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Autor: Warner, R.F.

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Fatigue of Partially Prestressed Concrete Beams

Fatigue de poutres en béton partiellement précontraint

Ermüdung teilweise vorgespannter Betonbalken

R.F. WARNER
Professor
University of Adelaide
Adelaide, Australia

SUMMARY
Constant cycle and cumulative damage fatigue tests were carried out on 5 mm dia crimped prestressing wire and 12.5 mm dia prestressing strand. The fatigue data from both test series, as well as from previous strand tests, correlate well when the stress range, defined as the maximum stress level minus the fatigue limit, is used as the main stress variable. Progressive inelastic changes in concrete beam behaviour under fatigue loading are discussed. It is suggested that fatigue life calculations need to be based on a stress analysis for the mid-life phase of behaviour rather than for the early load cycles.

RESUME
Des essais de fatigue sous cycle constant et de dommage cumulatif furent réalisés sur des fils de précontrainte profilés de 5 mm de diamètre ainsi que sur des torons de 12.5 mm de diamètre. La corrélation des deux séries d'essais ainsi que d'essais antérieurs est bonne lorsque l'on utilise comme variable la différence de contraintes, égale à la contrainte maximum moins la contrainte limite de fatigue. Des remarques sont faites concernant des modifications inélastiques progressives du comportement de poutres en béton soumises à des charges de fatigue. Il est proposé de baser les calculs de durée de vie de fatigue sur une analyse des contraintes correspondant à la demi-période de vie plutôt qu'aux premiers cycles de charge.

ZUSAMMENFASSUNG
An profilierten Vorspanndrähten mit Durchmesser 5 mm und an Vorspannlitzen mit Durchmesser 12.5 mm wurden Einstufen- und Mehrstufen-Versuche mit Schadenakkumulation durchgeführt. Die Ermüdungsergebnisse der beiden Versuchsserien sowie auch früherer Versuche an Litzen stimmen gut überein, wenn als Hauptvariable die Differenz der Maximalspannung zur Ermüdungsgrenzspannung benützt wird. Progressive, nicht elastische Veränderungen des Verhaltens von Betonbalken unter Ermüdungsbelastung werden diskutiert. Es wird vorgeschlagen, für Lebensdauerberechnungen eher eine Spannungsanalyse nach halb durchlaufener Lebensdauer zu benützen als nach den ersten Lastwechseln.

1. INTRODUCTION

Previous studies have shown clearly that fatigue in prestressed concrete beams is not a practical design problem provided the prestressing force is large enough to prevent opening and closing of flexural cracks[1]. Fully prestressed concrete is by definition uncracked at full design load and is one of the most suitable materials available for the construction of members subject to fatigue loading. However, partial prestressing is often preferred to full prestressing for reasons of economy and improved deflection control. Partially prestressed concrete members may undergo significant cracking at design load, and fatigue resistance is therefore a relevant design consideration when such members are called on to resist large numbers of repeated loads.

Fatigue failure of a normal, under-reinforced concrete flexural member, with or without prestress, occurs by fatigue in the tensile steel rather than in the compressive concrete[1]. Two distinct forms of information are therefore needed for the evaluation of the fatigue life of a partially prestressed concrete member:

- firstly, data (usually experimental) on the fatigue resistance of the reinforcing steel and prestressing tendon are required;
- secondly, a stress analysis procedure is required which transforms the cyclic load history of the member into cyclic stress histories for the reinforcing steel and prestressing steel in critical sections.

Both the reinforcing steel and the prestressing steel are in a state of near uniform tension in a flexural member, so that the required fatigue properties can be obtained from simple tests of bars and tendons subjected to cycles of uniaxial tensile stress. Results of a program of fatigue tests on two types of prestressing steel are briefly discussed below.

The analysis of stress in a cracked, partially prestressed concrete member under long term and repeated load is complicated by various inelastic and non-linear effects which, even in the case of a section subjected to constant cycles of moment, produce a complex history of progressively changing stress cycles. The main factors contributing to progressive changes in beam response are discussed in Section 3 of this paper.

2. FATIGUE PROPERTIES OF PRESTRESSING STEEL

Constant cycle and cumulative damage tests were carried out on 5 mm dia crimped prestressing wires and 12.5 mm dia 7-wire prestressing strand. All tests were of naked specimens of 900 mm length.

A special end gripping arrangement was used, whereby the ends of the specimen are bound with a fibreglass bandage covered with fresh araldite paste. A snug fitting aluminium tube is slipped over the bandage before the araldite sets. This grip, which deforms considerably when clamped in the jaws of the test machine, provides a simple, cheap and effective means of applying force to the ends of the specimen without causing fatigue failure there.

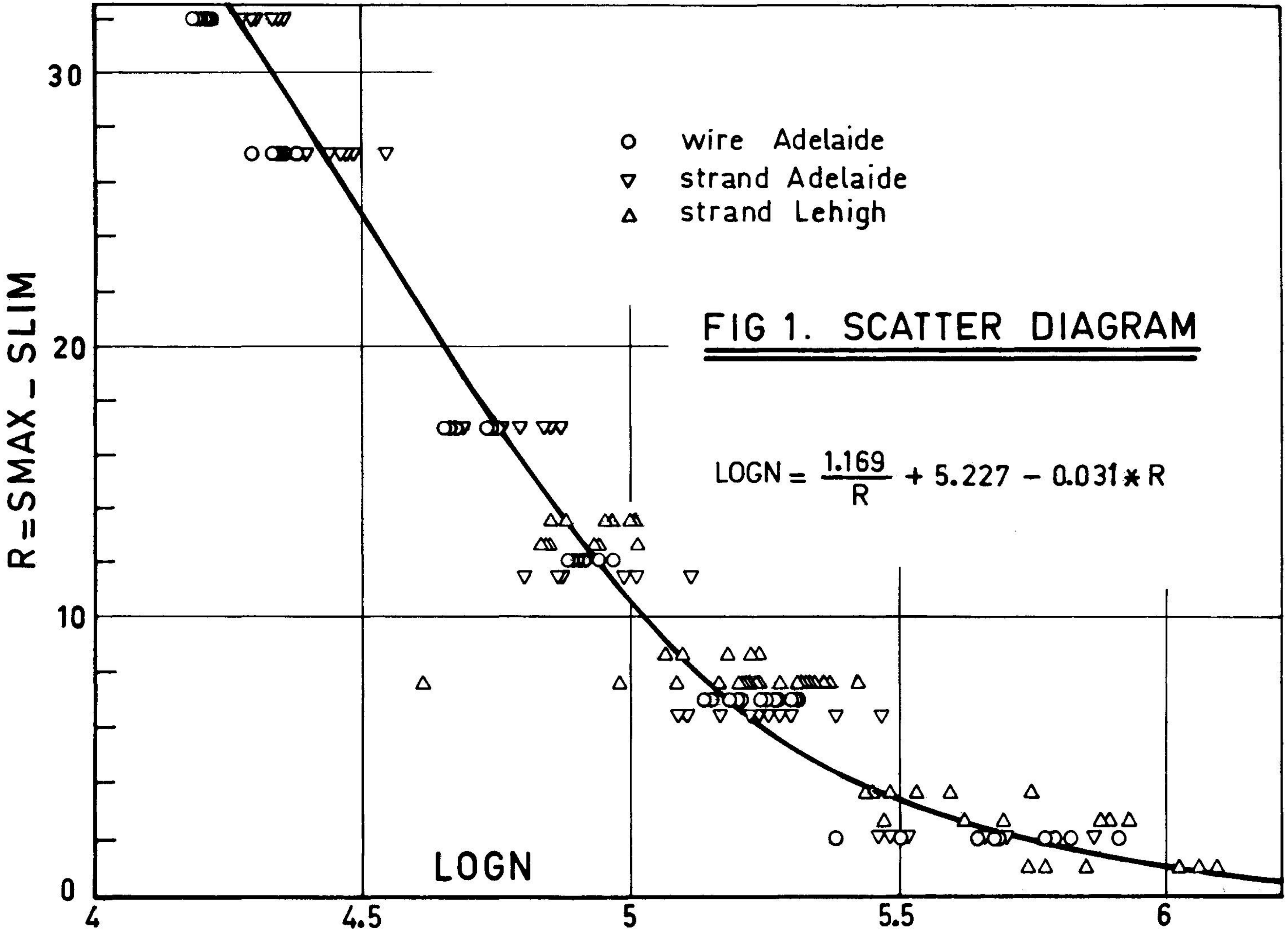

FIG 1. SCATTER DIAGRAM

Constant Cycle Tests

Constant cycle tests were carried out on both wire and strand at minimum stress levels of 40 and 60 per cent of the static ultimate stress. Various maximum stress levels were used to study the relation between stress level and number of cycles to failure. For evaluation of the test results, the stress increment R was defined as follows:

$$R = SMAX - SLIM \qquad (1)$$

where SMAX is the maximum stress in the cycle, and SLIM is the fatigue limit corresponding to the minimum stress level SMIN in the cycle. The stress increment was found to be superior to the commonly used stress range, SMAX-SMIN, in correlating the constant cycle results.

An unexpected feature of the test results was the good correlation between the wire data and the strand data, when R is related to fatigue life N. The correlation appears to extend to data from other test programs. In the scatter diagram in Fig 1, R is plotted against the logarithm of N. About 100 data points for the current wire and strand tests are shown together with those from an extensive series of tests on 7/16 inch (11mm) dia prestressing strands which were carried out at Lehigh University [2]. The three sets of data display a common trend in this diagram and the relation between R and LOGN is well represented by the curve in Fig 1 which has the following equation:

$$LOGN = \frac{1.169}{R} + 5.227 - 0.031*R \qquad (2)$$

The scatter around the mean line in Fig 1 is significant, as is to be expected for fatigue behaviour, and suggests that probability should be included in the representation of the test data. Although the scatter in the Lehigh data is somewhat larger than that in the present tests, this may well indicate differences in test procedures rather than inherent differences in material properties.

One reason why the stress increment R provides a better basis for data correlation than the stress range is because it treats the fatigue limit as an open, variable property of the material. Variations in the fatigue notch effect from material to material are thus allowed for indirectly in Eq 2 by possible variations in SLIM. An estimate of the fatigue limit SLIM is required before Eq 1 can be used to calculate mean fatigue life. Values of SLIM for the wire and strand tests and also for the Lehigh tests are summarised in Table 1.

Ambient temperature was found to be a secondary but nevertheless significant factor affecting observed fatigue life in both the wire and the strand tests.

Cumulative Damage Tests

The cumulative damage tests were designed to provide information on the following:
- the applicability of the linear damage hypothesis to mixed stress cycles in which the maximum stress level varies;
- the applicability of the linear damage hypothesis to progressively varying stress cycles in which the minimum stress level decreases with time; and
- the effect of mixing small 'non-damaging' cycles with larger damaging cycles.

The cumulative damage tests are not due for completion until 1982, but the results so far obtained are not seriously in conflict with the linear hypothesis.

Table 1 Fatigue Limit for Test Data

Test	Minimum Stress Level %	Fatigue Limit %
Wire: Adelaide	40	53
Strand: Adelaide	40	53
Strand: Lehigh	40	56.5
Wire: Adelaide	60	73
Strand: Adelaide	60	73
Strand: Lehigh	60	73

3. PROGRESSIVE CHANGES IN BEAM BEHAVIOUR DURING FATIGUE LOADING

The fatigue life of a partially prestressed member can be estimated from the fatigue properties of the component materials if an analytic method is available for determining the stress cycle histories from the known or assumed load cycle history. Such methods are usually based on the assumption of time-independent and cycle-independent structural behaviour[3]. Various inelastic effects are thereby ignored on the grounds that their influence is secondary.

However, laboratory tests have shown that overall deflection, as well as local deformations in high moment regions, may increase substantially in a beam which is subjected to fatigue loading. In Figs 2 and 3, progressive increases in deflection and concrete deformation at the steel level are plotted against number of load cycles. The data, which come from Ref 4, appear to be typical for a beam with a fatigue life in the order of a million cycles. There is a 34 per cent increase in deflection up to fatigue failure and a 44 per cent increase in deformation.

The main inelastic effects which produce progressive changes in the behaviour of a beam section are:
- shrinkage and static creep under minimum moment conditions;
- dynamic creep under cyclic moment;
- permanent deformation caused by repeated cycles of moment.

Shrinkage and static creep both contribute to deferred prestress losses and hence to a gradual decrease in the minimum stress levels in the prestressing steel and reinforcing steel. The stresses occurring in a section during short term moment cycles are also affected by the previous history of sustained moment. However, the magnitude of the minimum moment also has an important effect on the deferred losses. For example, if the minimum moment is large enough to cause decompression of the 'tensile' fibres of the section, then creep losses will be very small.

Dynamic creep occurs in concrete during rapid stress cycling. Balagura[5] has drawn attention to its effect on the fatigue behaviour of partially prestressed members. Dynamic creep is of most significance in cases of high speed fatigue loading, such as occurs in laboratory tests. In many practical situations, peak fatigue loads occur infrequently and dynamic creep may then be much less

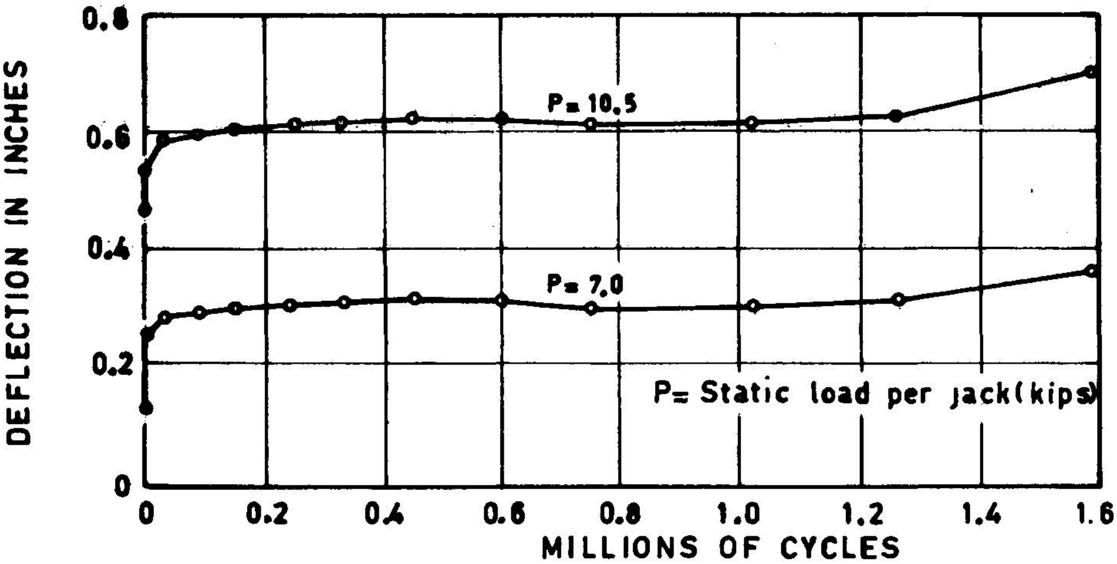

Fig 2. Mid_span deflection, Beam F8 (ref. 4)

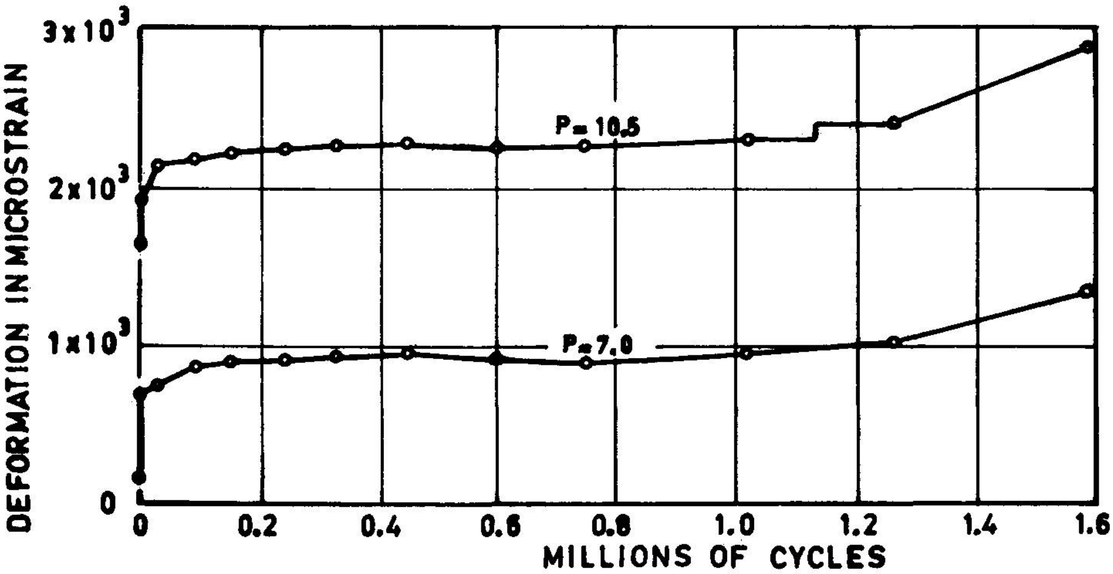

Fig 3. Concrete deformation, Beam F8 (ref.4)

important than in the laboratory.

Some of the main factors which contribute to permanent deformations during moment cycling include:
- inelastic concrete strains in the compressive zone due to cyclic stressing;
- progressive cracking of the tensile zone and gradual loss of tension stiffening;
- progressive bond breakdown near the main cracks, especially between the concrete and the prestressing tendons.

These factors do not account completely for the permanent deformations which are observed when moment is removed from a section [4,6]. Further possible factors include:
- non-closure of cracks due to mis-match of adjacent crack surfaces and the presence of concrete debris;
- inelastic fatigue softening of the steel [5].

While the combination of such effects obviously has a significant influence on deformations and deflections, their effect on stress levels and fatigue life has not been adequately studied. Their importance lies partly in the fact that the fatigue life of a member in the long life range (eg greater than a million cycles) is sensitive to even very small variations in stress level. On the other hand, long term variations in stress level may not be comparable in magnitude with the observed changes in deformation. For example, loss of tension stiffening and bond breakdown result in an increase in average steel stress throughout the high moment regions, but may not significantly change the peak steel stress at the primary cracks. The end result of bond breakdown and loss of tension stiffening may thus be little significant change in the fatigue life of the section of maximum moment, but an increased probability of fatigue failure in adjacent sections. This conclusion is speculative and awaits the results of a theoretical study of inelastic effects which is at present being undertaken. An analysis of the effect of dynamic creep on fatigue life has recently been published[5].

It is significant that inelastic effects appear to have most influence on beam behaviour in the early load cycles. In Figs 2 and 3, the main increases in deflection and deformation occur in the first 20 per cent of the fatigue life of the beam. Variations in stress level presumably occur at the same time. It therefore seems reasonable to base fatigue life calculations on an assumed constant beam response (constant stress-moment relation). However, the middle life phase of beam behaviour should be considered and not the initial behaviour in the early load cycles.

4. SUMMARY AND CONCLUSIONS

Constant cycle fatigue data obtained from tests on prestressing wire and strand correlate well when the stress increment, R=SMAX-SLIM, is plotted against number of cycles to failure. Eq 2 fits the test data for prestressing wire and prestressing strand, as well as data obtained in a previous series of strand tests. The stress increment appears to be more appropriate than the stress range, SMAX - SMIN, for the treatment of fatigue data for prestressing steel.

Various inelastic effects cause progressive changes in the deformations and stresses in a partially prestressed concrete member and hence affect the fatigue life of a member. Fatigue life calculations should not therefore be based on an analysis of stresses in the first load cycle, but rather on stress-moment relations which represent stabilised beam behaviour in the middle life phase after some thousands of load cycles have taken place.

5. ACKNOWLEDGEMENTS

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