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Autor: Abeles, Paul William

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Le comportement du béton précontraint après fissuration
(Données pour le projet d'un tel ouvrage)

Das Verhalten von vorgespanntem Beton bei Rissebildung
(Folgerungen für den Entwurf)

The behaviour of prestressed concrete at cracking
(Conclusions for the design)

PAUL WILLIAM ABELES
D. Sc. (Vienna), M. I. Struct. E. London

In ordinary reinforced concrete permanent deformation takes place; thus cracks remain visible on removal of the load. A certain breathing of cracks was shown already by Professor E. Probst in a film at the Congress in Vienna in 1928. Also some healing of cracks has been ascertained. However, in spite of breathing and healing, too wide cracks exceeding a definite width (say 0.01 in i.e. 0.25 mm) represent a danger from the point of view of corrosion. Moreover in the event of excessive loading, permanent deformation of such magnitude occurs that the structure cannot be used further.

Quite different is the case with prestressed concrete. The outstanding characteristic of a prestressed concrete beam is its extraordinary resilience. Its behaviour is illustrated by typical load deflection lines obtained from beam tests made by the London & North Eastern Railway, London (L. N. E. R.) on prestressed concrete sleepers some of which had been in the track for 2 1/2 years [1] (fig. 1).

A sleeper is strained by tension on its under side below the chairs near its ends, and on the upper side in the centre portion; the magnitude of the stresses depending on the packing of the ballast. In view of this strain, the imparted pre-compression stresses are almost uniform over the whole section as indicated in fig. 1. The effective concrete stresses were approximately 1 650 to 1 800 lb per sq. in (115 to 125 kg/cm²). The numerical

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(1) See *Concrete and Constructional Engineering*, April and May 1947, London.

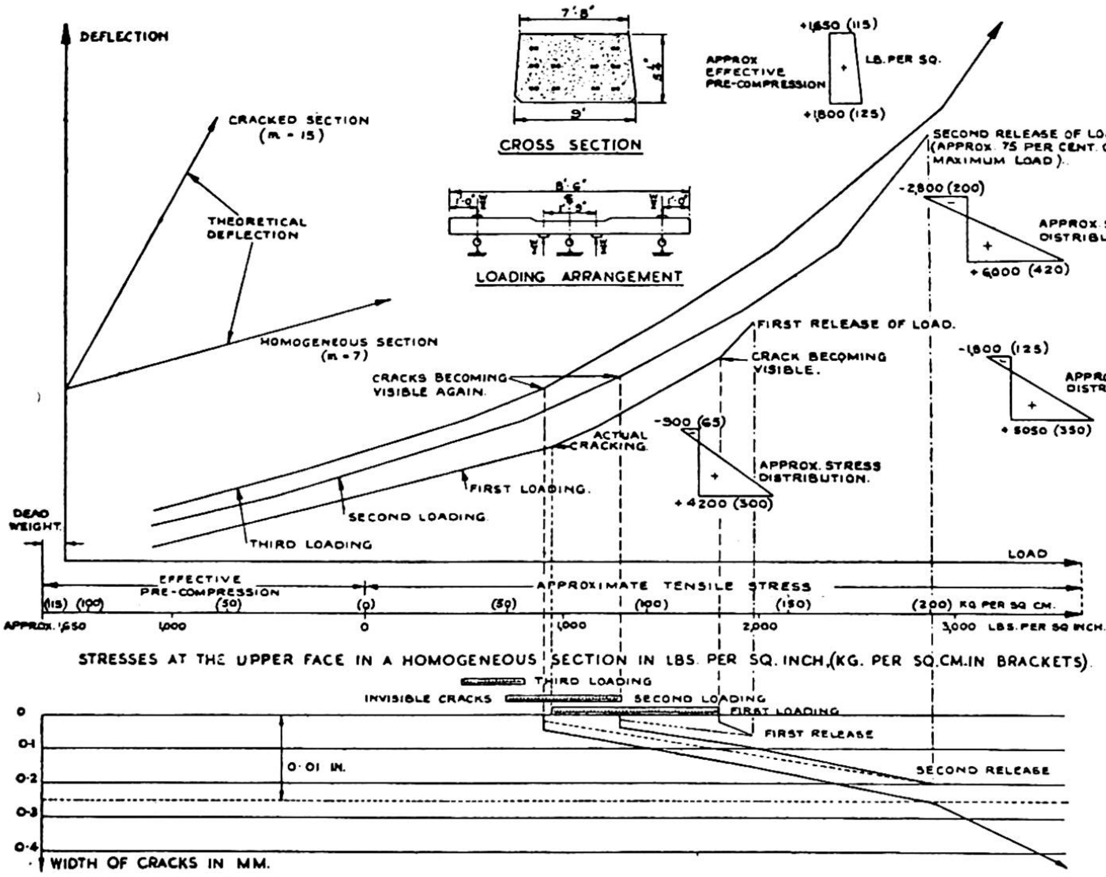

Fig. 1. Typical load deflection curves L. N. E. R. tests.

values of load and deflection are not plotted, but the concrete tensile stresses in a homogeneous section at the upper fibre are indicated.

The sleepers were loaded as simply supported beams, two point loads acting upwards, as indicated in fig. 1. The cycle of loading was to increase the load to somewhat above half of the ultimate load, then to reduce it nearly to zero, increase it again to 70 to 90 per cent of the ultimate load, to reduce it again nearly to zero and finally to increase it until the sleeper failed.

It can be seen from fig. 1 that before cracking occurs, the load-deflection line is approximately parallel to the theoretical line for a homogeneous section computed for a modular ratio $m = 7$. It can be assumed that very fine hair cracks developed at a load slightly in excess of that load for which a change in the inclination of the deflection curves is noticeable. These cracks, invisible to the naked eye, developed at a loading corresponding to a concrete tensile stress of approx. 900 lb per sq. in (63 kg/cm^2) but they became visible only at a loading corresponding to a much higher tensile stress, e.g. 1 800 lb per sq. in (126 kg/cm^2).

After cracking, the deflection curve is almost parallel to the theoretical line, calculated according to the standard method for a modular ratio $m = 15$ and neglected concrete tensile zone.

A cycle of loading, carried out as indicated in fig. 1 shows that after reduction of the load, the inclination of the deflection line is again parallel to that of the stage before cracking. This occurs even after the second

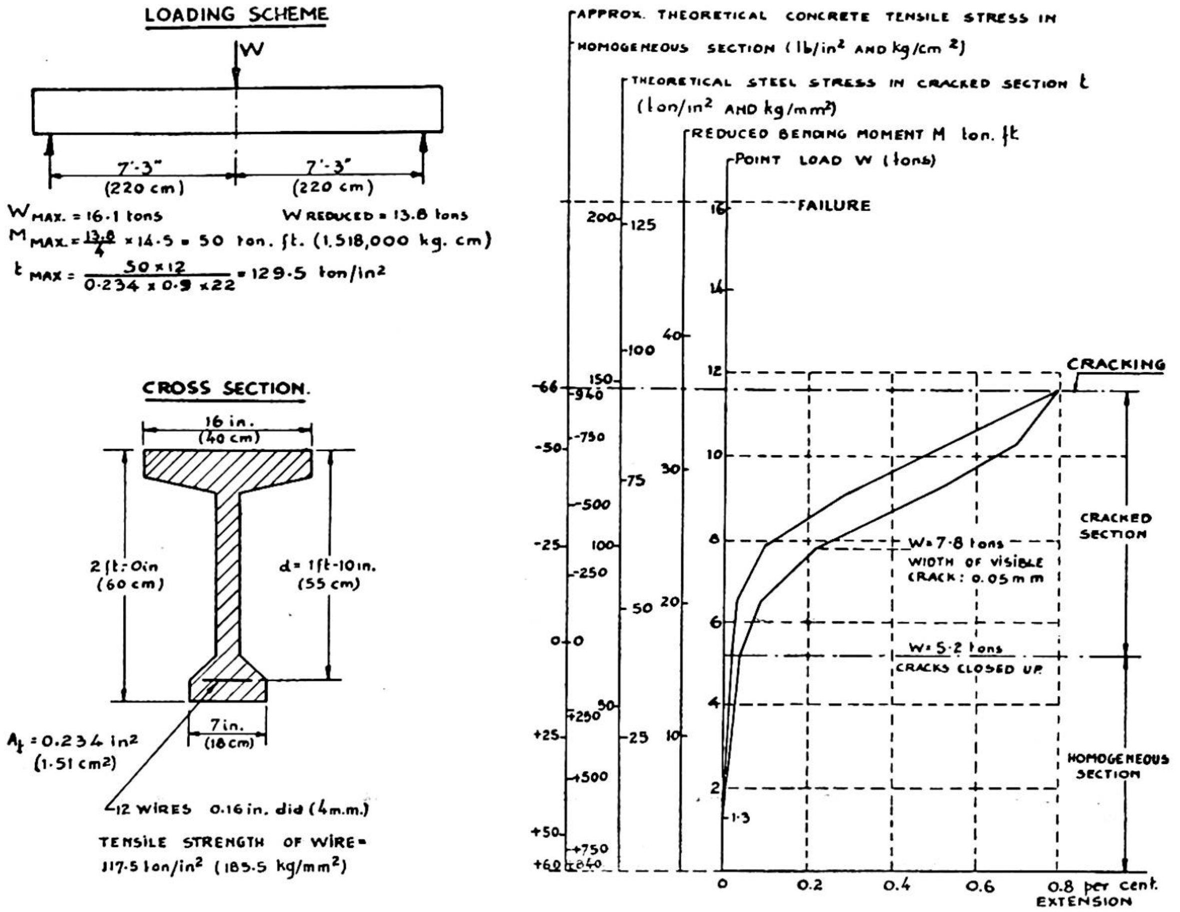

Fig. 2. Fine measurements of extensions over cracks according to E. M. P. A.
Note : These extensions have been measured after cracks had occurred.

reduction of load at 70 to 90 per cent of the ultimate load, which corresponds to a nominal concrete tensile stress in a homogeneous section of 2 500 lb per sq. in (175 kg/cm²) or more.

In fig. 1 is also shown the size of the widest cracks, observed during the tests. A width of 0.01 in (0.25 mm) is plotted for comparison, as this is generally accepted as the width of cracks which may develop in ordinary reinforced concrete and is therefore considered as permissible. It is seen that such a width occurs in fig. 1 only under loads exceeding 70 per cent of the ultimate load.

From fig. 1 the remarkable properties of prestressed concrete are clearly seen, notably the fact that cracks become invisible on reduction of the load, an entire closing of the craks apparently being ensured, when the concrete tensile stresses are reversed into compressive stresses. At this stage, the pre-compression which was previously temporarily interrupted at the cracks, is again in force along the entire length.

The cracks close, in fact, completely, as can be seen from fig. 2, representing the results of fine measurements of extensions of the steel carried out by the E. M. P. A., Zurich, for the Swiss Federal Railways. In this figure the cross section of the prestressed beam and the loading arrangement are indicated. The point load at failure of 16.1 tons is, according to E. M. P. A., reduced to 13.8 tons to obtain the actual bending moment at failure which would occur if two spaced point loads were acting instead of one, ensuring a bending moment of definite magnitude at the centre. The theoretical steel stresses in a cracked section, indicated in fig. 2 are based on this reduced load, whereas the approximate concrete tensile stresses in a homogeneous section are based on the bending moment corresponding to cracking.

The graph which is a mean of several measurements represents a hysteresis curve, no permanent extensions remaining at removal of the load. The cracks thus completely close at a concrete stress approx. zero. On the other hand the tests of the L. N. E. R. London mentioned before as well as tests carried out by the E. M. P. A., Zurich, have shown that an entire closing of cracks cannot be ensured when repetition of the maximum load, causing fatigue, takes place.

A special feature of prestressed concrete beams, reinforced with high strength wire, is the fact that in many cases the wire breaks at failure, the maximum theoretical steel stress being nearly always in excess of the tensile strength or at least equal to it, even if the wire does not break. For example, the stress at failure according to fig. 2 is 10 per cent in excess of the tensile strength of the wire. This excess of strength is not limited to prestressed concrete but occurs also with ordinary reinforced concrete, if a high degree of adhesion is ensured and the bond is destroyed in the immediate vicinity of the cracks only.

The author has tried to explain this phenomenon by a stress redistribution in the crack; in this connection it must be acknowledged that Dr. h. c. L. Herzka of Vienna suggested in 1935 that the behaviour in a crack of a reinforced concrete member may be similar to the stress concentration in a notch of a steel bar. The author has investigated this idea and shown a comparison with Professor Timoshenko's studies on stress concentrations in holes, published on the occasion of the Congress of Applied Mechanics in Zurich 1932. Another diagram was shown at the 2nd Congress of the Association in Berlin (2). From this figure it is seen that the strength increases when the length of a notch is reduced. This phenomenon of apparently increased strength can be explained by a greatly reduced contraction in a short notch so that, in fact, the ultimate stress related to the net area is in all cases the same.

In a reinforced concrete section in which an efficient adhesion is ensured between concrete and steel near to a crack, a similar behaviour may be assumed to that in a notched bar.

When drawing the conclusion from the behaviour of prestressed concrete, discussed in connection with figs. 1 and 2 the following may be said :

(1) In constructions in which repetition of the maximum load occurs including impact (such as railway bridges, sleepers, and certain factory floors), the development of any cracks ought to be avoided and only compressive stresses should be allowed at present under working load.

(2) In constructions in which the maximum load occurs only occasionally (such as road bridges, poles, roofs, or certain floors), there is no need to exclude the appearance of concrete tensile stresses, even occasionally exceeding the modulus of rupture, provided that, under dead weight, concrete tensile stresses do not occur.

This limitation has the effect that any fine hair cracks which may

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(2) See Figure 15, *Yield Limits and characteristic Deflection Lines* by Prof. RINAGL; *Preliminary Publication*, 2nd Congress Intern. Assoc. for Bridge and Struct. Eng.

have developed instantaneously under an occasional maximum load, will close immediately when the load is removed. Nominal tensile stresses of 600 to 1 200 lb per sq. in (42 to 84 kg/cm^2) and even more may be considered as permissible in such a design according to the report of the L. N. E. R. of 1947.

A member in which concrete tensile stresses appear under working load may be called partially prestressed as distinct from a fully prestressed member in which only compressive stresses occur under working load. No cracks will occur under sustained loading, if the tensile stress is below 75 per cent of the modulus of rupture.

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Résumé

Se basant sur les résultats d'essais anglais et suisses, l'auteur discute les propriétés principales du béton précontraint. Celui-ci se comporte comme matériau homogène *avant* sa fissuration et comme le béton armé ordinaire *après* sa fissuration. Après décharge, les fissures se referment entièrement dès changement de sens des tensions et la construction est de nouveau homogène. Cette propriété élastique remarquable constitue une des différences capitales par rapport au béton armé.

Cette propriété permet d'admettre, comme pour un matériau homogène, jusqu'à fissuration, une distribution linéaire, même s'il se présente auparavant quelques fines fissures, à condition toutefois de n'avoir aucune sollicitation de fatigue ou de choc. Dans le cas contraire, comme par exemple pour les ponts-rails ou traverses de chemin de fer, il faut éviter les fines fissures et même toute sollicitation de traction dans le béton.

Zusammenfassung

Gestützt auf englische und schweizerische Versuchsergebnisse, werden die wichtigsten Eigenschaften von vorgespanntem Beton besprochen : Er verhält sich wie ein homogenes Material *vor* der Rissebildung und wie gewöhnlicher armierter Beton *nach* der Rissebildung. Bei der Entlastung schliessen sich die Risse vollständig, sobald die Zugspannungen verschwunden sind und der Bauteil verhält sich wieder wie einer aus homogenem Material. Diese bemerkenswerte Elastizität ist einer der Hauptunterschiede gegenüber gewöhnlichem Eisenbeton.

Es kann daher wie in einem homogenen Material bis zur Rissebildung eine geradlinige Spannungsverteilung angenommen werden, auch wenn sich schon vorher einige temporäre, feine Risse gebildet haben. Dies aber nur unter der Voraussetzung, dass keine Ermüdung und keine Stossbelastung vorkommt. Wenn dies nicht der Fall ist, wie z.B. bei Eisenbahnbrücken und -Schwellen, sollte das Auftreten von feinen Rissen, besser überhaupt das Auftreten von Zugspannungen im Beton vermieden werden.

Summary

On the basis of British and Swiss test results, the essential feature of prestressed concrete is discussed : it behaves like a homogeneous material before cracking and like ordinary reinforced concrete after cracking, but when the loading is reduced, the cracks close entirely on reversal of the tensile stresses into compressive stresses, whereupon it behaves again similarly to a homogeneous material. This remarkable resilience is one of the main distinctions from ordinary reinforced concrete.

A straight line stress distribution in homogeneous material can therefore be assumed below cracking stresses, independently of whether repeated temporary fine cracks have already developed or not, provided fatigue and impact strain (as with railway bridges and sleepers) do not occur. In the latter case the development of fine cracks and even the occurrence of any concrete tensile stresses ought to be avoided.