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VI 2

Restraint and Stress Redistribution in Composite Prestressed Concrete Beams

Redistribution des efforts intérieurs dans les constructions précontraintes composées

Spannungsumlagerung in vorgespannten Verbundkonstruktionen

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In composite construction with a highly stressed skin, a redistribution of stresses must take place, as can be concluded from numerous static and fatigue tests carried out between 1949 and 1960 by the Chief Civil Engineer's Department, Eastern Region, in conjunction with the Research Department, British Railways. The added concrete is restrained by the prestressed component from excessive deformation, although micro-cracks develop as soon as the tensile strength of the added concrete, and thus the limit of its extensibility, is reached, these micro-cracks remain invisible to the unaided eye and fit later into other cracks which develop in the restraining part. This may be illustrated by the example of the so called «wafer» deck slab, which is a composite construction, cast and prestressed in two stages. As is seen from Fig. 1, there is a great difference in effective prestress between parts, which are prestressed in both stages and those which are stressed only at the second stage. This applies, for example, to the joints between the prefabricated units. Under loading there appears a nominal tensile stress of more than 2,000 p.s.i (140 kg/cm^2) at the joints during a stage at which in the adjacent parts of the prefabricated joists compressive stresses still occur. Numerous micro-cracks must have occurred, but they did not become visible, before cracks developed at the tensile face of the highly prestressed parts and afterwards the cracks were not wider within the small strips (which were under excessively high tension) than in the remaining parts, as can be seen from a photograph of a slab tested at Liège in 1958 (see p. 9, Third Congress F.I.P. Berlin 1958, Discussion).

As already mentioned, in consequence of the restraining effect of adjacent prestressed portions, a stress redistribution must take place. This is indicated in the diagram, Fig. 2, for a composite beam with a highly prestressed plank at the outer tensile skin.

In order to investigate this problem, some fatigue tests were carried out last year by British Railways in accordance with the programme shown in Fig. 3. Different types of connection were investigated with regard to their

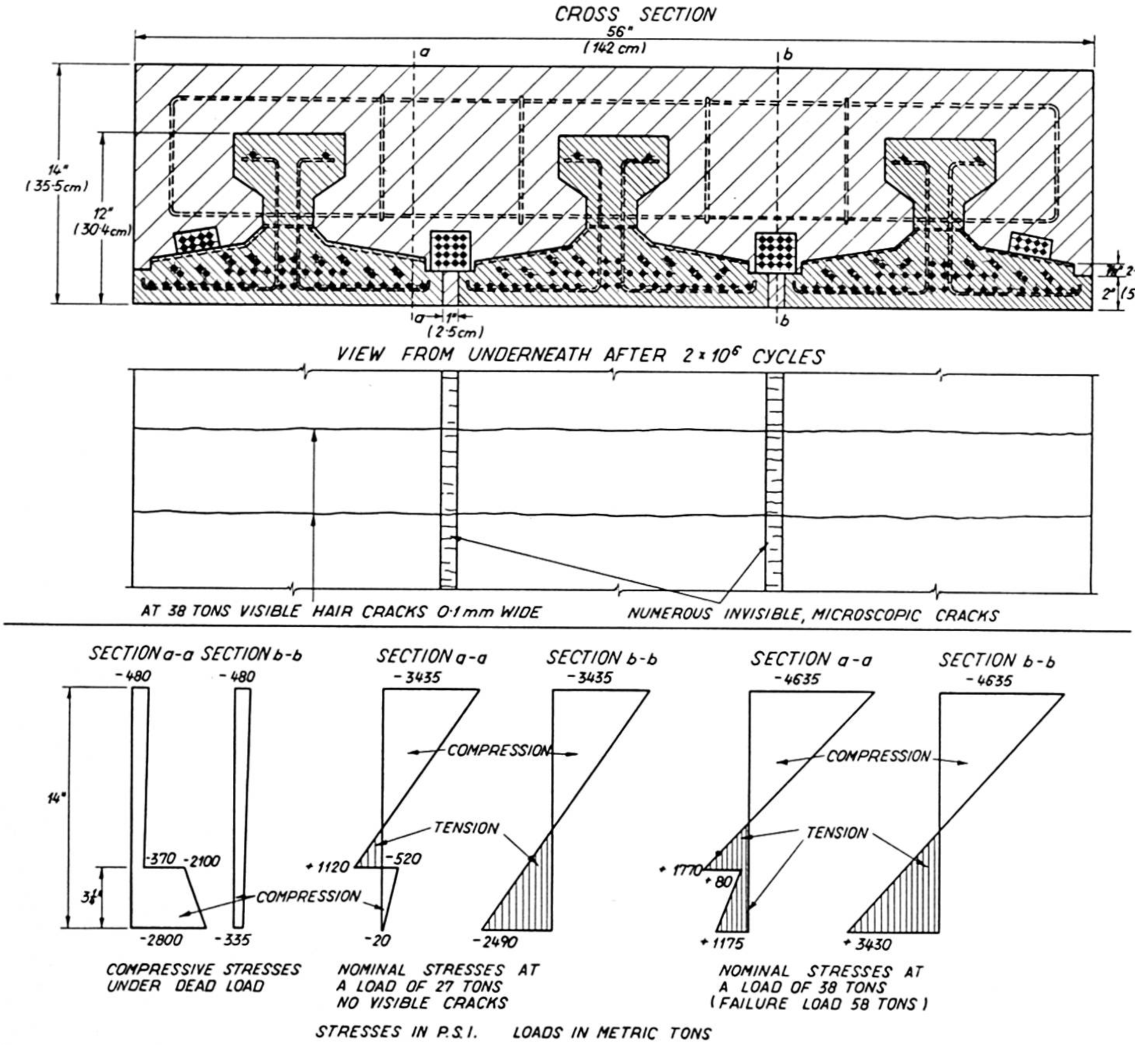

Fig. 1.

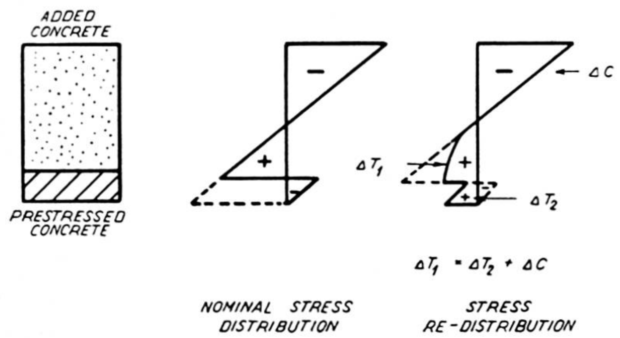

Fig. 2. Stress Re-distribution in Prestressed Composite Beams.

influence upon the development of cracking and failure. Three kinds of connection were examined: 1. rough surface of the precast planks; 2. smooth surface with alternating castellations, and 3. stirrups and smooth surface of the concrete.

With regard to failure, all three types proved to be satisfactory, even after millions previous pulsating loadings. However, so far as cracking was concerned, the rough surface proved to be a much better interlocking medium than either castellations or stirrups with smooth concrete surface. When the two latter types of connections are compared, stirrups proved to be better than castellations, as can be concluded from these tests. It would, however, require more tests to state this on a broader basis.

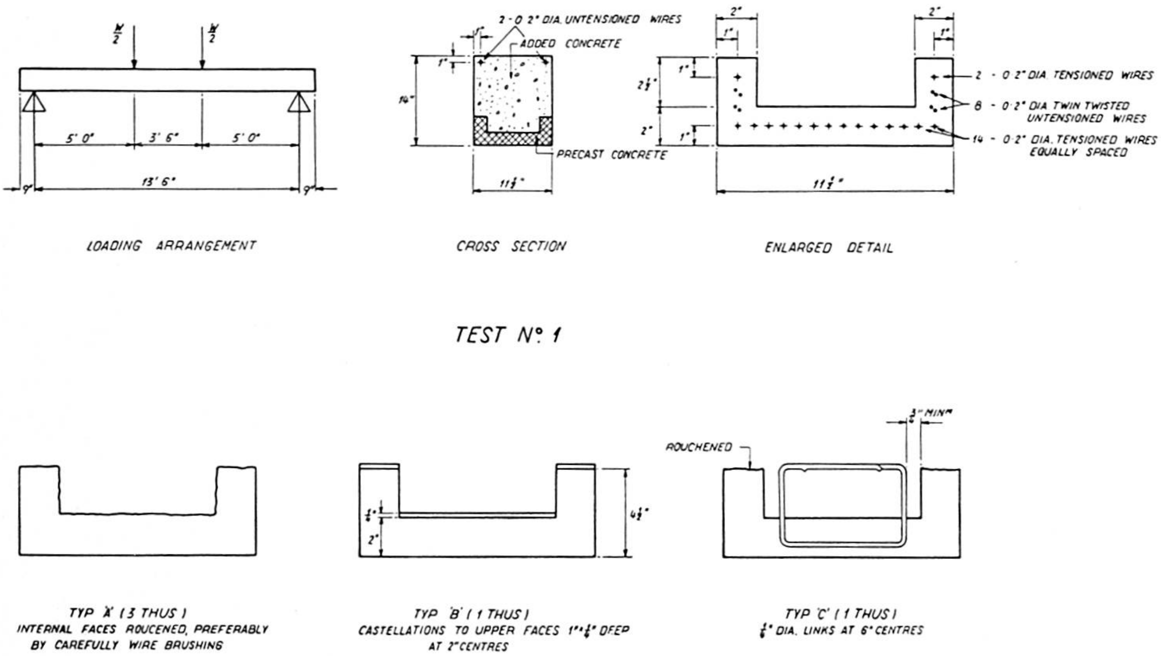

Fig. 3. Cube Strength at Transfer 7500 lbs./Squ. in. Initial Tensioning Force 2.2 Tons/Wire.

One point must be emphasized, i. e. the need for sufficient shear reinforcement to resist the high principal tensile stresses in the added non-stressed concrete which occur as a combination of shear and bending due to point-loads. These stirrups are required solely in the added concrete and are unnecessary as shear connections between the precast and added concrete, provided that satisfactory co-operation is obtained by roughening, castellations or separate short stirrups.

The stress conditions in such composite constructions are, unfortunately, very obscure in view of the effect of differential shrinkage and creep. Their theoretical effect is illustrated by three examples in Fig. 4 for a differential shrinkage strain. It is seen that only in composite constructions, example 1, additional tensile stresses occur at the tensile edge of the prestressed component caused by differential shrinkage of the added concrete.

In both other examples additional compressive stresses appear in the tensile zone of the prestressed component, whilst additional tensile stresses occur in the added concrete. This means that another stress redistribution will take place and most likely the influence of such differential shrinkage stresses can be safely ignored except perhaps in certain cases according to example 1.

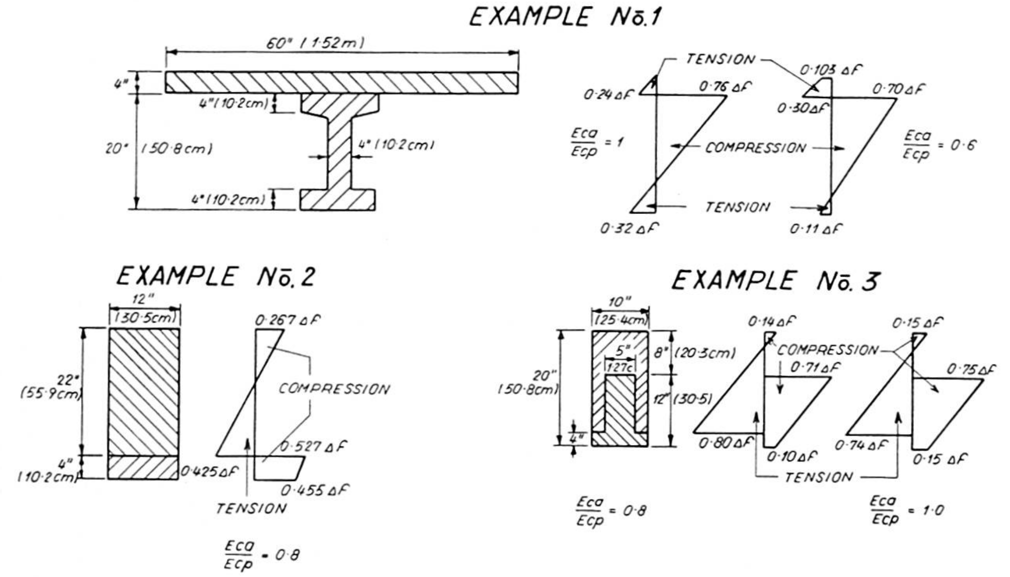

Fig. 4. Examples. Stresses Due to Differential Shrinkage and Creep in Composite Sections

Stress $\Delta fs = \Delta\,\delta \times E_C$. For Example:

$(\Delta\,\epsilon = 0.0001 \quad E_C = 5 \times 10^6$ psi. $\quad \Delta fs = 500$ psi.)

$(\Delta\,\epsilon = 0.0001 \quad E_C = 3.5 \times 10^5$ kg/cm² $\Delta fs = 35$ kg/cm²)

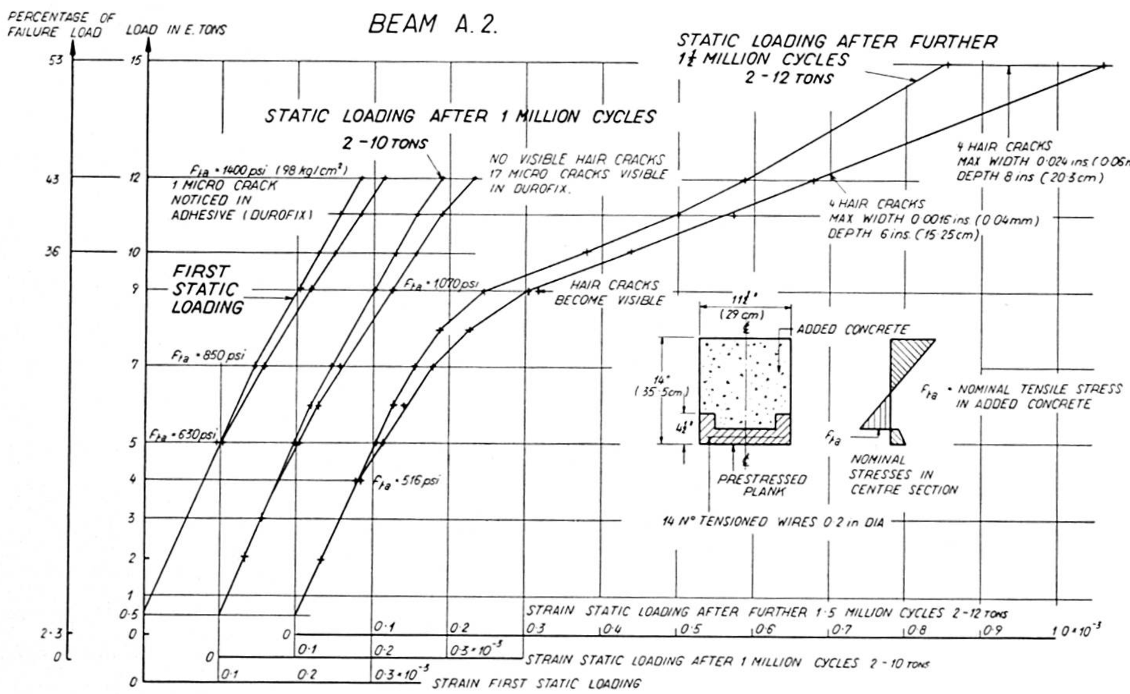

Fig. 5. Strain in Tensioned Wires.

It has not yet been possible to clarify the stress conditions of the last British Railway tests and additional investigations are planned to examine the strain and stress conditions due to differential shrinkage and creep. However, two interesting part results of these fatigue tests may be seen in the following.

Fig. 5 shows measurements taken by electrical resistance strain gauges fixed to the wires before tensioning; the first two curves relate to the first static test up to the loading at which micro-cracks develop. The second set of curves shows again maximum and minimum strain after one million repetitions between 2 and 10 tons. Instead of one micro-crack 17 micro-cracks were now visible, but there is hardly any difference in the shape of the curves and the maximum strain amounted to approximately 0.3×10^{-3}, corresponding to a steel stress of 9000 p.s.i. After a further two million cycles between 2 and 12 tons, visible cracks developed, as can clearly be seen from the change in the strain curves and they became visible at a load of 9 tons.

Fig. 6 shows the behaviour of a sister beam which was loaded statically until cracks became visible though none had developed during 1.5 million cycles between 2.4 and 9.4 tons. Afterwards, a further static loading was carried out up to 15 tons and cracks became visible at a load of 13.4 tons, corresponding to a nominal tensile stress of 1780 p.s.i. (125 kg/cm²). The

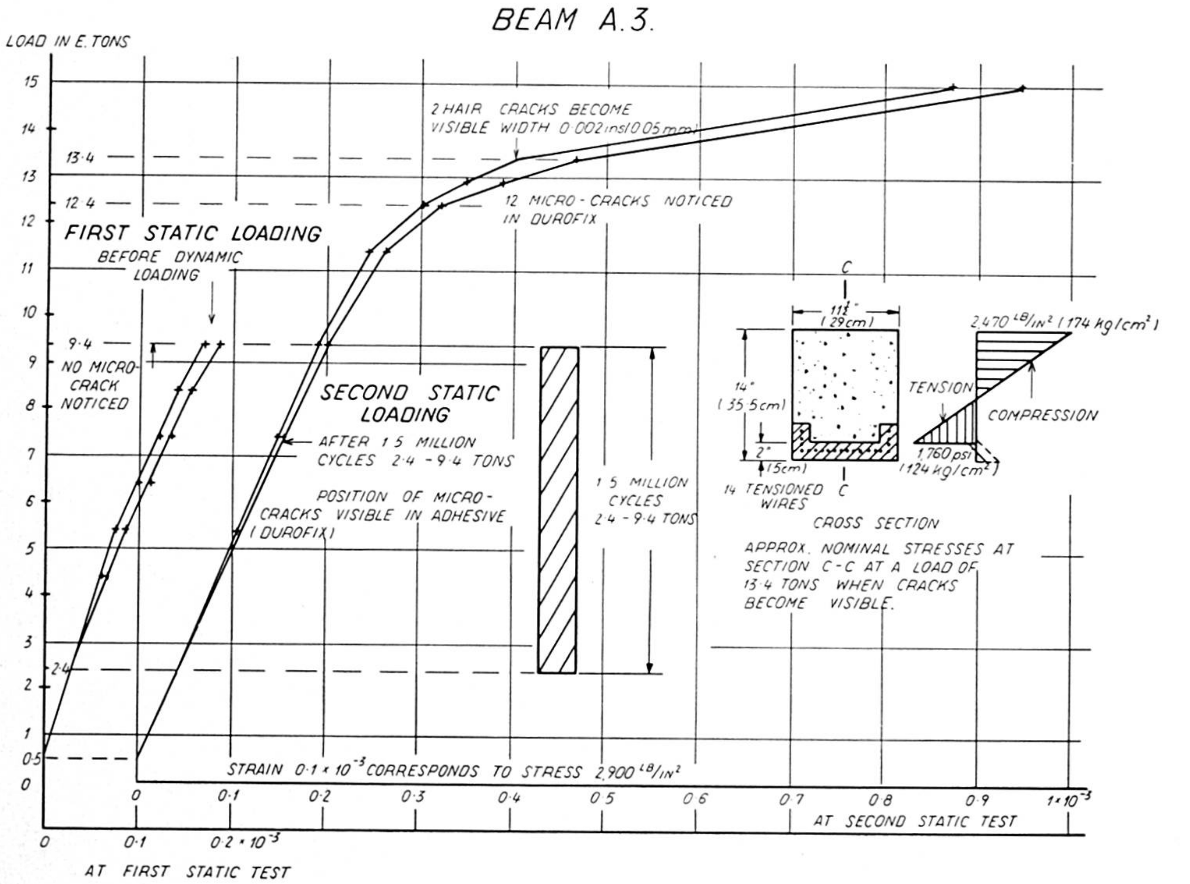

Fig. 6. Strain in Tensioned Wires.

maximum strain in the steel at that load was 0.4×10^{-3} corresponding to a steel stress of 12,000 p.s.i. (840 kg/cm²). We may remember that in the previous case these cracks became visible at 9 tons after a previous 2 million cycles between 2 and 12 tons.

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

Summary

The Chief Civil Engineer's Department, British Railways, Eastern Region, has successfully employed a composite prestressed concrete bridge deck for more than 10 years. The added concrete fully co-operates with the prestressed component and is restrained by the latter from visible cracking; apparently a stress redestribution takes places. Recently fatigue tests were carried out by British Railways to investigate this problem, and 3 types of connection were examined: 1. rough surface, 2. smooth surface with castellations, and 3. smooth surface with stirrups. All 3 types were satisfactory at failure, but the type with rough surface was superior at cracking. It is, however, difficult to determine the resultant stresses, because of the stress redistributions due to stress difference in prestressed and added components and those due to differential shrinkage and creep.

Résumé

Depuis plus de 10 ans, la division des ouvrages d'art des chemins de fer britanniques (Eastern Region) utilise avec succès un tablier précontraint de construction composée. Le béton normal participe à la résistance d'ensemble et le béton précontraint empêche l'apparition de fissures visibles; il doit donc se produire une redistribution des contraintes. Afin d'étudier ce problème, les chemins de fer ont effectué une série d'essais à l'endurance. Trois types de liaison ont été examinés: surface de contact rugueuse, surface lisse munie de crénelures, surface lisse munie d'étriers. Les trois types se sont avérés satisfaisants lors de la rupture, mais le premier (surface rugueuse) était supérieur aux autres en ce qui concerne la fissuration. Il est difficile de déterminer les tensions résultantes; il se produit en effet une redistribution des contraintes due d'une part à la différence des contraintes entre le béton précontraint et le béton normal et, d'autre part, à la différence du fluage et du retrait des deux matériaux.

Zusammenfassung

Das Chefingenieurdepartement der Britischen Bahnen (Eastern Region) hat seit mehr als 10 Jahren eine Brückenfahrban in vorgespannter Verbundkonstruktion erfolgreich verwendet. Der nichtvorgespannte Beton wirkt mit dem vorgespannten Teil voll zusammen und der letztere behindert das Auftreten von sichtbaren Rissen; dabei muß eine Spannungsumlagerung stattfinden. Kürzlich wurden Ermüdungsversuche von den Britischen Bahnen durchgeführt, um dieses Problem zu untersuchen, wobei 3 Ausführungen von Verbindungen verwendet wurden: 1. rauhe Oberfläche, 2. glatte Oberfläche mit Verdübelungen und 3. glatte Oberfläche mit Bügeln. Alle 3 Arten erwiesen sich beim Bruch als zufriedenstellend, aber die Ausführung mit rauher Oberfläche war bei der Rißbildung überlegen. Es ist schwierig, die resultierenden Spannungen zu bestimmen, da einerseits eine Spannungsumlagerung infolge der Spannungsdifferenz zwischen vorgespanntem und zusätzlichem Beton entsteht und überdies eine solche infolge verschiedenen Schwindens und Kriechens erfolgt.