hitherto carried out show that the strength of concrete subjected to frequently repeated loading (surge loads) such as compression, tension and bending, is at least half the strength as obtained in ordinary (static) rupture tests. If stationary loads are acting in conjunction with repeated loadings then the limits for live loads which the concrete is capable of withstanding, are reduced. The resistance to stationary loads is to be estimated at $^4/_5$ of the strength produced by ordinary rupture tests.

As regards the fatigue strength of reinforced concrete test results are only available for slabs and beams. Tests have shown that the reinforcing steel in con-

[11] See, for instance, Handbuch für Eisenbetonbau, Vol. 1, 4th edition, pages 46 and following, and the references given therein.

crete behaves similarly to steel subjected to fatigue tests. It is advisable to employ steels of high yield limit for the reinforcement of structures chiefly subjected to stationary loads only. The resisting power of concrete of beams which have to undergo frequently repeated loading is mostly exceeded at the places where the bars are bent up or at the location of hooks. This in particular if the arrangement of the reinforcement follows prevailing practice.

In view of these facts the German Commission for Reinforced Concrete (Deutscher Ausschuß für Eisenbeton) has decided to arrange further investigations concerning the resistance against slipping and the anchorage of bars, for reinforced concrete subjected to frequently repeated loading.