IVb1

Prestressed Concrete Bridges. Cumulative Effect and Range of Fatigue Loading

Ponts en béton précontraint. Effet cumulatif et domaine des sollicitations à la fatigue

Spannbetonbrücken. Kumulativer Effekt und Bereich bei Ermüdungsbelastung

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Bridges are normally designed for a factor of safety against failure of at least two and this is mostly based on the maximum load which occurs only intermittently. The maximum working load is thus not more than half the failure load, and hence the compressive stress ensures a sufficiently high factor of safety against fatigue, since fatigue failure load is usually in excess of 60 % of the static failure load.

With regard to the concrete tensile stresses, the conditions are different and fatigue must be taken into account. Full freedom from any concrete tensile stress is essential only where an infinite number of cycles of great loading range occurs combined with heavy vibrations, as in hammer foundations. However, with road bridges an infinite number of cycles takes place only for a limited range of stresses and heavy loadings occur only intermittently. Consequently, it seems to be feasible to allow, under infrequent loading, substantial tensile stresses and at the same time to ensure that visible cracks do not develop even after a great number of such intermittent loadings have taken place.

It has been established that micro-cracks develop in prestressed concrete as soon as the resultant concrete tensile stress reaches a value equal to the tensile strength which may be approximately 500 p.s.i. (35 kg/cm²) with high strength concrete. At that stage the limit of extensibility of the concrete is reached and completely harmless micro-cracks develop which may have widths of 1/10,000th to 1/15,000th in. [1]. This stage is independent of the dimension, percentage and distribution of steel and magnitude of prestress. These micro-cracks later become visible to the unaided eye at a much higher stress, the

magnitude of which depends on many conditions, such as the distribution and bond of the steel and may normally vary with pre-tensioned steel between 1,000 and 1,200 p.s.i. (70 to 84 kg/cm²), but even higher values may occur with high percentages of well distributed steel. When such cracks become visible to the unaided eye they usually have a width of 0.001 in. (0.025 mm) but they may be identified at a lesser width if their position is known from a previous loading. The limit at which cracks may still be considered as harmless from the point of view of corrosion in a dense concrete is 10 times the width mentioned above. The author showed the representative widths of such cracks at the last Congress in Lisbon [2].

Fatigue tests carried out by British Railways Research Department and Chief Civil Engineer's Department, Eastern Region, have proved that freedom from visible cracks can be obtained for a limited stress range after the development of micro-cracks for many cycles during which such cracks open and close. In a subsequent static loading test, these micro-cracks became visible at approximately the same load as that expected when no fatigue loading had previously taken place.

In a test carried out by the Research Department, British Railways, at Derby in 1954, 1 million loading cycles were first applied corresponding to a stress range between 30 p.s.i. and 650 p.s.i. tension. As soon as the range was extended by 300 p.s.i. compression without increasing the upper limit of the tensile stress, some of the micro-cracks became visible.

In the entire fatigue loading of the same beam almost 10 millions of cycles were applied with the upper limit of the range gradually increasing. In this case the beam was loaded first statically until cracks became visible and the whole dynamic loading was carried out in a cracked state. It may be noted that these cracks closed completely on removal of the load until 7 million cycles had been applied and only afterwards, at a higher range of stresses, did the cracks remain visible. Other tests were carried out at Liège in 1951 and 1957/58 on composite specimens with similar results.

In all these tests the same specimen was used for various loading stages and thus a cumulative effect was obtained and in view of the uncertainty about this effect upon the various ranges of pulsating loading, the author suggested that basic fatigue tests should be carried out to determine the influence of stress range and magnitude of the tensile stress upon the development of visible cracks. This suggestion was accepted in 1958 by the Chief Civil Engineer of the Eastern Region, British Railways, and by the Railway Research Department. Twelve beams were, therefore, manufactured for testing early in 1959 as shown in Fig. 1. They were produced in two pre-tensioning beds and have thus approximately the same prestress. One beam of each bed was loaded to failure statically and two beams are intended to be subjected to a sustained loading for the purpose of comparison with dynamic loading. Of the remaining eight beams four have already been tested by pulsating loading in

this year. From Fig. 1, the testing arrangement is seen as well as the stresses at transfer together with the effective prestress and those for zero load. They have been calculated on the one hand for probable losses of prestress to be expected at the time of testing and, on the other hand for maximum possible losses. The former were computed for two-thirds of shrinkage and creep losses, as considered in the British code, CP. 115, and a relaxation of steel of 5,000 p.s.i., whilst the maximum losses were computed for the entire shrinkage and creep and a relaxation loss of 10,000 p.s.i. according to British code. It must be
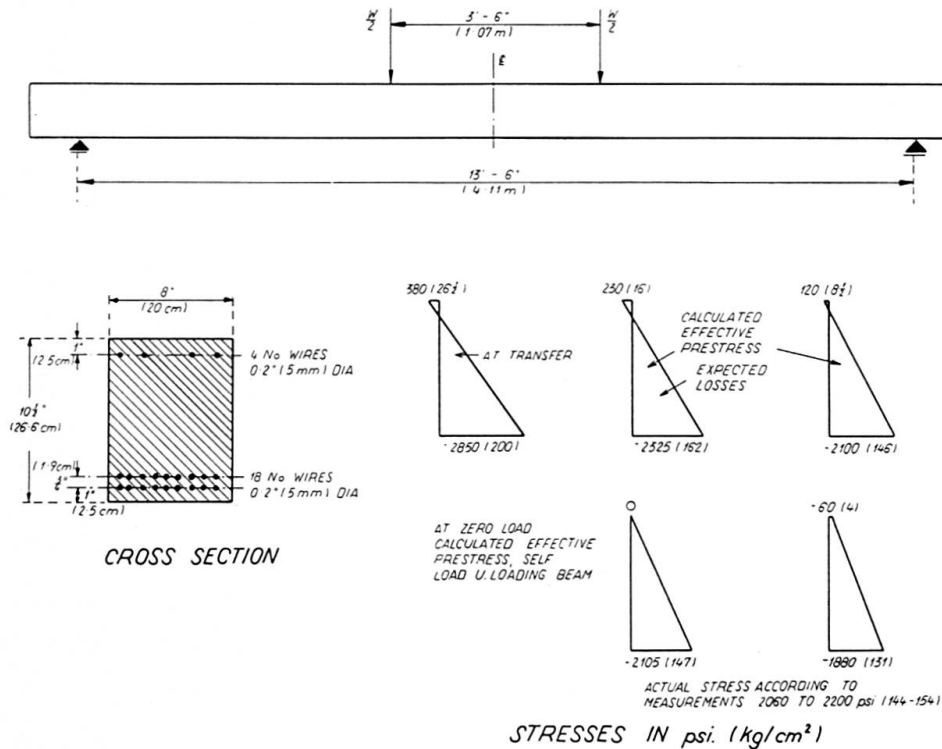

STRESSES IN psi. (kg/cm²)

Fig. 1.

appreciated that these beams were tested at an age of more than one year and were exposed to appreciable shrinkage and creep during the hot summer of 1959. From exact strain measurements before transfer of the prestress, and at testing, stresses were obtained for each individual beam. As is seen from Fig. 1, the stresses thus computed for the bottom edge at zero load indicate very good agreement with the calculated and expected value.

It was considered permissible to separate the dynamic loading with regard to micro-cracks from that of failure, it being assumed that the dynamic loading, during which cracks are invisible, does not influence the fatigue failure resistance, and so far the tests have proved this assumption to be correct.

The Research Engineers of British Railways developed a new method of ascertaining micro-cracks during dynamic loading by the provision of thin copper wires which fractured when their elongation slightly increased. It was

thus possible by this fracture to stop the working of the pulsator by the inclusion of the copper wire in an electric circuit. However, it has not been possible to ascertain exactly how many repetitions occurred between the actual development of micro-cracks and the fracture of the wire when the pulsator stopped; but this unknown number of cycles cannot be very great. In connection with these crack detection wires it was possible also to ascertain the number of micro-cracks. The wires were fixed by means of "Durofix" adhesive to the face of the concrete, and the Research Engineers discovered that the individual micro-cracks were visible in the "Durofix" coating to the unaided eye, but in the concrete only by the use of a high-powered magnifier.
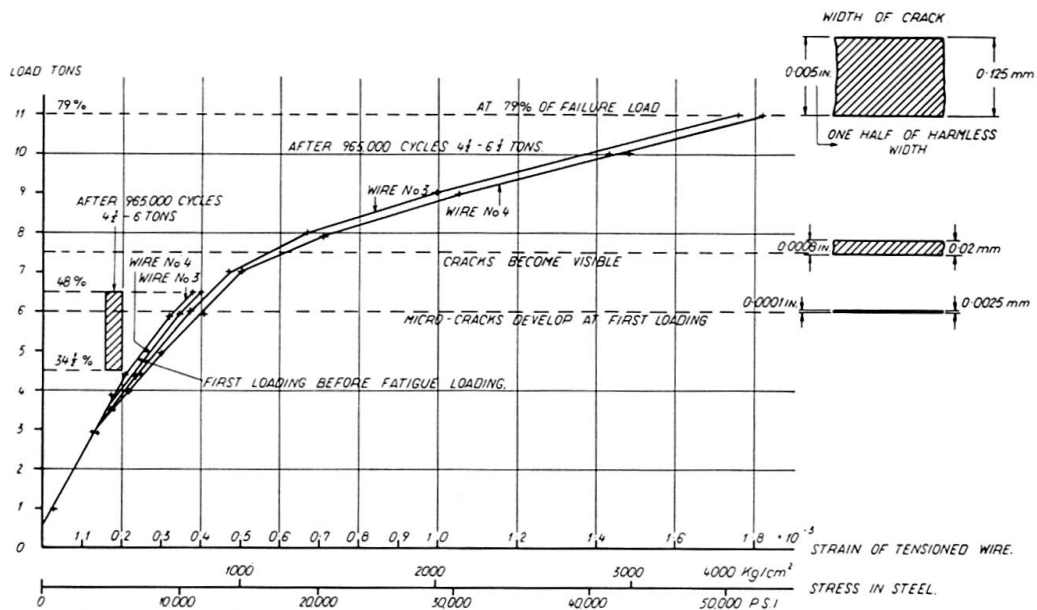
STRAIN DIAGRAM OF WIRES AT STATIC LOADING UP TO II TONS (79% F.L.)

Fig. 2.

Fig. 2 shows strain measurements obtained at static loading tests from electric resistance strain gauges affixed to the pre-tensioned wires of beam E. 3. The strain readings of the gauges on wires 3 and 4 at the first static loading are seen as well as those taken after 965,000 cycles between $4^1/_2$ and $6^1/_2$ tons. Micro-cracks occurred at a loading of 6 tons and in a sister beam, having similar stress conditions, these cracks became visible at a load of $7^1/_2$ tons. In the various beams micro-cracks occurred at a resultant tensile stress at the outer tensile face which, at present, may be assumed between 500 and 645 p.s.i. (35 to 45 kg/cm²) and the corresponding stress at which cracks became visible amounted to 1145 and 1290 p.s.i. (80 and 90 kg/cm²). When the micro-cracks were noticed, they had a width of 0.001 in. (0.0025 mm), but the experienced research workers, with their skilled eyes, were unable to observe them without aid when they were only 0.0007 in. (i. e. 0.0175 mm) wide although their posi-

tion was revealed in the adjacent "Durofix" coating. They were, however, just able to see them when the cracks became 0.0008 in. i. e. 0.02 mm wide. Obviously no generalisation can be made since the degree of visibility depends also on the surface conditions of the concrete and any surface damage at the cracks.

From the static loading tests a good agreement between calculated and actual failure load was obtained and it is thus possible to relate each loading to a percentage of the failure load. It will be seen that 11 tons correspond

CRACK PATTERN AT LOAD OF 11 TONS
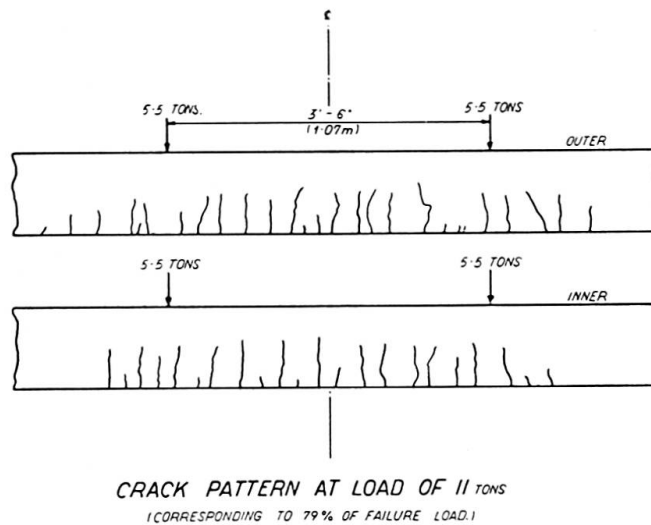(CORRESPONDING TO 79% OF FAILURE LOAD.)

Fig. 3.

to 79 per cent of the failure load. Figure 3 shows the crack pattern of the beam E 3 at a static loading of 11 tons after 965,000 cycles between $4^{1}/_{2}$ and $6^{1}/_{2}$ tons. It is noteworthy that at a load of approximately 80 per cent of the failure load the maximum width of the cracks amounted to 0.005 in. which is approximately half the limit of width generally considered as harmless.

Fig. 4 shows some results of these tests. An attempt has been made to plot Wöhler curves or some kind of Goodman diagrams based on four beams tested so far. This cannot be considered as definite, particularly since the magnitude of the stresses are not completely certain, as the tests are not yet completed. For example, Beam E 6 stood up to 99,000 cycles over a large loading range $1^{1}/_{2}$ to $6^{1}/_{2}$ tons, i.e. between 14 % and 48 % of the failure load, corresponding to a stress range of 2,120 p.s.i. (148 kg/cm²) with a maximum tensile stress of about 650 p.s.i. (45 kg/cm²). The beam E. 10 was tested solely within the tensile range by applying loads between 5 and $6^{1}/_{2}$ tons, corresponding to 38 to 48 % of the failure load and sustained 2,777,000 cycles, before the cracks became visible at one side and 3,144,000 cycles before this occurred at the other one. In order to detect this loading, new crack detecting wires were placed above the position at which micro-cracks had been detected. As

soon as micro-cracks developed at this higher position, the pulsation was
again automatically stopped and it was possible to investigate whether the
micro-cracks had become visible during a static loading test. In this case the
dynamic loading was further continued until 5×10^6 cycles had been completed.

Another example is Beam E 3, already discussed before. In this case cracks
became visible after 709,000 cycles on one side and at 965,000 cycles on the
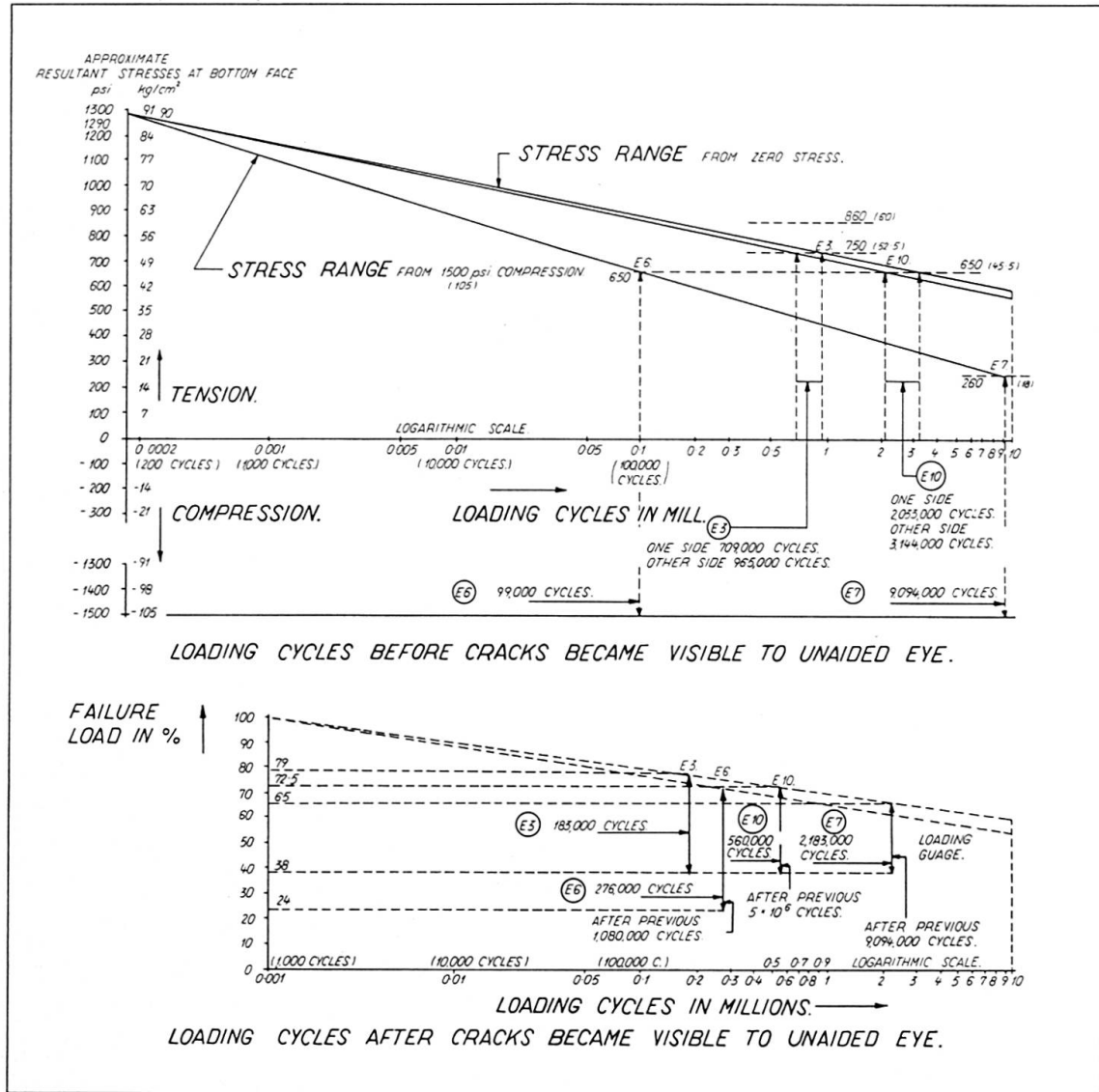

Fig. 4.

other one. The 4th beam E 7 was dynamically loaded between 1 and 5.6 tons
and initially micro-cracks did not occur. However, after 30,000 cycles the
crack detecting wire stopped the pulsation and micro-cracking was noticed;
normally at first stopping 6—10 micro-cracks between the loading points were
visible in the "Durofix". In this case, the tensile stress may have originally
been only about 260 p.s.i., and it is not unlikely that it soon became much
larger owing to fatigue creep, until micro-cracks developed.

In the upper graph the author has attempted to show curves, indicating the upper limit of stress related to the number of cycles at which cracks became visible and these are plotted in logarithmic scale. These curves start from a tensile stress of 1290 p.s.i., at which cracks seem to have become visible at the static loading. Two almost straight lines were obtained for the two lower limits of the different loading ranges i.e. zero stress and compressive stress of 1,500 p.s.i.

In the lower graph, curves are plotted for failure conditions. Only the cycles at the failure loading have been considered and the dynamic loading during the previous cracking examination has been disregarded. It is seen that these two loadings appear to be completely independent of each other. The maximum number of cycles has so far been reached for the same beam E 7 after 9 million previous cycles. In this case there were over 2 million cycles between 38 and $65\frac{1}{2}\%$ of the failure load. With the beam E 7, 560,000 cycles occurred between 38 and $72\frac{1}{2}\%$ of the failure load; but the number of cycles was less, when the range of loading was increased without changing the upper limit. After 276,000 cycles failure took place for a range between 24 and $72\frac{1}{2}\%$ of the failure load. Beam E 3 failed for a range between 38 and 79% of the failure load after 183,000 cycles. In all these cases first one prestressed wire fractured, later a second and a third followed and sometimes up to 6 wires ruptured before sudden fatigue failure took place.

If these curves are taken to be representative it can be expected that even for an infinite number of cycles e.g. 100 million cycles there appears to be a substantial range of stresses which can be considered, without risking the development of visible cracks provided that this range is limited to tensile stresses only. Similarly for ultimate load an infinite number of million cycles seems to be permissible for an appreciable range of loading.

If time had permitted, it would have been possible to continue the pulsating loading for each range after the cracks had become visible to ascertain how many cycles can be applied before they become wider than the permissible width of 0.01 in. or before they do not close completely on removal of load. In this case a third family of curves would have been obtained for this condition. However it was not within the scope of these tests to carry out such further investigations.

Finally the author would like to thank the Chief Civil Engineer, British Railways, Eastern Region, and the Director of Research British Railways for permission to publish these test results.

References

1. R. H. Evans, "Extensibility and Modulus of rupture of concrete". Str. Eng. Dec. 1946.
2. P. W. Abeles, "Safety against cracking and permissible stresses in prestressed concrete". 5th Congress IABSE Final Report. Fig. 6.

Summary

The magnitude of the permissible concrete tensile stress at working load under fatigue conditions is of basic importance, as with bridges repetitions of maximum loading occur rarely; hence higher stresses may be allowed for this maximum loading and still freedom from visible cracking be ensured.

Basic fatigue tests are being carried out by British Railways for various loading (i. e. stress) ranges to ascertain when micro-cracks develop, when they become visible and when failure takes place. These tests have not yet been completed, but S.N. curves are shown based on intermediate results.

Résumé

La grandeur des tractions admissibles dans un béton sollicité à la fatigue par les charges de service normales est de la plus haute importance. En effet, les charges maxima ne se présentent que très rarement dans les ponts; pour ces charges, on peut donc admettre des tensions plus élevées sans avoir à craindre de fissuration visible.

Les Chemins de fer Britanniques entreprennent actuellement des essais fondamentaux de fatigue pour divers domaines de charges (ou de contraintes); il s'agit de déterminer l'instant où se forment des fissures microscopiques, à quel moment elles deviennent visibles et quand se produit la rupture. Bien que ces essais ne soient pas encore achevés, l'auteur donne des courbes de fatigue établies à l'aide de résultats intermédiaires.

Zusammenfassung

Die Größe der zulässigen Betonzugspannungen unter Gebrauchslast bei Ermüdungsbelastung ist von grundlegender Wichtigkeit, da bei Brücken die Größtlast nur selten erfolgt; daher können höhere Spannungen für dieselben zugelassen werden und trotzdem kann Freiheit von sichtbaren Rissen garantiert werden. Grundlegende Ermüdungsversuche werden derzeit von den Britischen Bahnen für verschiedene Belastungs- (d. i. Spannungs-) Bereiche durchgeführt, um festzustellen, wann mikroskopische Risse entstehen, wann dieselben sichtbar werden und wann es zum Bruche kommt. Obwohl diese Versuche noch nicht beendet sind, werden auf Grund von Zwischenresultaten Wöhlerkurven gezeigt.