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EFFECT OF SPECTRUM EDITING ON FATIGUE CRACK INITIATION AND PROPAGATION IN A NOTCHED MEMBER

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Accelerating component fatigue tests by editing nondamaging events from field loading histories will result in substantial reductions in test time. This report describes analytical techniques for editing the spectra as well as experimental varification of the procedures.

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ABSTRACT

Many techniques for estimating crack initiation lives of notched members subjected to variable amplitude loading have been developed over the last ten years. The common feature of all successful approaches is a cycle counting method that identifies large overall events as cycles and treats smaller events as interruptions to large events. Fairly accurate life estimates can be obtained using constant amplitude fatigue data and the Palmgren-Minor linear damage rule if range pair or rainflow cycle counting procedures are used. These techniques can then be used to edit the least damaging events from field service histories so that accelerated fatigue testing can be performed on actual components.

A method of estimating fatigue crack initiation lives for notched members and reducing field service histories on the basis of crack initiation is described. It is based on a knowledge of the local stresses and strains at the notch root. Load histories were analytically edited so that they contained 80 percent of the original fatigue damage. Analytic estimates of crack initiation lives are compared to experimental data on full and edited load histories. This data is part of the SAE Cumulative Fatigue Damage Test Program.

Results of this test program indicate that fatigue crack propagation can account for as much as 90 percent of the total life in notched members, depending on the geometry and type of load history. A method for estimating fatigue crack propagation lives of notched members subjected to irregular loading histories is also described. Crack propagation is calculated from constant amplitude materials data using an effective stress intensity concept. Finite element techniques are used to determine residual stress and strains due to notch geometry. A modified form of rainflow counting is used to reduce the irregular load history into equivalent constant amplitude events. Analytical estimates of crack propagation lives are compared to experimental data for full and edited load histories.

Experimental tests were conducted using the transmission, suspension, and bracket histories from the SAE test program. Reductions in size of the loading histories of 92%, 97%, and 90% were obtained for the three histories. Theoretical initiation lives were increased approximately 20%. Within reasonable scatter, the test results using the edited histories on seventeen specimens followed both theoretical predictions and experimental full history test results very closely. Edited history tests, on the average, differed from predicted initiation, propagation and full fatigue lives by factors of 3.4, 2.3, and 2.7, respectively. These same tests, on the average, differed from the full SAE history tests by factors of 2.8, 2.8, and 2.3 for the experimental initiation, propagation, and full fatigue lives, respectively.

The results show the procedure to be a powerful tool, not only to reduce fatigue testing time, but also to give a designer an indication of the fatigue damage induced by certain cycles.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. Background

For many years the problem of fatigue has plagued all designers who work on structures and components subjected to cyclic loads. The main problem in dealing with fatigue in design is that the mechanisms of fatigue are very complex and even though much research is being done in this area, a complete understanding of the subject is still a long way off.

For this reason, many varied groups have been responsible for establishing programs to investigate various aspects of fatigue. One typical group dealing primarily in the ground vehicle industry established a round robin test program through the SAE. This work has produced a great deal of test data and a considerable number of theoretical concepts for fatigue analysis.

Since this initial work consisted of such a thorough test program and analysis, it establishes a baseline for yet another investigation to go one step further. This next step is to establish a procedure to edit small non-damaging events from a random fatigue history without significantly changing the fatigue damage done by the original history.

B. Objectives

The purpose of this investigation was to test a procedure for editing irregular load fatigue histories and to check the procedure, both theoretically and experimentally, to see if a majority of the fatigue cycles could be eliminated without a significant change in the fatigue initiation life. This was done to see if the procedure could be employed to decrease fatigue testing time for components and structures.

C. Approach

The basic procedure will be to edit the SAE random fatigue histories using a rainflow counting technique. This will establish the amount of fatigue damage in each load cycle. The cycles can then be ordered so that the cycles producing the least amount of fatigue damage can be eliminated first. Cycles can then be eliminated until a significant change in the fatigue initiation life for each remaining cycle requires the editing procedure to stop.

Once the edited history is established, tests can be made at the same test conditions as the original SAE round robin test program.

This will enable both analytical and experimental comparison for the SAE edited fatigue data.

II. SAE TEST PROGRAM

Since early 1970, the SAE has been involved in a test program to study fatigue under complex loading (1). The program was responsible for the establishment of load histories, specimens, materials, and testing programs.

A. Histories

Initial load histories were established as typical of the ground vehicle industry histories in general. Of these 30 different analog histories considered, only three were finally selected. This was done merely to keep the test program to a more manageable size. The final three histories were:

(1) Bracket - a vibration of a mounting bracket attached to a vehicle operating on a rough road. It is a good example of random vibration about a mean value.

(2) Suspension - a history of a suspension part in bending attached to a vehicle driven over a durability course. It is a good example of random excitation with superimposed maneuvering forces. The mean value of this history is compressive.

(3) Transmission - a history of the transmission part attached to a tractor engaged in front-end work. It is a good example of large deviations from a mean value in tension.

Each history was originally recorded as an analog signal of an actual component in the field. This signal was then reduced to a series of digital integral values representing the analog peaks between -999 and +999. The absolute maximum corresponded to the value of 999. Each digital history was then further reduced to eliminate any changes less than 20% of the absolute maximum stress. In other words, valleys and peaks were separated by at least 200.

The order of the peaks was always preserved; however, the absolute maximum peak was designated as the starting point. One complete history was defined as a block. Although the values and orders of peaks were preserved, there was no attempt to model the history frequency. As measured in the field, this was nominally 1 to 30 Hertz. Figure 1 shows the three SAE histories.

B. Specimens and Materials

The test specimen, Fig. 2, was used for the entire program. Loads were applied to the specimen through a monoball fixture, which allowed both tensile and compressive loads to be applied.

This design provided both axial and bending stresses and strains at the notch root. Also, it permitted the study of both crack initiation and crack propagation.

In addition, the specimen was typical of a component design. All dimensions and surfaces were either as supplied or machined, and the stress concentration factor at the notch was also typical.

Two commonly used structural steels, U. S. Steel's Man-Ten and Bethlehem Steel's RQC-100, were used in the program. Mechanical properties of these steels are listed in Table I.

III. INITIATION AND PROPAGATION CALCULATIONS

A. Background

The basic concepts of fatigue life analysis have been a culmination of the works of many individuals. A brief summation of the concepts used for the theoretical analysis of the study follows. Much of the work to establish the actual computer algorithms and theoretical models has been done for the full SAE history tests (2). This work supplied the tools for further investigation and study dealing with spectrum editing and its analysis. Both material properties and fatigue analysis methods are discussed.

B. Initiation Analysis

Fatigue resistance of metals can be characterized by a strain-life curve. These curves are determined from polished laboratory specimens that are tested under completely reversed strain control. The relationship between total strain amplitude, $\Delta\varepsilon/2$, and reversals to failure, $2N_f$, can be expressed as the sum of the elastic and plastic component of strain and has the following form:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \qquad [1]$$

where

σ_f'	fatigue strength coefficient
b	fatigue strength exponent
ε_f'	fatigue ductility coefficient
c	fatigue ductility exponent

Elastic and plastic components of the total strain are obtained from stable hysteresis loops taken during the fatigue test. Cyclic stress-strain curves are obtained by plotting the tips of stable hysteresis loops and passing a smooth curve through them. By manipulating Eq. 1 to eliminate life, it can be shown that the cyclic strain hardening exponent, n', is determined by the fatigue strength and ductility exponents as follows:

$$n' = \frac{b}{c} \qquad [2]$$

Similarly, it can be shown that the cyclic strength coefficient, K', can be determined from the fatigue properties as follows:

$$K' = \frac{\sigma'_f}{{\varepsilon'_f}^{n'}} \qquad [3]$$

Mean stress effects may be included in a variety of ways. For the purpose of this formulation of fatigue properties of metals, it is convenient to incorporate mean stress effects as an equivalent change in static strength. This results in an expression of the following form:

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma'_f - \sigma_o)}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad [4]$$

where σ_o = mean stress

When the fatigue properties for a given metal are known and the service environment is defined, the problem of fatigue life prediction becomes one of determining the local strain amplitude and mean stress for each reversal so that Eq. 4 can be solved for life.

Recall that fatigue properties are determined from constant amplitude testing. An irregular load history must be reduced into a series of constant amplitude events each with its corresponding mean and amplitude for comparison with the smooth specimen data. The concept of a cycle in an irregular history is difficult to define; however, a reversal can easily be defined as a change in sign in the loading. A constant amplitude sinusoidal cycle would contain two reversals. Cycle counting techniques combine reversals in such a manner as to form cycles. Of the various counting techniques in use today, rainflow or its equivalent range pair has been shown to yield superior life estimates.

A simple example of the rainflow counting technique is attached to show how a complex load history can be reduced to a series of discrete events. These events can then be counted or measured to give an indication of the fatique damage produced by any given cycle. Figure 3 shows a typical strain time history along with its corresponding stress time history. Events C-D and E-D have identical mean strains and strain ranges but have quite different mean stresses and stress ranges. Following the elastic unloading (B-C), the material exhibits a discontinuous accumulation of plastic strain upon deforming from C to D. When point B is reached, the material "remembers" its prior deformation (i.e., A-B), and deforms along path A-D as if event B-C never occurred.

In this simple sequence, four events that resemble constant amplitude cycling are easily recognized: A-D-A, B-C, D-E, and F-G. These events are closed hysteresis loops, each event is associated with a strain range and mean stress. The apparent reason for the superiority of rainflow counting is that it combines load reversals in a manner that defines cycles by closed hysteresis loops. Each closed hysteresis loop has a strain range and mean stress associated with it that can be compared with the constant amplitude fatigue data in order to calculate fatigue damage.

Once the cycles have been defined and the stress-strain response determined, the appropriate fatigue parameters can be determined, so that a damage analysis can be performed.

Cumulative damage fatigue analysis is based on the Palmgren-Miner linear damage rule. Fatigue damage is computed by linearly summing cycle ratios for the applied loading, as indicated in the following equation.

$$\text{Damage} = \sum \frac{n_i}{N_{fi}}$$

where n_i = observed cycles at amplitude, i

N_{fi} = fatigue life at constant amplitude, i

After the fatigue damage for a representative segment or block of load history has been determined, the fatigue life in blocks is calculated by taking the reciprocal.

This procedure gives the theoretical fatigue initiation life (N_i). Details of the procedure are found in Ref. (3).

The definition of an initiated crack has been the subject of much controversy. No satisfactory solution to this problem exists. Fatigue cracks start with dislocation movement on the first load cycle and end with fracture on the last. Crack initiation lies somewhere between the two. For purposes of strain cycle fatigue analysis, crack initiation is defined as a crack in the structure or component that is the same size as the cracks observed in the strain cycle fatigue specimen. Frequently, this is the specimen radius which is on the order of 2.5 mm. Dowling (4) proposed reporting strain cycle fatigue data in terms of the number of cycles required to form a crack of fixed length. He found that for steels below the transition fatigue life, cracks 0.25 mm long were formed at approximately one-half of the life required for specimen separation. For longer lives where the bulk behavior of the material is primarily elastic, the first crack is observed just prior to specimen fracture.

The definition of crack initiation applied to strain cycle fatigue analysis always includes a portion of life where the crack is indeed propagating. It should be noted, however, that the behavior of small cracks (less than .25 mm) is different than long cracks cycled under equal stress intensities. As a result, the analysis described in the next section does not apply to them. For design purposes, crack initiation is defined as the formation of a crack between .25 mm and 2.5 mm long.

Immediately following crack initiation, the crack goes through a period of propagation before the final fracture. The fatigue crack propagation life (N_p) together with the fatigue initiation (N_I) may be summed to obtain the total fatigue life of the part.

$$N_T = N_I + N_p \qquad [6]$$

C. Propagation Analysis

Perhaps the most widely accepted correlation between constant amplitude fatigue crack growth and applied loads has been proposed by Paris. The rate of crack propagation per cycle, da/dN, is directly related to cyclic stress intensity, ΔK, in the following form:

$$\frac{da}{dN} = C(\Delta K)^m \qquad [7]$$

where

C crack growth coefficient

m crack growth exponent

Crack propagation data for both U. S. Steel's Man-Ten and Bethlehem's RQC-100 are listed in Table I. In the simplest form, crack propagation lives are obtained by substituting an effective stress intensity and integrating Eq. [7] with the following result:

$$N_p = \int_{a_o}^{a_f} \frac{da}{C(\Delta K)^m} \qquad [8]$$

where

a_o	initial crack size
a_f	final crack size
N_p	crack propagation life
ΔK	stress intensity range

Several models have been proposed for determining effective stress intensities that account for load ratio, sequence and crack closure effects.

Crack propagation life, taking the effect after a crack has been initiated, must be determined by analyzing the crack-tip behavior over the total part length. One assumption used is that the crack will move only when the crack opens; however, the external load required to open the crack tip is not equal to zero, but can be either tensile or compressive depending on the load history and specimen geometry. For this reason a modification to the crack growth in Eq. 7 to include an effective stress intensity range, ΔK_{eff}, is introduced. Fatigue cracks can grow only during that portion of the load cycle where the crack tip is open.

$$\frac{da}{dN} = C_o(\Delta K_{eff})^m \qquad [9]$$

The effective stress intensity is defined as follows:

$$\Delta K_{eff} = K_{max} - K_{min} \qquad \text{if } K_{min} > K_{open}$$

$$= K_{max} - K_{open} \qquad \text{if } K_{min} < K_{open}$$

where K_{open} is the applied stress intensity required to open the crack.

For constant amplitude zero to maximum loading, the following empirical relationship is applicable:

$$K_{open} \simeq 0.3\ K_{max} \qquad [10]$$

This has been verified both experimentally and with finite element analysis.

Crack opening loads obtained from the computer simulations are summarized in Table II for the various combinations of load and history used in the SAE Test Program. These crack opening loads represent stabilized values attained after several constant amplitude reversals. The constant amplitude cycles consisted of the maximum and minimum in each history. This maximum range sets up the overall residual stress fields that cause crack closure. The crack length for all of crack opening determinations was 0.15 in. from the notch root. This results in a total crack length of 1.35 in.

The crack closure load was assumed constant in the notch plastic zone and to exponentially decay to 0.3 P_{max} at the specimen edge. Plastic zone sizes are listed in Table III.

Since fatigue cracks propagate only when the crack tip is open, the knowledge of the crack opening load is essential for the prediction of fatigue crack growth rates in notched members that are loaded in the plastic range.

The complex problem of estimating fatigue crack growth rates under irregular load histories reduces to one of determining the appropriate effective stress intensity for each load cycle in the history.

Irregular loading histories must be reduced into equivalent constant amplitude cycles in order to use crack propagation models, since they were determined from constant amplitude tests. Therefore, a rational cycle counting scheme must be employed.

A rainflow counting scheme was used to count that portion of the load history that is above the crack opening load. In this counting scheme, small load excursions are treated as interruptions of larger overall events.

The growth rate per block, $\Delta a/\Delta B$, is calculated by considering the crack length as being fixed at the initial crack size and summing the incremental crack extension for each cycle.

$$\frac{\Delta a}{\Delta B} = \sum_{1}^{N} a \qquad [11]$$

Simpson's rule was used to numerically integrate this curve in order to obtain the desired crack length as a function of loading blocks, N_B.

$$N_B = \int_{a_o}^{a} \frac{\Delta B}{\Delta a}\, da \qquad [12]$$

Figure 4 shows the logic used to calculate total fatigue lives. Details of the procedures for estimating initiation and propagation lives are found in Ref. (5).

IV. EDITING TECHNIQUE

A. Basic Editing Procedure

For the initial editing of histories, the initiation analysis previously defined was used as a guide. This was accomplished, not only by the use of this analysis in omitting peak points but, by checking the final edited history for initiation life.

Peak points were omitted using a computer algorithm which would omit any points which would add hysteresis loop less than a specified value. The limiting value, designated as a threshold value, could be changed to make the final edited history as large as the original history or as small as two points. The algorithm compared each successive range to the previous range which had fit the specified conditions. If the new range had a change larger than the threshold, the new range would be kept, and then become the comparison range. If, on the other hand, the new range did not produce a change greater than the specified threshold value, the range would merely be omitted. In this manner, a history could be edited and still keep the original sequence of events.

Once an edited history was established, it was checked using an initiation analysis to compare the original initiation data with the initiation data of the new edited history. Material parameters for the initiation analysis were for Man-Ten steel. The load histories were scaled to 3500 lb. (15.6 kN) maximum load. A maximum increase in the initiation life of approximately 20% was used as a criteria for the extent of editing. This editing limit reduced the histories 90% for the bracket history, 92% for the transmission history, and 97% for the suspension history. Table IV gives the initial and final history sizes and their percent reduction in size.

The final three edited histories were used for both materials at all loads. This was done merely to keep the number of edited histories to a more manageable number. It also enabled a comparison of initiation life change with material and load.

Figure 5 shows the effect of editing level calculated initiation life. The solid curve is the cumulative damage percent up to a given strain range. The dashed line represents cumulative peak percent up to a given strain range. The steps in the curves are due to the algorithm which breaks strains down into fifty finite categories. Increasing the number of strain ranges would tend to smooth out the curve.

The two examples in the figure show how to read the curves. Points A and A' show that 92% of the cycles account for 3% of the fatigue initiation damage of a block. Points B and B' show how the editing of the transmission actually occurred. Since a 20% increase in life was proposed, Eq. 13 could be used to find the percent of cumulative damage.

$$\frac{100 + \%\ \text{increase}}{100\%} = \frac{100\%}{\text{cumulative damage }\%} \qquad [13]$$

or $\qquad X\% = 83.3\%$ cumulative damage

Therefore, only 16.7% of the cumulative damage can be removed (100%-83.3%). Using Fig. 5, 16.7% of the cumulative damage is shown at B'. Projecting this point up shows that this corresponds to approximately a 94% reduction in size the original history.

Figures 6, 7 and 8 give a pictorial representation of the full and edited transmission, bracket, and suspension histories.

B. Materials Effect on Editing

During the editing procedure material properties and scaling factors for maximum load were needed for the initiation analysis. Immediate questions arose as to effect of material properties and maximum load level on editing level. Also, since some of the full history tests showed shorter fatigue lives than the estimated lives, the possibility of changing the material properties to overstrained properties was investigated.

In order to establish a basis for comparison of different materials, the total cumulative damage and total cumulative cycles were compared for Man-Ten and RQC-100. The results did show that the material had an effect on the editing outcome; however, the general shape of the curves remained unchanged as shown in Fig. 9. Changing properties from Man-Ten to RQC-100 moved the percent damage curves to the right for every test condition indicating that the smaller cycles are less damaging in the stronger material. The actual amount of shift in the curve depended on the history and load level used. In most cases the shift was less than 15% along the percent load axis, which had little or no effect in the region where the final editing level took place. For this reason the editing of each history for each material was not done. Man-Ten material properties were used to edit the histories for both Man-Ten and RQC-100 tests. The results show that the single edited history is sufficient for both material tests.

C. Load Effect on Editing

To compare the effect of the load level on the editing process, a similar procedure was followed. The results were very similar to those dealing with a change in material. The cumulative damage curve kept its general shape with increasing load levels but was shifted slightly to the left indicating that the smaller cycles do more damage at higher loads. However, the shift still had only a slight effect on the editing level. This shift produced a change in the editing level on the order of about 15% for most test conditions. All test conditions were evaluated with varying load levels. A typical curve is shown in Fig. 10. The top solid line represents the cumulative percent cycles in both loads. The lower solid line is the cumulative percent damage with a maximum load of 3500 lb. (15.6 kN). The slightly shifted dashed line represents the corresponding cumulative percent damage with an 8000 lb. maximum load (35.5 kN).

Since the effect of material properties and load level had relatively small effect on the editing level, it was decided that only one load level would be used to initially decide upon edited histories. This results in a single edited history for all tests.

D. Effect of Overstrain Data Properties for Analysis

Finally, a change in material properties to Man-Ten and RQC-100 with overstrain was checked. Recent studies changed material properties to explain experimental fatigue lives on low-load tests being over an order of magnitude short of theoretical fatigue life values. Overstrain data makes lower loads more significant with respect to fatigue damage. An initiation analysis was performed for all conditions using both regular material properties and overstrain material properties. The results shown in Fig. 11 were typical for every test condition. In each case the cumulative damage with an overstrain curve was to the left of the other cumulative damage curve; however, the shift was more pronounced in the lower part of the curve. This was as expected, except that this change resulted in only about a 20% shift in the worst case. This shift reduced to zero at the top of the curve. A change of at least an order of magnitude on the damage caused by small cycles was needed to explain the difference between theoretical and experimental results.

Since changing the material properties to overstrain properties does not cause enough of a change in the analysis to explain the difference of over an order of magnitude between the theoretical and experimental results at low-load levels, overstrained material properties were not used for the initial editing of histories.

Man-Ten material properties at a low-load level were used for editing the load histories. The load level was 3500 lb. (15.6 kN) for the bracket and transmission histories, and 6000 lb. (26.7 kN) for the suspension history.

This is not to say that load level and material have an insignificant effect on the editing outcome for all histories and geometries, but merely that they should be checked to see exactly what effect they do have. For these three histories and two materials, the effect was very small at the loads tested. In fact, the change was small enough to use only three edited histories for all tests.

V. TEST RESULTS

The edited tests were conducted using an MTS test system which consisted of a small computer with feedback equipment, sending signals to operate a hydraulic ram. Crack length measurements were taken manually using an optical scale. Crack length readings were taken on one side of the test members only. Crack initiation, N_i, was defined as a crack 0.1 in. to be consistent with the original test program.

Tabulated results of the testing program using edited histories is listed in Table V. Propagation and total life results are also listed with the crack initiation data. As a check of the editing technique, the edited history data should be compared not only against theoretical fatigue models, but also against the original full history data. To do this, Table VI, VII, and VIII show theoretical full history data and edited history data, respectively. All three tables have been setup using the original SAE test specimen identifications. Propagation and total life also has been included. For data with identical test conditions, the results tabulated Tables VII and VIII are an average of the test results for the specified test condition.

For comparison purposes, the SAE edited history data will be compared against the predicted results as well as against the full SAE test results. As an indication of the correlation between fatigue lives, a factor difference will be used. This will be defined as:

$$\text{Factor Difference} = \begin{cases} \dfrac{\text{Test Results}}{\text{Predicted Results}}; & \text{Test Results} \geq \text{Predicted Results} \\[2ex] \dfrac{\text{Predicted Results}}{\text{Test Results}}; & \text{Test Results} \leq \text{Predicted Results} \end{cases}$$

This, of course, means that if the predicted results and the edited test results were identical, the correlation would result in a factor difference of 1.

If the edited history test results are compared with the full history results, the full history results take the place of predicted results in the equation.

This gives a meaningful indication of the comparison of fatigue lives, instead of merely a plus or minus difference as tested. Also, since the scatter in the data is large, and the fact that the edited history data points were not consistently above or below the predicted lives, a sign convention of plus or minus would seem to have no physical significance.

As can be seen, there is a definite correlation between the edited spectrum test results and both theoretical and full test data. Keeping in mind the statistical nature of the tests and the relatively small number of specimens for any specific test condition, the tests show the use of the editing technique as a valuable tool for editing fatigue histories. Since only initiation life was used to edit the three histories, it seems suitable to compare initiation life first.

Initiation life for the edited history tests had the best correlation to theoretical and full history SAE tests. Comparison with theoretical values show eight of the eleven initiation lives were longer than theoretically predicted with three lives less than predicted. All tests included show that the tests varied by a factor of 3.37 from predicted results. However, test BR3 varied by a factor of almost 20, which tends to give a false indication to the other tests. If this data point is omitted, the data varies from the predicted values by a factor of only 1.8 with the maximum deviation of 2.8. To compare this to full history data gives an even better indication to the value of the editing method. Taking all data points into account shows only an average difference from previous tests to be off by a factor of 1.8. This in itself does not appear to be especially outstanding except that the maximum error varied from previous full history tests by a factor of only 3.2 and that test BR3, which was theoretically off by a factor of almost 20, varied from full history data by a factor of only 1.5. Also, of the eleven edited history test conditions, six had initiation lives longer than previous full history tests with five test conditions having shorter edited than full history lives.

Propagation results, even though the histories were not edited as such, also had very good correlation to full history tests. In the worst case, the edited history propagation lives were a factor of seven longer than full history propagation lives, but the average deviation differed by a factor of only 2.8. Comparing this to the theoretical results, the maximum difference was off by less than a factor of 3.5 with the average of 2.3. Five of the eleven tests were below the predicted theoretical propagation lives with six of the tests having longer propagation lives than predicted.

Since both initiation and propagation lives of the tests correlated so well with both theoretical and full history test data, the total fatigue life also must correspond. Comparison of edited history test data with theoretical predictions shows similar results to initiation data. If test BR3 is omitted, the tests are off by an average factor of only 1.5 with five above and five below the predicted total lives. Including the BR3 test point, which is off by a factor of 12 from the predicted total life, makes the edited tests off by an average factor of less than 2.7. Compared to the full history test results, the edited history total life change by an average factor of 2.3.

Figures 12 through 20 show the correlation of full test data, predicted lives, and edited test data. Figures 12 through 14 show suspension, bracket, and transmission initiation lives, respectively. The maximum load is plotted against the log of initiation life in blocks. Figures 15 through 17 show load versus log of the propagation life in blocks for suspension, bracket, and transmission histories, respectively. The analysis predicts the longer crack propagation lives that were observed. Finally, Figs. 18 through 20 show the maximum load versus the log of total fatigue life for suspension, bracket, and transmission histories, respectively. A legend is included on each graph for explanation of the symbols used.

VI. CONCLUSIONS

1. Strain-cycle fatigue concepts may be employed to edit nondamaging events from field load histories for component fatigue testing.
2. Crack propagation concepts may be employed to predict the effect of spectrum editing on fatigue crack propagation lives.
3. Spectra edited to have equal crack initiation lives do not have equal crack propagation lives. Therefore, it is essential to determine the dominant failure mode before editing load histories.

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TABLE I MECHANICAL PROPERTIES OF MAN-TEN AND RQC-100

	Man-Ten		RQC-100	
Monotonic Properties				
Elastic Modulus, E	206 GPa	(30 x 10^3 ksi)	206 GPa	(30 x 10^3 ksi)
Yield Strength, S_y	324 MPa	(47 ksi)	827 MPa	(120 ksi)
Tensile Strength, UTS	565 MPa	(82 ksi)	863 MPa	(125 ksi)
Reduction in Area, %RA		65%		55%
True Fracture Strength, σ_f	1000 MPa	(145 ksi)	1190 MPa	(173 ksi)
True Fracture Ductility, ε_f		1.19		0.78
Strength Coefficient, K	965 MPa	(140 ksi)	1200 MPa	(174 ksi)
Strain Hardening Exponent, n		0.21		0.08
Cyclic Properties				
Fatigue Ductility Coefficient, ε_f'		0.26		1.06
Fatigue Ductility Exponent, c		-0.47		-0.75
Fatigue Strength Coefficient, σ_f'	917 MPa	(133 ksi)	1160 MPa	(168 ksi)
Fatigue Strength Exponent, b		-0.095		-0.075
Cyclic Strength Coefficient, K'	1200 MPa	(174 ksi)	1150 MPa	(167 ksi)
Cyclic Strain Hardening Exponent, n'		0.20		0.10
Cyclic Yield Strength, S_y'	331 MPa	(48 ksi)	586 MPa	(85 ksi)
Fracture Properties				
Crack Growth Coefficient, c	3.0 x 10^{-9} mm/cycle MPa^{-m}	(8.6 x 10^{-11}) in/cycle ksi^{-m}	5.2 x 10^{-9}	(1.5 x 10^{-10})
Crack Growth Exponent, m		3.43		3.25
Fracture Toughness, K_c (10 mm Thickness)	121 MPa$\sqrt{in}$	(110 ksi$\sqrt{in}$)	154 MPa$\sqrt{in}$	(140 ksi$\sqrt{in}$)

TABLE II

PREDICTED CRACK OPENING LOADS

LOAD RANGES				CRACK OPENING LOADS			
Minimum		Maximum		RQC-100		Man-Ten	
lb	K-Nt	lb	K-Nt	lb	K-Nt	lb	K-Nt
0	0	16,000	71.2	5,500	24.5		
0	0	8,000	35.6	2,500	11.1		
0	0	3,500	15.6	900	4.0		
SUSPENSION							
-16,000	-71.2	5,500	24.5	-4,500	-20.0	-8,000	-35.6
- 9,000	-40.0	3,100	13.8	600	2.7	-2,150	- 9.6
- 7,000	-31.1	2,400	10.7	900	4.0		
- 6,000	-26.7	2,060	9.2			- 440	- 2.0
- 4,500	-20.0	1,550	6.9				
BRACKET							
-16,000	-71.2	11,800	52.5	-1,700	- 7.6	-3,200	-14.2
- 8,000	-35.6	5,900	26.2	1,025	4.6	- 100	- 0.4
- 3,500	-15.6	2,580	11.5	790	3.5	665	3.0
TRANSMISSION							
- 7,900	-35.1	16,000	71.2	-1,500	- 6.7	-2,500	-11.1
- 3,950	-17.6	8,000	35.6	1,625	7.2	500	2.2
- 1,730	- 7.7	3,500	15.6			1,100	4.9

TABLE III

MONOTONIC PLASTIC ZONE SIZES

Test Designation	Size, in.	Size, cm
SR1	.41	1.04
SR2	.21	.53
SR3	.13	.33
SM1	1.51	3.84
SM2	.56	1.42
SM3	.34	.86
BR1	.41	1.04
BR2	.16	.41
BR3	.02	.05
BM1	1.51	3.84
BM2	.51	1.30
BM3	.13	.33
TR1	.41	1.04
TR2	.16	.41
TM1	1.51	3.84
TM2	.51	1.30
TM3	.13	.33

TABLE IV

PERCENT REDUCTION OF LOAD HISTORIES

History	No. of Peaks Originally	No. of Peaks Edited History	% Reduction
Bracket	5,936	610	89.7%
Suspension	2,506	68	97.2%
Transmission	1,708	130	92.3%

TABLE V

EDITED HISTORY TEST RESULTS

Test No.	Test Type	Maximum Load		Initiation	Propagation	Total Life
		lb	K-Nt			
1	SR2	9,000	40.0	1,698	24,371	26,069
2	SM2	9,000	40.0	566	3,007	3,573
3	TM2	8,000	35.6	282	119	401
4	TR2	8,000	35.6	503	351	854
5	TM3	3,500	15.6	18,356	1,914	20,270
6	SM3	6,000	26.7	3,734	41,488	45,222
7	SR3	7,000	31.1	9,328	50,812	60,140
8	TM3	3,500	15.6	11,226	1,570	12,796
9	TR3	3,500	15.6		Grips Bent	
10	BM3	3,500	15.6	3,556	1,811	5,367
11	BR3	3,500	15.6	2,027	1,957	3,984
12	BM3	3,500	15.6	1,645	1,241	2,886
13	BR3	3,500	15.6	2,722	1,607	4,329
14	BM2	8,000	35.6	43	53	96
15	BR2	8,000	35.6	76	287	354
16	BR3	3,500	15.6	2,799	2,615	5,414
17	BM3	3,500	15.6	2,647	1,621	4,268

TABLE VI

THEORETICAL TEST RESULTS

Specimen	Maximum Load		Initiation		Propagation		Total	
	(lb)	(K-Nt)	Full	Edited	Full	Edited	Full	Edited
SM1	16,000	71.2	34	51	5.4	13.7	39.4	64.7
SM2	9,000	40.0	506	635	310	1,155	816	1,790
SM3	6,000	26.7	3,988	4,424	9,984	30,041	13,792	34,465
SM4	4,500	20.0	20,750	21,837	--	--	--	--
SR1	16,000	71.2	42	54	88	307	130	361
SR2	9,000	40.0	689	704	12,657	37,799	13,346	38,503
SR3	7,000	31.1	4,564	4,605	75,942	213,772	80,506	218,377
SR4	6,000	26.7	22,920	23,091	--	--	--	--
BM1	16,000	71.2	1.2	2.0	.5	1.3	1.7	3.3
BM2	8,000	35.6	25	39	33	64	58	103
BM3	3,500	15.6	2,000	2,410	4,418	5893.2	6,418	8,303
BM4	3,000	13.3	5,524	6,366	--	--	--	--
BR1	16,000	71.2	1.3	2.6	2.6	5.6	3.9	8.2
BR2	8,000	35.6	30	36	166	248.4	196	284.4
BR3	3,500	15.6	47,750	48,250	5,402	7,046	53,152	55,296
TM1	16,000	71.2	10	11	1.5	2.1	11.5	13.1
TM2	8,000	35.6	200	221	34	61	234	282
TM3	3,500	15.6	13,410	13,594	1,295	3,923	14,705	17,517
TR1	16,000	71.2	12	14	3.0	5.4	15	19.4
TR2	8,000	35.6	200	202	58	164	258	366
TR3	3,500	15.6	276,290	276,328	--	--	--	--

TABLE VII

SAE TESTS USING FULL HISTORIES

Specimen	Maximum Load (lb)	Maximum Load (K-Nt)	Number Tested	Average Initiation	Average Propagation	Average Total Life
SM1	16,000	71.2	3	18	11	29
SM2	9,000	40.0	3	267	917	1,177
SM3	6,000	26.7	3	5,400	26,251	31,651
SM4	4,500	20.0	1	4,700	19,966	24,666
SR1	16,000	71.2	3	36.1	79.1	115.2
SR2	9,000	40.0	1	1,710	--	--
SR3	7,000	31.1	1	11,200	39,924	51,124
SR4	6,000	26.7	1	48,000	--	--
BM1	16,000	71.2	3	3	.7	3.7
BM2	8,000	35.6	3	18.4	13.3	31.7
BM3	3,500	15.6	3	789	2,085	2,874
BM4	3,000	13.3	1	2,666	1,410	4,076
BR1	16,000	71.2	3	4.2	2.2	6.4
BR2	8,000	35.6	3	82.5	86.2	168.7
BR3	3,500	15.6	2	3,846	6,250	1,010
TM1	16,000	71.2	3	11.2	1.7	12.9
TM2	8,000	35.6	3	216	56	262
TM3	3,500	15.6	3	4,608	1,611	6,219
TR1	16,000	71.2	3	25.2	3.3	28.5
TR2	8,000	35.6	3	368	50	418
TR3	3,500	15.6	0	--	--	--

TABLE VIII

EDITED HISTORY TESTS USING SAE DESIGNATIONS

Specimen	Maximum Load		Number Tested	Test Order	Initiation	Propagation	Full Life
	(lb)	(K-Nt)					
SM1	16,000	71.2					
SM2	9,000	40.0	1	2	566	3,007	3,573
SM3	6,000	26.7	1	6	3,734	41,488	45,222
SM4	4,500	20.0					
SR1	16,000	71.2					
SR2	9,000	40.0	1	1	1,698	24,371	26,069
SR3	7,000	31.1	1	7	9,328	50,812	60,140
SR4	6,000	26.7					
BM1	16,000	71.2					
BM2	8,000	35.6	1	14	43	53	96
BM3	3,500	15.6	3	10,12,17	2,619	1,558	4,177
BM4	3,000	13.3					
BR1	16,000	71.2					
BR2	8,000	35.6	1	15	76	278	354
BR3	3,500	15.6	3	11,13,16	2,516	2,060	4,576
TM1	16,000	71.2					
TM2	8,000	35.6	1	3	282	119	401
TM3	3,500	15.6	2	5,8	14,791	1,742	16,533
TR1	16,000	71.2					
TR2	8,000	35.6	1	4	503	351	854
TR3	3,500	15.6					

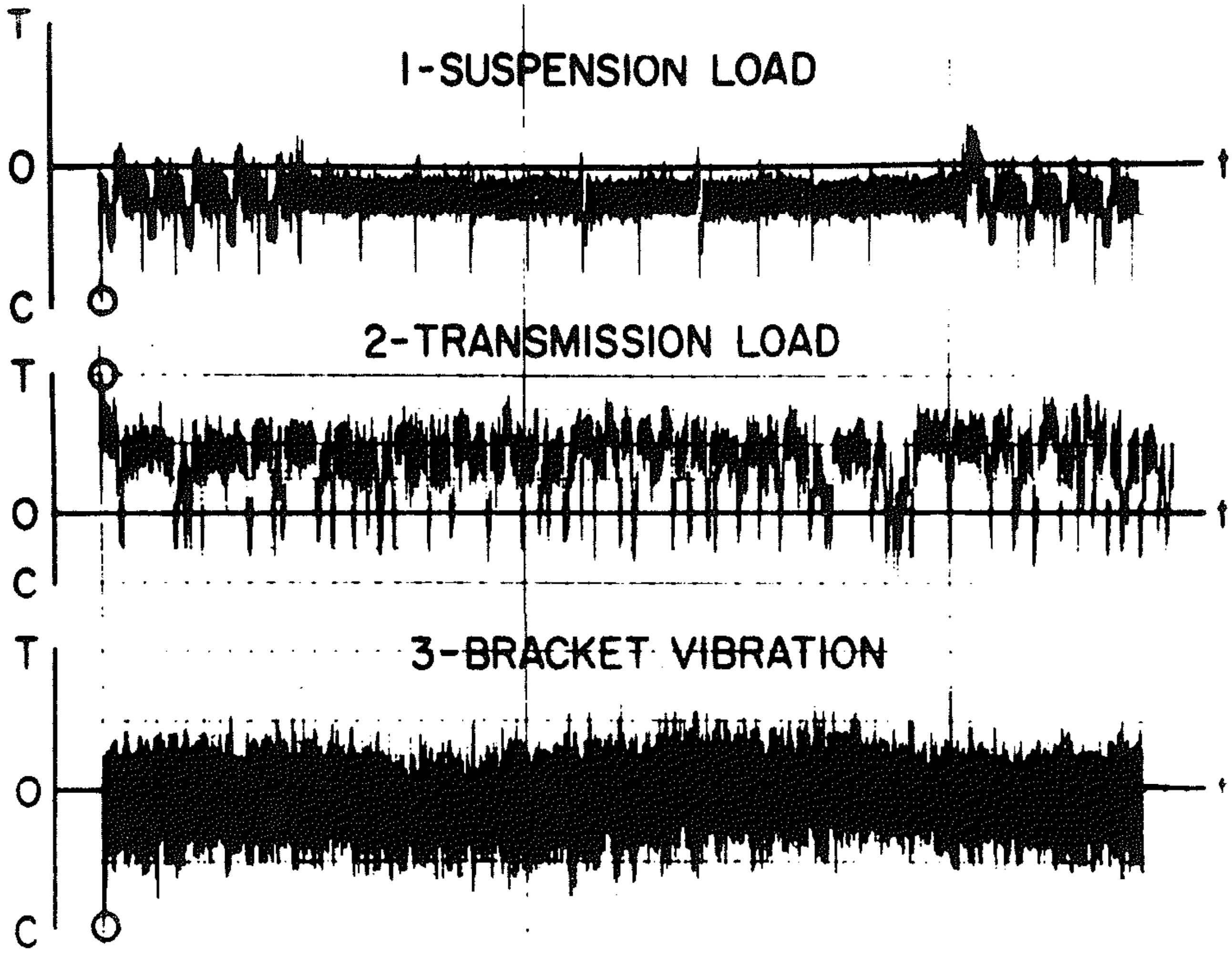

Fig. 1 Original SAE Load Histories

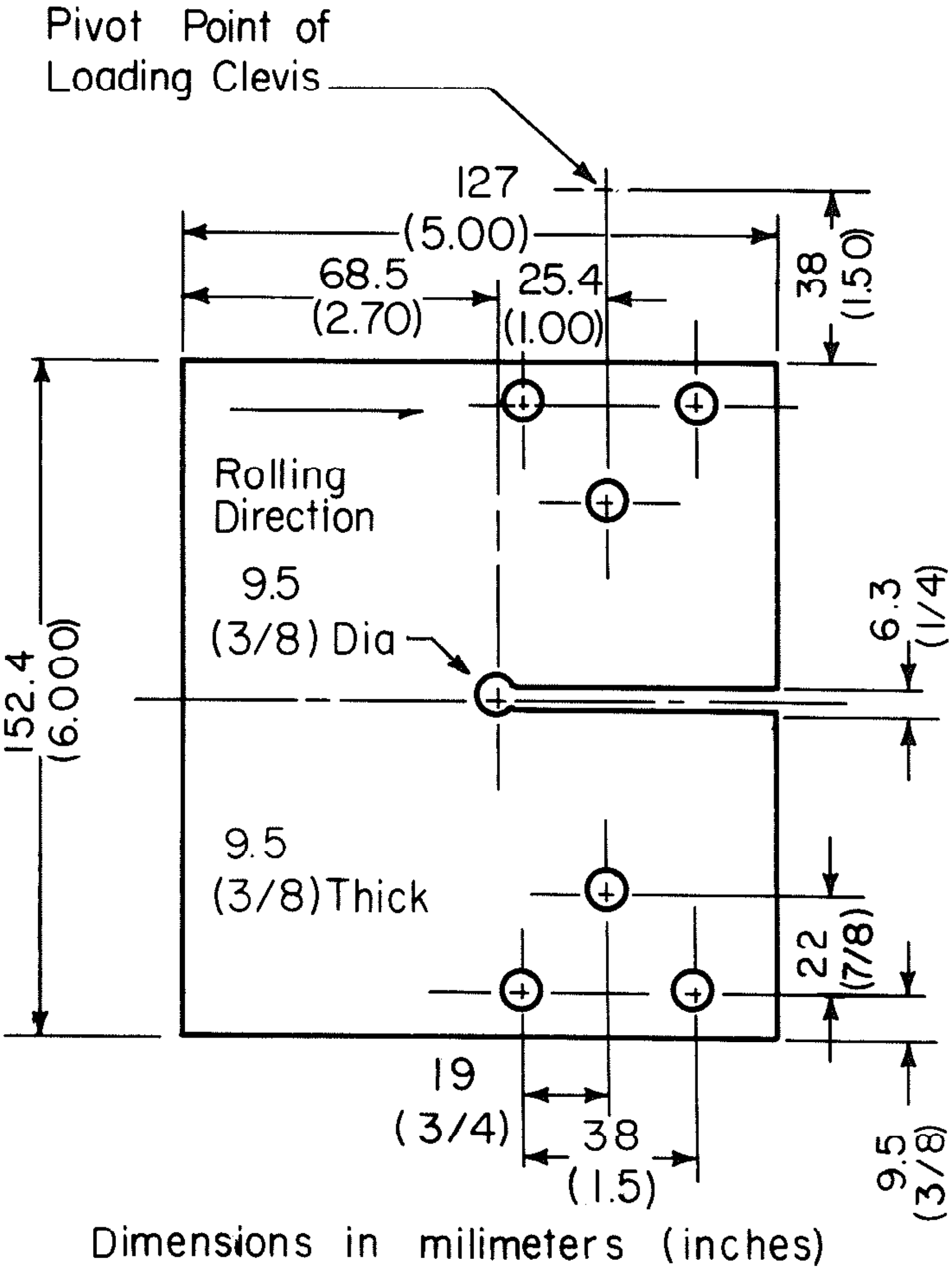

Fig. 2 SAE Keyhole Specimen

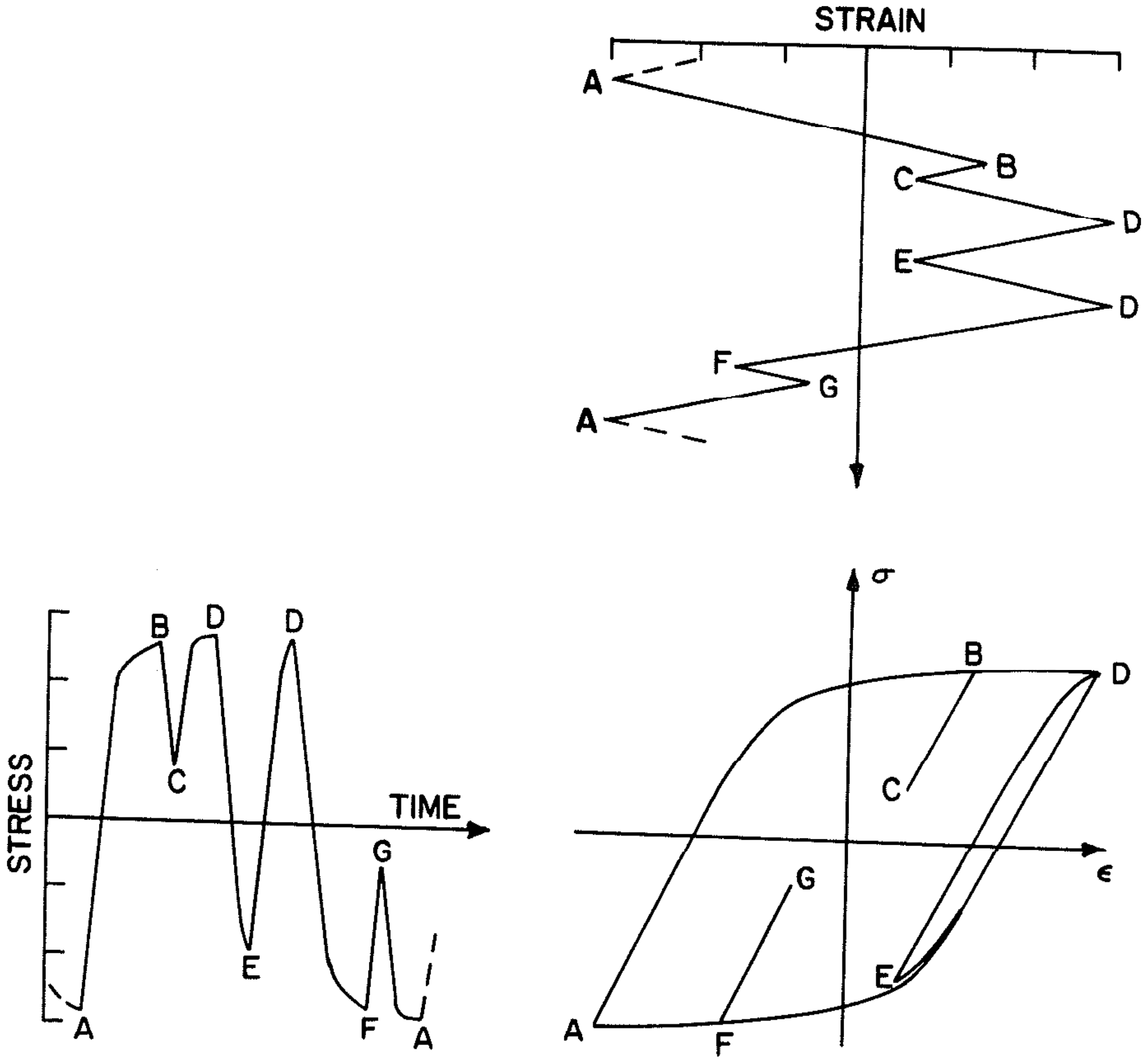

Fig. 3 Rainflow Counting Example

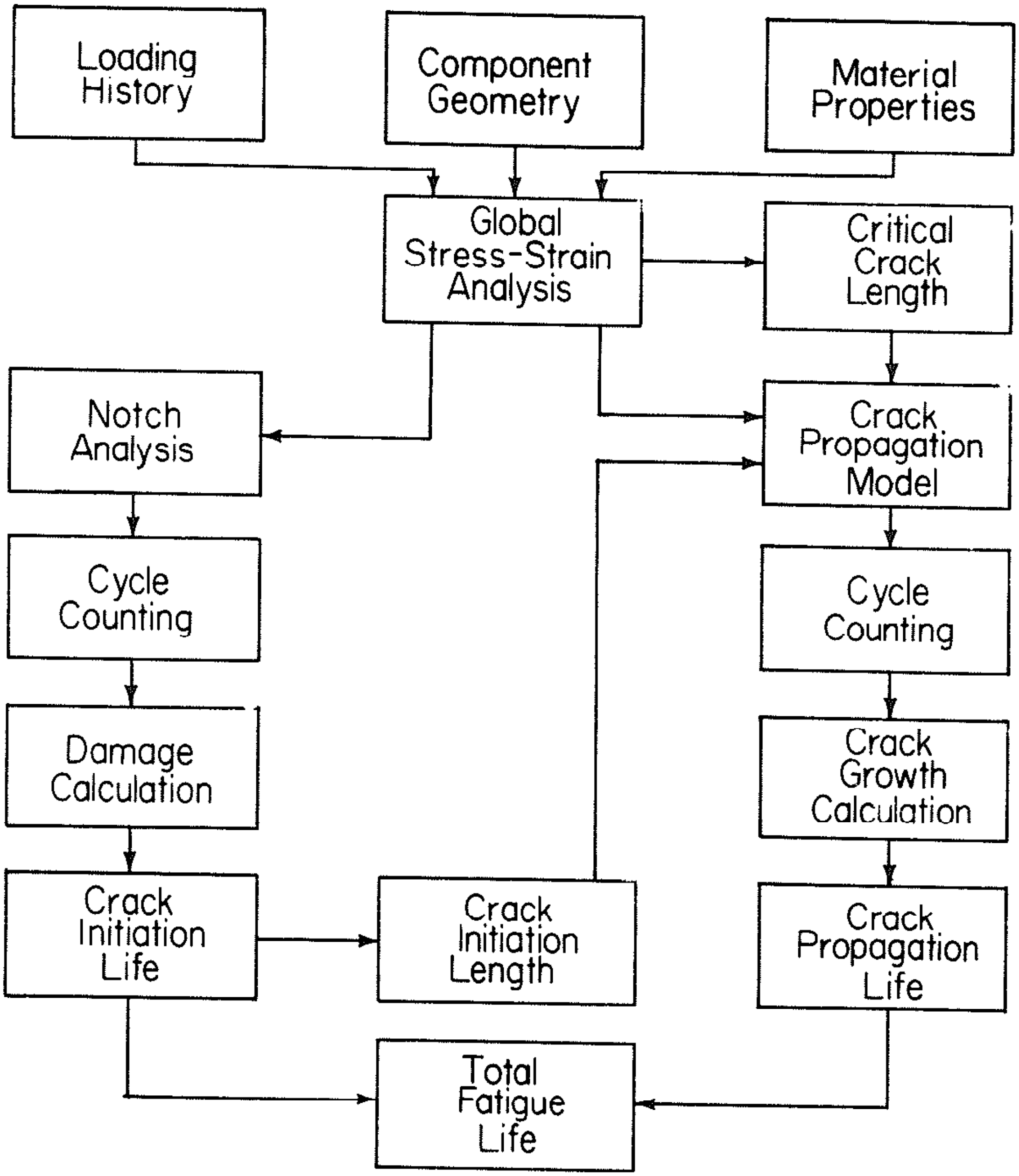

Fig. 4 Overall Fatigue Life Estimation Procedure

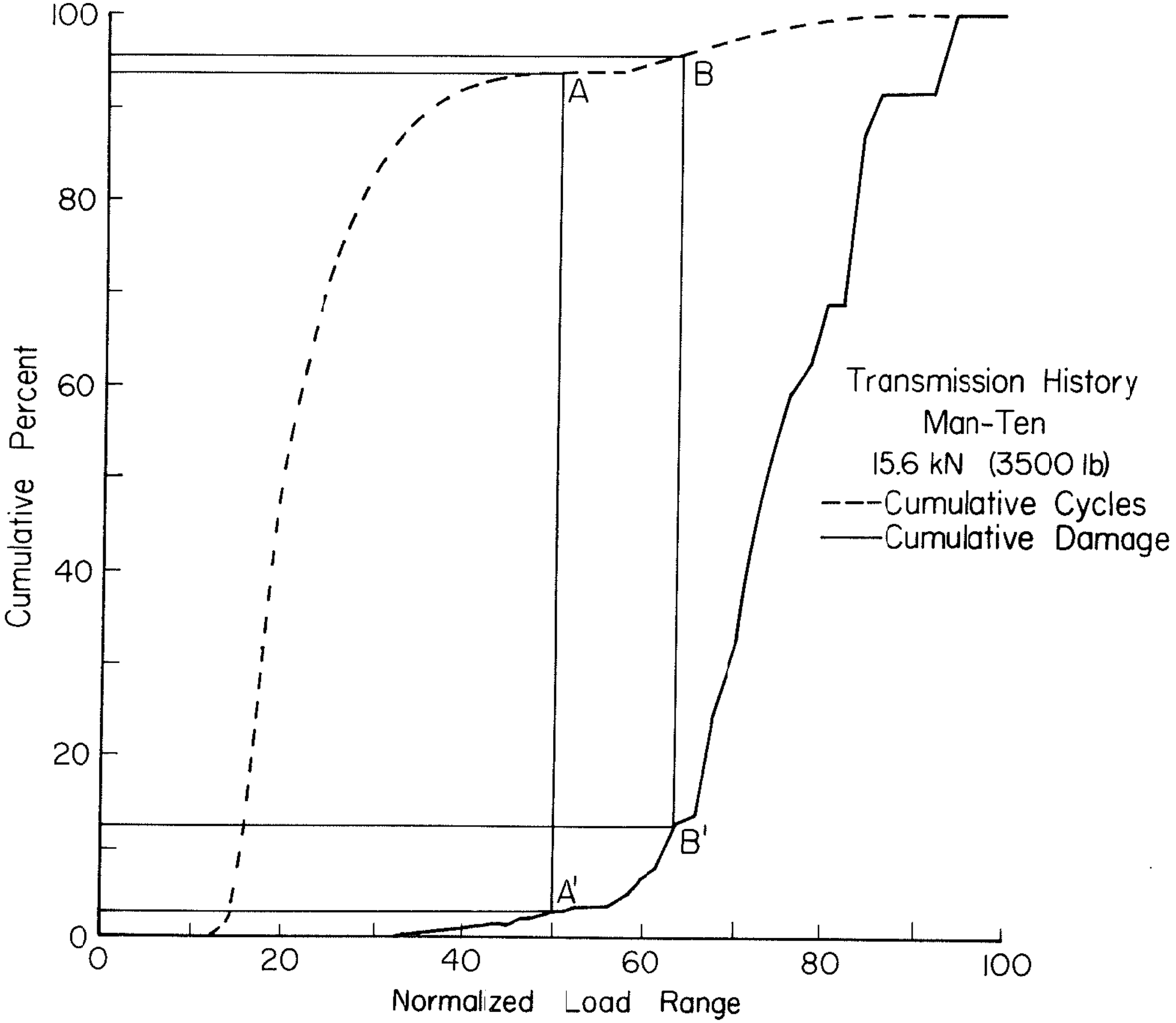

Fig. 5 Cumulative Distribution of Fatigue Damage and Cycles

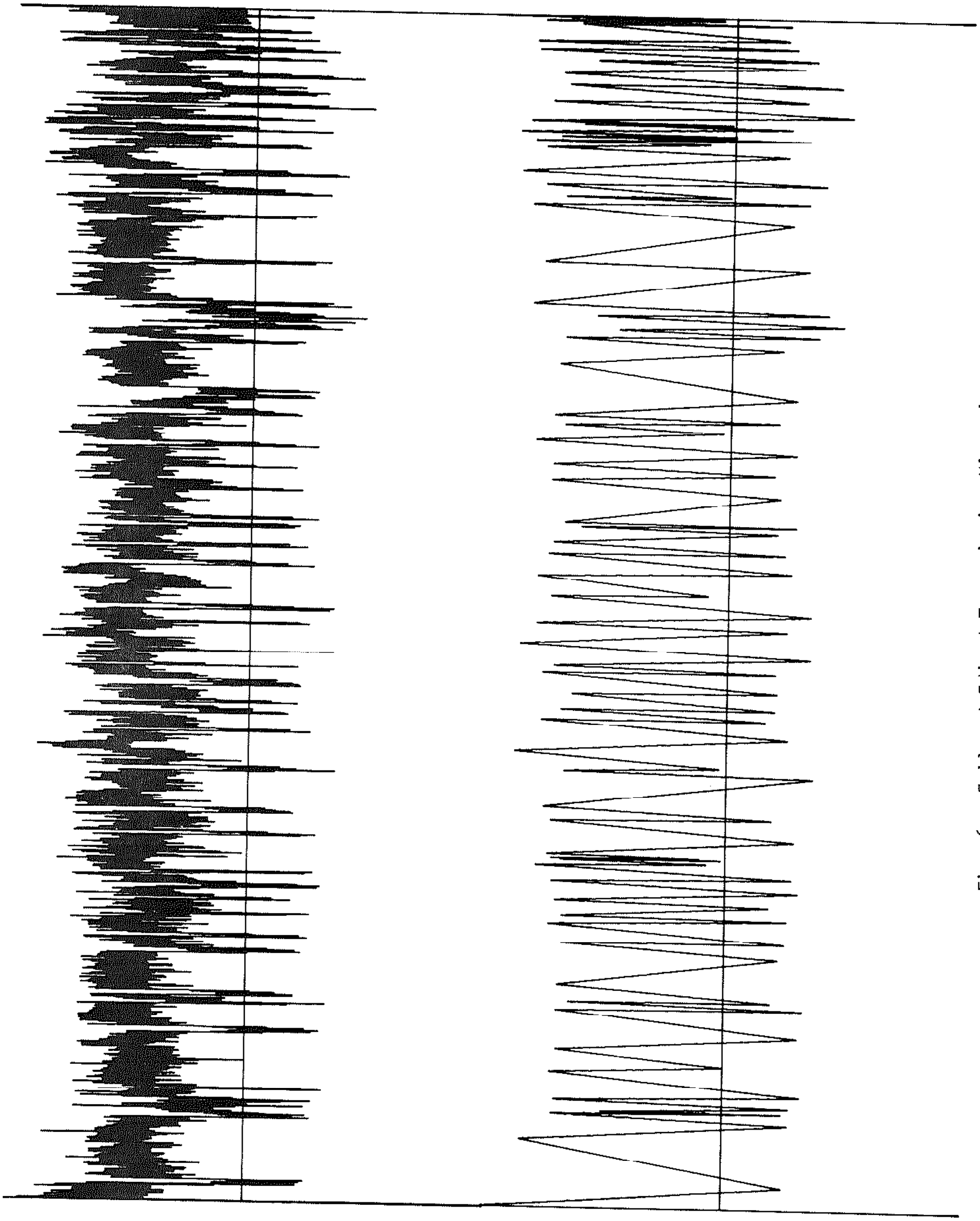

Fig. 6 Full and Edited Transmission Histories

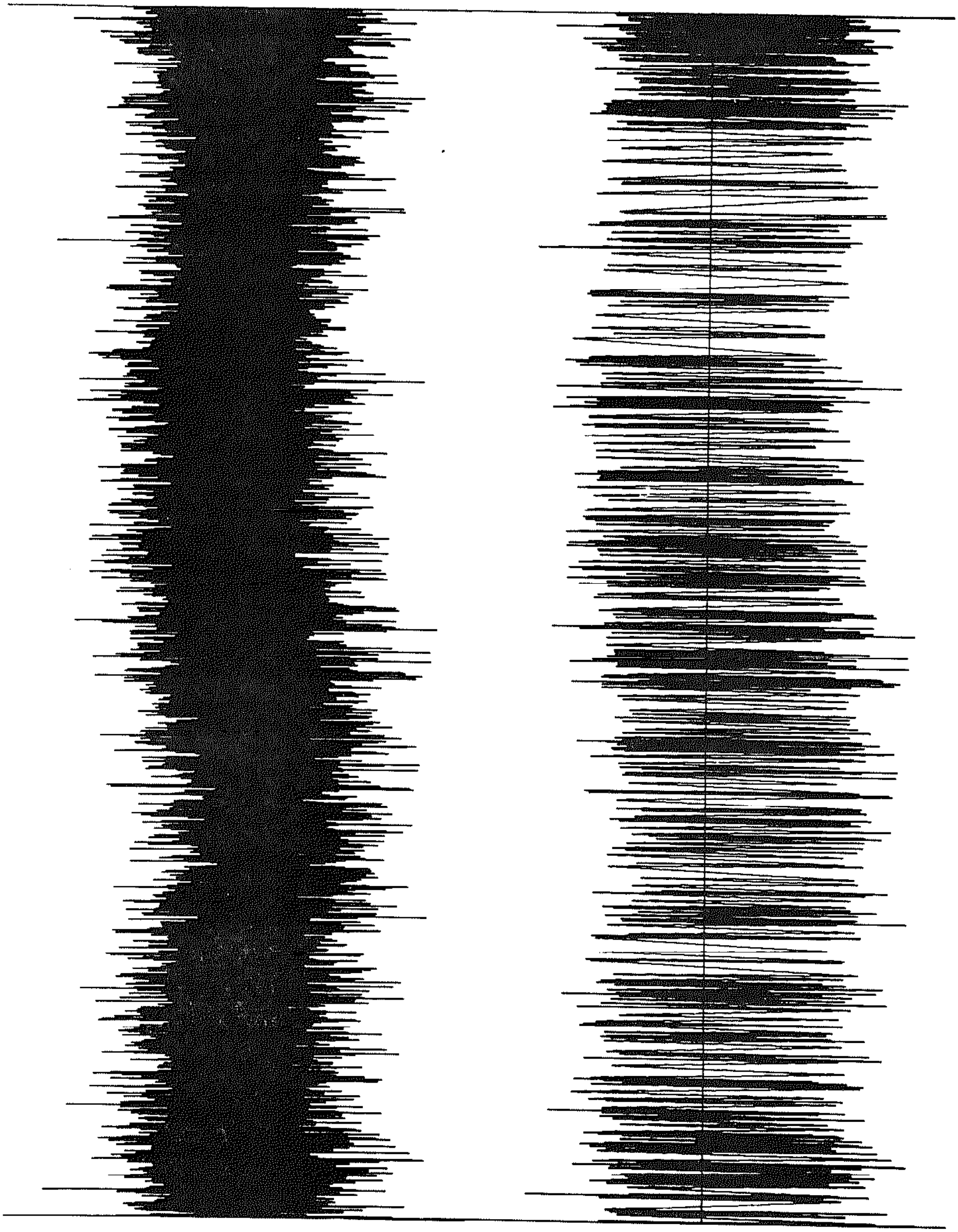

Fig. 7 Full and Edited Bracket Histories

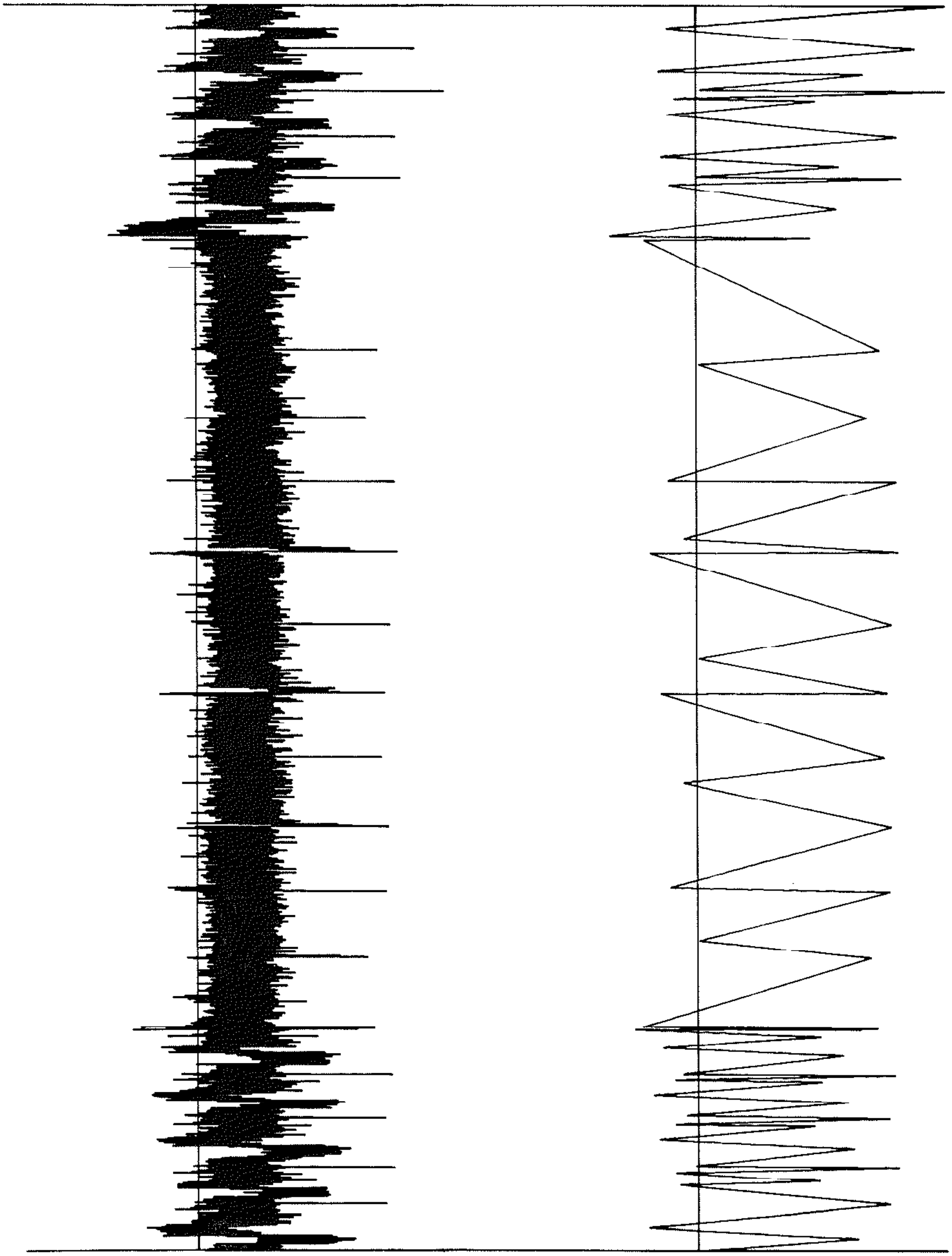

Fig. 8 Full and Edited Suspension Histories

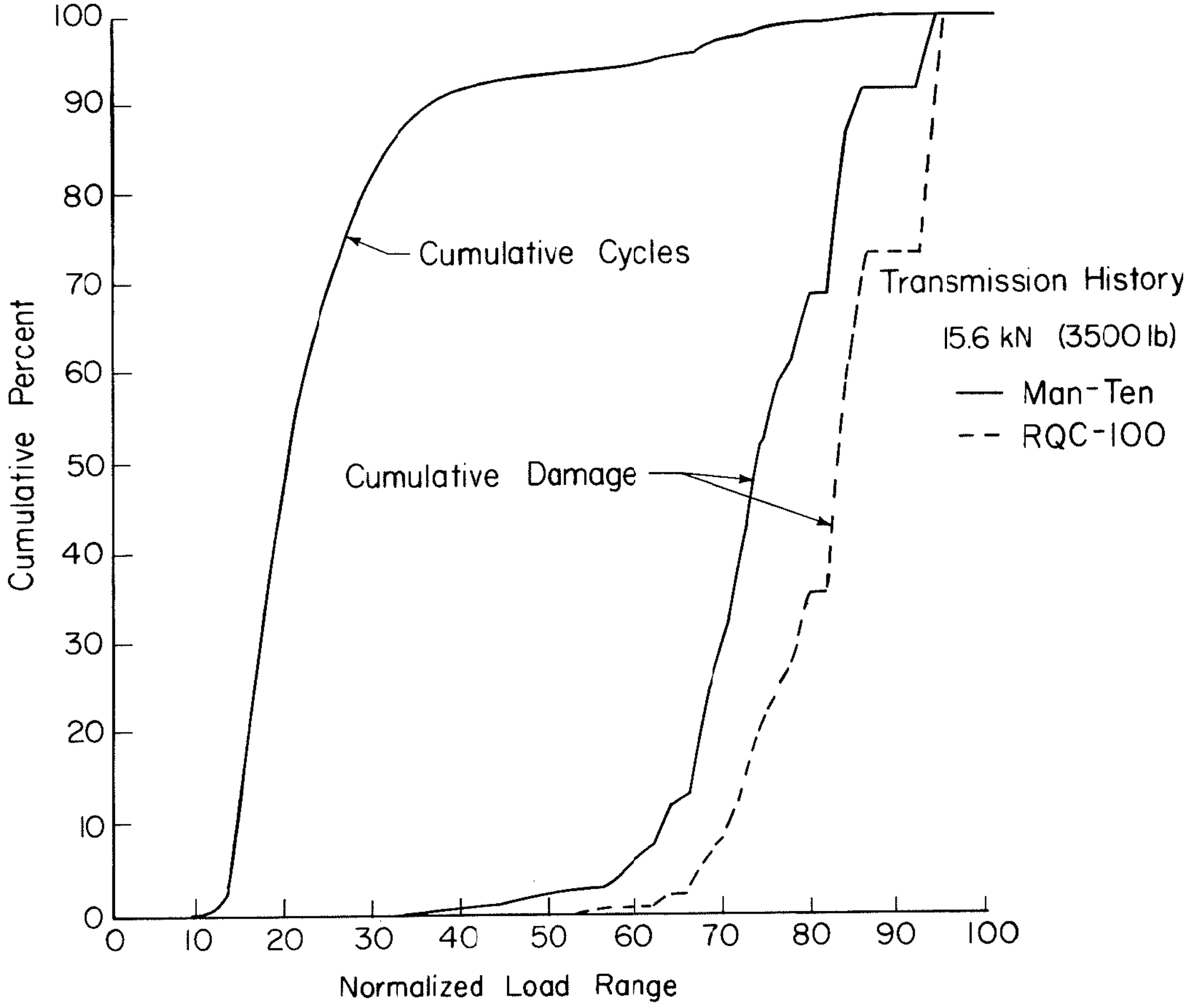

Fig. 9 Effect of Material Properties on the Cumulative Distribution of Fatigue Damage

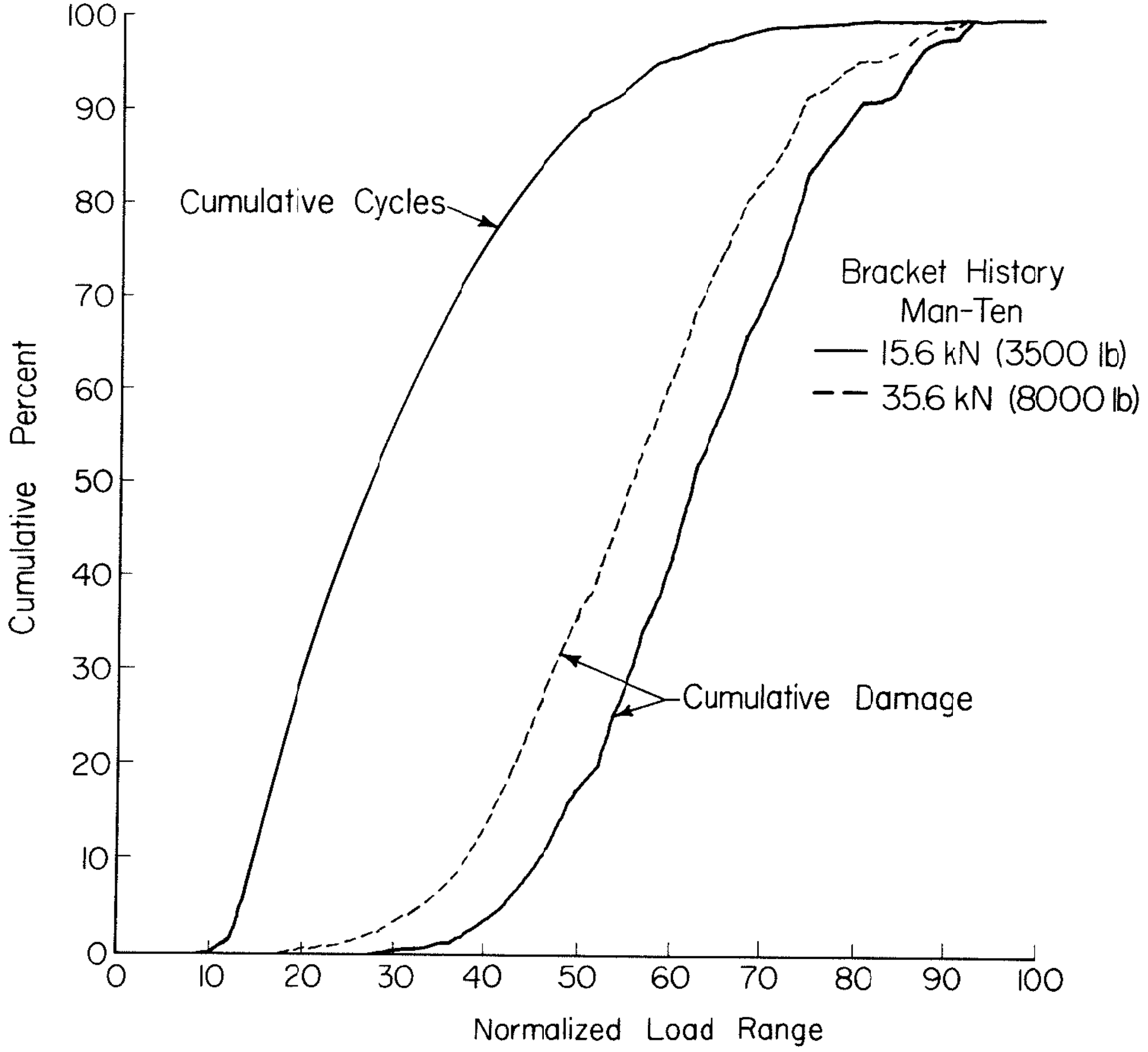

Fig. 10 Effect of Load Level on the Cumulative Distribution of Fatigue Damage

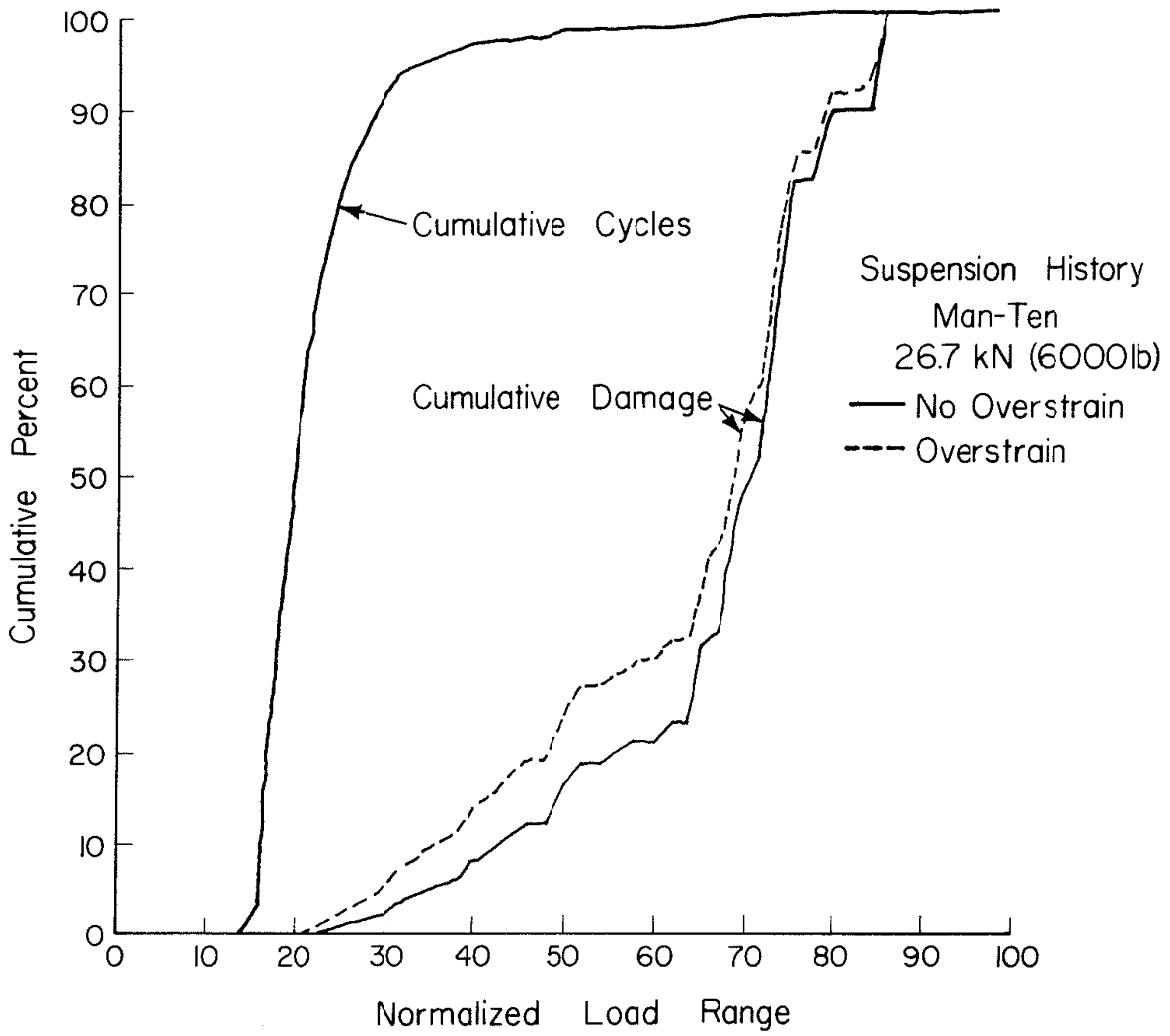

Fig. 11 Effect of Overstrained Material Properties on the Cumulative Distribution of Fatigue Damage

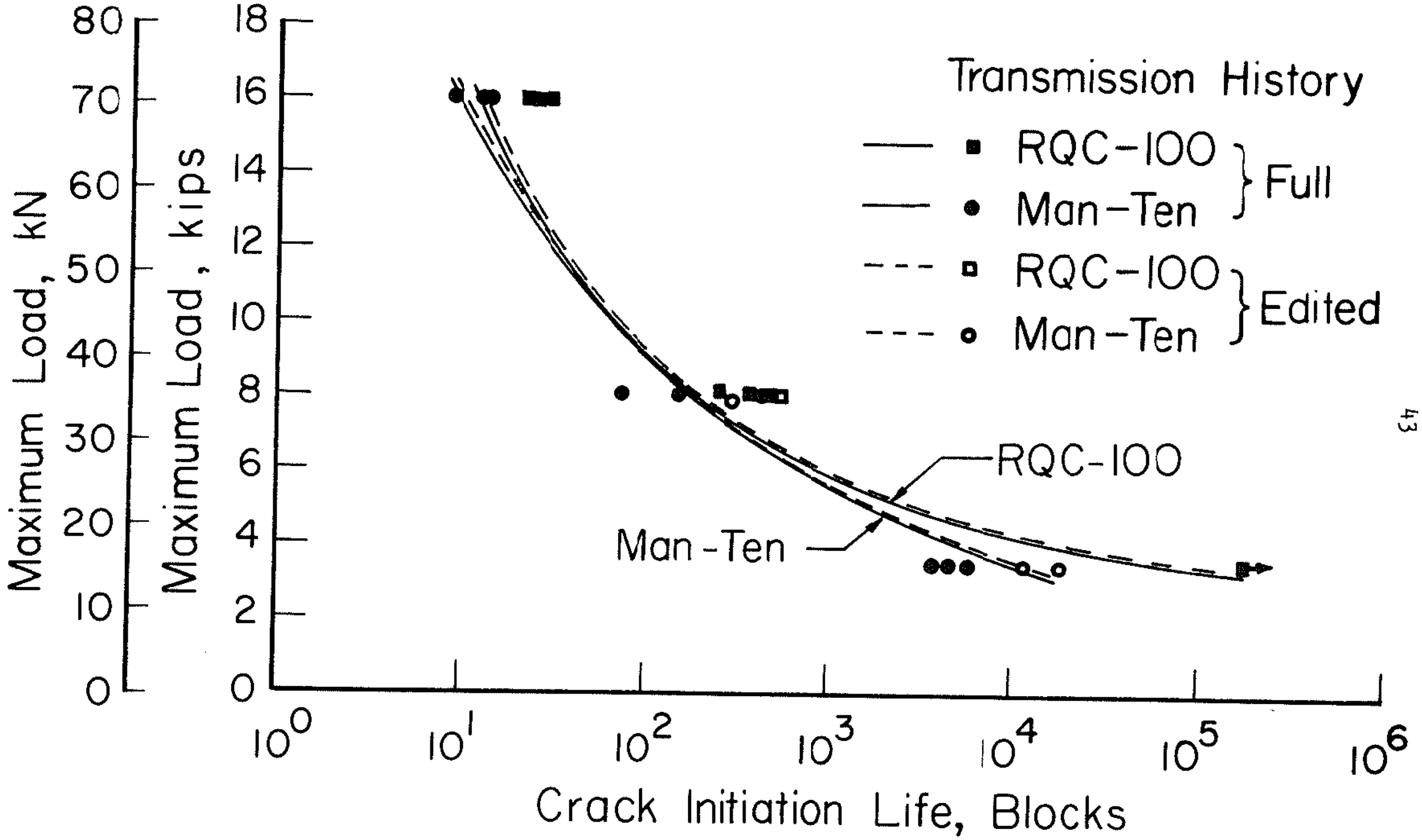

Fig. 12 Predicted and Actual Crack Initiation Lives for Full and Edited Transmission History Tests

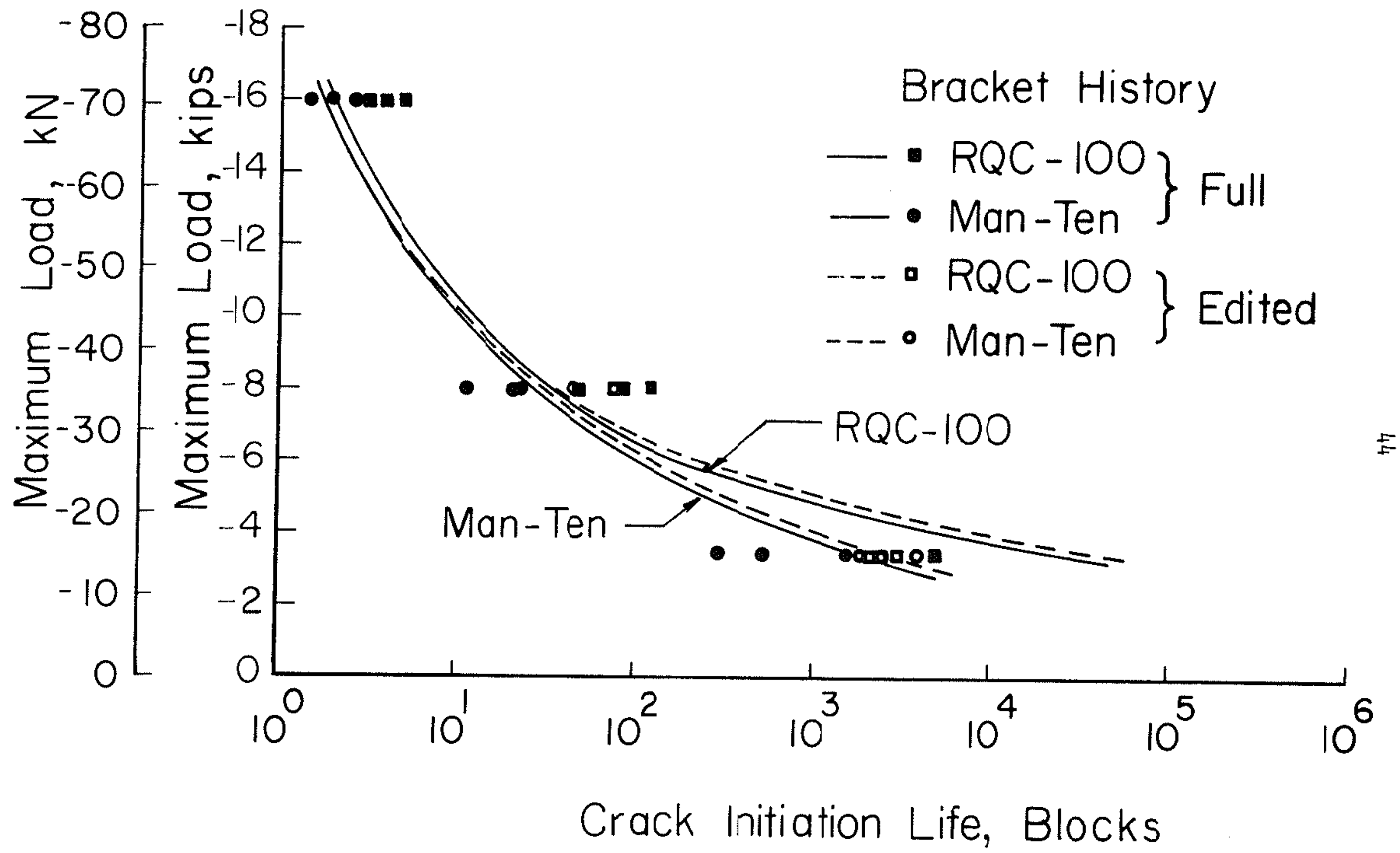

Fig. 13 Predicted and Actual Crack Initiation Lives for Full and Edited Bracket History Tests

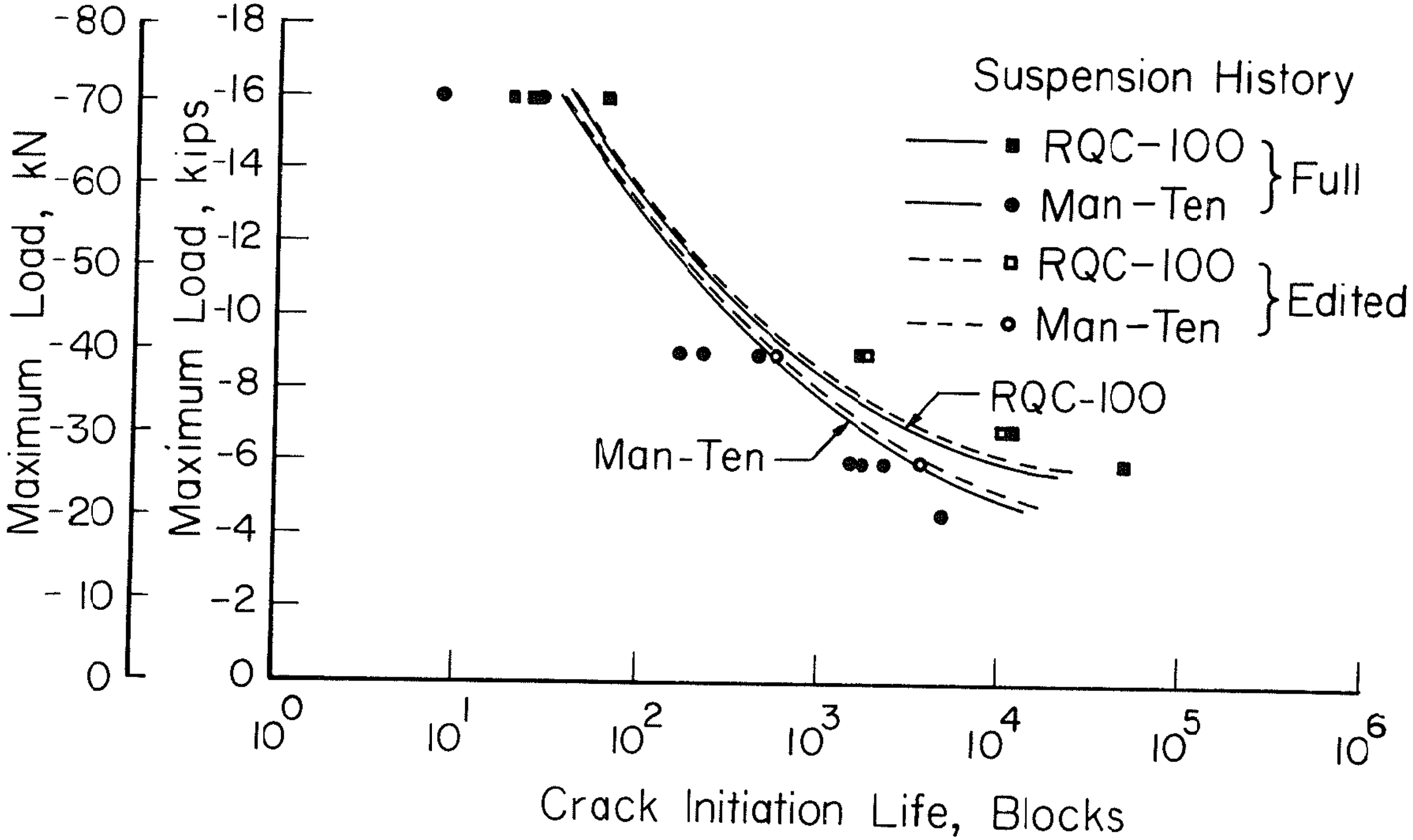

Fig. 14 Predicted and Actual Crack Initiation Lives for Full and Edited Suspension History Tests

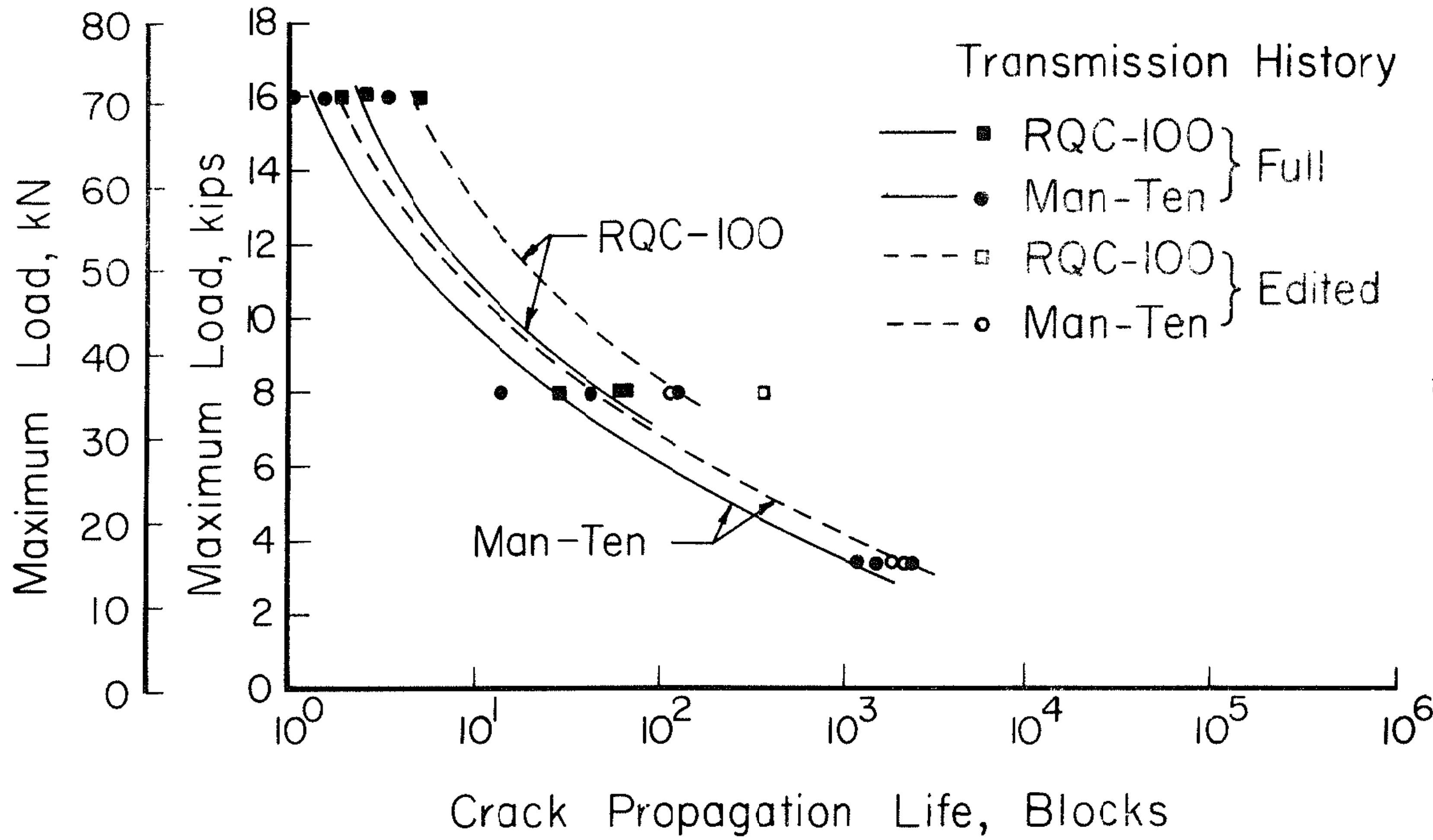

Fig. 15 Predicted and Actual Crack Propagation Lives for Full and Edited Transmission History Tests

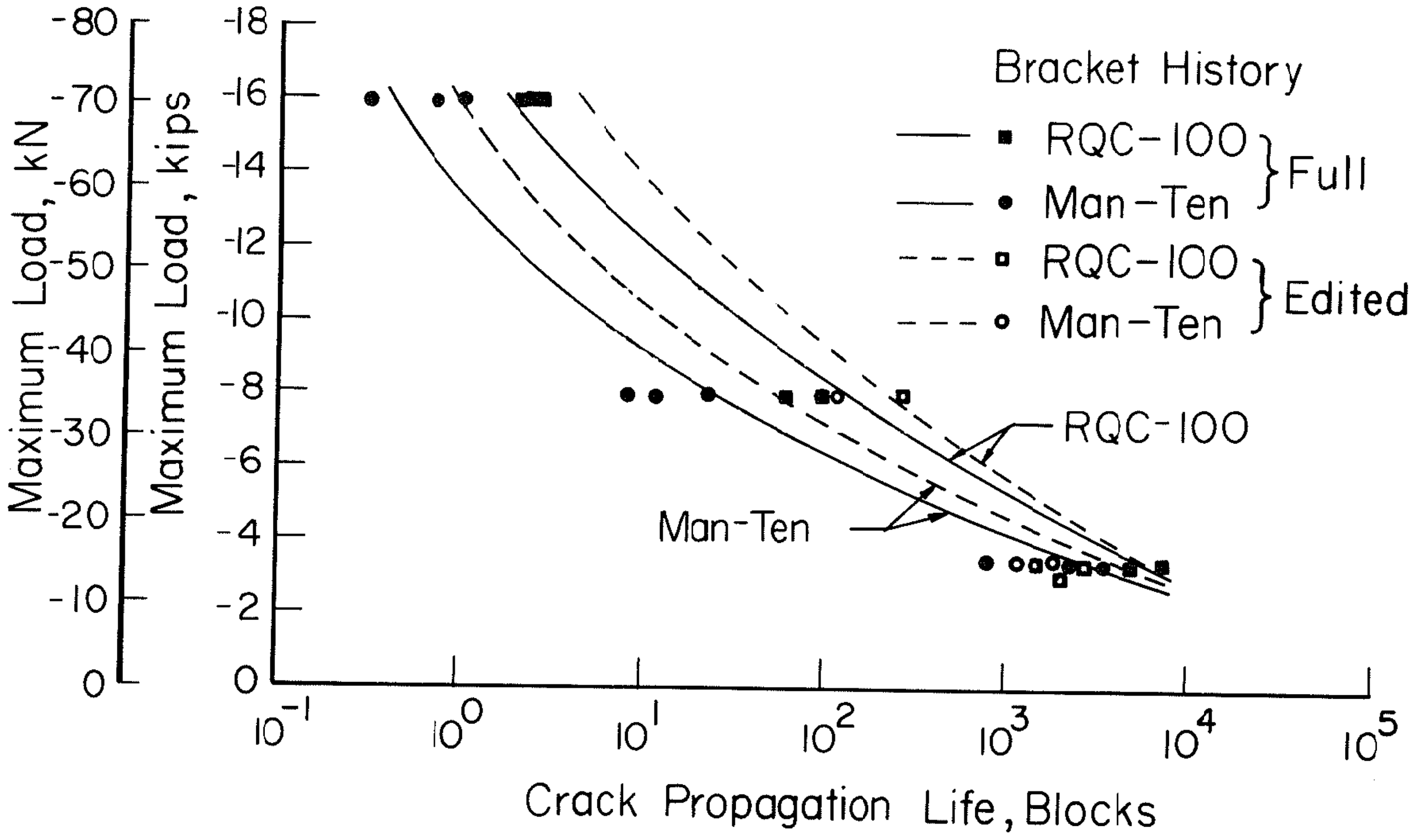

Fig. 16 Predicted and Actual Crack Propagation Lives for Full and Edited Bracket History Tests

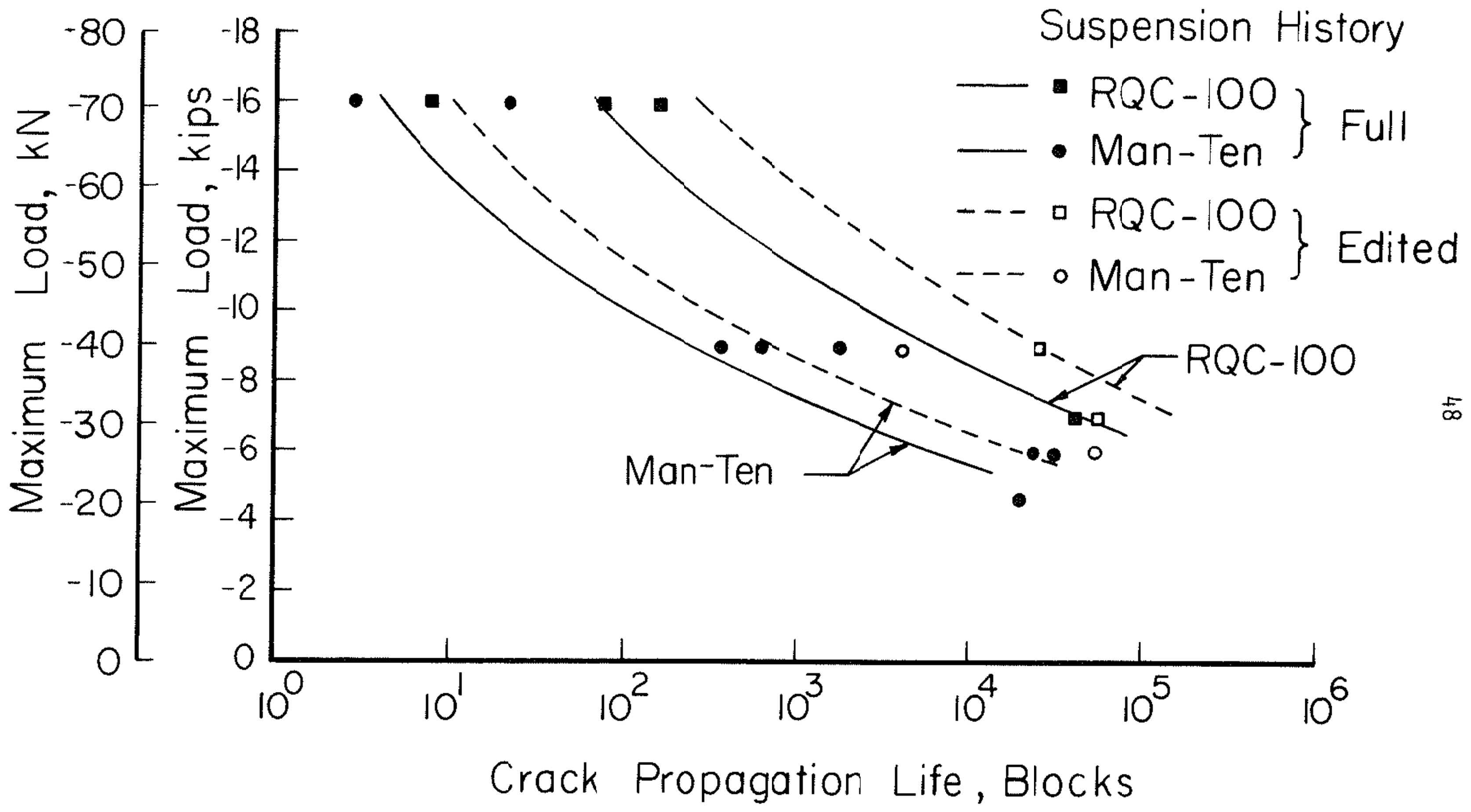

Fig. 17 Predicted and Actual Crack Propagation Lives for Full and Edited Suspension History Tests

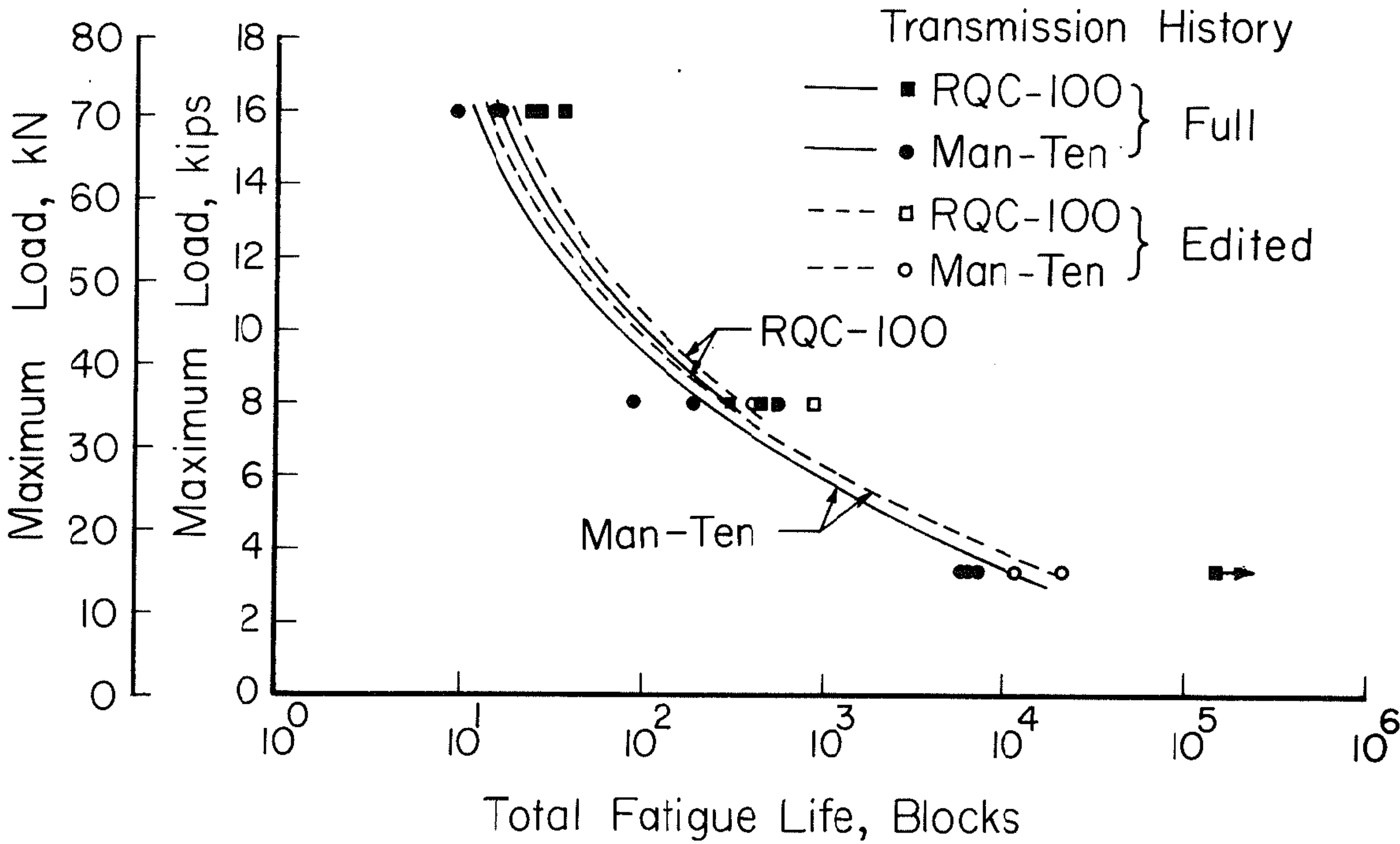

Fig. 18 Predicted and Actual Total Fatigue Lives for Full and Edited Transmission History Tests

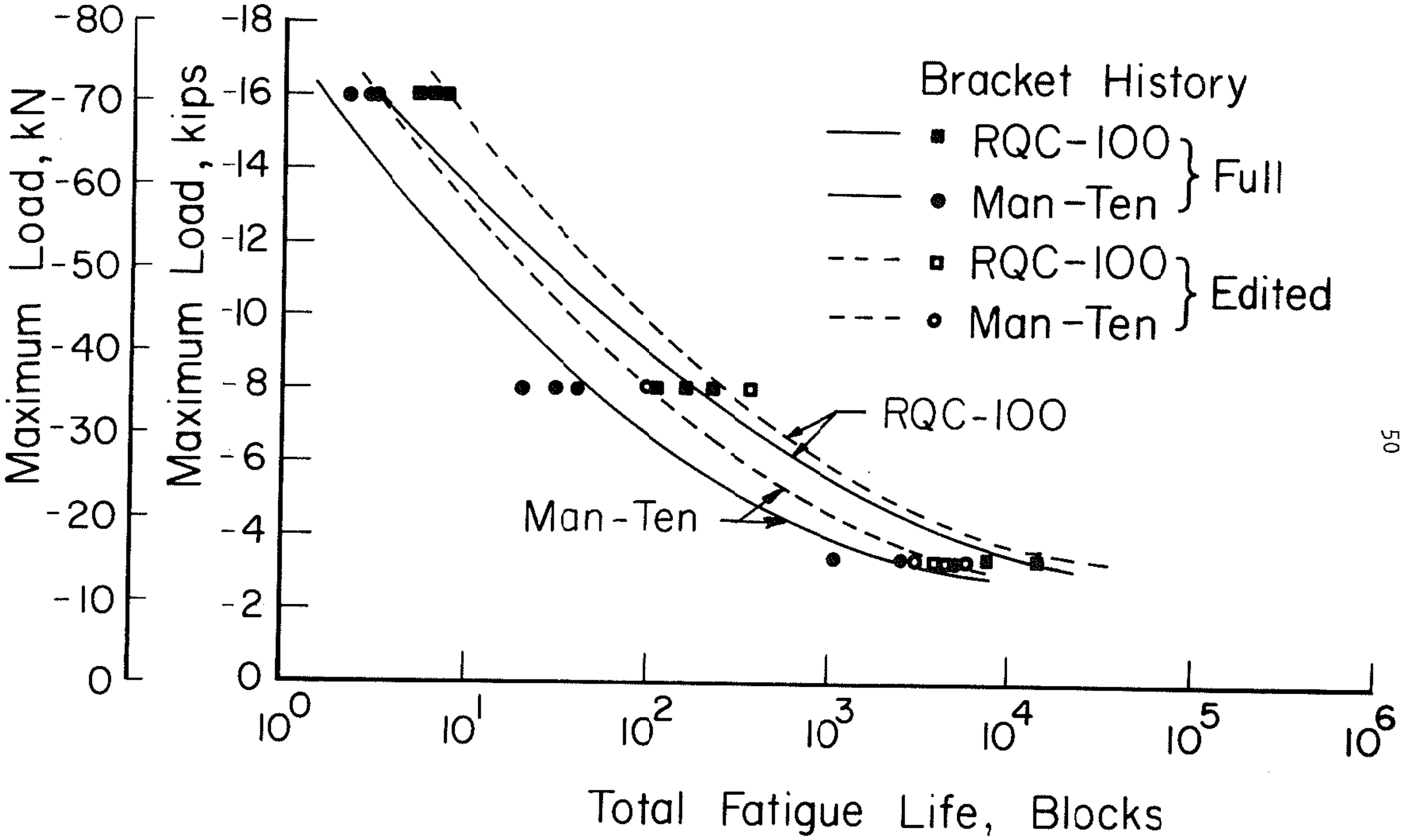

Fig. 19 Predicted and Actual Total Fatigue Lives for Full and Edited Bracket History Tests

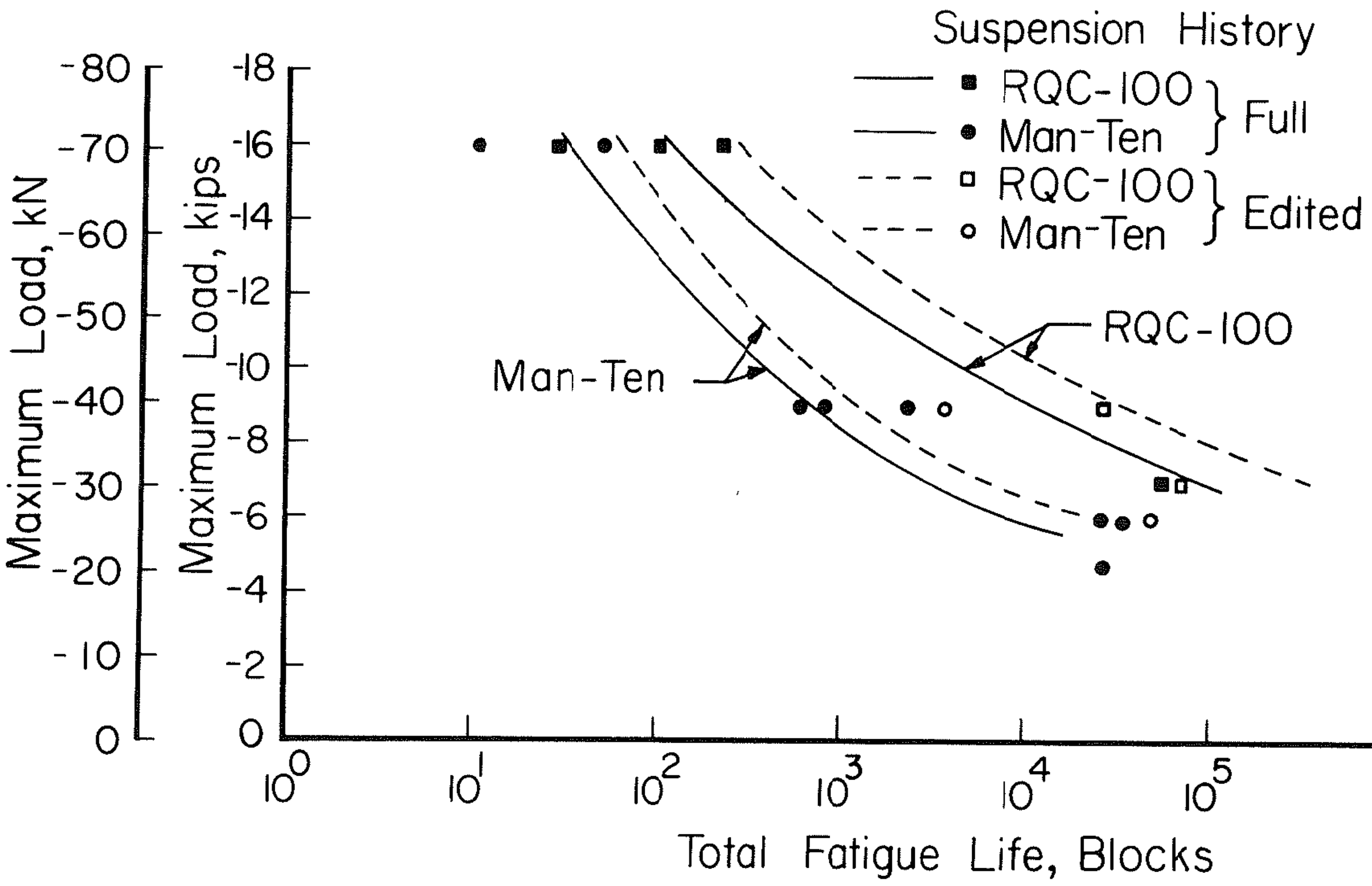

Fig. 20 Predicted and Actual Total Fatigue Lives for Full and Edited Suspension History Tests

APPENDIX A

EDITED LOAD HISTORIES

```
      PROGRAM EDIT(INPUT,OUTPUT,DATA,TAPE8=DATA,EDHIST,
     1   TAPE9=EDHIST,ORIG,TAPE10=ORIG)
      INTEGER A(6000),B(6000)
      COMMON A,B
C    HISTORY EDITING PROGRAM. HISTORY ISREAD FROM TAPE FILE,
C    WITH THE FIRST LINE BEING THE TITLE AND THE SECOND LINE
C    BEING THE NUMBER OF POINTS.  TAPE ORIG IS THE ORIGINAL
C    HISTORY WITH INITIAL AND FINAL POINTS AT ABSOLUTE MAX.
C    TAPE EDHIST IS THE RESULTING EDITED HISTORY.
C
      READ(8,11) ID
   11 FORMAT(6A10)
      READ(8,I5)NPEAKS
      READ(8,12)  (A(I),I=1,NPEAKS)
   12 FORMAT(14I5)
      CALL NORMAL (NPEAKS,A,B)
      PRINT(10,11) ID
      PRINT(10,15) NPEAKS
      PRINT(10,12)  (B(I),I=1,NPEAKS)
C
      PRINT 10
   10 FORMAT(//,"  INPUT INTEGER THRESHOLD VALUE.")
      READ*,ITHRES
   15 FORMAT (I5)
      I=1
      J=1
      NUM=B(I)
      IF(I.EQ.NPEAKS) GO TO 50
   20 I=I+1
      IF(I.EQ.NPEAKS) GO TO 50
      LO=B(I)-NUM
      IF(IABS(LO).GT.ITHRES) GO TO 40
   23 I=I+1
      IF(I.EQ.NPEAKS) GO TO 50
      IF(LO.GT.0) GO TO 25
      IF(B(I).GT.NUM)NUM=B(I)
      GO TO 20
   25 IF(B(I).LT.NUM) NUM=B(I)
      GO TO 20
   40 A(J)=NUM
      J=J+1
      NUM=B(I)
      GO TO 20
   50 A(J)=NUM
      IF(IABS(A(J)).EQ.999) GO TO 60
      J=J+1
      A(J)=B(NPEAKS)
   60 CONTINUE
C
C    EDITED MATRIX COMPLETED.
C
      PRINT(9,110)
  110 FORMAT(" EDITED HISTORY.")
      PRINT(9,15) J
      PRINT(9,12)(A(K),K=1,J)
      STOP
      END
```

```
C
C     THIS SUBROUTINE SETS INITIAL MATRIX SO START AND END
C     AT THE ABSOLUTE MAXIMUM.
C
      SUBROUTINE NORMAL(NPEAKS,A,B)
      INTEGER A(6000),B(6000)
      MAX=1
      MIN=1
      DO 10 I=1,NPEAKS
      IF(A(I).GT.A(MAX)) MAX=I
      IF(A(I).LT.A(MIN)) MIN=I
   10 CONTINUE
      ISTART=MAX
      IF(IABS(A(MIN)).GT.IABS(A(MAX))) ISTART=MIN
      DO 20 I=ISTART,NPEAKS
      IOFF=I-ISTART+1
   20 B(IOFF)=A(I)
      JSTART=ISTART-1
      DO 30 I=1,JSTART
      IOFF=NPEAKS-ISTART+I+1
   30 B(IOFF)=A(I)
      IF(B(1).EQ.B(NPEAKS)) GO TO 40
      NPEAKS=NPEAKS+1
      B(NPEAKS)=B(1)
   40 RETURN
      END
```

```
EDITED VERSION OF TRANSMISSION HISTORY.
 131
  999 -254   844 -277   716 -249   507 -281   705 -325   725    0   701 -309
  703 -331   851 -197   696 -227   683 -254   738 -261   662 -184   712 -308
  727 -276   796   78   690   18   731  100   748 -266   733 -191   765 -362
  660   30   887 -256   777 -161   698 -202   650 -211   776 -201   727 -350
  871 -246   803 -350   744   82   790 -264   753 -237   732 -208   618 -283
  667 -215   744 -169   739 -260   812   27   693 -204   739 -276   717 -219
  696 -367   474 -470   566 -406   835 -320   769 -251   840 -318   703   14
  789 -387   869 -227   789  104   832 -318   728   -7   695 -239   632   11
  855 -495   764 -301   695 -448   721 -286   577 -341   822 -258   834 -222
  645 -229   798   51   999
```

```
EDITED VERSION OF SUSPENSION HISTORY.
  69
 -999   -41  -646   193  -773    71  -489    69  -805     6  -626   154  -467    69
 -767    43  -603   176  -497    91  -769    57  -581   137  -493   250  -651    70
 -720   220  -695    -6  -770   107  -776    53  -750   142  -763   -10  -779   185
 -806    51  -800   113  -664    -9  -732   208  -456   345  -561   109  -822    -4
 -572   140  -804   115  -478    69  -997   -18  -672   150  -879   115  -999
```

```
EDITED VERSION OF BRACKET HISTORY.
 611
 -999   255  -575   433  -768   359  -565   360  -757   408  -565   433  -492   738
 -679   310  -556   319  -664   403  -511   472  -516   383  -639   314  -595   280
 -550   329  -703   383  -605   344  -679   390  -521   393  -644   546  -626   359
 -787   462  -772   442  -713   408  -541   472  -521   516  -693   413  -634   349
 -649   339  -575   437  -551   497  -447   423  -575   349  -506   378  -659   433
 -462   423  -472   649  -580   423  -541   408  -570   477  -492   551  -639   467
 -654   339  -565   418  -467   541  -442   467  -575   383  -546   501  -728   354
 -674   408  -561   418  -654   393  -506   433  -516   408  -497   418  -521   521
 -565   506  -541   452  -546   359  -561   531  -595   433  -743   393  -570   354
 -600   595  -477   374  -698   408  -728   378  -575   452  -477   433  -565   383
 -624   477  -556   497  -570   442  -497   457  -511   472  -634   329  -634   319
 -610   408  -536   344  -621   290  -610   354  -620   418  -624   280  -703   383
 -595   428  -575   305  -595   467  -654   250  -664   182  -748   305  -624   270
 -610   403  -644   265  -570   408  -561   334  -620   388  -644   329  -649   206
 -723   236  -654   305  -762   354  -634   359  -595   398  -679   295  -659   265
 -629   260  -634   369  -639   369  -767   482  -752   501  -629   319  -536   344
 -762   334  -639   265  -767   359  -546   364  -654   477  -605   433  -733   339
 -772   388  -546   393  -615   329  -649   369  -713   413  -516   531  -575   349
 -639   378  -590   349  -674   295  -624   344  -590   378  -590   305  -615   319
 -575   344  -565   369  -629   433  -428   433  -595   364  -772   556  -615   280
 -797   403  -728   433  -718   423  -531   324  -531   374  -631   369  -615   565
 -497   472  -615   413  -826   378  -556   383  -669   363  -482   413  -472   413
 -649   349  -656   393  -684   526  -629   511  -482   639  -688   423  -506   378
 -551   388  -698   270  -684   344  -605   447  -492   393  -556   467  -541   310
 -541   452  -457   413  -501   531  -649   285  -624   418  -501   580  -644   492
 -536   339  -624   521  -497   575  -624   536  -649   447  -506   452  -615   457
 -610   585  -447   462  -423   575  -654   492  -585   344  -526   433  -536   585
 -477   462  -497   467  -472   506  -511   344  -521   516  -536   511  -565   497
 -570   413  -521   472  -423   541  -639   457  -595   447  -556   442  -447   551
 -511   457  -575   364  -536   462  -639   462  -462   413  -442   472  -585   511
 -536   467  -462   437  -428   521  -418   492  -497   492  -551   639  -487   570
 -497   457  -467   511  -516   433  -501   433  -418   457  -664   585  -565   565
 -600   629  -797   447  -433   423  -639   482  -477   531  -546   551  -310   544
 -457   492  -487   482  -437   561  -477   393  -477   482  -418   467  -492   418
 -492   369  -511   487  -447   506  -575   492  -570   437  -482   423  -541   408
 -556   708  -560   324  -575   369  -624   428  -575   408  -531   506  -521   457
 -560   354  -728   359  -723   378  -644   472  -629   378  -620   359  -561   428
 -556   374  -536   452  -497   374  -541   433  -654   433  -551   354  -639   393
 -570   359  -743   506  -521   457  -684   437  -752   437  -467   447  -595   295
 -807   418  -590   305  -546   403  -561   295  -693   305  -595   275  -580   295
 -600   324  -570   393  -546   402  -561   300  -649   359  -556   383  -546   383
 -506   388  -497   437  -679   457  -659   497  -743   398  -624   536  -664   324
 -546   359  -561   378  -531   388  -772   644  -536   437  -590   447  -624   295
 -649   349  -561   349  -629   398  -546   388  -999
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APPENDIX B

RAW DATA

TM3 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM^2)	
18,093	1.14	.045	10.9	.333
18,270	1.50	.059	14.3	.337
18,442	3.10	.122	29.5	.354
18,722	5.61	.221	53.4	.381
18,910	7.47	.294	71.1	.400
19,062	8.97	.353	85.4	.416
19,223	10.34	.407	98.5	.431
19,332	11.43	.450	109.0	.443
19,477	13.23	.521	126.0	.462
19,576	14.45	.569	138.0	.475
19,677	15.72	.619	150.0	.488
19,753	16.87	.664	161.0	.500
19,807	17.58	.692	167.0	.508
20,116	17.70	.697	169.0	.509
20,183	26.77	1.054	255.0	.606
20,270		Specimen	Failed	

SR2 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
1,657	1.30	.051	12.4	.335
1,698	2.54	.100	24.2	.350
1,712	3.39	.133	32.3	.357
1,759	3.58	.141	34.1	.359
1,790	4.11	.162	39.1	.365
1,898	4.29	.169	40.9	.367
2,004	4.29	.169	40.9	.367
2,228	4.37	.172	41.6	.367
2,551	4.39	.173	41.8	.368
2,639	4.39	.173	41.8	.368
3,200	4.57	.180	43.5	.370
3,439	4.65	.183	44.3	.370
5,760	5.08	.200	48.4	.375
7,170	5.26	.207	50.1	.377
8,556	7.95	.313	75.7	.406
8,791	8.10	.319	77.1	.407
9,521	8.13	.320	77.4	.407
9,782*	8.38	.330	79.8	.410
10,063	8.38	.330	79.8	.410
11,972	9.70	.382	92.4	.424
12,220	9.91	.390	94.4	.426
12,562	10.26	.404	97.7	.430
13,371	10.57	.416	101.0	.433
13,887	12.29	.484	117.0	.452
14,553	12.67	.499	121.0	.456
14,732	13.03	.513	124.0	.460
15,275	13.21	.520	126.0	.461
15,634	13.82	.544	132.0	.468
16,250	14.35	.565	137.0	.474

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*Second crack observed

SR2 EDITED HISTORY (Continued)

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
16,721	14.43	.568	137.0	.474
17,187	15.27	.601	145.0	.483
18,262	15.93	.627	152.0	.490
18,691	17.02	.670	162.0	.502
19,165	17.91	.705	171.0	.511
19,776	18.44	.726	176.0	.517
20,203	19.18	.755	183.0	.525
20,806	20.19	.795	192.0	.536
20,861	20.32	.800	194.0	.537
21,085	20.93	.824	199.0	.544
21,669	21.97	.865	209.0	.555
22,653	23.88	.940	227.0	.575
22,828	24.23	.954	231.0	.579
23,741	26.03	1.025	248.0	.598
24,546	28.57	1.125	272.0	.625
24,961	30.33	1.194	289.0	.644
25,405	32.38	1.275	308.0	.666
25,929	36.75	1.447	350.0	.712
25,995	37.13	1.462	354.0	.716
26,037	39.57	1.558	377.0	.742
26,063	40.84	1.608	389.0	.756
26,069		Specimen	Failed	

SM2 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM^2)	
544	1.27	.050	12.1	.334
566	2.54	.100	24.2	.348
626	3.81	.150	36.3	.361
725	6.07	.239	57.8	.386
787	7.19	.283	68.5	.397
821	7.87	.310	84.5	.405
849	8.51	.335	81.1	.411
887	9.02	.355	85.9	.417
919	9.09	.358	86.6	.418
998	10.41	.410	99.2	.432
1,053	10.54	.415	100.0	.433
1,121	11.53	.454	110.0	.444
1,157	12.22	.481	116.0	.451
1,236	12.32	.485	117.0	.452
1,288	12.70	.500	121.0	.456
1,357	13.00	.512	124.0	.459
1,560	13.79	.543	131.0	.468
1,855	16.41	.646	156.0	.496
2,006	16.79	.661	160.0	.500
2,135	18.24	.718	174.0	.515
2,216	18.75	.738	179.0	.520
2,360	19.00	.748	181.0	.523
2,433	19.53	.769	186.0	.529
2,555	20.29	.799	193.0	.537
2,697	21.56	.849	205.0	.550
2,843	22.55	.888	215.0	.567
2,926	22.68	.893	216.0	.562
3,018	22.81	.898	217.0	.564
3,091	23.24	.915	221.0	.568
3,245	24.36	.959	232.0	.580
3,355	26.34	1.037	251.0	.601
3,470	26.62	1.048	254.0	.604
3,573		Specimen Failed		

TM2 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM2)	
282	2.67	.105	25.4	.349
289	3.91	.154	37.2	.363
310	5.46	.215	52.0	.379
347	7.75	.305	73.8	.403
376	11.35	.447	108.0	.442
394	17.93	.706	171.0	.512
401		Specimen	Failed	

TR2 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM2)	a/W
539	4.24	.167	40.4	.366
548	5.00	.197	47.6	.374
559	5.33	.210	50.8	.378
571	5.79	.228	55.1	.383
589	6.43	.253	61.2	.389
609	6.60	.260	62.9	.391
639	7.42	.292	70.7	.400
683	9.47	.373	90.2	.422
707	10.72	.422	102.0	.435
739	11.94	.470	114.0	.448
779	15.06	.593	143.0	.481
797	15.80	.622	150.0	.489
820	19.13	.753	182.0	.524
847	24.92	.981	237.0	.586
853	29.41	1.158	280.0	.634
853	53.34	2.100	508.0	.889
854		Specimen	Failed	

SM3 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
2,602	.61	.024	5.81	.327
2,767	.76	.030	7.24	.329
2,875	1.09	.043	10.40	.332
2,943	1.19	.047	11.30	.334
3,048	1.30	.051	12.40	.335
3,221	1.75	.069	16.70	.340
3,356	2.03	.080	19.30	.342
3,562	2.31	.091	22.00	.346
	Second Crack Started			
32,021	22.43	.883	214.00	.560
36,571	25.27	.995	241.00	.590
45,222	Specimen Failed			

SR3 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM^2)	
8,716	1.98	.078	18.9	.342
9,085	2.39	.094	22.8	.346
9,187	2.39	.094	22.8	.346
9,328	2.59	.102	24.7	.349
12,172	2.77	.109	26.4	.350
	Second Crack Started			
24,096	12.90	.508	123.00	.458
25,611	14.17	.558	135.00	.472
25,681	14.22	.560	135.00	.472
33,674	19.68	.775	187.00	.530
36,662	21.51	.847	243.00	.550
46,245	28.40	1.118	271.00	.623
48,714	31.22	1.229	335.00	.653
54,155	33.71	1.327	321.00	.680
57,970	49.53	1.950	472.00	.848
60,140	Specimen Failed			

TM3 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
11,135	1.30	.051	12.4	.335
11,178	1.93	.076	18.4	.341
11,192	1.93	.076	18.4	.341
11,226	2.57	.101	24.5	.348
11,598	6.35	.250	60.5	.389
12,243	13.82	.544	132.0	.468
12,639	22.28	.887	212.0	.561
12,796		Specimen	Failed	

BM3 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM)	
3,303	1.42	.056	13.5	.336
3,449	1.52	.060	14.5	.337
3,511	1.73	.068	16.5	.339
3,536	2.36	.093	22.5	.346
3,545	2.44	.096	23.2	.347
3,556	2.72	.107	25.9	.350
3,828	5.36	.211	51.0	.378
4,018	7.65	.301	72.9	.402
4,203	9.42	.371	89.7	.421
4,266	10.29	.405	98.0	.430
4,662	14.23	.572	136.0	.476
5,367	46.48	1.830	443.0	.816
5,367		Specimen Failed		

BR3 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM2)	
1,395	--	--	--	--
2,660	10.19	.401	97.1	.429
2,954	15.14	.596	144.0	.482
3,122	16.21	.638	154.0	.493
3,401	20.09	.791	191.0	.535
3,498	20.89	.822	199.0	.543
3,675	25.22	.993	240.0	.589
3,885	31.52	1.241	300.0	.656
3,984		Specimen	Failed	

BM3 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM2)	
1,613	2.34	.092	22.3	.346
1,626	2.36	.093	22.5	.346
1,633	2.39	.094	22.8	.346
1,645	2.67	.105	25.4	.349
1,846	5.46	.215	52.0	.379
2,085	8.81	.347	83.9	.415
2,536	16.41	.646	156.0	.496
2,886		Specimen Failed		

BR3 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
2,662	1.78	.070	16.9	.340
2,722	2.62	.103	24.9	.349
2,950	5.84	.230	55.6	.383
3,110	8.05	.317	76.7	.407
3,333	11.40	.449	109.0	.442
3,414	12.45	.490	119.0	.453
3,659	16.51	.650	157.0	.497
4,329		Specimen	Failed	

BM2 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
41	--	--	--	--
43	2.57	.101	24.5	.348
50	5.64	.222	53.7	.381
56	7.26	.286	69.1	.398
64	10.41	.410	99.2	.432
74	13.16	.518	125.0	.461
83	16.54	.651	157.0	.497
89	21.16	.833	201.0	.546
96		Specimen	Failed	

BR2 EDITED HISTORY

Blocks	Crack Length		Crack Area	$\frac{a}{W}$
	(MM)	(IN)	(MM)	
59	.74	.029	7.05	.329
67	.127	.050	1.21	.334
76	2.90	.114	27.60	.352
128	5.38	.212	51.20	.378
148	6.63	.261	63.10	.391
268	15.82	.623	151.00	.489
354		Specimen	Failed	

BR3 EDITED HISTORY

Blocks	Crack Length (MM)	Crack Length (IN)	Crack Area (MM^2)	$\frac{a}{W}$
2,388	.79	.031	7.52	.329
2,465	.97	.038	9.24	.331
2,585	1.90	.075	18.10	.341
2,763	2.29	.090	21.80	.345
2,834	3.05	.120	29.00	.353
3,576	6.35	.250	60.50	.389
3,824	8.31	.327	79.10	.409
4,041	9.73	.383	92.70	.424
4,258	11.96	.471	114.00	.448
4,501	13.74	.541	131.00	.467
5,283	30.76	1.211	293.00	.698
5,414		Specimen Failed		

BM3 EDITED HISTORY

Blocks	Crack Length		Crack Area	a/W
	(MM)	(IN)	(MM^2)	
2,418	.97	.038	9.24	.331
2,550	1.98	.078	18.90	.342
2,556	2.01	.079	19.10	.342
2,647	2.72	.107	25.90	.350
2,956	6.10	.240	58.10	.386
3,156	8.74	.344	83.20	.414
3,485	12.19	.480	116.00	.451
4,268		Specimen	Failed	