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## SUMMARY

The validity of a previously proposed method of predicting cumulative fatigue damage in smooth 1/4-inch-diameter specimens based on the concept of a double linear damage rule was investigated. This method included simplified formulas for determining the crack initiation and the propagation stages and indicated that each of these stages could be represented by a linear damage rule. The present study provides a critical evaluation of the earlier proposal, further illuminates the principles underlying cumulative fatigue damage, and suggests a modification of the original proposal.

The data were obtained in two-stress-level tests with maraging and SAE 4130 steels in rotating bending. Also, two-strain-level tests were conducted in axial reversed strain cycling with a maraging steel. The investigation showed that in most cases the double linear damage rule when used in conjunction with originally proposed equations for determining crack initiation and propagation predicted fatigue life with equal or greater accuracy than the conventional linear damage rule. An alternative viewpoint of the double linear damage rule is suggested. This viewpoint requires that a limited number of simple two-stress-level tests be run to establish effective fatigue curves for what may be defined as Phases I and II of the fatigue process. These fatigue curves may then be used in the analysis of any spectrum of loads involving as loading extremes the two stresses used for their determination. Only limited verification of the new method has been obtained to date, and it must presently be limited to the study of smooth, 1/4-inch-diameter specimens. However, it may be considered as a first step in the direction of eventually predicting the effect of a complex loading history on the life of more complex geometrical shapes.

## INTRODUCTION

The subject of cumulative fatigue damage is extremely complex, and various theories have been proposed (refs. 1 to 10) to predict fatigue life in advance of service. The most widely known and used procedure is the linear damage rule commonly called the Miner rule (ref. 7). The linear damage rule, which indicates that a summation of cycle ratios is equal to unity, is not completely accurate; however, because of its simplicity and

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because of its agreement with experimental data for certain cases it is frequently used in design. If a new method is to replace the linear damage rule in practical design, much of the simplicity of the linear damage rule must be retained. The double linear damage rule, considered herein, retains much of this simplicity and at the same time attempts to overcome some of the limitations inherent in the conventional linear rule.

One of the limitations of the linear damage rule is that it does not consider the effect of order of loading. For example, in a two-stress-level fatigue test in which a high load is followed by a low load, the cycle ratio summation is less than 1, whereas a low load followed by a high load produces a cycle ratio summation greater than 1. The effect of residual stress is also not properly accounted for by the conventional linear damage rule, nor does it consider cycle ratios applied below the initial fatigue limit of the material. Since prior loading can reduce the fatigue limit, cycle ratios of stresses applied below the initial fatigue limit should be accounted for (ref. 10). In addition, coaxing effects present in some strain-aging materials (ref. 11) in which the appropriate sequence of loading may progressively raise the fatigue limit are not accounted for by the linear damage rule. Various methods have been proposed as alternatives to the linear damage rule. None overcomes all the deficiencies, and many introduce additional complexities that either preclude or make their use extremely difficult in practical design problems.

The possibility of improving the predictions of a linear damage rule by breaking it up into two phases, a linear damage rule for crack initiation and a linear damage rule for crack propagation, was first suggested by Grover in reference 12. Neither a rational basis for this approach was indicated nor were definite expressions provided for separating the two phases. These aspects were considered in greater detail in reference 13. Total life was considered as consisting of two important phases, one for initiating a crack and one for propagating a crack, and a linear damage rule was applied to each of these phases. This double linear damage rule was intended to correct the deficiencies associated with order of loading; the other limitations previously cited were not directly considered. Simplified formulas derived from limited data for determining the crack initiation and the propagation stages were tentatively presented.

The present study was conducted to provide a critical evaluation of the proposal of reference 13, specifically, the analytical expressions for separating the two phases. Additional data were obtained in two-stress-level tests in rotating bending and two-strain-level tests in axial reversed strain cycling. The materials investigated were maraging and SAE 4130 steels. Fatigue life predictions by the double linear damage rule and the conventional linear damage rule are compared with experimental data. In addition, instead of using the analytical expression given in reference 13 to represent the crack propagation stage in the application of the double linear damage rule as originally proposed, a more generalized expression is suggested that involves the separation of the fatigue process into two experimentally determined phases. These phases are not necessarily the physical processes of crack initiation and propagation.

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# CONCEPT OF THE DOUBLE LINEAR DAMAGE RULE

## Analytical Application

In reference 13 it is proposed that the crack propagation period $(\Delta N)_f$ and crack initiation $N_o$ can both be expressed in terms of total fatigue life $N_f$ by the following equations:

$$(\Delta N)_f = PN_f^{0.6} \tag{1}$$

and

$$N_o = N_f - (\Delta N)_f = N_f - PN_f^{0.6} \tag{2}$$

where the coefficient $P = 14$. The experimental basis for the selection of this value of coefficient is given in references 13 and 14 and is also further described subsequently herein.

The equations expressing cumulative fatigue damage in terms of the double linear damage rule, as proposed in reference 13, are as follows:

For the crack initiation phase,

$$\sum \frac{n}{N_o} = 1 \quad \begin{array}{l} \text{(when } N_f > 730 \text{ cycles, } N_o = N_f - 14\,N_f^{0.6} \\ \\ \text{when } N_f < 730 \text{ cycles, } N_o \approx 0) \end{array} \tag{3}$$

If any part of the loading spectrum includes a condition where $N_f < 730$ cycles, an effective crack is presumed to initiate upon application of that first loading cycle.

For the crack propagation phase,

$$\sum \frac{n}{(\Delta N)_f} = 1 \quad \begin{array}{l} \text{(when } N_f > 730 \text{ cycles, } (\Delta N)_f = 14\,N_f^{0.6} \\ \\ \text{when } N_f < 730 \text{ cycles, } (\Delta N)_f = N_f) \end{array} \tag{4}$$

where

$N_o$     cyclic life to initiate effective crack at particular strain or stress level

$(\Delta N)_f$     cyclic life to propagate crack from initiation to failure at particular strain or stress level

$N_f$ cyclic life to failure of specimen

n number of cycles applied at particular strain or stress level

An example of the manner of applying these equations for simple two-stress-level loading is given in appendix A. Further discussion of the equation relating crack initiation and propagation to total fatigue life is presented in reference 14. It should be emphasized that these equations were derived on the basis of data obtained with 1/4-inch-diameter (6.35-mm) specimens of notch ductile materials and have thus far been shown to be valid only for this size specimen (ref. 14). Of course, most materials would be notch ductile for such a small specimen size. This aspect is discussed more fully in reference 13.

By comparison, the conventional linear damage rule is expressed as
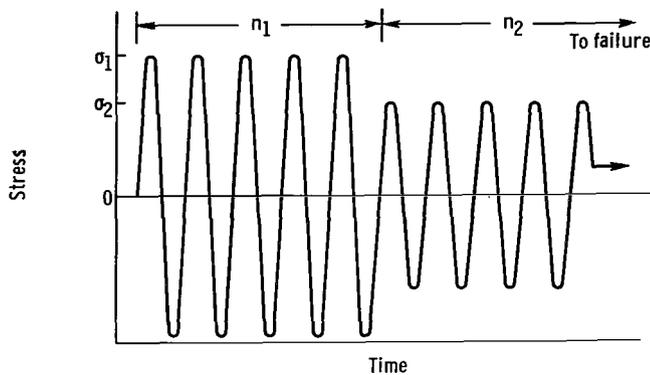


(a) Schematic drawing of loading pattern.

$$\sum \frac{n}{N_f} = 1 \qquad (5)$$

Equation (5) states that a single summation of cycle ratios applied at different stress or strain levels is equal to 1.

## Graphical Representation of Double Linear Damage Rule Applied to Two-Stress-Level Fatigue Test

Figure 1 illustrates the graphical representation of the double linear damage rule plotted in terms of the remaining cycle ratio $n_2/N_{f,2}$ at a second stress level against the cycle ratio $n_1/N_{f,1}$ applied at an initial stress level. Also shown is a dashed 45° line, which represents the conventional linear damage rule. The figure is illustrative of the case in which the prestress condition is the high stress, and this condition is followed by operation to failure at a lower stress. The position of lines AB and BC would be located on the other



(b) Interpretation of fatigue damage by linear damage rules.

Figure 1. - Two-stress-level fatigue tests.

side of the 45$^O$ line for the condition of low prestress followed by operation to failure at a high stress. According to the double linear damage rule, if the cycle ratio applied $n_1/N_{f,1}$ is less than that required to initiate an effective crack at a particular stress level, then the remaining predicted cyclic life ratio $n_2/N_{f,2}$ would be along AB (fig. 1). The linearity of AB is implicit in the assumption of a linear damage rule for crack initiation. Point B represents the cycle ratio applied at the first stress level, which is sufficient to initiate an effective crack, so that upon changing to the second stress level the remaining cycle ratio at that stress level is exactly equal to the total propagation stage. The coordinates of this point are designated as $N_{o,1}/N_{f,1}$ and $\Delta N_2/N_{f,2}$. Beyond this initial cycle ratio $N_{o,1}/N_{f,1}$, the first applied cycle ratio is more than that required to initiate an effective crack, and the crack propagation phase is entered. This phase is represented by the line BC, which is also straight and reflects the second assumed linear relation. The remaining cyclic life ratio then is along line BC. Thus, in two-step tests in which a single stress level was applied for a given cycle ratio and the remainder of the life taken up at a second stress level, two straight lines positioned as shown would be expected. It should also be emphasized that point B is significant since it permits determination of both the effective crack initiation and the propagation periods for both stress levels used in the test.

A final point should be made with respect to the graphical application of the double linear damage rule. Since lines AB and BC are straight and since points A and C are fixed, ideally only two tests are required to establish the positions of these lines and, consequently, the point B. The only requirement for selecting these tests is that in one test the cycle ratio applied at the initial stress level should be relatively large, and for the other test it should be relatively small, in order to ensure that the remaining cycle ratios $n_2/N_{f,2}$ do not both fall on the same straight line, either AB or BC. The significance of obtaining point B in this simple fashion is apparent in the illustrative examples of appendixes B and C.

# EXPERIMENTAL PROCEDURE

## Materials

Two steels, SAE 4130 and an 18-percent nickel maraging steel (consumable electrode vacuum melted), were investigated. Their compositions, heat treatments, and hardnesses are listed in table I and their tensile properties in table II. Two different types of test specimens were used to accommodate the R. R. Moore and Krouse rotating bending test machines. A third type of specimen was used for axial strain cycling tests. All three specimen types are shown in figure 2. The 4130 steel test specimens were
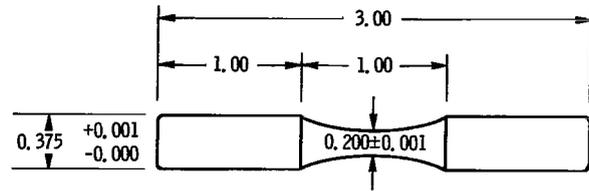
(a) Krouse rotating bending specimen.
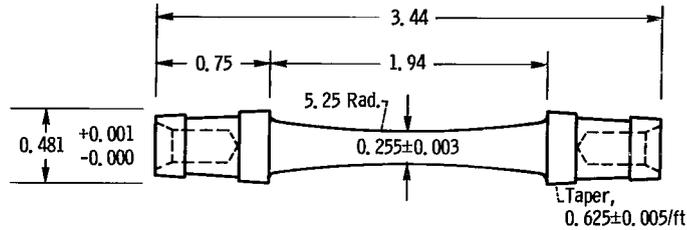
(b) R. R. Moore rotating bending specimen.
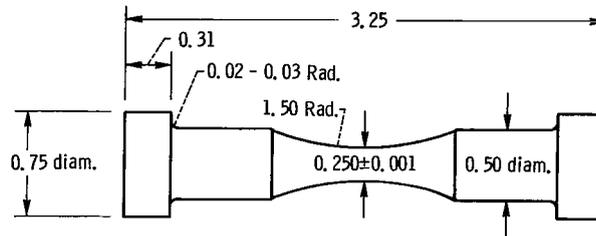
(c) Axial fatigue test specimen.

Figure 2. - Fatigue specimens. (Dimensions are in
inches. Conversion factor, 1 in. = 2.54 cm.)

machined after heat treatment. The maraging steel specimens were machined prior to aging and after aging were finish ground to remove the final 0.015 inch (0.38 mm) from the test section. In addition, all rotating bending specimens were machine polished with abrasive cloth of three grit sizes (320, 400, and 500). After final polishing the specimens were subjected to a microscopic examination at a magnification of 20.

## Tests

Specimens were subjected to rotating bending in modified R. R. Moore and Krouse (200 in.-lb capacity) rotating-beam fatigue machines and to axial reversed strain cycling in hydraulically actuated axial fatigue machines. In the rotating bending tests, a rotational speed of 5000 rpm (83.3 Hz) was employed at the lower stress levels. In order to avoid the detrimental effect of severe heat accumulation due to hysteresis, rotational speeds as low as 100 rpm (1.67 Hz) were employed at the higher stresses, and jets of

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cooling air were directed at the specimens. A specimen runout no greater than 0.001 inch (0.025 mm) full indicator reading was permitted upon installation into the fatigue machines. Additional details regarding the rotating bending test procedure are given in references 9 and 10. Axial fatigue tests were run at 20 cycles per minute (0.33 Hz). Details of the test procedure are given in reference 15.

The fatigue curves for each material were obtained by fairing the best visual-fit curves through the median data points obtained at each stress or strain range level. In conducting the investigation, specimens were prestressed at a single stress (in rotating bending tests) to the desired percentage of material life as determined from the fatigue curves of the original material and to a single strain range (axial fatigue tests) as determined from strain-range - life curves of the original material. The specimens were then run to failure at various stress (or strain range) levels. The specific test conditions are indicated on the figures that present the data and in tables III to VI. There was one exception to this procedure. For one test series, an alternating two-stress-level test was employed in rotating bending. This test is described in appendix C and table VII.

## RESULTS AND DISCUSSION

### Comparison of Experimental and Predicted Fatigue Life by Originally Proposed Double Linear Damage Rule and Conventional Linear Damage Rule

Figure 3 shows the results reported previously in reference 13 for maraging steel,
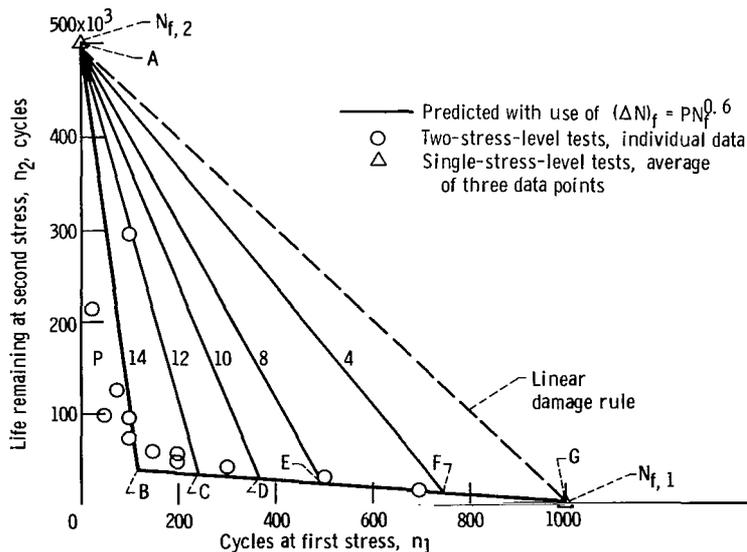
Figure 3. - Two-stress-level rotating bending fatigue tests for determination of coefficient in expression for crack propagation. Material, maraging steel.

which were obtained from rotating bending tests. The stress levels were so chosen that life at the initial stress was approximately 1000 cycles and at the second stress 500 000 cycles. Experimental data are shown by the circles. The solid lines represent predicted behavior by the double linear damage rule with the use of different values of the coefficient in equation (1). For a value of coefficient equal to 14, the predicted behavior was represented by the line ABG; for a coefficient of 12, it was ACG, etc. If a linear damage rule applied for the total life values, the behavior would be that shown by the dashed line AG. A reasonable agreement with the experimental data was obtained for a coefficient of 14. Since these data represent only one material and one combination of high and low stress, equation (1) was only tentatively proposed (ref. 13) as being representative of cumulative fatigue damage behavior.

In extending this approach, many additional tests were conducted with the same and
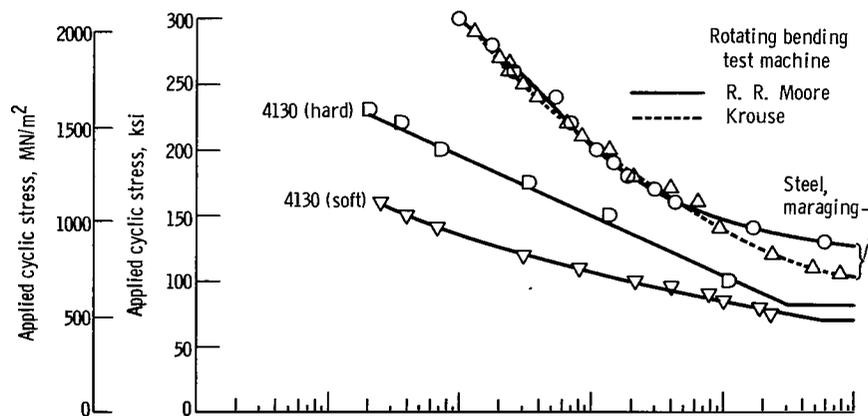


(a) Rotating bending fatigue life.
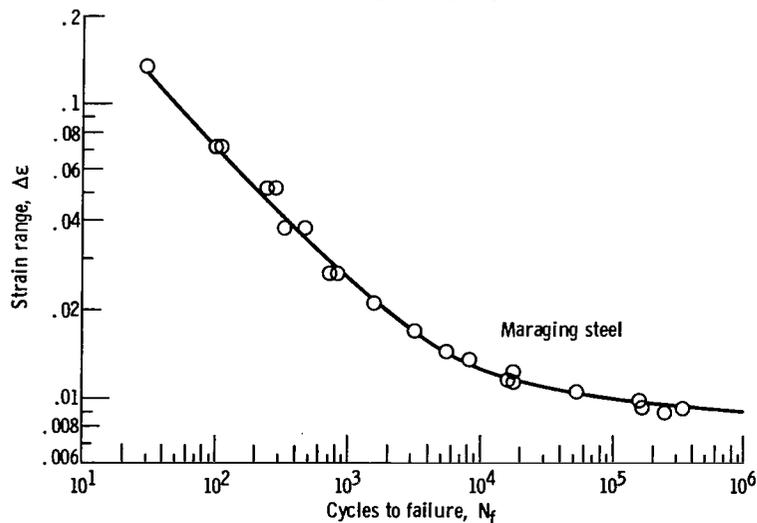
(b) Axial fatigue life of maraging steel.

Figure 4. – Fatigue curves for materials investigated.

with other materials in rotating bending and axial reversed strain cycling. Figure 4 shows the fatigue curves of these materials, maraging steel and hard and soft SAE 4130 steel. Since both Krouse and R. R. Moore machines were used for the maraging steel tests, the fatigue curves obtained with each machine are shown (fig. 4(a)). The curves are nearly coincident. Figure 4(b) shows the fatigue curve for maraging steel obtained in axial reversed strain cycling.

Predictions of fatigue behavior by the double linear damage rule (with the expression $14 \, N_f^{0.6}$ representing the crack-propagation stage) and by the conventional linear damage rule are compared with experimental data in figures 5 and 6. Different combinations of load that correspond to different life levels were chosen. Figure 5(a) presents the results from rotating bending tests for maraging steel designed to give relatively low fatigue lives of 1280, 2050, and 2350 cycles at the initial stress level. The loads at the second stress level were chosen to give lives up to 940 000 cycles. Generally, the greater the difference between the initial and the final life level (i.e., initial and final stress applied), the greater the deviation between the experimental data and the predicted behavior by the conventional linear damage rule shown by the $45^\circ$ dashed line; also, the steeper is the first (corresponding to line AB, fig. 1, p. 4) of the two solid lines, which predicts fatigue behavior by the double linear damage rule. Agreement between predicted fatigue behavior by the double linear damage rule and experimental data is good for these test conditions. This agreement might be expected since the higher stress level as well as some of the lower stress levels are generally of the same order as those selected originally for determining equation (1) for this same material in reference 13.

Figure 5(b) deals with the same material but considers other combinations of test conditions in which the initial life level is relatively high. The greatest discrepancies between experimental data and predicted fatigue behavior by the double linear damage rule as originally proposed occur when both the initial and the final life levels are high. The double linear damage rule would be expected to predict almost the same fatigue behavior as the conventional linear damage rule because the crack propagation period as determined from equation (1) would be relatively small. This behavior is readily seen by using equation (1) for values of $N_{f,1}$ of 15 925, 47 625, 44 000, etc., specific conditions which are considered in figure 5(b). The experimental data show appreciably lower values of remaining cycle ratio $n_2/N_{f,2}$ than would be expected by either rule.

Figure 5(c) illustrates the results obtained under conditions of axial strain cycling with maraging steel. The initial life level was chosen in all cases to be less than 730 cycles. For this case the major part of the fatigue life would be taken up by the crack-propagation period according to the expressions thus far assumed for crack propagation and initiation in applying the double linear damage rule. Since there is essentially no crack-initiation stage, the predictions by the double linear damage rule should coincide with those by the conventional linear damage rule. These predictions did coincide for the
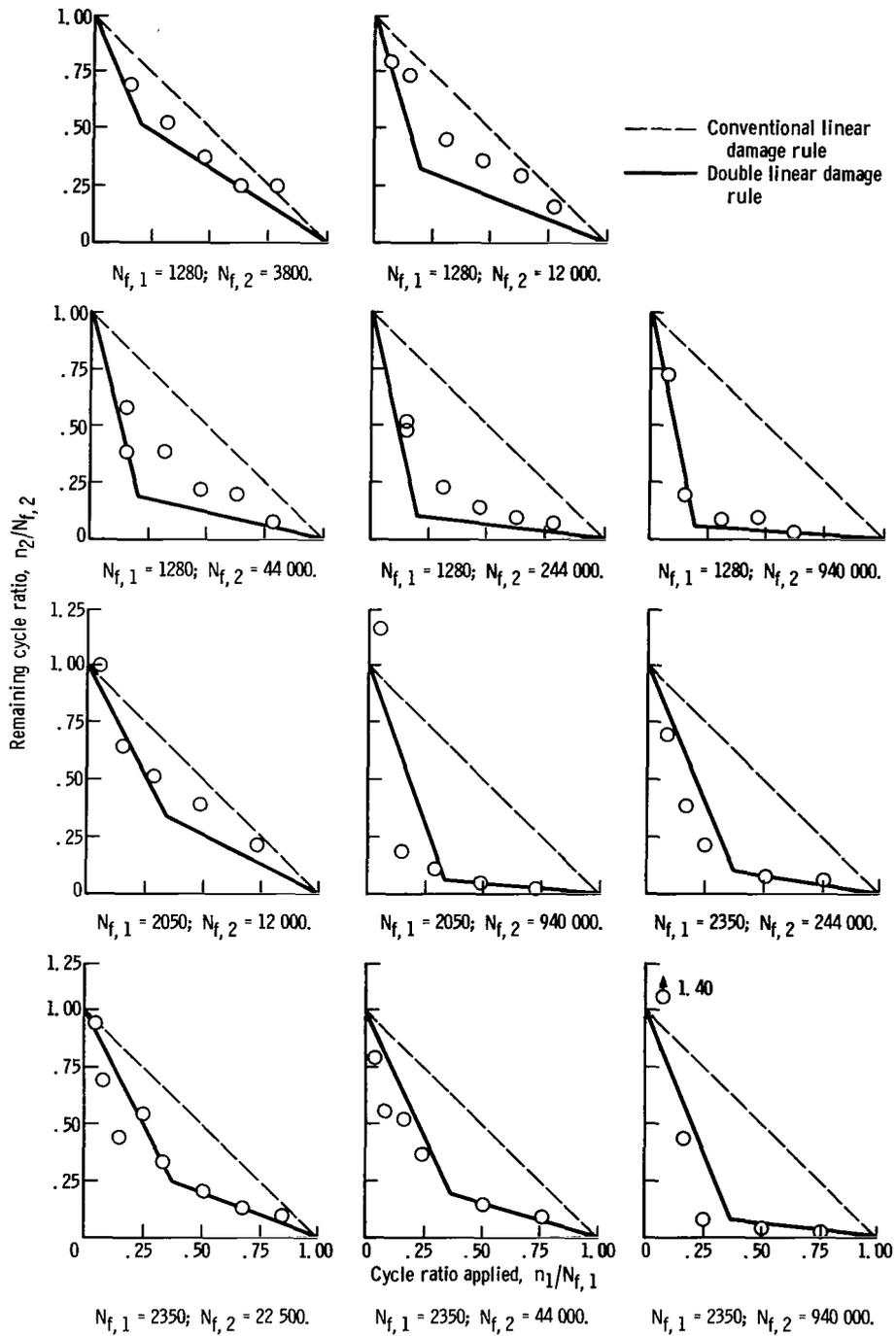
(a) Krouse rotating bending, high to low stress with low initial life.

Figure 5. – Comparison of predicted fatigue behavior by conventional and double linear damage rules with experimental data for two-stress (strain)-level tests. Material, maraging steel.

$N_{f,1} = 3800;\ N_{f,2} = 94\,000;$
Krouse machine.

$N_{f,1} = 9000;\ N_{f,2} = 94\,000;$
Krouse machine.

$N_{f,1} = 12\,000;\ N_{f,2} = 44\,000;$
Krouse machine.

$N_{f,1} = 15\,925;\ N_{f,2} = 584\,750;$
R. R. Moore machine.

$N_{f,1} = 47\,625;\ N_{f,2} = 584\,750;$
R. R. Moore machine.

$N_{f,1} = 12\,000;\ N_{f,2} = 244\,000;$
Krouse machine.

$N_{f,1} = 44\,000;\ N_{f,2} = 244\,000;$
Krouse machine.

Remaining cycle ratio, $n_2/N_{f,2}$

Cycle ratio applied, $n_1/N_{f,1}$
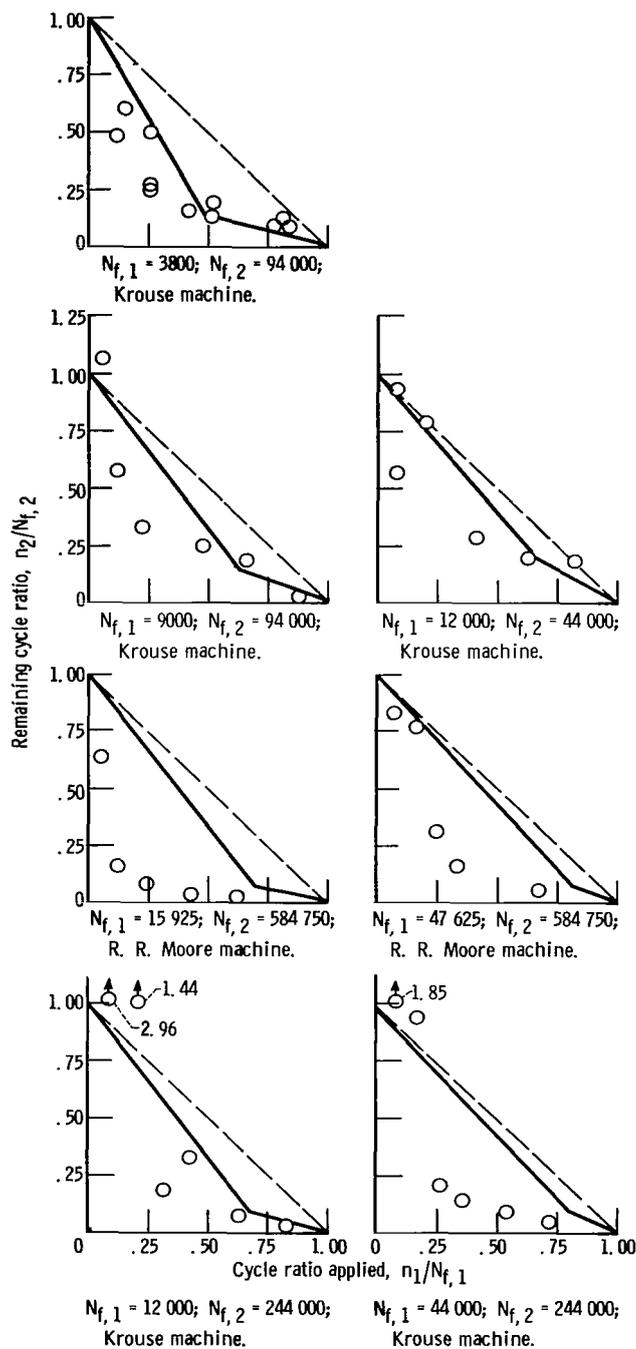
(b) Rotating bending, high to low stress with high initial life.

Figure 5. - Continued.

two conditions in which the final stress level was so chosen as to give a low value of life $N_{f,2}$, and the experimental data agreed well with the predictions. When the second stress level was so chosen as to give a long life, $N_{f,2} = 15\,950$ cycles, however, the predicted fatigue life by the double linear damage rule was less than that obtained experimentally. From figures 5(b) and (c), it is apparent that the experimental data fall on both sides of the predictions made by the double linear damage rule when the expression $14\,N_f^{0.6}$ was used to represent the crack-propagation stage.

Thus far, consideration has been given only to the general case in which the high stress or strain (for strain cycling tests) was applied first. Figure 5(d) illustrates the opposite case in which the low stress or strain was applied first. Except for the single axial strain cycling case and one case of the rotating bending tests $(N_{f,1} = 94\,000$ and $N_{f,2} = 3800)$, the predictions by the double linear damage rule show general agreement with the experimental data. Regardless of deviations of individual data points from the predictions, however, the figure shows that the order effect of loading is accounted for by the double linear damage rule.

The results for SAE 4130 steel are shown in figure 6. Figure 6(a) deals with tests in which the initial life level was low and loads at the second stress level were chosen to give various life values up to 203 000 cycles. Figure 6(b) considers an initial relatively high life

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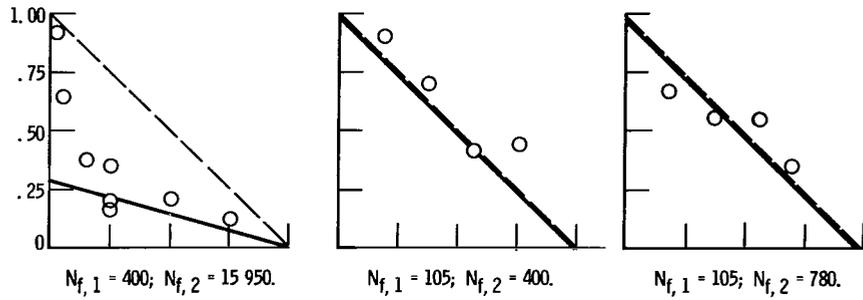
(c) Axial strain cycling, high to low strain with low initial life.
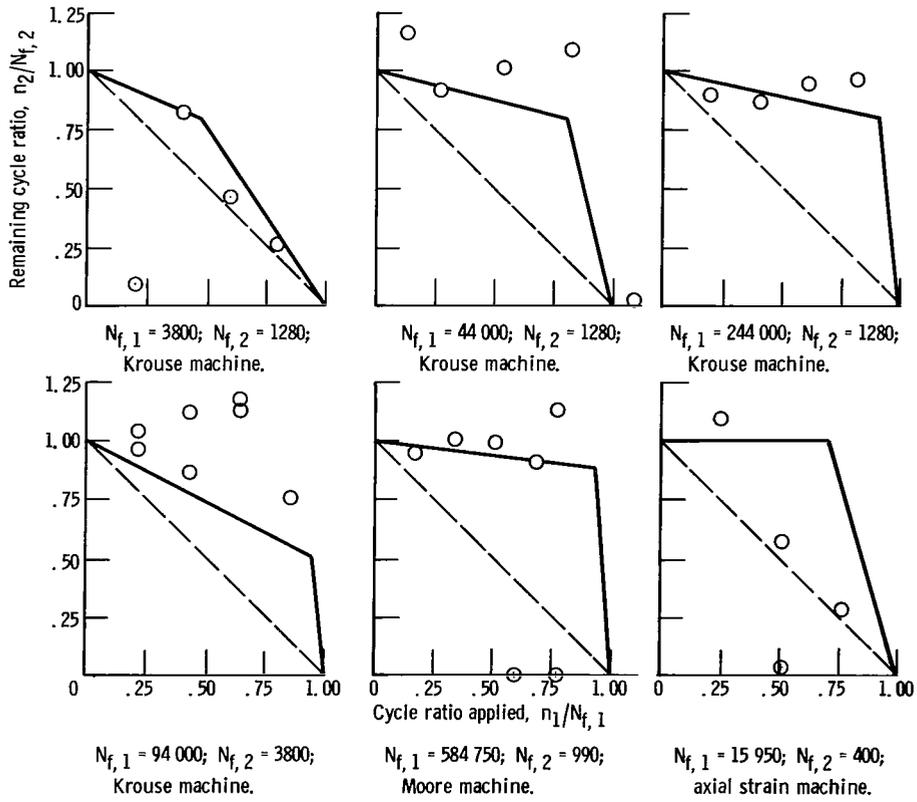
(d) Rotating bending and axial strain cycling, low to high stress (strain).

Figure 5. - Concluded.

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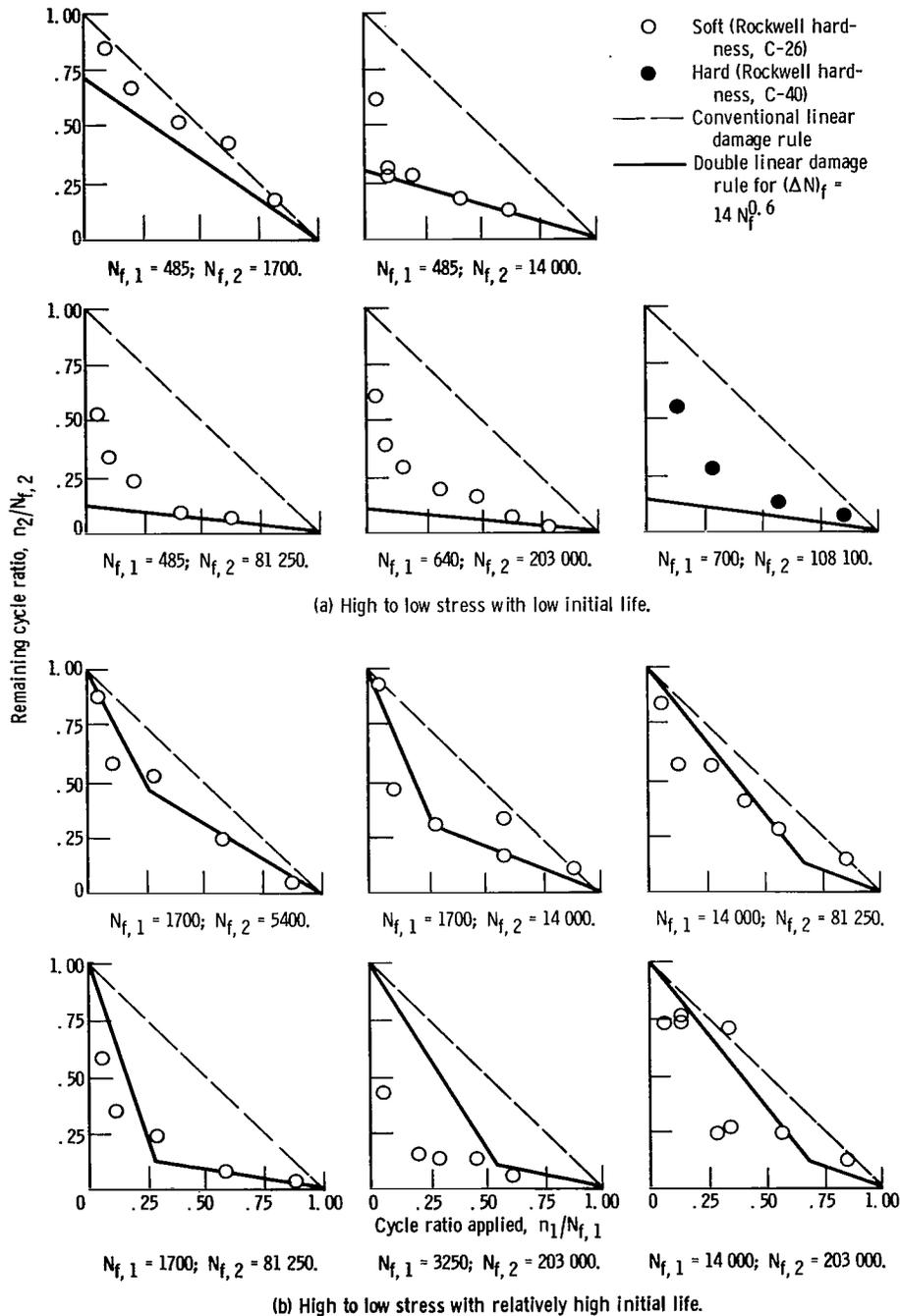
Figure 6. - Comparison of predicted fatigue behavior by conventional and double linear damage rules with experimental data for two-stress-level tests. Material, SAE 4130 steel; R. R. Moore rotating bending tests.

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level.  In both cases, however, the order of load application was that of high stress followed by low stress.  In general, the results obtained with 4130 steel are the same as those obtained with the maraging steel for similar test conditions.  For the most part, agreement between predictions by the double linear rule with $(\Delta N)_f = 14 \, N_f^{0.6}$ and experimental data was good, although deviations between predictions and data are clearly present in some cases.  As in the case of the maraging steel, a more conservative prediction was always provided by the double linear damage rule than by the conventional linear damage rule when the high stress was applied first if the expression $14 \, N_f^{0.6}$ was assumed to be representative of the crack propagation stage.

## Examination of the Assumed Relation for Crack Propagation $(\Delta N)_f$

In view of the deviations noted between predictions and experimental results, closer examination of the assumption that the crack-propagation period $(\Delta N)_f$ may be expressed by the relation $14 \, N_f^{0.6}$ was clearly in order.  Before considering the possibility of improving this relation by changing the coefficient or exponent or both, however, attempts were made to determine experimentally if the propagation period $(\Delta N)_f$ was uniquely dependent upon fatigue life, $N_f$.  The results of one such investigation are shown in figure 7.  Values of $\Delta N_1$ and $\Delta N_2$ were obtained from two-stress-level tests with SAE 4130 soft steel in which $N_{f,1}$ was 485 cycles and $N_{f,2}$ was 14 000 cycles with the use of the graphical method previously described and illustrated in figure 1 (p. 4).  These values are plotted in figure 7 as points B and A'.  The values of $\Delta N_1$ and $\Delta N_2$
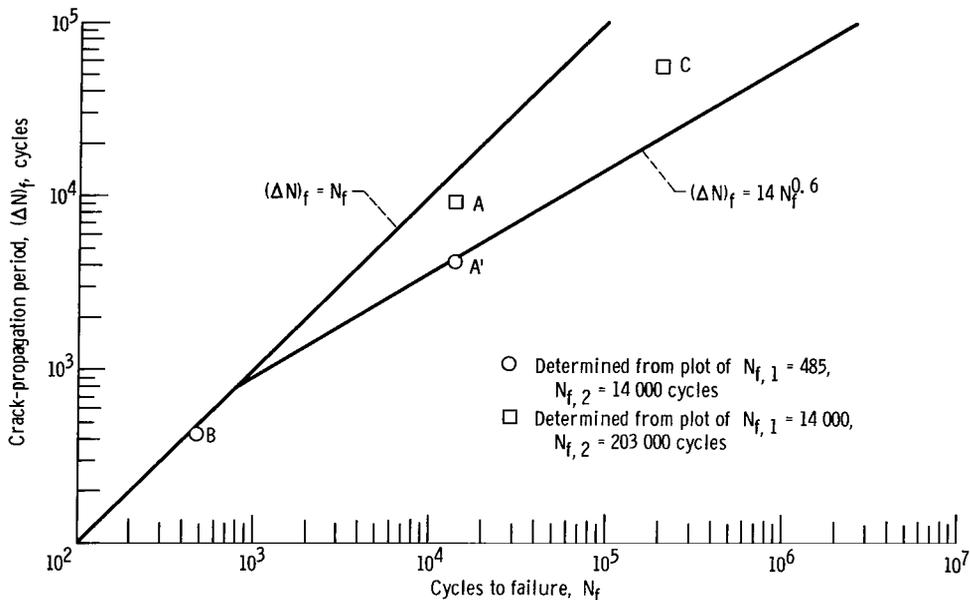


Figure 7. – Effect of stress combinations in determination of crack-propagation period.  Material, 4130 soft steel; R. R. Moore rotating bending tests.

similarly obtained from another set of data in which $N_{f,1}$ was 14,000 cycles and $N_{f,2}$ was 203 000 cycles are also plotted in figure 7 as points A and C. Obviously, points A' and A, both of which relate to determinations for a life of 14 000 cycles, do not coincide as they would be expected to if $\Delta N$ were solely a function of $N_f$. Thus, whether a given stress (corresponding to a fixed life) is used as the first or the second stress in a two-stress-level fatigue test is clearly significant, and entirely different results can be obtained. If the representation of the crack-propagation period by the expression $14\,N_f^{0.6}$ were correct, the points determined as previously mentioned would fall on the line with a slope of 0.6 when $N_f$ values were greater than 730 cycles. It must therefore be concluded that the concept of representing crack propagation by a universal relation in terms of $N_f$, whether the coefficient is 14 or any other number, produces some discrepancies. Other tests of the same type for other combinations of stress were also made, which gave similar results to those shown in figure 7.

There are probably several reasons why the crack-propagation period is not uniquely related to total fatigue life (i.e., life to failure of the specimen). Reexamination is in order of the concepts that the effective crack length for crack initiation is the same at all stress levels and that extending a crack at a stress level different from that at which it was initiated is simply a continuation of the same process. The mechanisms involved are not so readily explainable. What may correspond to a crack length for effective crack initiation at one stress level may not be so at another stress level.

Another reason for the discrepancies relates to the hardening and softening characteristics of materials. Upon changing to a new strain level in a two-step test, a material that hardens or softens extensively will not reach the same stress level for a given applied strain as it would have, had that same strain been maintained throughout the test. This concept is illustrated in figures 8 and 9. Figure 8 shows the stress



Figure 8. – Stress response in axial strain cycling for constant strain amplitude tests of maraging steel.
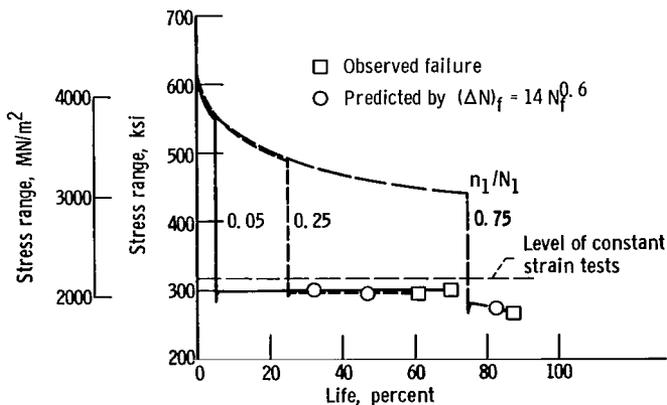


Figure 9. – Stress response in axial strain cycling two-strain-level tests of maraging steel.

response in axial strain cycling at constant strain amplitude for maraging steel. Two tests were run at each of two values of total strain. These values were chosen to give lives on the order of 400 and 16 000 cycles. Agreement between the two tests run at each condition was good and demonstrated the ability to maintain and control approximately the same strain level on the fatigue machines used. Figure 9 illustrates the stress response in axial strain cycling two-strain-level tests for maraging steel when the higher of these two-strain levels was applied first and the lower strain level subsequently applied. Maraging steel is a cyclic strain-softening material. As continually increasing percentages of the life were applied at the higher strain level, the stress required to maintain that strain level progressively decreased. Also shown on the figure are the results of running for 5, 25, and 75 percent of the total life at the initial strain followed in each case by operation to failure at the lower strain level. In each case, the stress required to maintain the lower level of constant strain in these two-step tests was lower than that required to maintain this level of strain in a single-strain-level test. Thus, the material was oversoftened as a result of the initial application of a high strain level. As a consequence, a longer life would be expected than that predicted by the double linear damage rule using the expression $14 \, N_f^{0.6}$ as representing the crack propagation stage. Figure 9 shows this to be true. The circles represent the predicted lives according to the double linear damage rule using $(\Delta N)_f = 14 \, N_f^{0.6}$; the squares represent the experimentally determined lives.

In order to describe the cumulative fatigue damage process more accurately, methods must be sought to account for the factors discussed. The double linear damage rule concept may be retained as discussed in the next section.

## An Alternative Viewpoint of the Double Linear Damage Rule

In the suggested alternative approach, the concept of crack initiation and propagation in the literal sense is altered to represent two effective phases of the fatigue process, which might be designated as Phases I and II. The assumption of a linear damage rule for each of these two phases, however, would be retained. That such an assumption is reasonable may be seen by inspection of the data obtained in this investigation, particularly some of the rotating bending test results obtained with SAE 4130 steel (fig. 6(a)). These results are replotted in figure 10 to illustrate how well two straight lines originating at ordinate and abscissa values of 1.0 fit the data. The coordinates of the intersection of these lines (as defined in fig. 1) determine the values of $N_o$ and $\Delta N$ used to establish the fatigue curves, which represent Phases I and II of the fatigue process. In keeping with this change in concept, the form of the rule would be different for different materials and for different extreme loads that might be applied in a test. Additional
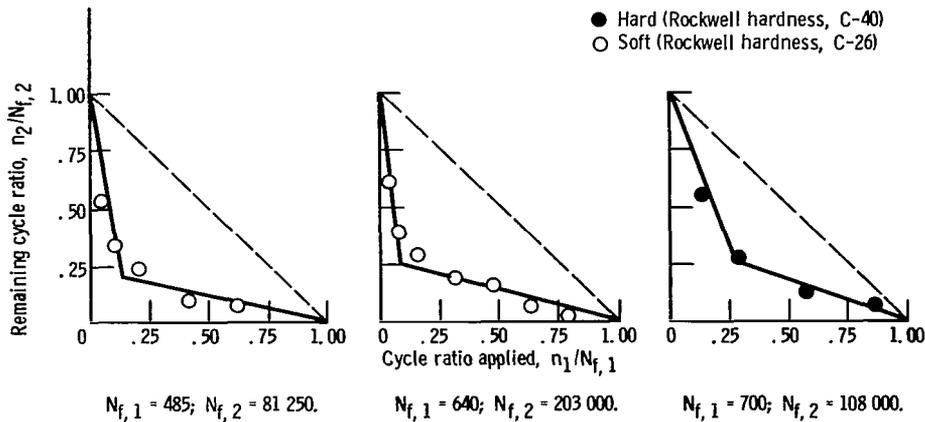
Figure 10. – Illustration of fit of two straight lines to rotating bending data obtained from two-stress-level tests with SAE 4130 steel.

experimental verification of this approach is still needed; however, the complexities discussed are accounted for in an approximate fashion. The use of a new fatigue curve different from that of the original material in predicting remaining fatigue life after prestressing is not inconsistent with other methods such as that of Corten and Dolan (ref. 4). In general, such previous approaches have assumed that the modified fatigue curves are best determined from a consideration of the highest and the lowest stress levels of the applied spectrum. This basic approach will also be adopted in the following treatment.

The double linear damage rule may be applied in the light of this revised concept to any anticipated loading spectrum for a given material if a decision is first made as to which are the highest and the lowest loads of importance. Stress levels below the fatigue limit will not be considered for the present. A series of two-stress-level tests would be run in which the highest stress level would be applied first, followed by operation to failure at the lowest stress level of significance within the loading spectrum. This procedure should bring into play the important variables such as any extremes of hardening or softening of the material and extremes of crack length involved in initiating and propagating an effective crack. From such a series of tests and for that particular combination of stress levels, the values of $N_0$ and $\Delta N$ may be determined for both stresses by using the graphical procedure for applying the double linear damage rule as previously described. These values may then be plotted as shown in figure 11 at the two stress levels, and curves may be sketched between these points that are consistent with the appearance of the original fatigue curve. It would then be possible to analyze by the double linear damage rule the effect of block or spectrum loading of any pattern that could also include loadings between the highest and the lowest levels. The $N_0$ and the $\Delta N$ curves would be used for determining the effective values of Phases I and II of the fatigue process. These curves would replace the expression $(\Delta N)_f = 14\, N_f^{0.6}$ or any other variation of such a formula. One example of applying this procedure is given in appendix B.

17
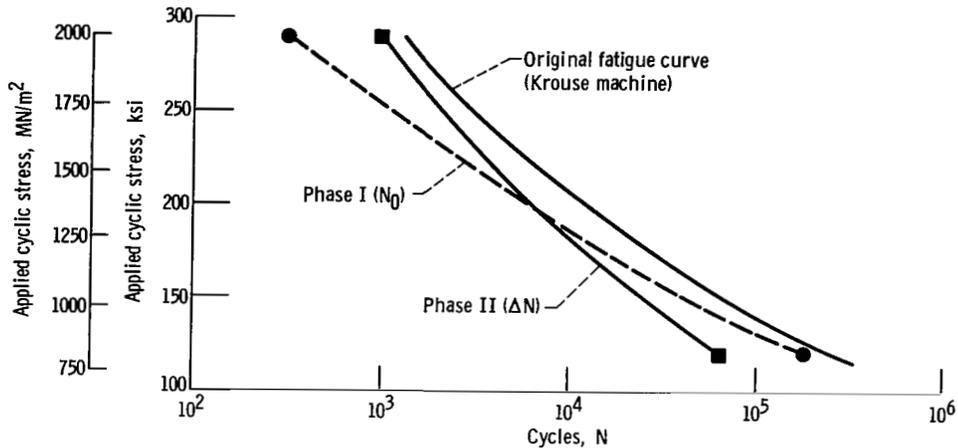
Figure 11. - Determination of Phases I and II of fatigue process from two-stress-level tests at highest and lowest stress levels of loading spectrum. Material, maraging steel.

Although at this early stage of the development of this approach, it seems most convenient to use a two-level test as illustrated in figure 1 (p. 4) to determine the effective values of Phases I and II for given extremes of stress or strain level within a given loading spectrum, further consideration may reveal better approaches for particular circumstances. For example, it may be desirable to use a block loading with the highest and the lowest significant stresses in the spectrum of service loading for establishing the point of effective transition between the two phases (point B in fig. 1), rather than merely following the high stress cycles by continuous loading at the lower stress. Since only two unknowns are involved (the points of effective transition from Phase I to Phase II for each of the two stress levels when applied in conjunction with the other), only two tests would be required to determine the two unknowns. This approach is further discussed in the CONCLUDING REMARKS.

## Limited Experimental Verification of Alternative

## Viewpoint of Double Linear Damage Rule

In order to provide an indication of the validity of the alternative viewpoint of the double linear damage rule, a series of repetitive alternating two-stress-level block tests was conducted. Such a test may be considered as the next step in complexity to the single block two-stress-level test, which provided most of the data obtained in this investigation. The manner of conducting the test is fully described in appendix C. Briefly, a two-stress-level single block base was selected. Equal fractional portions of the number of cycles at each stress level in the block were applied in a repetitive fashion. The double linear damage rule was applied to predict the summation of the cycle ratios required to cause failure
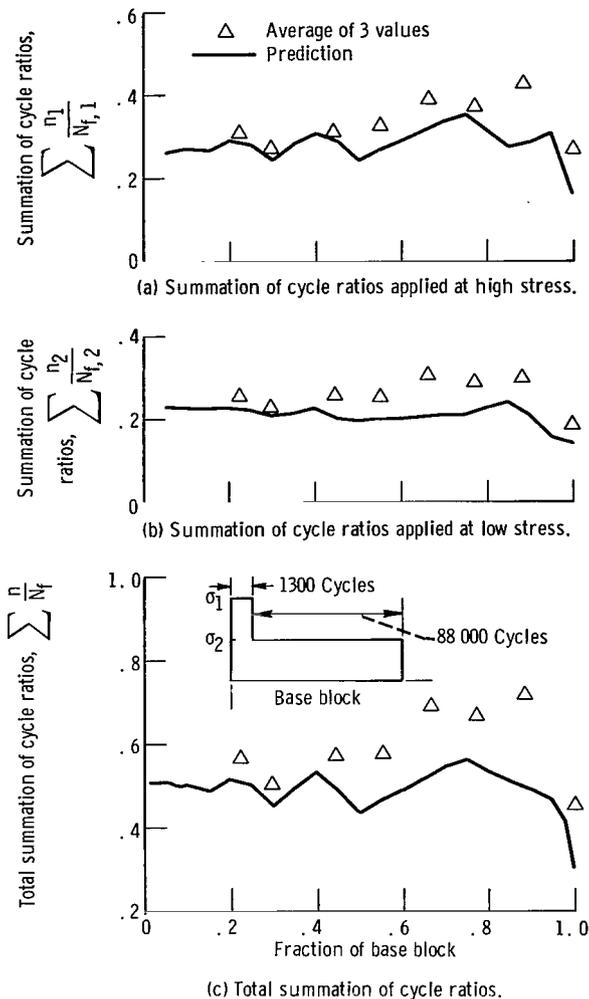
Figure 12. - Comparison of experimental and predicted summation of cycle ratios for alternating two-stress-level tests. Predictions made by double linear damage rule using experimental data to define Phases I and II of the fatigue process.

with the use of experimentally determined curves representing Phases I and II of the fatigue process. A numerical example illustrating this method is also given in appendix C.

The experimental results of these tests as well as the predictions are shown in figure 12. The summations of the cycle ratios are plotted against the fractions of the basic block considered. Figure 12(a) deals with the summation of cycle ratios applied at the high stress; figure 12(b) deals with the summation of cycle ratios at the low stress; and figure 12(c) deals with the total summation. The experimental data shown represent the arithmetic averages of three data points obtained at each fraction of the block considered. In general, reasonable agreement exists between the predicted results and the experimental data. The irregularity in the predicted results is associated with abrupt numerical changes that are introduced when predicted failure changes from the high to the low portions of the block loading pattern. In all cases, the predictions by the double linear damage rule are conservative. Much additional experimental verification is needed to establish fully the usefulness of the double linear damage rule in predicting remaining fatigue life for more complex loading spectra. The single series of tests contained in figure 12 serves more to illustrate the approach than to prove validity of the method.

# CONCLUDING REMARKS

Cumulative fatigue damage in two-stress-level tests was predicted with reasonable accuracy for smooth 1/4-inch-diameter specimens by a previously proposed method based on the concept of a double linear damage rule. While a double linear damage rule

used with the assumption that $(\Delta N)_f = 14\, N_f^{0.6}$ gives better results than the conventional linear damage rule, it is not adequate where crack initiation and propagation are expressed solely in terms of total life. Other representations of crack initiation and propagation might be more accurate, but they must take into account the hardening and the softening characteristics of the material and more particularly the effect of the stress levels involved. An alternative viewpoint of the double linear damage rule, in which the concept of crack initiation and propagation in the literal sense is altered to represent two effective phases of the fatigue process designated as Phases I and II which can be determined experimentally, appears to overcome some of the limitations of the original proposal. The form of the rule then becomes different for different materials and for different extreme loads that might be applied. In principle, only two tests are required to determine the point of transition between the two effective phases of the fatigue process. The actual number of tests employed can, of course, be greater, depending on the degree of accuracy desired. A suggested approach is to conduct the first test by applying a cycle ratio $n_1/N_{f,1}$ of approximately 0.2 at the high stress and then to operate to failure at the low stress. For the second test, apply a cycle ratio $n_1/N_{f,1}$ of approximately 0.5 at the high stress before running to failure at the low stress. Two straight lines emanating from ordinate and abscissa values of one on a plot of $n_2/N_{f,2}$ against $n_1/N_{f,1}$ may then be drawn, each of which passes through one of the data points describing these tests. The coordinates of the intersection of these two straight lines will determine the values of $N_o$ and $\Delta N$ used to establish the fatigue curves which represent Phases I and II of the fatigue process.

It is emphasized that the purpose of the two-step test is to provide a determination of the transition between these two phases of fatigue and, thereby, to enable the investigator to construct effective fatigue curves for each phase as shown in figure 11. Once these two curves are constructed, their application is intended for all spectrums of loading involving as loading extremes the two stresses used for their determination. Thus, use of these curves is not limited to two-step tests. Until further research is conducted to extend the application, the procedure must be limited to the study of smooth 1/4-inch-diameter specimens. It may, however, be regarded as a first step in the direction of eventually predicting the effect of a complex loading history on the life of more complex structures.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 14, 1966,
129-03-15-06-22.

# APPENDIX A

## APPLICATION OF DOUBLE LINEAR DAMAGE RULE TO A TWO-STRESS-LEVEL TEST USING THE RELATION $14\,N_f^{0.6}$ TO DEFINE THE CRACK PROPAGATION PERIOD

Two stress levels 1 and 2, at which the total lives of the original material are $N_{f,1}$ and $N_{f,2}$, respectively, and a prestress cycle ratio $n_1/N_{f,1}$ are given; it is desired to find the number of cycles that can be applied at the second stress level. The values of $\Delta N_1$ and $\Delta N_2$ are first determined from equation (1). The values of $N_{o,1}$ and $N_{o,2}$ can then be obtained with the use of equation (2). Next, the ratio $N_{o,1}/N_{f,1}$ is determined. Where $N_{f,1} > 730$ cycles, if $n_1/N_{f,1}$ is equal to $N_{o,1}/N_{f,1}$, the crack-initiation stage has just been completed, and the cyclic life remaining at the second stress level is exactly equal to that making up the crack-propagation period, or

$$n_2 = N_{f,2} - N_{o,2} = \Delta N_2 \tag{A1}$$

If the ratio $n_1/N_{f,1} > N_{o,1}/N_{f,1}$, the life remaining at the second stress level may be expressed as

$$n_2 = \left(1 - \frac{n_1 - N_{o,1}}{\Delta N_1}\right)\Delta N_2 \tag{A2}$$

If the ratio $n_1/N_{f,1} < N_{o,1}/N_{f,1}$, the life remaining at the second stress level may be expressed as

$$n_2 = \left(1 - \frac{n_1}{N_{o,1}}\right)N_{o,2} + \Delta N_2 \tag{A3}$$

Where $N_{f,1} < 730$ cycles, it is assumed that there is no lengthy crack-initiation period, but rather that total life consists only of crack propagation. Then, the life remaining at the second stress level can be determined from the expression

$$n_2 = \left(1 - \frac{n_1}{N_{f,1}}\right)\Delta N_2 \tag{A4}$$

In effect then for the latter case, total life at stress 2 is determined from the linear damage rule for crack propagation only.

# APPENDIX B

## APPLICATION OF DOUBLE LINEAR DAMAGE RULE USING EXPERIMENTAL
## DATA TO DEFINE PHASES I AND II OF FATIGUE PROCESS

In this appendix, detailed examples are given to show how the Phase I and Phase II curves of figure 11 (p. 18) were obtained and how these curves might possibly be used to predict the life of a three-stress-level fatigue test.

To define the two phases of the fatigue process, some two-stress-level tests must first be conducted with the use of the highest and the lowest stresses of importance in the particular loading spectrum under consideration. For this illustration, the material chosen was the maraging steel, and the two stresses chosen were 290 000 psi (2000 $MN/m^2$) and 120 000 psi (827 $MN/m^2$). From the original fatigue curve of figure 11 for this material (obtained on a Krouse machine), $N_{f,1}$ and $N_{f,2}$ equal 1280 and 244 000 cycles, respectively. The data obtained from a series of tests conducted by applying various cycle ratios $n_1/N_{f,1}$ at the high stress and operating to failure at the low stress are plotted in figure 13. Straight lines were then fitted through the data. These lines were required to originate from cycle-ratio values of 1.0 on the ordinate and the abscissa. The coordinates of the intersection point B are $n_1/N_{f,1}$ and $n_2/N_{f,2}$ and have numerical values of 0.25 and 0.24, respectively. Since these ratios are equivalent to $N_{o,1}/N_{f,1}$ and $\Delta N_2/N_{f,2}$ as shown in figure 1 (p. 4), the values of $N_{o,1}$, $\Delta N_1$, $N_{o,2}$, and $\Delta N_2$ were calculated to be 320, 960, 185 000, and 59 000 cycles, respectively. These values were then plotted at their corresponding stresses as shown in figure 11 and were connected by curves, the shapes of which are guided by the shape of the original fatigue curve. These curves may then be used in separate linear summations for Phases I and II of the fatigue process.

As a numerical example of the method of applying the double linear damage rule using these Phase I and Phase II curves, a three-stress-level test in which the highest and the lowest stresses are 290 000 and 120 000 psi is considered. It is required to predict the remaining life at a third stress level, 200 000 psi (1380 $MN/m^2$), after 200 and 40 000 cycles, respectively, have been applied at the



Figure 13. - Two straight lines fitted to data from two-stress-level tests of maraging steel. $N_{f,1}$ = 1280; $N_{f,2}$ = 244 000.

highest and the lowest stresses. Values of $N_{o,3}$ and $\Delta N_3$ can be obtained from the Phase I and Phase II curves of figure 11. Thus, $N_{o,3}$ equals 5900 cycles and $\Delta N_3$ equals 6100 cycles. The application of 200 cycles at stress 1 results in a ratio of

$$\frac{n_1}{N_{o,1}} = 0.63 < 1$$

which indicates that Phase I has not been completed and that it is continued at the second stress level. The application of 40 000 cycles at the second stress results in a ratio of

$$\frac{n_2}{N_{o,2}} = 0.22$$

Summing the cycle ratios applied at stresses 1 and 2 results in

$$\frac{n_1}{N_{o,1}} + \frac{n_2}{N_{o,2}} = 0.63 + 0.22 = 0.85 < 1$$

The portion $x$ of the number of cycles applied at stress 3 needed to complete Phase I is, from equation (3),

$$\frac{x}{N_{o,3}} = 1 - \left( \frac{n_1}{N_{o,1}} + \frac{n_2}{N_{o,2}} \right)$$

or

$$x = 885 \text{ cycles}$$

The portion of the number of cycles appli d at stress 3, that is needed to complete Phase II is, from equation (4),

$$\frac{y}{6100} = 1$$

or

$$y = 6100 \text{ cycles}$$

Then, the total number of cycles remaining at the third stress level is equal to

$$x + y = 885 + 6100 = 6985 \text{ cycles}$$

# APPENDIX C

## APPLICATION OF DOUBLE LINEAR DAMAGE RULE TO ALTERNATING
## TWO-STRESS-LEVEL TESTS IN WHICH EXPERIMENTAL DATA ARE
## USED TO DEFINE PHASES I AND II OF FATIGUE PROCESS

Alternating two-stress-level tests were conducted as follows: Initially, two-stress-level tests were conducted at various cycle ratios, $n_1/N_{f,1}$, at a high stress, 190 000 psi (1310 MN/m$^2$), and the remaining cyclic life ratios $n_2/N_{f,2}$ were determined at a second stress, 110 000 psi (785 MN/m$^2$). At 190 000 psi, $N_{f,1}$ was 8000 cycles. At 110 000 psi, $N_{f,2}$ was 625 000 cycles. These $N_f$ values were obtained with specimens from a different heat of maraging steel from that for which the R. R. Moore machine data previously described herein for this material were obtained. The results of the tests in which different cycle ratios were applied at 190 000 psi were plotted as shown in figure 14. Best visual-fit straight lines were drawn through the data, which again met the requirement that they originate from a value of cycle ratio of 1.0 on the ordinate and the abscissa. From the coordinates of the intersection point B and the values of $N_{f,1}$ and $N_{f,2}$, the Phase I and Phase II parameters were determined. Thus, $N_{o,1}$ equaled 1300 cycles; $\Delta N_1$, 6700 cycles; $N_{o,2}$, 537 000 cycles; and $\Delta N_2$, 88 000 cycles. Several alternating two-stress-level block tests were then specified such that various fractions of 1300 cycles were applied at the high stress of 190 000 psi and identical fractions of 88 000 cycles were applied at the low stress.

The following numerical example illustrates the manner of applying the double linear damage rule to an alternating two-stress-level test. The example considers an alternating block test in which the alternating or repeated block is taken to be one-half of the number of cycles at each stress level in the base block. Both the base block and the alternating half block are shown diagrammatically in figure 15. The base block for this example (as well as for all tests of fig. 12, p. 19) is defined as consisting of 1300 cycles at the first stress and 88 000 cycles at the second stress. To determine the number of cycles to complete Phase I equation (3) is applied. Since



Figure 14. – Experimental determination of Phase I and Phase II transition used in conjunction with double linear damage rule. Material, maraging steel; $N_{f,1}$ = 8000; $N_{f,2}$ = 625 000.

$$\frac{650}{1300} + \frac{44\ 000}{537\ 000} < 1$$
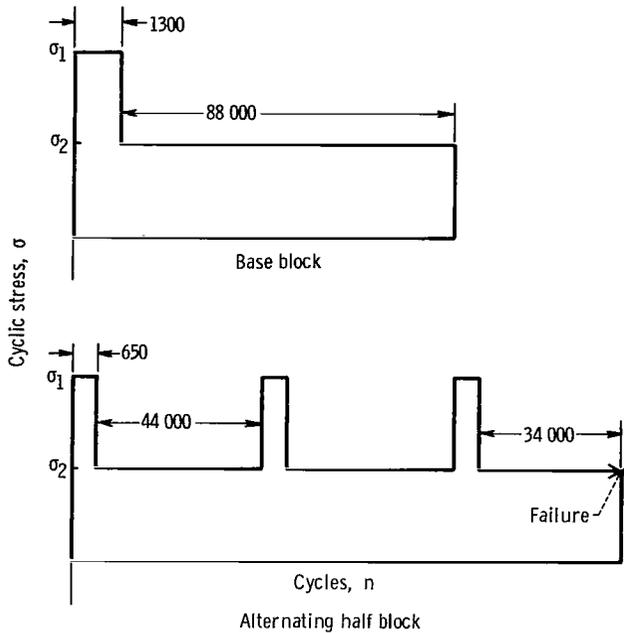
Figure 15. - Diagram of loading pattern for numerical example of appendix C.

it is apparent that Phase I has not been completed in the first loading block. To determine if Phase I is completed in the high-stress portion of the second loading block, again equation (3) is applied:

$$\frac{650}{1300} + \frac{44\ 000}{537\ 000} + \frac{x}{1300} = 1$$

or $x = 543$ cycles, at which Phase I is complete. Next, the number of cycles needed to complete Phase II is determined. Equation (4) is applied to determine whether Phase II is completed in the second loading block. This application gives

$$\frac{650 - 543}{6700} + \frac{44\ 000}{88\ 000} < 1$$

which indicates that Phase II has not been completed in block 2. Therefore, it is necessary to determine whether Phase II is completed in the high-stress portion of block 3. Thus,

$$\frac{650 - 543}{6700} + \frac{44\ 000}{88\ 000} + \frac{y}{6700} = 1$$

and

$$y = 3243$$

Since $y > 650$, Phase II has not been completed in the high-stress portion of block 3, and the next step is to determine whether it is completed in the low-stress portion of this block. Thus,

$$\frac{650 - 543}{6700} + \frac{44\ 000}{88\ 000} + \frac{650}{6700} + \frac{z}{88\ 000} = 1$$

and $z = 34\ 000$. Since $z < 44\ 000$ cycles, Phase II has been completed, and failure occurs during the low-stress portion of block 3. The total summation of cycle ratios $\sum n/N_f$ for this example then is

$$\sum \frac{n}{N_f} = \frac{650}{8000} + \frac{44\ 000}{625\ 000} + \frac{650}{8000} + \frac{44\ 000}{625\ 000} + \frac{650}{8000} + \frac{34\ 000}{625\ 000} = 0.44$$

In the same manner, other apportionments of the cycles sustained at the intersection point of a two-stress-level test (analogous to point B of fig. 1, p. 4) can be computed, and the expected number of cycles to failure can be predicted for alternating block loading applications.

# REFERENCES

1. Kaechele, Lloyd: Review and Analysis of Cumulative-Fatigue-Damage Theories. Rep. No. RM-3650-PR, Rand Corp., Aug. 1963.

2. Richart, F. E., Jr.; and Newmark, N. M.: An Hypothesis for the Determination of Cumulative Damage in Fatigue. ASTM Proc., vol. 48, 1948, pp. 767-800.

3. Marco, S. M.; and Starkey, W. L.: A Concept of Fatigue Damage. ASME Trans., vol. 76, no. 4, May 1954, pp. 627-632.

4. Corten, H. T.; and Dolan, T. J.: Cumulative Fatigue Damage. International Conference on Fatigue of Metals. Vol. 1. Inst. of Mech. Engrs., 1956, Session 3, paper no. 2.

5. Freudenthal, Alfred M.; and Heller, Robert A.: On Stress Interaction in Fatigue and a Cumulative Damage Rule. Part I - 2024 Aluminum and SAE 4340 Steel Alloys. (WADC TR 58-69, pt. 1, DDC No. AD-155687), Columbia Univ., June 1958.

6. Palmgren, Arvid: Die Lebensdauer von Kugellagern. Z. Ver. Deut. Ing., vol. 68, no. 14, Apr. 5, 1924, pp. 339-341.

7. Miner, Milton A.: Cumulative Damage in Fatigue. J. Appl. Mech., vol. 12, no. 3, Sept. 1945, pp. 159-164.

8. Henry, D. L.: A Theory of Fatigue-Damage Accumulation in Steel. ASME Trans., vol. 77, no. 6, Aug. 1955, pp. 913-918.

9. Manson, S. S.; Nachtigall, A. J.; and Freche, J. C.: A Proposed New Relation for Cumulative Fatigue Damage in Bending. ASTM Proc., vol. 61, 1961, pp. 679-703.

10. Manson, S. S.; Nachtigall, A. J.; Ensign, C. R.; and Freche, J. C.: Further Investigation of a Relation for Cumulative Fatigue Damage in Bending. J. Eng. Industry, vol. 87, no. 1, Feb. 1965, pp. 25-35.

11. Rally, F. C.; and Sinclair, G. M.: Influence of Strain Aging on the Shape of the S-N Diagram. Rep. No. 87, Dept. of Theoretical and Appl. Mechanics, Univ. of Illinois, June 1955.

12. Grover, Horace J.: An Observation Concerning the Cycle Ratio in Cumulative Damage. Symposium on Fatigue of Aircraft Structures. Spec. Tech. Publ. No. 274, ASTM, 1960, pp. 120-124.

13. Manson, S. S.: Interfaces between Fatigue, Creep, and Fracture. Intern. J. Fracture Mech., vol. 2, no. 1, Mar. 1966, pp. 327-363.

14. Manson, S. S.; and Hirschberg, M. H.: Prediction of Fatigue of Notched Specimens by Consideration of Crack Initiation and Propagation. NASA TN D-3146, 1966.

15. Smith, Robert W.; Hirschberg, Marvin H.; and Manson, S. S.: Fatigue Behavior of Materials Under Strain Cycling in Low and Intermediate Life Range. NASA TN D-1574, 1963.

## TABLE I. - MATERIAL DESCRIPTION

| Material | Nominal composition, weight percent | Condition | Hardness, Rockwell C - |
|---|---|---|---|
| 4130 (soft) | C, 0.030; Mn, 0.50; P, 0.040; S, 0.040; Si, 0.28; Cr, 0.95; Mo, 0.20; Fe remainder | 1700° F, 1/2 hr in salt, water quench; 1200° F, 1/2 hr in salt, air cool | 25 to 27 |
| 4130 (hard) | C, 0.030; Mn, 0.50; P, 0.040; S, 0.040; Si, 0.28; Cr, 0.95; Mo, 0.20; Fe remainder | 1600° F, 1/2 hr in salt, water quench; 750° F, 1 hr in salt, air cool | 39 to 40 |
| Maraging steel | C, 0.03 max.; Si, 0.10 max.; Mn, 0.10 max.; S, 0.010 max.; P, 0.010 max.; Ni, 18.50; Co, 9.00; Mo, 4.80; Al, 0.10; Ti, 0.60; B, 0.003; Zr, 0.02 added; Ca, 0.05 added | 1500° F, 3/4 hr, air cool; 900° F, $3\frac{1}{2}$ hr, air cool  }(a) | 52 |
| | | 1700° F, 1/2 hr, air cool; 1500° F, 1 hr, air cool; 900° F, $3\frac{1}{2}$ hr, air cool  }(b) | 52 |

[a] Heat treatment for material used in R. R. Moore and axial tests.

[b] Heat treatment for material used in Krouse tests and R. R. Moore tests of specimens designated R, S, T, U, or V in tables III, V, and VII.

## TABLE II. - TENSILE PROPERTIES OF TEST MATERIALS

| Material | Yield strength, 0.2 percent offset, ksi (a) | Ultimate strength, ksi (a) | Fracture strength, ksi (a) | Reduction in area, percent | Modulus of elasticity, ksi (a) |
|---|---|---|---|---|---|
| 4130 (soft) | 113 | 130 | 245 | 67.3 | $32\times10^{6}$ |
| 4130 (hard) | 197 | 207 | 302 | 54.7 | 29 |
| Maraging steel | --- | 295 | 380 | 50.7 | 27 |

[a] Multiply by 6.8948 to convert to $MN/m^2$.

TABLE III. - ROTATING BENDING FATIGUE TEST DATA OBTAINED AT CONSTANT NOMINAL STRESS AMPLITUDE

| Specimen | Stress level, ksi (a) | Test frequency, rpm (b) | Cycles to failure | Specimen | Stress level, ksi (a) | Test frequency, rpm (b) | Cycles to failure | Specimen (c) | Stress level ksi (a), (d) | Test frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Maraging steel; Krouse machine | | | | Maraging steel; Krouse machine | | | | Maraging steel; R. R. Moore machine | | | |
| 8B18 | 290 | 100 | 1117 | 8G16 | 200 | 5000 | 13100 | 8B37 | 300AC | 1000 | 625 |
| 8K7 | 290 | 100 | 1166 | 8K17 | 200 | 5000 | 13700 | 8A37 | 300AC | 1000 | 700 |
| 8C5 | 290 | 100 | 1203 | 8H2 | 200 | 5000 | 13800 | 8C32 | 300 | 100 | 836 |
| 8P18 | 290 | 100 | 1267 | 8G10 | 200 | 3000 | 14100 | 8C18 | 300 | 100 | 915 |
| 8H6 | 290 | 100 | 1307 | 8J15 | 200 | 5000 | 15000 | 8C22 | 300AC | 100 | 942 |
| 8J12 | 290 | 100 | 1356 | 8F3 | 180 | 3000 | 19300 | 8C2 | 300AC | 100 | 991 |
| 8N17 | 290 | 100 | 1369 | 8H13 | 180 | 5000 | 20400 | 8A38 | 300AC | 100 | 1060 |
| 8L14 | 290 | 100 | 1392 | 8D15 | 180 | 3000 | 23200 | 8B11 | 290AC | 100 | 1201 |
| 8K16 | 290 | 1000 | 1400 | 8F11 | 170 | 5000 | 32700 | 8C12 | 280 | 1000 | 825 |
| 8F18 | 278 | 100 | 1741 | 8C1 | 170 | 5000 | 38900 | 8B4 | 280AC | 1000 | 1725 |
| 8G3 | 270 | 100 | 1807 | 8E7 | 170 | 5000 | 42300 | 8B1 | 280AC | 1000 | 1825 |
| 8G1 | 270 | 100 | 1918 | 8A11 | 160 | 5000 | 42500 | 8A22 | 260 | 100 | 2093 |
| 8J3 | 270 | 100 | 1996 | 8D11 | 160 | 5000 | 47500 | 8B7 | 260 | 100 | 2160 |
| 8F3 | 270 | 100 | 2129 | 8G18 | 160 | 3000 | 50000 | 8B21 | 260 | 100 | 2502 |
| 8D7 | 270 | 100 | 2187 | 8K3 | 160 | 5000 | 63000 | 8B14 | 260AC | 1000 | 2800 |
| 8O13 | 266 | 100 | 2100 | 8F5 | 160 | 5000 | 75500 | 8B39 | 260AC | 1000 | 3150 |
| 8L18 | 266 | 100 | 2357 | 8F7 | 160 | 5000 | 82600 | 8C4 | 240AC | 1000 | 5050 |
| 8N7 | 266 | 100 | 2415 | 8F1 | 160 | 3000 | 224100 | 8A20 | 240AC | 1000 | 5425 |
| 8C3 | 260 | 5000 | 2000 | 8C9 | 150 | 4000 | 70900 | 8A3 | 220 | 100 | 5527 |
| 8H17 | 260 | 100 | 2166 | 8E14 | 140 | 5000 | 54600 | 8A11 | 220 | 100 | 5994 |
| 8A10 | 260 | 5000 | 2200 | 8H7 | 140 | 5000 | 84100 | 8C26 | 220AC | 1000 | 7575 |
| 8G2 | 260 | 100 | 2230 | 8J14 | 140 | 5000 | 92100 | 8C31 | 220AC | 1000 | 7975 |
| 8G7 | 260 | 100 | 2394 | 8K5 | 140 | 5000 | 103000 | 8A19 | 200 | 1000 | 9000 |
| 8E10 | 260 | 100 | 2561 | 8G12 | 140 | 5000 | 149500 | 8B29 | 200 | 1000 | 9500 |
| 8E1 | 260 | 100 | 2663 | 8H12 | 120 | 5000 | 76800 | 8A17 | 200 | 1500 | 10770 |
| 8D1 | 260 | 100 | 2695 | 8H14 | 120 | 5000 | 100400 | 8B9 | 200AC | 1000 | 13125 |
| 8A6 | 250 | 100 | 2917 | 8A9 | 120 | 5000 | 140200 | 8B13 | 200AC | 1000 | 13200 |
| 8J4 | 250 | 5000 | 3000 | 8C6 | 120 | 5000 | 232800 | 8B19 | 190 | 1500 | 11800 |
| 8C2 | 250 | 100 | 3018 | 8K11 | 120 | 5000 | 346400 | 8C33 | 190AC | 1000 | 13275 |
| 8F13 | 250 | 100 | 3062 | 8A2 | 120 | 5000 | 380800 | 8A30 | 190AC | 1000 | 15925 |
| 8H4 | 240 | 100 | 3000 | 8D8 | 120 | 5000 | 836000 | 8A25 | 190AC | 1000 | 16425 |
| 8A15 | 240 | 100 | 3315 | 8M14 | 110 | 5000 | 472600 | 8B10 | 180 | 2000 | 15500 |
| 8A16 | 240 | 100 | 3417 | 8L10 | 110 | 5000 | 475000 | 8A39 | 180 | 2000 | 17000 |
| 8B1 | 240 | 100 | 3559 | 8D4 | 110 | 5000 | 814500 | 8C21 | 180 | 2000 | 18600 |
| 8G4 | 240 | 100 | 3713 | 8M15 | 105 | 5000 | 660300 | 8C24 | 180 | 1600 | 18650 |
| 8K4 | 240 | 1000 | 3800 | 8D7 | 105 | 5000 | 766600 | 8C34 | 180AC | 1000 | 25200 |
| 8A3 | 240 | 5000 | 4000 | 8B14 | 105 | 5000 | 1555400 | 8B28 | 180AC | 1000 | 26775 |
| 8A4 | 240 | 5000 | 4100 | | | | | 8A16 | 170 | 2000 | 29500 |
| 8F10 | 240 | 3000 | 4200 | | | | | 8B20 | 160 | 2000 | 32250 |
| 8F14 | 240 | 5000 | 4800 | | | | | 8C25 | 160 | 1800 | 33250 |
| 8J2 | 240 | 3000 | 4800 | | | | | 8C16 | 160 | 2000 | 34250 |
| 8K13 | 220 | 5000 | 5600 | | | | | 8C10 | 160 | 2000 | 42680 |
| 8J8 | 220 | 3000 | 7200 | | | | | 8A33 | 160AC | 1000 | 44000 |
| 8C4 | 210 | 3000 | 7500 | | | | | 8A40 | 160AC | 1000 | 47625 |
| 8C10 | 210 | 3000 | 8300 | | | | | 8C6 | 160AC | 1000 | 79825 |
| 8F9 | 210 | 3000 | 11000 | | | | | 8A28 | 140 | 2000 | 44000 |
| 8D1 | 200 | 3000 | 11500 | | | | | 8A8 | 140 | 1800 | 165500 |
| 8P16 | 200 | 3000 | 12100 | | | | | 8B26 | 140AC | 3000 | 292700 |
| 8G11 | 200 | 4000 | 12200 | | | | | 8C11 | 130AC | 5000 | 251000 |

[a] Multiply by 6.8948 to convert to MN/m$^2$.

[b] Multiply by 0.0167 to convert to Hz.

[c] Specimens with letter designations R, S, T, U, or V were from a different heat, and these data were used only in appendix C.

[d] The letters AC designate air-cooled specimen.

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| Specimen (c) | Stress level, ksi (a), (d) | Test frequency, rpm (b) | Cycles to failure | Specimen | Stress level, ksi (a), (d) | Test frequency, rpm (b) | Cycles to failure | Specimen | Stress level, ksi (a), (d) | Test frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Maraging steel; R. R. Moore machine | | | | SAE 4130 (soft) steel; R. R. Moore machine | | | | SAE 4130 (soft) steel; R. R. Moore machine | | | |
| 8836 | 130AC | 2000 | 406700 | 2M6 | 160 | 530 | 225 | P26 | 110 | 5000 | 8000 |
| 9827 | 130AC | 5000 | 594750 | 2M33 | 160 | 530 | 250 | 029 | 110 | 200 | 8549 |
| 8A36 | 130AC | 5000 | 855000 | 2M28 | 160 | 500 | 250 | 033 | 110 | 5000 | 10000 |
| 8A31 | 130AC | 5000 | 1570250 | 2K25 | 150AC | 100 | 391 | 010 | 110 | 5000 | 11750 |
| 9A10 | 124AC | 5000 | 9631250 | 1S3 | 140AC | 100 | 412 | Q22 | 100 | 100 | 11158 |
| 8817 | 120AC | 5000 | 2296000 | A11 | 140 | 500 | 450 | 1S18 | 100AC | 3000 | 11250 |
| 835 | 120AC | 5000 | 4399500 | 1S30 | 140AC | 100 | 485 | 1T12 | 100AC | 3000 | 14000 |
| 9C15 | 116AC | 5000 | 989000 | 1T33 | 140AC | 100 | 540 | V32 | 100 | 5000 | 15000 |
| 8A9 | 116AC | 5000 | 2772000 | M22 | 140 | 500 | 550 | 1S11 | 100AC | 2000 | 15525 |
| 8338 | 112AC | 5000 | 80750 | 2J25 | 140AC | 100 | 610 | 2M20 | 100 | 5000 | 16000 |
| 9A15 | 112AC | 5000 | 2537000 | 2010 | 140AC | 100 | 669 | 2N1 | 100 | 5000 | 17500 |
| 9A19 | 112AC | 5000 | 7093500 | 2N8 | 140AC | 100 | 711 | S6 | 100 | 5000 | 19000 |
| 8332 | 112 | 5000 | e9999999 | 2M16 | 140AC | 500 | 725 | S38 | 100 | 5000 | 19000 |
| 8C5 | 112 | 5000 | e9999999 | 2A3 | 140AC | 500 | 750 | S37 | 100 | 5000 | 19000 |
| 9U12 | 190AC | 100 | 6237 | 2M29 | 140AC | 500 | 775 | 2L39 | 100 | 5000 | 19700 |
| 9V8 | 190AC | 100 | 7792 | 2M31 | 140AC | 500 | 825 | P2 | 100 | 10000 | 19750 |
| 8814 | 190AC | 100 | 7998 | 2A31 | 140AC | 500 | 850 | T37 | 100 | 5000 | 20000 |
| 9U1 | 190AC | 100 | 8720 | 1S21 | 120AC | 100 | 1670 | 024 | 100 | 5000 | 21000 |
| 9T11 | 190AC | 100 | 9570 | 1S32 | 120AC | 100 | 1678 | 2N12 | 100 | 5000 | 21250 |
| 8815 | 190AC | 1000 | 11275 | 1S4 | 120AC | 1000 | 1700 | 2DH | 100 | 5000 | 22000 |
| 8U16 | 190AC | 1000 | 12675 | 1T13 | 120AC | 100 | 1842 | 2K5 | 100 | 5000 | 22250 |
| 8U10 | 190AC | 1000 | 13150 | 1T16 | 120AC | 100 | 1992 | 05 | 100 | 5000 | 23000 |
| 9R2 | 130AC | 7000 | 49000 | 07 | 120 | 5000 | 2000 | T5 | 100 | 5000 | 24000 |
| 8T10 | 130AC | 5000 | 53750 | 2M30 | 120AC | 5000 | 2250 | Z30 | 100 | 5000 | 25000 |
| 8V16 | 130AC | 5000 | 59000 | 2M23 | 120AC | 100 | 2317 | 2K4 | 100AC | 5000 | 27500 |
| 8R16 | 130AC | 9000 | 60250 | 022 | 120 | 5000 | 2500 | 2N11 | 100AC | 5000 | 29250 |
| 8S10 | 130AC | 5000 | 66750 | 2M4 | 120AC | 5000 | 2500 | 2M27 | 100AC | 5000 | 31750 |
| 8V7 | 130AC | 5000 | 75000 | 2N3 | 120AC | 5000 | 2500 | P3 | 100 | 5000 | 33500 |
| 8S5 | 130AC | 5000 | 98000 | 2026 | 120AC | 100 | 2506 | 035 | 100 | 5000 | 34000 |
| 8S15 | 130AC | 7000 | 178500 | 2L13 | 120AC | 5000 | 2750 | 2L7 | 100AC | 5000 | 41500 |
| 9V6 | 130AC | 5000 | 225500 | 2034 | 120AC | 1000 | 2950 | P30 | 100 | 5000 | 45700 |
| 8U8 | 130AC | 5000 | 321250 | 2M32 | 120AC | 500 | 3025 | 037 | 95 | 5000 | 37000 |
| 9S13 | 120AC | 5000 | 190000 | 2M17 | 120AC | 3000 | 3050 | P6 | 95 | 10000 | 39000 |
| 8V13 | 120AC | 5000 | 326250 | P4 | 120 | 5000 | 3250 | P37 | 95 | 5000 | 40000 |
| 8S1 | 110AC | 7000 | 293250 | 028 | 120 | 5000 | 3250 | P22 | 95 | 5000 | 51750 |
| 8T6 | 110AC | 7000 | 366250 | 040 | 120AC | 5000 | 3250 | 038 | 93 | 10000 | 53000 |
| 8V12 | 110AC | 7000 | 624500 | 015 | 120 | 200 | 3314 | P10 | 90 | 5000 | 69000 |
| 8S14 | 110AC | 7000 | 654500 | P5 | 120AC | 5000 | 3500 | 012 | 90 | 5000 | 77000 |
| 8T7 | 110AC | 7000 | 756500 | P21 | 120AC | 5000 | 3500 | P15 | 90 | 10000 | 78000 |
| | | | | 03 | 120AC | 5000 | 3500 | P8 | 89 | 5000 | 60000 |
| | | | | 2N7 | 120AC | 1000 | 3550 | 025 | 89 | 5000 | 67000 |
| | | | | 2N2 | 120AC | 1000 | 3750 | 1S19 | 85AC | 5000 | 69250 |
| | | | | P20 | 120AC | 5000 | 3750 | V8 | 85 | 5000 | 71000 |
| | | | | 036 | 120 | 200 | 4003 | V26 | 85 | 5000 | 72000 |
| | | | | P18 | 120AC | 5000 | 6750 | 1T7 | 85AC | 5000 | 91250 |
| | | | | 2K22 | 120AC | 5000 | 6750 | 032 | 85 | 5000 | 83000 |
| | | | | 1V13 | 110 | 100 | 3610 | 014 | 85 | 5000 | 97000 |
| | | | | 1T23 | 110AC | 1000 | 5925 | 2N4 | 85 | 5000 | 89500 |
| | | | | 1T29 | 110AC | 1000 | 6100 | T21 | 85 | 5000 | 94000 |
| | | | | | | | | 1T5 | 85AC | 5000 | 96000 |

[a] Multiply by 6.8948 to convert to MN/m$^2$.

[b] Multiply by 0.0167 to convert to Hz.

[c] Specimens with letter designations R, S, T, U, or V were from a different heat, and these data were used only in appendix C.

[d] The letters AC designate air-cooled specimen.

[e] Designates a runout; specimen did not fail after 10 million cycles.

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# TABLE III. - Concluded. ROTATING BENDING FATIGUE TEST DATA OBTAINED

## AT CONSTANT NOMINAL STRESS AMPLITUDE

| Specimen | Stress level (a), (d) | Test frequency, rpm (b) | Cycles to failure | Specimen | Stress level (a), (d) | Test frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|---|
| SAE 4130 (soft) steel; R. R. Moore machine | | | | SAE 4130 (hard) steel; R. R. Moore machine | | | |
| P16 | 85 | 5000 | 97000 | 9E6 | 230AC | 1000 | 200 |
| 2N5 | 85 | 5000 | 102250 | 9A5 | 220AC | 1000 | 300 |
| X26 | 85 | 5000 | 108000 | 9F17 | 220AC | 1000 | 400 |
| P33 | 85 | 5000 | 108000 | 9A12 | 200AC | 1000 | 550 |
| 2N25 | 85 | 5000 | 112250 | 9D16 | 200AC | 1000 | 575 |
| V33 | 85 | 5000 | 129000 | 9C15 | 200AC | 1000 | 650 |
| V11 | 85 | 5000 | 133000 | 9F35 | 200AC | 1000 | 650 |
| 2L9 | 85 | 5000 | 136000 | 9G26 | 200AC | 100 | 681 |
| 2J39 | 35 | 5000 | 139000 | 9F1 | 200AC | 1000 | 725 |
| W33 | 85 | 5000 | 194000 | 9F6 | 200AC | 1000 | 750 |
| 2K21 | 85 | 5000 | 210000 | 9B3 | 200AC | 100 | 769 |
| 1V31 | 80AC | 2000 | 91400 | 9B11 | 200AC | 100 | 795 |
| 1U34 | 80AC | 2000 | 110400 | 9E11 | 200AC | 2500 | 800 |
| O16 | 80 | 10000 | 118000 | 9C22 | 175AC | 1000 | 2870 |
| 1V30 | 80AC | 2000 | 135725 | 9C25 | 175AC | 1000 | 2900 |
| 1U20 | 80AC | 2000 | 144025 | 9E33 | 175AC | 1000 | 3120 |
| 2O11 | 80AC | 2000 | 147675 | 9F9 | 175AC | 1000 | 3280 |
| O23 | 80 | 5000 | 160000 | 9E36 | 175AC | 1000 | 3425 |
| 2K26 | 80 | 5000 | 168000 | 9F31 | 175AC | 1000 | 3520 |
| 2N18 | 80AC | 2000 | 169225 | 9B17 | 175AC | 1000 | 3680 |
| P9 | 80 | 5000 | 177000 | 9G3 | 150AC | 1000 | 11525 |
| 2M18 | 80 | 5000 | 178000 | 9F16 | 150AC | 1000 | 11625 |
| P36 | 80 | 5000 | 184000 | 9F30 | 150AC | 1000 | 12175 |
| 2N16 | 80AC | 2000 | 187050 | 9B36 | 150AC | 1000 | 12925 |
| 2M38 | 80 | 5000 | 204000 | 9F13 | 150AC | 1000 | 13900 |
| 2M13 | 80 | 5000 | 218000 | 9B31 | 150AC | 1000 | 14000 |
| 1U11 | 80AC | 2000 | 219325 | 9F4 | 150AC | 1000 | 15000 |
| 2L32 | 80 | 5000 | 231000 | 9B35 | 150AC | 1000 | 15525 |
| 2L16 | 80 | 5000 | 244000 | 9C39 | 100 | 3600 | 69250 |
| 2K38 | 80 | 5000 | 267000 | 9A27 | 100 | 1000 | 73600 |
| 2M5 | 80 | 5000 | 270000 | 9B29 | 100 | 1000 | 81500 |
| 2L26 | 80 | 5000 | 279000 | 9C8 | 100AC | 5000 | 82250 |
| 2K6 | 80 | 5000 | 282000 | 9A37 | 100 | 3600 | 88250 |
| 2L18 | 80 | 5000 | 292000 | 9D28 | 100 | 3600 | 95750 |
| 2L30 | 80 | 5000 | 296000 | 9E21 | 100 | 1000 | 120500 |
| 2L19 | 80 | 5000 | 354000 | 9B34 | 100 | 1000 | 142300 |
| 2M26 | 75AC | 5000 | 155750 | 9G24 | 100AC | 5000 | 158500 |
| 1T1 | 75AC | 5000 | 156750 | 9E3 | 100 | 1000 | 173025 |
| 1U3 | 75 | 100 | 157700 | 9B24 | 100 | 1000 | 253200 |
| 2N26 | 75AC | 5000 | 171500 | 9F37 | 100 | 1000 | 481500 |
| O4 | 75 | 5000 | 173000 | | | | |
| 1S38 | 75AC | 5000 | 203000 | | | | |
| 2O25 | 75AC | 5000 | 208500 | | | | |
| P14 | 75 | 5000 | 215000 | | | | |
| O1 | 75 | 5000 | 223000 | | | | |
| 1T35 | 75AC | 5000 | 231500 | | | | |
| O39 | 75 | 5000 | 252000 | | | | |
| O31 | 75 | 5000 | 264000 | | | | |
| P19 | 75 | 5000 | 319000 | | | | |
| O11 | 75 | 10000 | 355000 | | | | |
| O34 | 75 | 5000 | 358000 | | | | |
| P34 | 75 | 5000 | 369000 | | | | |
| O17 | 75 | 5000 | 548000 | | | | |
| O13 | 75 | 5000 | 551000 | | | | |

[a] Multiply by 6.8948 to convert to $MN/m^2$.

[b] Multiply by 0.0167 to convert to Hz.

[d] The letters AC designate air-cooled specimen.

## TABLE IV. - AXIAL FATIGUE TEST DATA

## OBTAINED AT CONSTANT STRAIN

## AMPLITUDE WITH

## MARAGING STEEL

| Specimen | Strain range, longitudinal total | Cycles to failure |
|---|---|---|
| V6 | 0.1361 | 30 |
| V19 | .0717 | 99 |
| V59 | .0717 | 110 |
| V13 | .0517 | 243 |
| V15 | .0517 | 283 |
| V60 | .0368 | 330 |
| V62 | .0368 | 474 |
| V65 | .0265 | 720 |
| V4 | .0264 | 848 |
| V5 | .0210 | 1 566 |
| V20 | .0170 | 3 170 |
| V3 | .0142 | 5 516 |
| V14 | .0135 | 8 234 |
| V9 | .0122 | 17 406 |
| V67 | .0115 | 15 780 |
| V69 | .0115 | 16 118 |
| V22 | .0112 | 17 775 |
| V12 | .0104 | 53 608 |
| V25 | .0097 | 156 630 |
| V7 | .0093 | 166 572 |
| V26 | .0092 | 338 140 |
| V1 | .0088 | 241 327 |

## TABLE V. - ROTATING BENDING FATIGUE DATA OBTAINED IN TWO-STRESS-LEVEL TESTS

| Specimen | First stress level, ksi (a) | First frequency, rpm (b) | Cycles applied, $n_1$ | Second stress level, ksi (a) | Second frequency, rpm (b) | Cycles to failure | Specimen | First stress level, ksi (a) | First frequency, rpm (b) | Cycles applied, $n_1$ | Second stress level, ksi (a) | Second frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maraging steel; Krouse machine | | | | | | | Maraging steel; Krouse machine | | | | | | |
| 8K9 | 290 | 100 | 200 | 240 | 100 | 2628 | 8B17 | 260 | 100 | 800 | 180 | 3000 | 7600 |
| 8B2 | 290 | 100 | 400 | 240 | 100 | 2008 | 8K1 | 260 | 100 | 1200 | 180 | 3000 | 4700 |
| 8H5 | 290 | 100 | 600 | 240 | 100 | 1444 | 8A7 | 260 | 100 | 1600 | 180 | 3000 | 3100 |
| 8H16 | 290 | 100 | 800 | 240 | 100 | 982 | 8E16 | 260 | 100 | 2000 | 180 | 3000 | 2300 |
| 8J17 | 290 | 100 | 1000 | 240 | 100 | 962 | 8N13 | 260 | 100 | 100 | 160 | 3000 | 35100 |
| 8L15 | 290 | 100 | 100 | 200 | 3000 | 9500 | 8M12 | 260 | 100 | 200 | 160 | 3000 | 24700 |
| 8N9 | 290 | 100 | 200 | 200 | 3000 | 8900 | 8L2 | 260 | 100 | 400 | 160 | 3000 | 23400 |
| 8P15 | 290 | 100 | 400 | 200 | 3000 | 5400 | 8P1 | 260 | 100 | 600 | 160 | 3000 | 16600 |
| 8P8 | 290 | 100 | 600 | 200 | 3000 | 4300 | 8D-- | 260 | 100 | 1200 | 160 | 3000 | 6400 |
| 8L16 | 290 | 100 | 800 | 200 | 3000 | 3500 | 8N5 | 260 | 100 | 1800 | 160 | 3000 | 4300 |
| 8P17 | 290 | 100 | 1000 | 200 | 3000 | 2000 | 8P13 | 260 | 100 | 200 | 120 | 3000 | 172500 |
| 8E9 | 290 | 100 | 200 | 160 | 5000 | 25500 | 8P10 | 260 | 100 | 400 | 120 | 3000 | 97000 |
| 8C11 | 290 | 100 | 200 | 160 | 5000 | 17000 | 8L17 | 260 | 100 | 600 | 120 | 3000 | 53600 |
| 8F8 | 290 | 100 | 400 | 160 | 5000 | 17100 | 8D2 | 260 | 100 | 1200 | 120 | 3000 | 20000 |
| 8K8 | 290 | 100 | 600 | 160 | 5000 | 9500 | 8N14 | 260 | 100 | 1800 | 120 | 3000 | 17300 |
| 8G15 | 290 | 100 | 800 | 160 | 5000 | 8600 | 8D4 | 260 | 100 | 200 | 105 | 5000 | 1319200 |
| 8G8 | 290 | 100 | 1000 | 160 | 5000 | 3097 | 8P3 | 260 | 100 | 400 | 105 | 5000 | 415600 |
| 8G17 | 290 | 100 | 200 | 120 | 5000 | 125600 | 8D16 | 260 | 100 | 600 | 105 | 5000 | 74100 |
| 8H6 | 290 | 100 | 200 | 120 | 5000 | 115700 | 8P12 | 260 | 100 | 1200 | 105 | 5000 | 40700 |
| 8G13 | 290 | 100 | 400 | 120 | 5000 | 54400 | 8N4 | 260 | 100 | 1800 | 105 | 5000 | 20100 |
| 8A6 | 290 | 100 | 600 | 120 | 5000 | 31800 | 8J9 | 240 | 3000 | 500 | 140 | 5000 | 45200 |
| 8E18 | 290 | 100 | 800 | 120 | 5000 | 21700 | 8D3 | 240 | 3000 | 600 | 140 | 5000 | 56200 |
| 8C12 | 290 | 100 | 1000 | 120 | 5000 | 15700 | 8E6 | 240 | 3000 | 1000 | 140 | 5000 | 47000 |
| 8L9 | 290 | 100 | 100 | 105 | 5000 | 684700 | 8A18 | 240 | 3000 | 1000 | 140 | 5000 | 24700 |
| 8U9 | 290 | 100 | 200 | 105 | 5000 | 178500 | 8B7 | 240 | 100 | 1000 | 140 | 5000 | 24000 |
| 8L4 | 290 | 100 | 400 | 105 | 5000 | 80200 | 8G5 | 240 | 3000 | 1600 | 140 | 5000 | 14800 |
| 8N11 | 290 | 100 | 600 | 105 | 5000 | 84700 | 8C13 | 240 | 3000 | 2000 | 140 | 5000 | 18300 |
| 8P-- | 290 | 100 | 900 | 105 | 5000 | 29100 | 8A3 | 240 | 100 | 2000 | 140 | 5000 | 12800 |
| 8H9 | 270 | 100 | 100 | 170 | 5000 | 24900 | 8D2 | 240 | 100 | 3000 | 140 | 5000 | 8600 |
| 8K12 | 270 | 100 | 200 | 170 | 5000 | 19300 | 8E2 | 240 | 3000 | 3100 | 140 | 5000 | 11800 |
| 8J10 | 270 | 100 | 400 | 170 | 5000 | 14000 | 8J5 | 240 | 3000 | 3200 | 140 | 5000 | 9300 |
| 8D9 | 270 | 100 | 800 | 170 | 5000 | 8800 | 8A14 | 210 | 100 | 500 | 140 | 3000 | 100400 |
| 8B10 | 270 | 100 | 1200 | 170 | 5000 | 4600 | 8K10 | 210 | 3000 | 1000 | 140 | 3000 | 53900 |
| 8C18 | 270 | 100 | 1600 | 170 | 5000 | 1500 | 8C17 | 210 | 3000 | 2000 | 140 | 3000 | 30700 |
| 8L13 | 266 | 100 | 100 | 200 | 3000 | 11900 | 8D6 | 210 | 3000 | 4000 | 140 | 3000 | 23400 |
| 8P4 | 266 | 100 | 300 | 200 | 3000 | 7700 | 8F15 | 210 | 3000 | 6000 | 140 | 3000 | 17200 |
| 8N2 | 266 | 100 | 600 | 200 | 3000 | 6200 | 8F2 | 210 | 3000 | 8000 | 140 | 3000 | 3000 |
| 8L5 | 266 | 100 | 1000 | 200 | 3000 | 4700 | 8P5 | 200 | 1000 | 1000 | 160 | 3000 | 40800 |
| 8M8 | 266 | 100 | 1500 | 200 | 3000 | 2600 | 8N10 | 200 | 1000 | 1000 | 160 | 3000 | 25000 |
| 8P14 | 266 | 100 | 100 | 105 | 5000 | 1094600 | 8N12 | 200 | 1000 | 2500 | 160 | 3000 | 34900 |
| 8M17 | 266 | 100 | 400 | 105 | 5000 | 180400 | 8D5 | 200 | 1000 | 500 | 160 | 3000 | 12500 |
| 8P9 | 266 | 100 | 600 | 105 | 5000 | 104200 | 8M7 | 200 | 1000 | 7500 | 160 | 3000 | 8600 |
| 8M4 | 266 | 100 | 1000 | 105 | 5000 | 51300 | 8L11 | 200 | 1000 | 10000 | 160 | 3000 | 8700 |
| 8L3 | 266 | 100 | 1500 | 105 | 5000 | 30100 | 8L7 | 200 | 1000 | 1000 | 120 | 5000 | 722400 |
| 8E12 | 260 | 100 | 100 | 180 | 3000 | 21300 | 8L6 | 200 | 1000 | 2500 | 120 | 5000 | 351400 |
| 8C8 | 260 | 100 | 200 | 180 | 3000 | 15800 | 8D7 | 200 | 1000 | 3700 | 120 | 5000 | 47000 |
| 8H3 | 260 | 100 | 400 | 180 | 3000 | 10000 | 8N15 | 200 | 1000 | 5000 | 120 | 5000 | 79400 |
| 8D13 | 260 | 100 | 600 | 180 | 3000 | 12500 | 8D12 | 200 | 1000 | 7500 | 120 | 5000 | 19100 |
| | | | | | | | 8M1 | 200 | 1000 | 10000 | 120 | 5000 | 8000 |

[a] Multiply by 6.8948 to convert to MN/m$^2$.

[b] Multiply by 0.0167 to convert to Hz.

| Speci-men (d) | First stress level, ksi (a) | First frequency, rpm (b) | Cycles applied, $n_1$ | Second stress level, ksi (a) | Second fre-quency, rpm (b) | Cycles to failure | Speci-men (d) | First stress level, ksi (a), (e) | First frequency, rpm (b) | Cycles applied, $n_1$ | Second stress level, ksi (a), (e) | Second fre-quency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maraging steel - Krouse machine | | | | | | | Maraging steel - R. R. Moore machine | | | | | | |
| 8P2 | 160 | 3000 | 4000 | 120 | 5000 | 451900 | 8B3 | 300AC | 100 | 25 | 130AC | 5000 | 215000 |
| 8M16 | 160 | 3000 | 8000 | 120 | 5000 | 230500 | 8B30 | 300AC | 100 | 50 | 130AC | 5000 | 97000 |
| 8L12 | 160 | 3000 | 12000 | 120 | 5000 | 50900 | 8C30 | 300AC | 100 | 50 | 130AC | 5000 | 98750 |
| 8N16 | 160 | 3000 | 16000 | 120 | 5000 | 34800 | 8C3 | 300AC | 100 | 75 | 130AC | 5000 | 126250 |
| 8L8 | 160 | 3000 | 24000 | 120 | 5000 | 22200 | 8A24 | 300AC | 100 | 100 | 130AC | 5000 | 74000 |
| 808 | 160 | 3000 | 32000 | 120 | 5000 | 11100 | 8B40 | 300AC | 100 | 100 | 130AC | 5000 | 95500 |
| 8B12 | 240 | 100 | 750 | 290 | 100 | 123 | 8C7 | 300AC | 100 | 100 | 130AC | 5000 | 295000 |
| 8D5 | 240 | 100 | 1500 | 290 | 100 | 1058 | 8A13 | 300AC | 100 | 150 | 130AC | 5000 | 59750 |
| 8G9 | 240 | 100 | 2250 | 290 | 100 | 589 | 8C27 | 300 | 100 | 200 | 130 | 5000 | 48000 |
| 8J18 | 240 | 100 | 3000 | 290 | 100 | 342 | 8C29 | 300AC | 100 | 200 | 130AC | 5000 | 56250 |
| 8D17 | 160 | 3000 | 6000 | 290 | 100 | 1484 | 8C23 | 300AC | 100 | 300 | 130AC | 5000 | 41500 |
| 8A17 | 160 | 3000 | 12000 | 290 | 100 | 1178 | 8C14 | 300AC | 100 | 500 | 130AC | 5000 | 30500 |
| 8J13 | 160 | 3000 | 24000 | 290 | 100 | 1302 | 8A6 | 300AC | 100 | 700 | 130AC | 5000 | 16500 |
| 8D18 | 160 | 3000 | 36000 | 290 | 100 | 1388 | 8A21 | 190AC | 1000 | 1000 | 130AC | 5000 | 374250 |
| 8E17 | 160 | 3000 | 48000 | 290 | 100 | 33 | 8A14 | 190AC | 1000 | 2000 | 130AC | 5000 | 94000 |
| 8J1 | 140 | 5000 | 20000 | 240 | 3000 | 4000 | 8C20 | 190AC | 1000 | 4000 | 130AC | 5000 | 46500 |
| 8H1 | 140 | 5000 | 20000 | 240 | 3000 | 3700 | 8C28 | 190AC | 1000 | 7000 | 130AC | 5000 | 26000 |
| 8J16 | 140 | 5000 | 40000 | 240 | 3000 | 4300 | 8A18 | 190AC | 1000 | 10000 | 130AC | 5000 | 19500 |
| 8H10 | 140 | 5000 | 40000 | 240 | 3000 | 3300 | 8A26 | 160AC | 1000 | 4000 | 130AC | 5000 | 486000 |
| 8D14 | 140 | 5000 | 60000 | 240 | 3000 | 4500 | 8B8 | 160AC | 1000 | 8000 | 130AC | 5000 | 454250 |
| 8D12 | 140 | 5000 | 60000 | 240 | 3000 | 4300 | 8C8 | 160AC | 1000 | 12000 | 130AC | 5000 | 182250 |
| 8C16 | 140 | 5000 | 70000 | 240 | 3000 | [c] | 8A27 | 160AC | 1000 | 16000 | 130AC | 5000 | 93750 |
| 8A12 | 140 | 5000 | 80000 | 240 | 3000 | 2900 | 8B22 | 160AC | 1000 | 32000 | 130AC | 5000 | 30000 |
| 8F17 | 140 | 5000 | 80000 | 240 | 3000 | [c] | 8B24 | 130AC | 5000 | 100000 | 300AC | 100 | 946 |
| 8C14 | 120 | 5000 | 50000 | 290 | 100 | 1145 | 8C19 | 130AC | 5000 | 200000 | 300AC | 100 | 1009 |
| 8H18 | 120 | 5000 | 100000 | 290 | 100 | 1103 | 9A32 | 130AC | 5000 | 300000 | 300AC | 100 | 989 |
| 8A15 | 120 | 5000 | 150000 | 290 | 100 | 1209 | 9B6 | 130AC | 5000 | 350000 | 300AC | 100 | [c] |
| 8H11 | 120 | 5000 | 200000 | 290 | 100 | 1230 | 8C9 | 130AC | 5000 | 400000 | 300AC | 100 | 905 |
| | | | | | | | 8B2 | 130AC | 5000 | 450000 | 300AC | 100 | [c] |
| | | | | | | | 8C1 | 130AC | 5000 | 450000 | 300AC | 100 | 1131 |
| | | | | | | | 8T16 | 190AC | 100 | 500 | 110AC | 7000 | 389000 |
| | | | | | | | 8S2 | 190AC | 100 | 1000 | 110AC | 7000 | 161500 |
| | | | | | | | 8S6 | 190AC | 100 | 2000 | 110AC | 7000 | 86000 |
| | | | | | | | 8V5 | 190AC | 100 | 4000 | 110AC | 7000 | 34500 |
| | | | | | | | 8V4 | 190AC | 100 | 6000 | 110AC | 7000 | 18750 |

[a] Multiply by 6.8948 to convert to MN/m$^2$.

[b] Multiply by 0.0167 to convert to Hz.

[c] Specimen failed at first stress level.

[d] Specimens with letter designations R, S, T, U, or V were from a different heat, and these data were used only in appendix C and fig. 14.

[e] The letters AC designate air-cooled specimen.

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TABLE V. - Concluded. ROTATING BENDING FATIGUE DATA OBTAINED IN TWO-STRESS-LEVEL TESTS

### SAE 4130 (soft) steel - R. R. Moore machine

| Specimen | First stress level, ksi (a), (e) | First frequency, rpm (b) | Cycle applied, $n_1$ | Second stress level, ksi (a), (e) | Second frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|
| 1T25 | 140AC | 100 | 50 | 120AC | 100 | 1449 |
| 1S34 | 140AC | 100 | 100 | 120AC | 100 | 1148 |
| 1T36 | 140AC | 100 | 200 | 120AC | 100 | 886 |
| 1T38 | 140AC | 100 | 300 | 120AC | 100 | 730 |
| 1S24 | 140AC | 100 | 400 | 120AC | 100 | 304 |
| 1S26 | 140AC | 100 | 25 | 100AC | 3000 | 8750 |
| 1S35 | 140AC | 100 | 50 | 100AC | 5000 | 4500 |
| 1S13 | 140AC | 100 | 50 | 100AC | 5000 | 4000 |
| 1T30 | 140AC | 100 | 100 | 100AC | 5000 | 4000 |
| 1S36 | 140AC | 100 | 200 | 100AC | 2000 | 2500 |
| 1S17 | 140AC | 100 | 300 | 100AC | 2000 | 1850 |
| 1T22 | 140AC | 100 | 25 | 85AC | 3000 | 43700 |
| 1T34 | 140AC | 100 | 50 | 85AC | 3000 | 27925 |
| 1T2 | 140AC | 100 | 100 | 85AC | 3000 | 19400 |
| 1S37 | 140AC | 100 | 200 | 85AC | 3000 | 8000 |
| 1T8 | 140AC | 100 | 300 | 85AC | 3000 | 6000 |
| 2N31 | 14CAC | 100 | 25 | 75AC | 5000 | 123000 |
| 1T20 | 140AC | 100 | 50 | 75AC | 5000 | 79000 |
| 2020 | 140AC | 100 | 100 | 75AC | 5000 | 59000 |
| 2013 | 140AC | 100 | 200 | 75AC | 5000 | 39750 |
| 2020 | 140AC | 100 | 300 | 75AC | 5000 | 32000 |
| 1V36 | 140AC | 100 | 400 | 75AC | 5000 | 12750 |
| 1T26 | 140AC | 100 | 500 | 75AC | 5000 | 4750 |
| 1S9 | 120AC | 100 | 100 | 110AC | 1000 | 4700 |
| 1S31 | 120AC | 100 | 200 | 110AC | 1000 | 3125 |
| 1T28 | 120AC | 100 | 500 | 110AC | 1000 | 2825 |
| 1S22 | 120AC | 100 | 1000 | 110AC | 1000 | 1300 |
| 1S29 | 120AC | 100 | 1500 | 110AC | 1000 | 250 |
| 1T31 | 120AC | 100 | 100 | 100AC | 3000 | 13000 |
| 1S15 | 120AC | 100 | 200 | 100AC | 3000 | 6500 |
| 1T19 | 120AC | 100 | 500 | 100AC | 3000 | 4250 |
| 1S25 | 120AC | 100 | 1000 | 100AC | 3000 | 2250 |
| 2N32 | 120AC | 100 | 1000 | 100AC | 3000 | 4750 |
| 1V16 | 120AC | 100 | 1500 | 100AC | 3000 | 1500 |
| 1T9 | 120AC | 100 | 100 | 85AC | 5000 | 47250 |
| 1S20 | 120AC | 100 | 200 | 85AC | 5000 | 28500 |
| 1T4 | 120AC | 100 | 500 | 85AC | 5000 | 19250 |
| 1S5 | 120AC | 100 | 1000 | 85AC | 5000 | 6500 |
| 1T39 | 120AC | 100 | 1500 | 85AC | 5000 | 3000 |
| 2O6 | 120AC | 100 | 200 | 75AC | 5000 | 86000 |
| 2J36 | 120AC | 100 | 500 | 75AC | 5000 | 44000 |
| 1T3 | 120AC | 100 | 1000 | 75AC | 5000 | 27250 |
| 2O35 | 120AC | 100 | 1500 | 75AC | 5000 | 26000 |
| 2N21 | 120AC | 100 | 2000 | 75AC | 5000 | 11000 |
| 1S12 | 100AC | 2000 | 1000 | 85AC | 3000 | 68250 |
| 1T21 | 100AC | 2000 | 2000 | 85AC | 3000 | 46500 |
| 1T37 | 100AC | 2000 | 4000 | 85AC | 3000 | 45750 |
| 1S27 | 100AC | 2000 | 6000 | 85AC | 3000 | 32750 |

### SAE 4130 (soft) steel - R. R. Moore machine

| Specimen | First stress level, ksi (a), (e) | First frequency, rpm (b) | Cycle applied, $n_1$ | Second stress level, ksi (a), (e) | Second frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|
| 1S6 | 100AC | 2000 | 8000 | 85AC | 3000 | 22500 |
| 1T10 | 100AC | 2000 | 12000 | 85AC | 3000 | 11750 |
| 1S7 | 100AC | 2000 | 1000 | 75AC | 5000 | 147250 |
| 1T6 | 100AC | 2000 | 2000 | 75AC | 5000 | 152750 |
| 2O16 | 100AC | 2000 | 2000 | 75AC | 5000 | 148000 |
| 1S23 | 100AC | 2000 | 4000 | 75AC | 5000 | 47000 |
| 1S14 | 100AC | 2000 | 5000 | 75AC | 5000 | 53750 |
| 2O12 | 100AC | 2000 | 5000 | 75AC | 5000 | 141500 |
| 1S1 | 100AC | 2000 | 8000 | 75AC | 5000 | 47250 |
| 1T24 | 100AC | 2000 | 12000 | 75AC | 5000 | 22750 |

### SAE 4130 (hard) steel; R. R. Moore machine

| Specimen | First stress level, ksi (a), (e) | First frequency, rpm (b) | Cycle applied, $n_1$ | Second stress level, ksi (a), (e) | Second frequency, rpm (b) | Cycles to failure |
|---|---|---|---|---|---|---|
| 9F26 | 200AC | 100 | 100 | 100AC | 5000 | 59750 |
| 9O13 | 200AC | 100 | 200 | 100AC | 5000 | 30000 |
| 9G27 | 200AC | 100 | 400 | 100AC | 5000 | 14000 |
| 9F33 | 200AC | 100 | 600 | 100AC | 5000 | 8500 |

[a] Multiply by 6.8948 to convert to MN/m$^2$.

[b] Multiply by 0.0167 to convert to Hz.

[e] The letters AC designate air-cooled specimen.

## TABLE VI. - AXIAL FATIGUE DATA OBTAINED IN TWO-STRAIN-LEVEL
## TESTS OF MARAGING STEEL

| Specimen | First strain level | Cycles applied, n | Second strain level | Cycles to failure |
|---|---|---|---|---|
| V53 | 0.0368 | 10 | 0.0115 | 14 866 |
| V50 | | 20 | | 10 400 |
| V49 | | 60 | | 6 060 |
| V74 | | 100 | | 2 708 |
| V75 | | 100 | | 3 205 |
| V47 | | 100 | | 5 720 |
| V48 | | 200 | | 3 365 |
| V51 | | 300 | | 1 965 |
| V54 | .0717 | 20 | .0265 | 532 |
| V63 | | 40 | | 440 |
| V56 | | 60 | | 435 |
| V52 | | 75 | | 285 |
| V55 | .0717 | 20 | .0368 | 364 |
| V57 | | 40 | | 284 |
| V58 | | 60 | | 168 |
| V64 | | 80 | | 180 |
| V66 | .0115 | 4 000 | .0368 | 444 |
| V72 | | 8 000 | | 15 |
| V73 | | 8 000 | | 230 |
| V70 | | 12 000 | | 116 |

TABLE VII. - SUMMARY OF ROTATING BENDING FATIGUE DATA OBTAINED IN

TWO-STRESS-LEVEL ALTERNATING BLOCK TESTS WITH MARAGING STEEL

[Test conditions: initial stress, $\sigma_1$, 190 000 psi (1310 $MN/m^2$); second stress, $\sigma_2$, 110 000 psi (758 $MN/m^2$); cycles to failure at initial stress, $N_{f,1}$, 8000 cycles; cycles to failure at second stress, $N_{f,2}$, 625 000 cycles; cycles of Phase I at initial stress, $N_{o,1}$, 1300 cycles.]

| Specimen | Cycle ratio, $n/N_{o,1}$ | Cycles applied per block | | Summation of cycles applied at initial stress, $\sum n_1$ | Summation of cycles applied at second stress, $\sum n_2$ | Cycle ratio summation, $\sum \dfrac{n}{N_f}$ |
|---|---|---|---|---|---|---|
| | | At initial stress, $n_1$ | At second stress, $n_2$ | | | |
| 8R1 | 0.22 | 285 | 19 750 | 1995 | 126 250 | 0.45 |
| 8U13 | .22 | 285 | 19 750 | 2280 | 147 750 | .52 |
| 8V14 | .22 | 285 | 19 750 | 3135 | 204 000 | .72 |
| 8U7 | .29 | 380 | 26 250 | 1900 | 118 250 | .43 |
| 8R12 | .29 | 380 | 26 250 | 1900 | 127 000 | .44 |
| 8T14 | .29 | 380 | 26 250 | 2739 | 183 750 | .64 |
| 8U3 | .44 | 570 | 39 250 | 1140 | 77 250 | .27 |
| 8R5 | .44 | 570 | 39 250 | 2850 | 193 000 | .66 |
| 8S12 | .44 | 570 | 39 250 | 3420 | 224 500 | .79 |
| 8R4 | .55 | 710 | 49 000 | 2130 | 129 750 | .47 |
| 8T5 | .55 | 710 | 49 000 | 2130 | 134 750 | .48 |
| 8U9 | .55 | 710 | 49 000 | 3550 | 208 750 | .78 |
| 8U2 | .65 | 850 | 58 750 | 1700 | 97 500 | .37 |
| 8U5 | .65 | 850 | 58 750 | 3400 | 225 500 | .79 |
| 8T2 | .65 | 850 | 58 750 | 4250 | 241 750 | .92 |
| 8R11 | .76 | 990 | 68 500 | 1980 | 134 250 | .46 |
| 8U6 | .76 | 990 | 68·500 | 2970 | 151 000 | .62 |
| 8T1 | .76 | 990 | 68 500 | 3960 | 257 500 | .91 |
| 8R8 | .87 | 1130 | 78 500 | 2260 | 90 000 | .43 |
| 8R9 | .87 | 1130 | 78 500 | 2260 | 139 000 | .51 |
| 8V1 | .87 | 1130 | 78 500 | 3390 | 178 000 | .71 |
| 8U4 | .87 | 1130 | 78 500 | 5650 | 325 000 | 1.23 |
| 8S15 | .99 | 1280 | 87 500 | 1280 | 70 500 | .27 |
| 8S3 | .99 | 1280 | 87 500 | 2560 | 128 500 | .53 |
| 8T13 | .99 | 1280 | 87 500 | 2560 | 150 000 | .56 |

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