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IVb

Fatigue Resistance of Partially Prestressed Concrete Beams to Large Range Loading

Résistance à la fatigue de poutres de béton partiellement précontraintes au cours d'une gamme variée de charges

Der Schwingungswiderstand von teilweise vorgespannten Balken gegenüber Lastwechsel von großem Bereich

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I. INTRODUCTION

The first named author has presented a paper under the same subject dealing with different classes of partially prestressed members in general and briefly covering fatigue.[1] The present paper includes research carried out at Duke University relating to large range fatigue tests on pretensioned beams. These tests were carried out in slow cycles because of large amplitude of deformation. They were based on the consideration that temporary cracks under rarely occurring "abnormal" loads are harmless, provided that the structure is "fully" prestressed (i.e., entirely in compression) under normal loads. The reliability of highway bridges depends on their fatigue resistance to action of both the normal and abnormal loadings over the expected lifetime. Previous fatigue tests by the first named author, published at the Liége Congress 1952,[2] had already shown that three million cycles within definite loading ranges at which cracks opened during all cycles did not affect the subsequent S.F.L. (static failure load).

Dr. Ekberg and Assoc.[3] were the first to show that the fatigue resistance of under-reinforced prestressed concrete beams is governed by the "Goodman" diagrams of steel and concrete. The authors are of the opinion that in addition, bond resistance and crack distribution are of influence. The Goodman Diagram is obtained from S-N curves based on various load ranges and applies for a specified number of load cycles. Originally this was 1 or 2 million; however, now it appears necessary to consider 10 million cycles or more. For highway bridges the lower level of the range (i.e., the dead load) may vary between 30 and 40% of S.F.L. Ten million cycles ought to be considered for the normal loading but for an "abnormal" loading which is investigated in this paper, a limited number of cycles applies, i.e., an "abnormal" load occurring once a week would amount to only 5,200 cycles in 100 years. The scope of the present investigation is limited to loading of a frequency less than 300,000 cycles. Figure 1 is a Goodman diagram of prestressing strands, based on 2 million cycles, showing the lower and upper limits of the ranges. In the diagram recent test results have been indicated for 10 million cycles based on (4). The probable stress ranges of the tensioned and nontensioned steel are indicated. No data is available for low cycle ranges and consequently it has been found necessary to investigate this problem on prestressed concrete beams to obtain L-N (load-number of cycles) curves. With highway bridges the frequency both of normal and abnormal loading has to be taken into account. A study of the abnormal loading was the basis of the research at Duke University 1966 to 1968.

In Fig. 2, two possible L-N curves are shown on the assumption that the dead load is 30% of S.F.L. and the effective prestress is 30 and 40% respectively of the S.F.L. The shape of the curves has been assumed to be similar to known shapes of S-N curves for various materials. In this diagram the range of cycles discussed in the following is indicated.

The authors are gratified that Professor Leonhardt in his report IVa[5] has come to similar conclusions. From his paper the following may be quoted which completely fits into the research consideration of the authors:

> It so happens that prestressed concrete girders are very little affected by occasional rare overloading; even if the concrete in the tensile flange cracks, the cracks completely close up again, as a result of the compression developed by the prestressing force, immediately after the abnormal loading of short duration has ceased. Tests have always confirmed this great capacity for recovery of prestressed concrete girders after brief overloading. It is therefore not a reasonable procedure to keep the tensile flanges of girders permanently in a state of very high compression in order to obviate the occurrence of tensile stresses in the concrete in rare extreme cases of loading, the more so as one then has to put up with the above-mentioned creep deformations which alter the gradients.
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> The appropriate choice of the degree of prestressing is not only of great importance to the economy of prestressed concrete bridges, but also to their behaviour under permanent load....Therefore with "limited" prestressing savings are effected and better behavior under sustained load is obtained, without sacrifice of safety.

In section II, statistics and probability in connection with limit states of design (serviceability and collapse) and with fatigue are discussed, (See reference 6.) In section III a survey is given on research carried out by the last named author.[7] In section

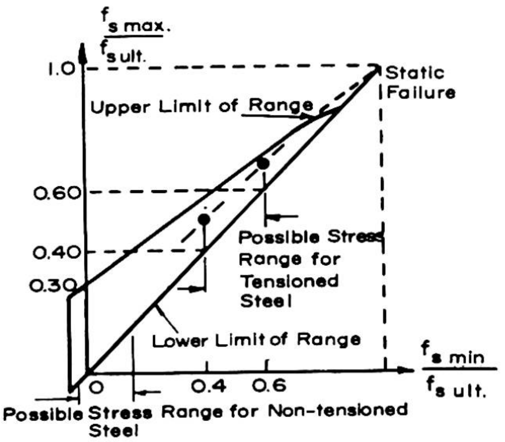


Fig. 1. Goodman Diagram

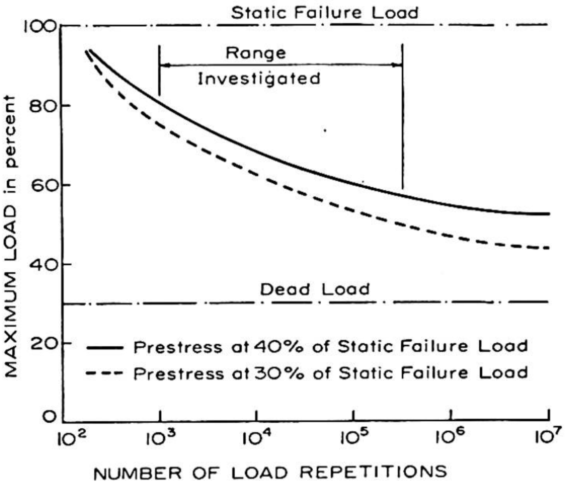


Fig. 2. Possible L-N Curves for Prestressed Concrete Beams

IV proposals are made for further research and conclusions are drawn in section V.

II. STATISTICS AND PROBABILITY IN CONNECTION WITH FATIGUE

Variations in the fatigue resistance of prestressed concrete beams may occur owing to differences in concrete strength and workmanship. There are also great variations in the loading not considered here. In the fabrication of prestressed concrete beams, excellent supervision and good workmanship are essential because otherwise no reliance can be made on the design assumptions, e.g., prestressing force and concrete strength. In Fig. 2, reference (1), it is shown that substantial differences in the behavior under service load may occur in partially prestressed beams if supervision is unsatisfactory. There are numerous examples of good agreement in the performance of prestressed members if sufficient supervision is available. It must be agreed that no structure is absolutely safe, but an acceptable minimum of safety should be achieved. This means that there will be a margin between extreme service conditions and failure.

The most frequent loads on bridges are automobiles of relatively low weights. Next are trailers which frequently pass over bridges but whose weights are still below the design load. In addition, there are "abnormal" loads which occur rarely and for which a permit is necessary before they are allowed to pass over bridges. These "abnormal" loads will likely include tanks or other heavy machinery. In these cases, the magnitude of the load will be known and it will be possible to determine whether a limited number of such loads passing over the bridge does affect the carrying capcity and if the required margin is maintained between fatigue failure and limit of reliability in loading.

Variability of performance in fatigue must be considered. S-N diagrams for prestressing steel exhibit variations which are based upon the inherent properties of the material under fatigue loading conditions. Variations have been established for such factors as different sizes, different heats, different manufacturers, and different wires and strands. These variations are further increased by fatigue loads. Tide and Van Horn[4] have shown such variables in S-N curves based upon 50% probability. However, the designer would prefer to know the minimum S-N curve. In any case, he would prefer 90% reliability as shown by Hilmes and Ekberg.[8] Bennett[9] has carried out fatigue tests on wires whereas the previous tests mentioned related to strands. Further research to obtain the fatigue resistance of prestressing steel is most important because, as already pointed out by Ekberg,[3] the Goodman diagram thus obtained offers a safe basis for the fatigue design of under-reinforced prestressed concrete beams.

There is relatively little recent research on plain concrete fatigue except that of Ople and Hulsbos[10] which was undertaken on eccentrically loaded prisms. Higher fatigue resistance was observed than for concentrically loaded comparison specimens.

Numerous fatigue tests on prestressed concrete beams have been carried out in addition to those reported.[2,3] Included are those of Bennett-Dave[11] who carried out comparative fatigue tests on beams containing the same number of crimped wires with varying arrangement of tensioned and nontensioned steel. For example, 5 such beams were subjected to fatigue tests to a stress of 2260 psi with the upper range varying in accordance with the respective prestress from

320 to 1620 psi nominal tensile stress. After 3 million load cycles, static load tests to failure were carried out with satisfactory results.

Tests mentioned above relate to individual beam investigations and were not intended to study fatigue on a statistical basis. Comparative tests on a statistical basis were carried out by Warner and Hulsbos[12] and Venuti.[13] In the former two sets of four beams each were tested. One beam of each set was loaded statically. The remaining three beams of each set were tested under fatigue loading. Beams of one set were subjected to the same constant cycle range of loading and those of the other set were loaded under a program of cumulative load cycles. There were appreciable differences in the fatigue resistance of the beams, but the highest ratio between the maximum and minimum observed fatigue life was not more than 1.6 for the constant cycle tests and 1.7 for the cumulative cycles tests.

The tests of Venuti[13] included very small specimens 6" wide and 4½" deep, with two 3/8" diameter strands, located 3" apart and 1.9" above the tensile face. The span was 6' with 2-point loads located 1' apart. The tests comprised 90 beam specimens, 18 for each of five maximum load levels of 50, 60, 70, 80 and 90% of the S.F.L. which was obtained from 16 other beams. The lower level of fatigue loading was 10% of S.F.L. There was much scatter in fatigue test results. These tests were carried out on two machines of constant amplitude type requiring periodic load adjustments. Venuti obtained early compression failures of some of the under-reinforced beams even at the lowest maximum load level while others failed in compression in the first cycle of loading at the highest fatigue level. These results, which would preclude any reliability considerations with regard to fatigue of prestressed concrete, are in the authors' view influenced by various conditions such as the small size of specimen, intentional omission of special supervision of manufacture, the type of test machine used, and the relatively large space between tendons resulting in little crack protection. This publication is very interesting because it represents the first statistical fatigue study of prestressed concrete beams and offers a challenge to prove that with larger size members and supervision of manufacture of prestressed concrete, a greater reliability in fatigue can be obtained.

III. THE RESEARCH AT DUKE UNIVERSITY 1967-68.

Comparative tests were carried out on prestressed beams of type A and type B; cross section using the loading arrangement shown in Fig. 3. The beams consisted of ordinary weight or of semi-light concrete, those of the latter are indicated by the letter "L". Some preliminary fatigue tests on beams AL were also reported.[15,16] (See report by Abeles, Figs. 15, 17, 18.) The lightweight specimens[15,16] were produced in a pretension bed of a prestressing works. The beams discussed in the following were produced at Duke University in a transportable prestressing bed allowing three specimens to be stressed in one casting. Two beams of each casting were tested in a fatigue and one statically. Resistance strain gages were attached to the tensioned strands. This was rather difficult because of the small size of the wires of the ¼" strands. It was even more difficult with the nontensioned strands of type B beams; however, strain measurements were obtained in a few cases.

Figure 4 shows the results of the fatigue tests. The S.F.L. of type B beams was only about 86% of that type of beams. This was due

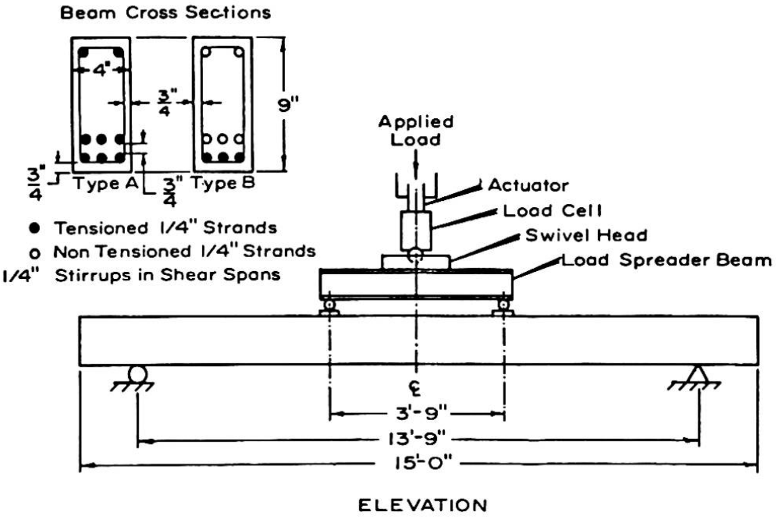


Fig. 3. Cross Sections and Loading Arrangement for Test Beams

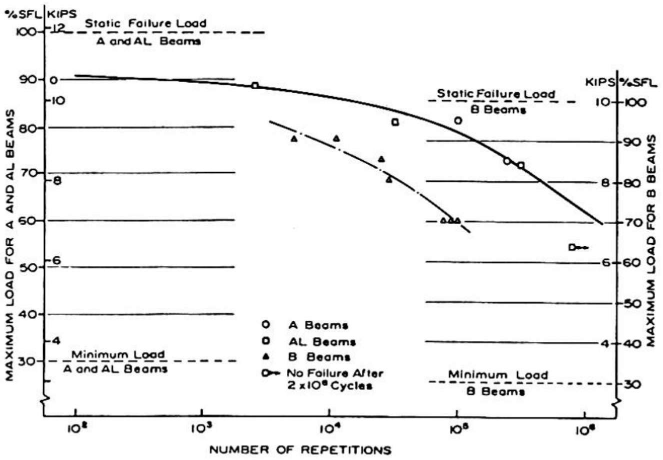


Fig. 4. Fatigue Test Results

to two conditions. The maximum stress reached at failure in the non-tensioned strands of B was less than in tensioned strands of A beams and also there was a slightly lower concrete strength in the B beams than in the A beams. There was no difference between the A and AL beams, and some results obtained for AL beams have been included in Fig. 4.

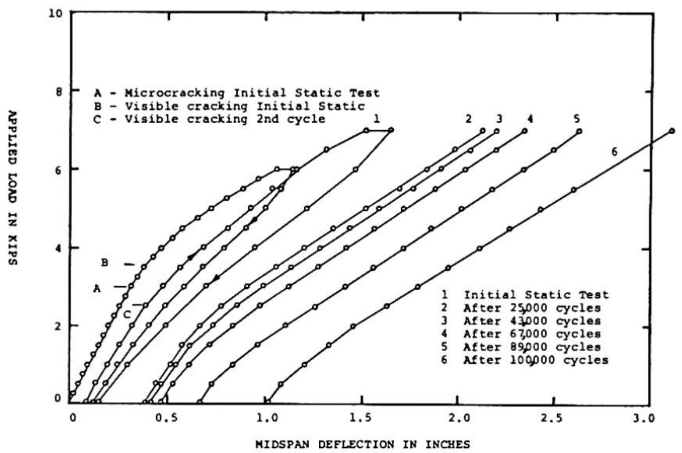


Fig. 5. Load-Deflection Characteristics After Repeated Loading, B8

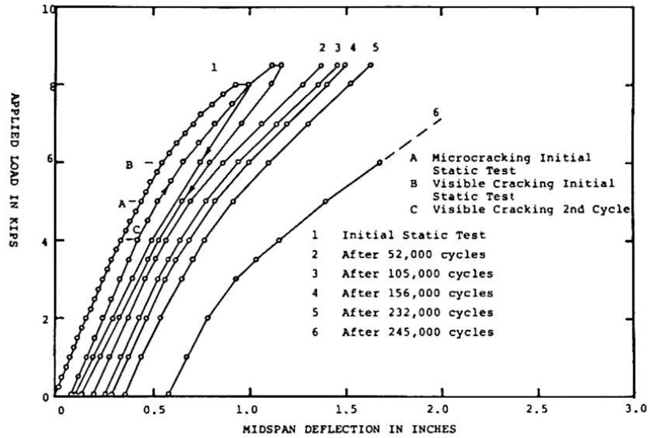


Fig. 6. Load-Deflection Characteristics After Repeated Loading, A1

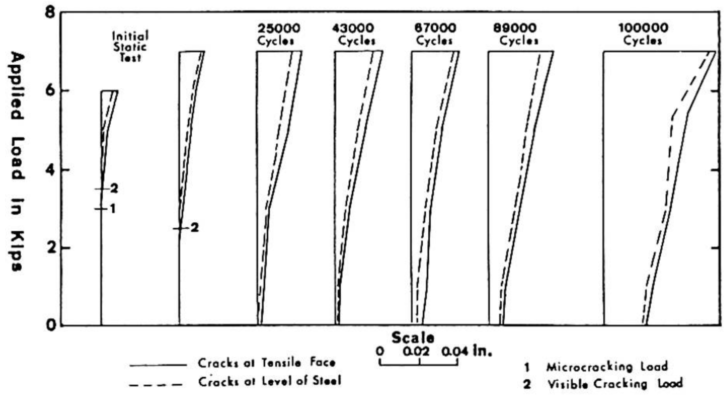


Fig. 7. Maximum Crack Width in Beam B8 After Repeated Loads

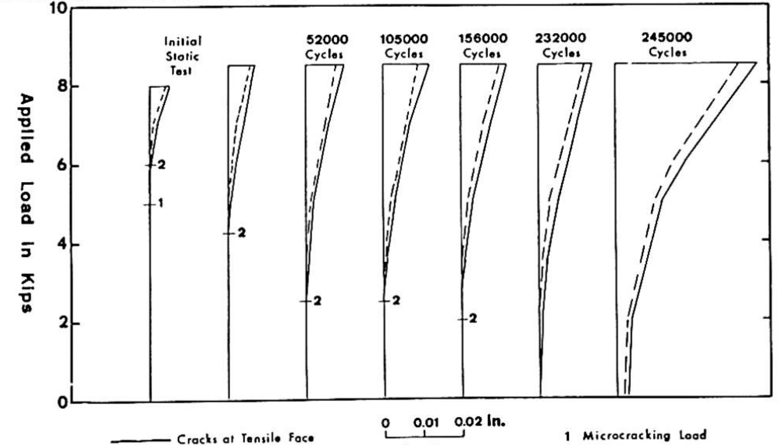


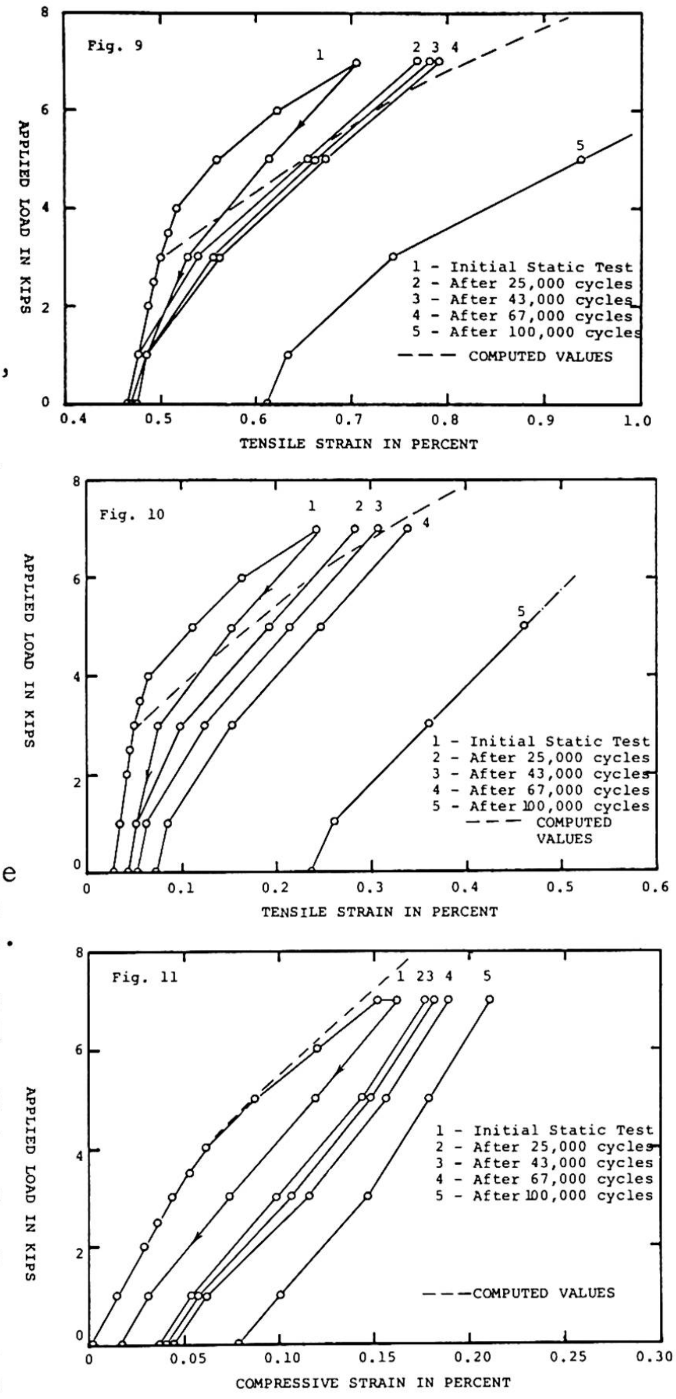
Fig. 8. Maximum Crack Width in Beam A1 After Repeated Loads

In Fig. 4 the ordinate is the upper range of the fatigue load. The percentage related to the S.F.L. is indicated separately for beams A and B. It is seen that the results with regard to the A beams show much greater resistance than those of the B beams related to absolute loading due to the higher prestress as was expected. However, if related to the percentage of the S.F.L., the B beams show more favorable results than the A beams for loads above 85% of the S.F.L. It may be noted also that the minimum load of 30% of the S.F.L., corresponding to dead load, was higher with beams A than with beams B.

Figures 5 and 6 illustrate load-deflection curves for beams A1 and B8 showing the difference in behavior of the two types of beams. The former beam was subjected to 245,000 cycles, whereas the latter failed after only 1000,000 cycles, in both cases the range being approximately between 30 and 70% of the respective S.F.L.

Figures 7 and 8 depict the crack measurements made up to the maximum level of the fatigue load for the same two beams. It is seen that with the A beam, having much higher prestress, the cracks closed completely after 232,000 cycles whereas they remained open only after 245,000 cycles, when 20 wires of the tensioned strands failed, two of which were in the upper layer. With beam B8 the cracks remained visible after only 25,000 cycles and became quite wide after 11 wires had fractured after 1000,000 cycles.

Figures 9 and 10 show the respective strain measurements in the tensioned and nontensioned steel of a B beam. It is seen that here the strain in the lower layer, i.e., pretensioned steel, did not have a great permanent set after 67,000 cycles. However it must be pointed out that this was observed only with some of the



Figs. 9, 10, and 11.

Load Strain Characteristics of a Bottom Strand, an Intermediate Strand and at the Compressive Face, Respectively of Beam B-8 After Repeated Loading.

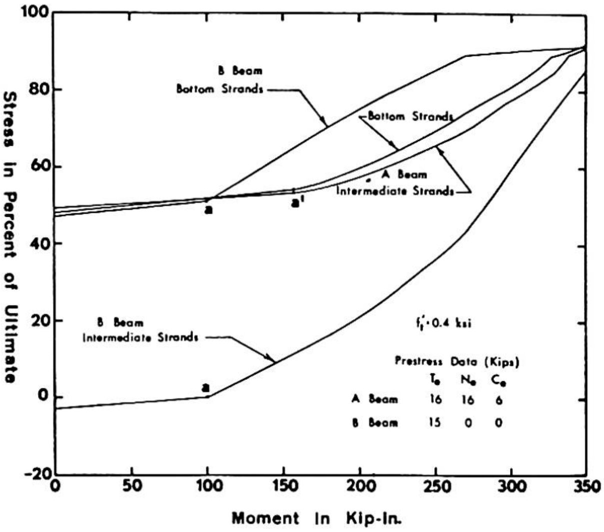


Fig. 12

Computed Static Stresses in Bottom and Intermediate Strands of A and B Beams

strain gages, whereas with other strain gages which were close to cracks, larger permanent sets were noticed owing to the cracks which had developed. It is seen in Fig. 10 that with the nontensioned strands, the permanents sets were not substantial up to 67,000 cycles, but in both cases the strains became quite large after failure of some of the wires in the bottom strands. The strain measurements obtained in A beams were similar to those shown in Fig. 9 for B beams where the position of the gage was not close to a crack and this applied both to the bottom and upper layers of the tensioned steel. Figure 11 shows the measurements of the compressive strain in the concrete near the top face of a B beam. This graph, which agrees with other tests[12], indicates that a change in curvature occurs in consequence of the fatigue loading.

The theoretical stresses obtained for tensile strands for A and B beams are indicated in Fig. 12 which shows that for the A beams the stresses in the two layers of strands are very close whereas at an earlier stage in the B beams much higher stresses occur in the bottom layer but those in the nontensioned steel in the second layer gradually increase when approaching failure.

It should be pointed out that in all cases in which the upper range of the fatigue loading did not exceed 80-85% of the S.F.L., some wires fractured, causing increase in deflection which resulted in automatic stoppage of the fatigue load. Afterwards, the fatigue test was continued with close observation, but after a limited number of cycles further wire fractures occurred; consequently, the first wire fracture can be considered as fatigue failure. When the upper load range was above 80-85% of the S.F.L. sudden collapse of the beam took place after a relatively low number of cycles due to the crushing of the concrete without wire fracture. The conditions with regard to the concrete are such that not only the magnitude of the stress at the outer face but also the stress gradient in the compression zone changes between the lower and upper load levels of each cycle (see reference 10), so that the change in gradient alone would not suffice to simulate the conditions in a prestressed beam. Suitable results might be obtained on highly over-reinforced flexural members in which the magnitude of the gradient of the concrete stresses of lower and upper ranges correspond to those occurring in the prestressed concrete beam.

The previous description is only of a quite general nature. It is intended that a more detailed report of this research will be prepared by the last mentioned author in conjunction with the two other authors.

IV. FUTURE RESEARCH REQUIRED.

When comparing the results shown in Fig. 4 with those of Venuti[13] it is seen that greater uniformity is obtained here in spite of the possibility of variation expected with fatigue tests. Results here seem to be in good agreement with those of Warner and Hulsbos,[12] although the variations of the latter are somewhat greater. In order to obtain statistical data about fatigue resistance it would be essential to repeat these tests (Strain measurements would not be necessary.) on a great number of similar beams, as Venuti did with his tests.[13] In addition, it would be most important to investigate other types of beams varying in shape, reinforcement, degree of prestress and other parameters including beams with post-tensioned tendons. It seems that the size of the beam selected is appropriate, i.e., neither too small to cause great scatter resulting from possible errors in positioning of the reinforcement and other defects of manufacture, nor too large to cause difficulties in handling. Nevertheless, for comparison purposes some full size beam tests would also be desirable, preferably with strain measurements on the reinforcement.

CONCLUSIONS

1. Large range, slow cycle fatigue tests undertaken at Duke University seem to be of great importance in ascertaining the reliability of prestressed concrete beams under a limited number of abnormal loads, as may occur on highway bridges.
2. S-N diagrams for prestressing steel are available but the data indicate considerable variation and thus further research is necessary to obtain not only the mean but also the minimum stress range for products of different manufacture and heat.
3. For concrete, the existing S-N curves and Goodman diagrams are based either on concentric or on eccentric loading of constant eccentricity. In fatigue loading both stress and stress gradient are different at the upper and lower load levels, and thus the Goodman diagram does not apply. This difficulty could be overcome in tests on over-reinforced beams, simulating gradients and stresses.
4. It is advisable to obtain L-N (load-number) curves, related to the S.F.L. for each type of beam, rather than S-N curves (related to the stresses of the materials), as crack distribution and width are also important. In these tests, the lower range relating to the influence of dead load was assumed as 30% of the S.F.L. (static failure load).
5. Tests were carried out at Duke University on two types of medium size, under-reinforced beams, having 6 strands, 3 in each of two layers in the tension zone. In type A, all 6 strands were pretensioned whereas in type B the 3 lower strands were pretensioned, the 3 upper strands remaining nontensioned. The static failure load of B beams was approximately 86% that of A.
6. Beam types A and B exhibited similar L-N curves, extending to about 10^5 cycles, type B showing a relatively better performance related to the lower static failure load of B as compared with A (although the actual failure loads were less). Type A showed great

superiority when a greater number of cycles apply for lesser upper load ranges.

7. Comparison of the load-deflection characteristics for A and B beams indicates an earlier change in slope occurring with B because of the lesser prestress. The load-deflection diagrams show that the deflection of type A remained on a relatively steep gradient (without much permanent set) at a number of cycles at which the type B already exhibited an appreciable deflection and permanent set. At the last comparison both beams were subjected to the same loading range related to the S.F.L. (range between 30 and 70% of the S.F.L. number of cycles with A: 245,000 and with B: 100,000).

8. The tests have demonstrated that it is possible to apply without failure over 200,000 load cycles (245,000 with A beams and 305,000 with AL beams) between 30 and 70% of the S.F.L. to type A beams. Similarly it was possible to apply about 100,000 cycles to B beams within the same range of the respective S.F.L. This should give a sufficient safety factor to apply, in addition to the large number of small range cycles of ordinary loading with increased frequency, about 75,000 large range cycles of abnormal loading of this magnitude, corresponding to two daily loadings during 100 years for A beams, and about half this amount for B beams.

9. The tests have further demonstrated that it was possible to apply about 100,000 load cycles between 30 and 80% of the S.F.L. to A beams and over 25,000 load cycles to B beams within the same respective range. This should give a sufficient safety factor to apply, in addition to the large number of small range cycles of ordinary loading with increased frequency, about 25,000 cycles of the large range abnormal loading for A beams, corresponding to approximately five weekly loadings during 100 years and to one weekly loading during 100 years with B beams.

10. Cracks occurred much earlier and increased in size to a much greater extent with type B than with type A. A comparison shows that for the same range with the B beam, cracks remained visible after only 25,000 cycles, whereas with the A beam they remained closed even after 230,000 cycles. As soon as some of the wires of the strands had fractured the cracks remained open.

11. The change of load-strain characteristics of type B containing nontensioned strands, show some similarity of the behavior of the tensioned and nontensioned steel. Obviously, the strains obtained from electrical resistance strain gages greatly depend on the location of the gage with respect to cracks. Regarding concrete strain, with increase in the number of cycles, a change in curvature has been noticed as is usual when concrete is subjected to a certain amount of cyclic loading

12. The mode of failure has been observed to be fracture of one or more wires of the steel for cyclic loading where the upper limit ranges below 80% of the static failure load, whereas with higher upper limits failure took place due to crushing of the concrete without wire fracture.

13. The present tests, carried out on medium size specimens were investigated on a comparative basis, but insufficient specimens were tested to study the results statistically. This will be essential to prove that a much greater reliability can be obtained than has been found in some investigations. Thus it will be essential to repeat the tests on the A and B beams for the same loading ranges on a great number of specimens, without however, the need of strain measurements.

14. It would also be important to extend the research to different types of beam with regard to size, shape and reinforcement to be conducted both on a scientific basis and on a statistical basis covering both pretensioned and post-tensioned tendons. This should include a number of full size beam tests to compare results on medium size specimens with those on full size beams.

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SUMMARY

The fatigue life of highway bridges need not be affected by a specific limited number of occasional "abnormal" loadings provided that cracks thus developing remain closed under "normal" loading. In spite of much greater frequency of "normal" loading, a satisfactory reliability of the structure can be obtained. Studies in this respect on pretensioned beams have been carried out at Duke University, based on fatigue tests extending over large loading ranges.

RÉSUMÉ

La fatigue des ponts d'autoroute n'est pas nécessairement affectée par un accroissement important d'un nombre limité spécifique de charges occasionnelles "anormales" pourvu que les fissures qui apparaissent restent fermées sous une charge "normale". Malgré une fréquence beaucoup plus grande des charges "normales", on peut obtenir une sécurité satisfaisante de la structure. Des études à ce sujet sur des poutres précontraintes ont été conduites à l'Université de Duke, basées sur des essais de fatigue au cours d'une gamme variées de charges.

ZUSAMMENFASSUNG

Es besteht keine Gefahr, dass die Lebensdauer von Strassenbrükken infolge von Ermüdung bei einer beschränkten Anzahl von Sonderlasten, die noch weiter erhöht werden dürften, verringert wird, vorausgesetzt dass hierbei aufgetretene Risse sich bei der üblichen Nutzlast vollständig schliessen. Trotz einer viel grösseren Frequenz dieser üblichen Nutzlasten kann eine zufriedenstellende Sicherheit dieser Konstruktion erzielt werden. Diesbezügliche Studien an im Spannbett hergestellten Balken werden an der Duke Universität gemacht, die auf einen grossen Lastbereich sich erstreckende Schwingungsversuche aufgebaut sind.