

Fatigue Analysis of Structural Components Through Math-model Simulation

The effect of geometry changes on the fatigue life of complex structural components can be evaluated by means of a new program that effectively analyzes damage caused by random-loading cycles

by Allan R. Michetti

ABSTRACT—A cumulative-fatigue-damage procedure that considers notch effects, mean-stress relaxation, and cyclic hardening and softening is being used at TEREX to evaluate structural reliability. Necessary inputs for the evaluation are: (1) a load-time history of the response of the material to its operating environment, (2) a listing of material characteristics with regard to both monotonic and cyclic properties, (3) an experimental sample with similar section which can be failed under constant-amplitude loading so that a fatigue-concentration factor can be developed, and (4) the appropriate computer 'soft ware' needed to simulate the material during its loading environment so that a life prediction can be made.

The actual procedure consists of: (1) instrumenting that particular section of interest on the vehicle or component with the appropriate strain gages and wiring, (2) recording the changes in strain on an FM magnetic-tape recorder, (3) digitizing the analog signal on the magnetic tape so that the data can be readily processed by the computer, and (4) inputting the data points, in sequence, to the computer soft ware so that the load history can be combined with other necessary information which allows the computerized model to calculate life prediction, damage estimations and severe stress-strain conditions.

List of Symbols

- A = transient-strength coefficient
- b = fatigue-strength exponent
- c = fatigue-ductility exponent
- E = modulus of elasticity, psi (N/m²)
- K = strength coefficient, psi (N/m²)
- K' = cyclic-strength coefficient
- M = relaxation coefficient
- Nt = transition-fatigue life, cycles
- n = monotonic strain-hardening exponent
- n' = cyclic strain-hardening exponent
- %RA = percent reduction in area
- $S-N$ = a plot of strain vs. life
- S_u = ultimate strength, psi (N/m²)
- S_y = monotonic yield strength, psi (N/m²)
- S_y' = cyclic yield strength, psi (N/m²)
- U_p = true toughness, in.-lb/in.³ (J/m³)
- α = transient-strength exponent

- e = true strain, $\mu\epsilon$
- e_f = true fracture ductility
- e_f' = fatigue-ductility coefficient
- σ = true stress, psi (N/m²)
- σ_f = true fracture strength, psi (N/m²)
- σ_f' = fatigue-strength coefficient

Introduction

In the analysis of structural failures, the term 'fatigue' plays an important role. Where some failures occur through either gradual wear or severe deformations, thus providing an indication of the oncoming failure, fatigue failures can, and often do, occur with no advance warning. On the other hand, since a larger number of load applications are necessary to cause a failure, changes made over an existing design can be difficult to evaluate without prolonged testing.

The evaluation of existing designs and subsequent improvements to these designs, based on a fatigue criterion, are the subject of this paper. No attempt is being made to delve into any of the various methods of stress analysis whereby a complete structure is tested to determine the areas of questionable strength. Past failures already indicate that fatigue cracks most often start in highly stressed regions adjacent to stress raisers such as welds, notches, fillets and bolt holes. It is assumed, then, that the overall integrity of the structure is based on the strength at these critical locations. If these areas are not exposed during lab tests, they will most likely be discovered as field failures. Consequently, our concern at this point will be in their evaluation, not in their initial discovery.

Consider this analogy. If a structure as a whole can be thought of as a chain made up of certain number of links, whereby each link represents one of the critical locations on the structure, the old adage "a chain is only as strong as its weakest link" holds true. However, our concern is *not* in determining which link is the weakest, but instead, to determine 'how weak' that 'weakest link' actually is.

Since this is an application paper, and not a research paper, the development of the major items used as a basis for the ideas presented herein will be kept to a minimum. These developments were based on work done by Morrow,¹ Wetzels,² Topper,³

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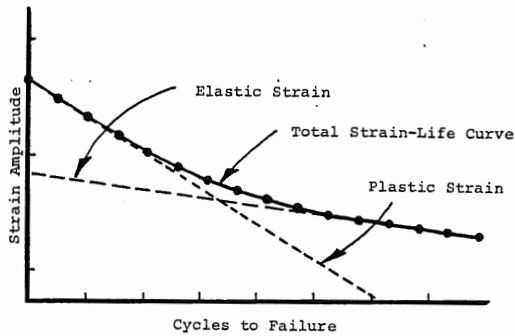


Fig. 1—The basic S-N curve

and others. The use of computers in simulating cyclic stress-strain behavior of materials was continued by Johnson^{4,5} and, at that stage, was modified to suit the individual needs of the author. Additional work continues at this point.

A Problem of Correlation

Various tests have been used during the past 20 years to expose potential problem areas on large and small structures. Both brittle lacquer and photoelasticity have been accepted approaches to troubleshooting and, for the most part, are fairly reliable. However, in certain cases, deficiencies in design are either overlooked completely or misjudged, leading to the discovery of structural failures in the field. At that point, a problem is evident and design changes must be made to correct the problem.

Assessing the degree of improvement as a result of a design change can often be a problem in itself. In some cases, static tests are performed on both the original and modified designs, and the resulting strain values are compared to determine if any benefit was obtained. However, the correlation between the amount of improvement obtained as a result of a decrease in strain level is often no more than an experienced guess.

Consider the following example. A component begins to exhibit fatigue cracks at a given 'critical lo-

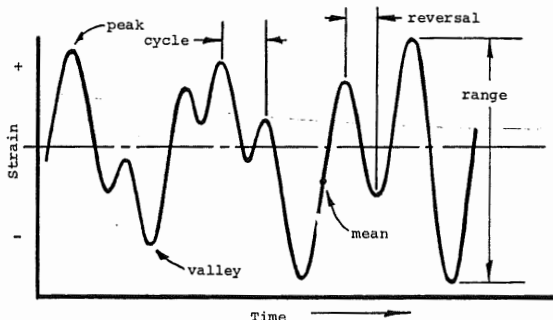


Fig. 2—Random-loading cycles

cation' after a half-million cycles. If an arbitrary static load is placed on the component in a direction similar to that of the random loads to which this component will be subjected during operation, a resultant static strain will be present at the 'critical location.' This is equated to an arbitrary strain amplitude and is measured using a strain gage. If a geometry change is made on the component and the same static load is re-applied, the resultant strain at the location in question may have either increased or decreased. It can be assumed that if the strain level as a result of the change has decreased over that prior to the change, the overall effect, at that point, would be increased life. But, how much increased life? Will a reduction in strain of 25 percent mean an increase in life of 33 percent? If the relation between the measured static-strain level and expected life was inversely proportional, the above statement would hold true. However, the relationship is *not* linear and, consequently, it is difficult to correlate the effect of the change.

The basic S-N curve, Fig. 1, illustrates these nonlinearities. The 'plastic strain-life curve' and the 'elastic strain-life curve' are combined and the resultant composite is the "total strain-life curve" which is obviously not linear.

An added complication is that typical operating loads, Fig. 2, are not of the sinusoidal, constant-amplitude, fully reversed type and, consequently, cannot be equated simply to the basic S-N curve. What must be done in this case is to determine the cycles in each of the amplitude ranges to which the operating loads apply, and using ratios as to the number of cycles to failure in each range, determine the resultant total number of cycles to failure.

This is the usual application of Miner's rule, and can be stated thusly:

$$\frac{c_1}{C_1} + \frac{c_2}{C_2} + \frac{c_3}{C_3} + \dots = f$$

or:

$$\sum \left(\frac{c_i}{C_i} \right) = f$$

where:

- c_i = number of cycles spent at range R_i and mean M_i
- C_i = number of cycles to failure, determined from a fatigue curve, at range R_i and mean M_i
- f = coefficient of life (according to the cumulative-damage rule, failure occurs when $f = 1.0$).

When only a few distinct ranges are evident, the effect can be resolved manually. However, in most random-loading cycles, many different ranges apply, and hand analysis would be very tedious, which leads the way for analysis using the computer.

Programmed Fatigue Analysis

Four basic phases are involved in the programmed fatigue analysis. These are: (1) material characterization, (2) component-strength measurement, (3) load-history determination and (4) the actual-analysis method which combines the first through third phases and produces the life prediction. Each of these

TABLE 1—MATERIAL-CHARACTERIZATION SHEET

Material: <u>RQC-100^a</u>	Specimen Ref. No.: <u>TX</u>
Condition: <u>Roller quenched and tempered, 3/8" plate - 298 BHN</u>	Test Cond.: <u>Room Temp.</u>
Monotonic Properties: Long/trans	Cyclic Properties: Long/trans
Mod. of Elast., E <u>29.4</u> x 10 ³ ksi	Yield Strength, 0.2% S _y ' <u>73/74</u> ksi
Yield Strength, 0.2% S _y <u>111/112</u> ksi	Strain Hard. Exp., n' <u>0.16/0.148</u>
Ultimate Strength, S _u <u>119</u> ksi	Strength Coeff., K' <u>197/200</u> ksi
Red. in Area, % RA <u>68.2/47.5</u>	Fatigue Strength Coeff., σ _f ' <u>147/132</u> ksi
True Frac. Strength, σ _f <u>197/162</u> ksi	Fatigue Ductility Coeff., ε _f ' <u>0.60/0.65</u>
True Frac. Ductility, ε _f <u>1.15/0.65</u>	Fatigue Strength Exp., b <u>-0.076/-0.052</u>
Strain Hard. Exp., n <u>0.114/0.075</u>	Fatigue Ductility Exp., c <u>-0.67</u>
Strength Coeff., K <u>192/165</u> ksi	Transition Fat. Life, 2N _t <u>2,900/3,500</u> rev
True Toughness, U _p <u>204,000/98,000</u> in-lb/in ³	
Comments:	
Chemistry (%)	
C Mn P S Si B	
.20 .24 .006 .023 .33 .003/.004	
Processing:	
Roller quenched from 1650°F, tempered at 500°F	
^a Product of Bethlehem Steel Corp.	
Source: <u>D. Parks (7)</u> Date: <u>7/71</u>	

$\alpha = 0.0001$
 $A = 1.0$
 $M = 334 \text{ KSI} = 2(\text{TFS}) = \sigma_f$
 $\text{FSC}/E = \sigma_f^{-1} = .00557$

will be discussed separately.

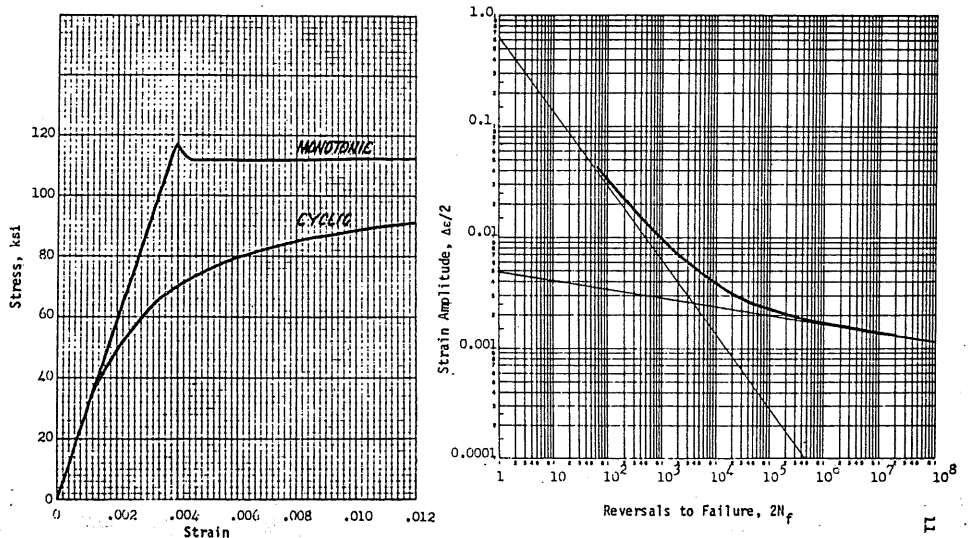
Material Characterization

Since a fatigue analysis involves *cyclical* loading of structure, additional information, outside of the commonly used *monotonic* properties of materials, was required. Cyclical stress-strain data were taken

from various sources including work done by Landgraf,⁶ Mitchell⁶ and LaPoint.⁶ Table 1 shows an example of a material characterization sheet for RQC-100. Note that both cyclic and monotonic properties are shown. Figure 3 shows the stress-strain response under both monotonic and cyclic loading. The monotonic curve was obtained by conventional methods.

Material: RQC-100 = EEMS 10072 (95 KSI Yield)
 Condition: Roller quenched and tempered, 3/8" plate - 298 BHN

Fig. 3—Stress-strain response



The cyclic curve was obtained by cycling a specimen through continually increasing strain limits. This method generates a series of nested hysteresis-loop tips, as shown in Fig. 4. Upon connecting the loop tips, the cyclic curve is formed. Note the difference in the start of the plastic stage.

Component-strength Measurement

Since most fatigue failures occur at notches, whether they are welds, fillets, grooves or joints, the stresses causing failure are seldom the nominal stresses in the component. Stress levels in these concentrations are generally much higher than on the adjacent surfaces and are often difficult to measure accurately.

In order to accurately consider the stress effects at these concentrations, a 'fatigue-concentration factor' is developed. Its manner of use is two-fold. One way is to obtain a sample component, similar in section to the one to be tested, and apply a constant-amplitude, fully reversed load to the part, noting the number of reversals required to fail at the 'critical location,' and the corresponding load amplitude. A second way is to take a component on a vehicle and obtain the number of operating hours or miles required to fail the part at the same location. Either way, through a constant-amplitude laboratory failure, or a varying-amplitude field failure, the data collected for the specific component are combined with material data to calculate the effect at the notch, and this effect is taken into account.

As an example, take the component mentioned earlier that fails after a half-million cycles with a

known amplitude of loading. With a 'basic backwards approach,' the actual strain at the root of the notch

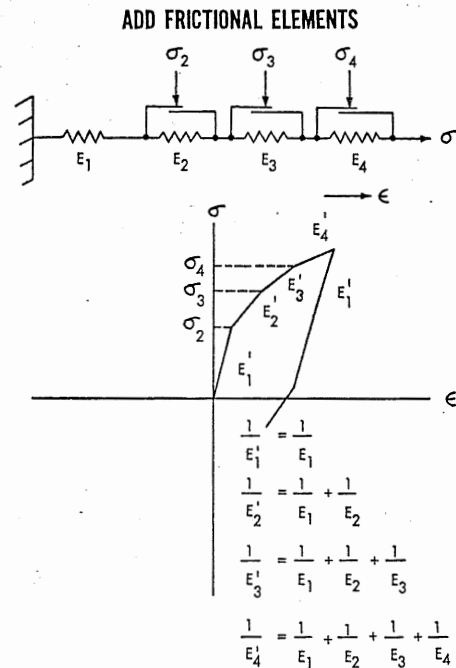


Fig. 6—Frictional elements and sliders

STEADY-STATE STRESS-STRAIN RESPONSE

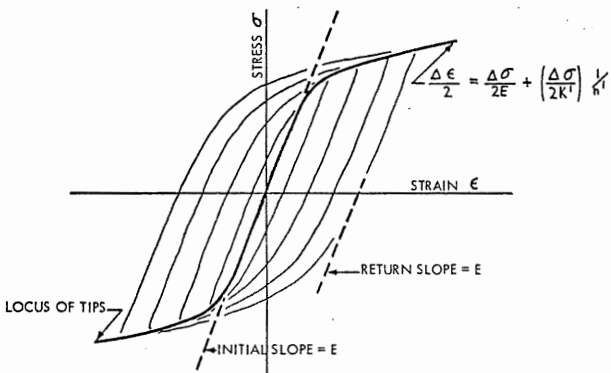


Fig. 4—Steady-state response

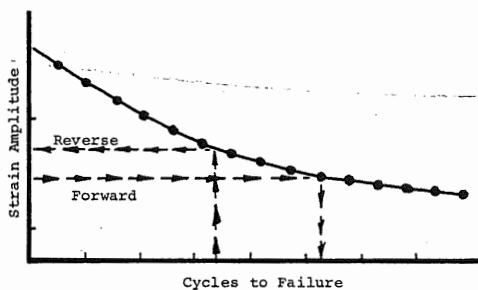


Fig. 5—The basic backwards approach

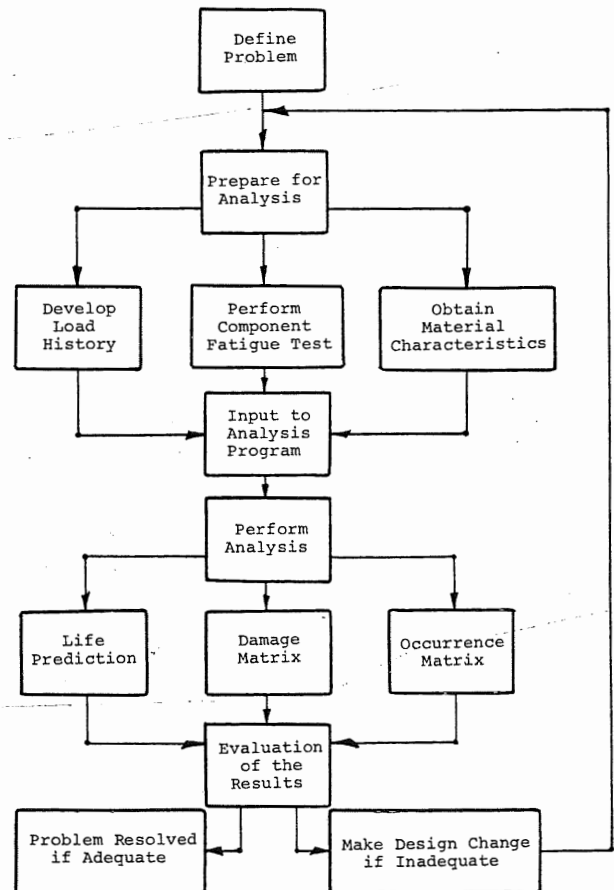


Fig. 7—Program flow

can be determined. As shown in Fig. 5, the S-N curve developed earlier is used in reverse. Where the curve usually determines the number of cycles to failure based on a given strain amplitude, the reverse method starts with the number of cycles to failure. It further states that in order for that component to fail after that many cycles, a certain amount of strain had to be present at that section whether or not that amount was measured. The difference between the 'measured strain' and the 'actual strain' is taken into account in the 'fatigue-concentration factor.' It is obvious that this factor is a catch-all for many other differences.

Load-history Determination

An FM tape recorder is used to record the changing strain values due to operating loads. Care should be taken to choose a representative history since too mild or too severe a loading cycle will lead to either a liberal or conservative analysis. The analog data, recorded on tape, must later be digitized so that it can be read by a digital computer. Since the prime

feature of a field-load history is a *time sequence of peaks and valleys*, these alone are the only points necessary to be permanently stored. Using data collected earlier, from both material and component properties, the fatigue-analysis program can then convert these strain levels to their corresponding stress levels and ultimately predict component life.

The Fatigue-analysis Method

The actual fatigue-analysis program calculates notch-root stresses and strains using a Neuber's-rule-based computer model to follow the material's plastic stress-strain state at the notch root. Frictional elements and sliders, as shown in Fig. 6, mathematically force the response of the material to behave as it 'would' in real life. Cycles are counted using a version of the rainflow-cycle counting method. Mean-stress-relaxation parameters are estimated and mean stresses are allowed to relax out. Mean stresses for each reversal were accounted for in the cumulative-damage procedure by using the product of maximum stress and strain range as the fatigue-damage parameter. Miner's linear-damage rule was used to sum cumulative damage.

This computer program combines the material characteristics accumulated in the first phase, the component properties developed in the second phase and the load history obtained in the third phase, and produces a range-mean damage matrix, a range-mean occurrence matrix, and a life prediction. Each of these three forms of output will be covered through examples.

Application of the Program

As a general review, Fig. 7 shows the basic procedure involved in performing a fatigue analysis of this type. Once again, there are three main inputs to the computer program and three main outputs. A specific example follows.

Consider the 'hypothetical' case where a spindle, used on the tractor of a self-loading scraper, was found to fail after 1500 h of normal operating cycles. If minimum life is expected to be 20,000 h, it is obvious that a deficiency was present.

The location of failure was found to be at the bear-

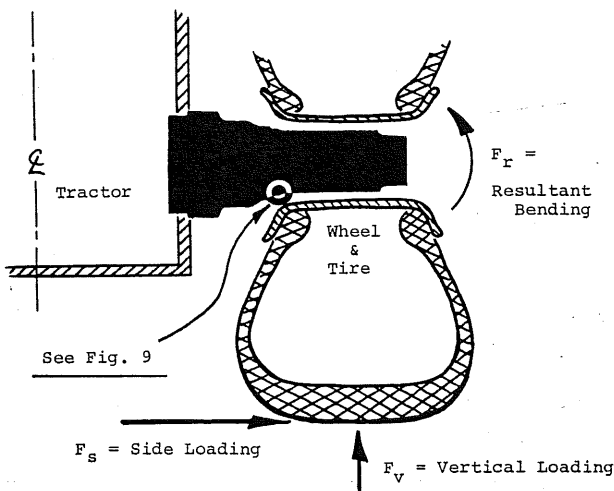


Fig. 8—Spindle environment

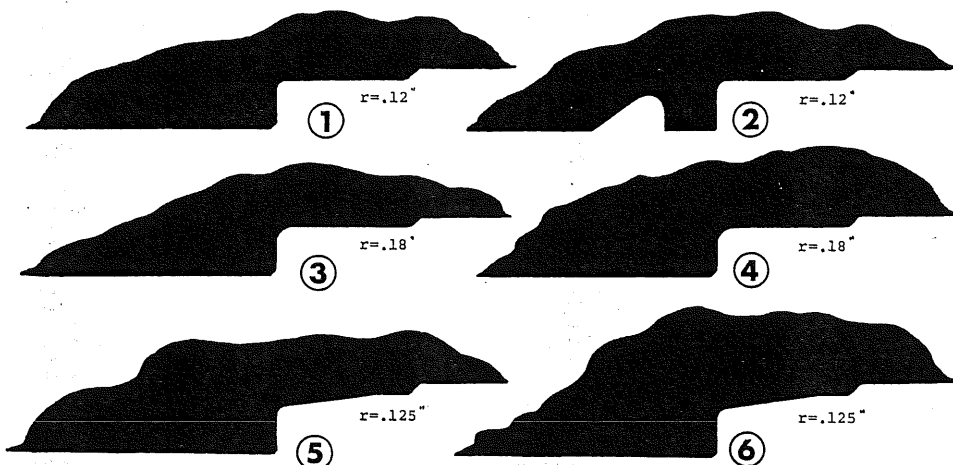
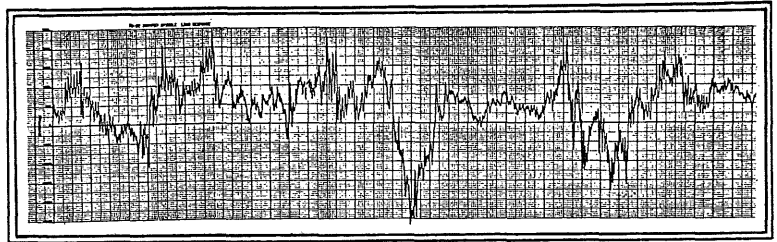


Fig. 9—Bearing-shoulder configurations

Total time in the example below --- 2.5 minutes
 Full scale deflection --- ±3125 microstrain

Fig. 10—Example of typical road-history-data curves



ing shoulder, and the cause of the problem was determined to be high vertical bending, especially evident when making sharp turns in a loaded state. Figure 8 shows the loading environment.

The original configuration of the spindle, along with the resulting changes, is shown in Fig. 9. It was basically a design which allowed for a shoulder upon which a bearing would rest. However, a stress concentration was created, and this concentration proved to be a critical location in the design of the spindle.

The modifications shown along with the original were developed in an attempt to increase the fatigue life of the spindle. Their evaluation, under past practices, would have been to fatigue test several of each configuration. Allowing for approximately two weeks' time to fail each spindle, it would take over a year's time to fail five samples of each.

As an alternative, material-model simulation was used. The material in question was determined to be SAE 4130 260BHN. Corresponding data based on the cyclic properties of this material were applied. The failure rates on various spindles were used to determine the fatigue-concentration factor. Load-history data were obtained during field operation. An example is shown in Fig. 10.

Upon applying the program to the original spindle,

the following results were obtained. Figure 11 shows the input data, Fig. 12, the damage profile, Fig. 13, the damage matrix, and Fig. 14, the occurrence matrix.

In this example, the fatigue-concentration factor, evident in Fig. 11, was adjusted so that the life prediction would be forced to 1500 h. This was the

** FATIGUE OF MATERIAL **
 SUMMARY SHEET

FATIGUE ANALYSIS OF TS-32 SPINDLE PRODUCTION CONFIGURATION 1		
** LIST OF PROPERTIES		
YOUNGS MODULUS.....	32000000.	PSI
CYCLIC STRAIN HARDENING EXPONENT.....	0.130	
STABLE CYCLIC STRENGTH COEFFICIENT.....	220000.	PSI
INITIAL CYCLIC STRENGTH COEFFICIENT.....	220000.	PSI
TRANSIENT STRENGTH EXPONENT.....	1.000	
TRANSIENT STRENGTH COEFFICIENT.....	0.0001	IN/IN
RELAXATION COEFFICIENT.....	412000.	PSI
FATIGUE CONCENTRATION FACTOR.....	22.300	
** FATIGUE PROPERTIES		
FATIGUE DUCTILITY COEFFICIENT.....	0.920	IN/IN
FATIGUE DUCTILITY EXPONENT.....	-0.630	
FATIGUE STRENGTH COEFFICIENT.....	0.005	IN/IN
FATIGUE STRENGTH EXPONENT.....	-0.083	
** MAGNETIC TAPE INFORMATION		
TAPE IDENTIFICATION.....	100	
CHANNEL USED.....	1	
FOOTAGE..... START 0 STOP.....	200	
DEADBAND.....	34.000	MICROSTRAIN
STATIC PRELOAD.....	0.000	MICROSTRAIN
CALIBRATION VALUE.....	1000.000	MICROSTRAIN
SENSITIVITY RATIO..RUN/CAL.....	1.000	
ZERO.. 250.000 SCALE... 2500.000		

Fig. 11—Input data

** FATIGUE OF MATERIAL **

FATIGUE ANALYSIS OF TS-32 SPINDLE PRODUCTION CONFIGURATION 1				
** DAMAGE REPORT **				
RANGE	NO. OF REV	DAMAGE FRACTION	CUMULATIVE DAMAGE	
0.000.....308.208	1404.	0.1386270E-10	0.1386270E-10	
308.208.....616.416	177.	0.2525653E-09	0.2664279E-09	
616.416.....924.624	94.	0.9475687E-08	0.9742114E-08	
924.624.....1232.832	47.	0.5267533E-07	0.6241744E-07	
1232.832.....1541.039	40.	0.5888964E-06	0.6513138E-06	
1541.039.....1849.248	12.	0.7668683E-06	0.1418182E-05	
1849.248.....2157.456	8.	0.1335069E-05	0.2753251E-05	
2157.456.....2465.664	12.	0.6280932E-05	0.9034183E-05	
2465.664.....2773.871	0.	0.0000000E 00	0.9034183E-05	
2773.871.....3082.079	1.	0.4389467E-05	0.1342365E-04	
3082.079.....3390.288	3.	0.2331765E-04	0.3674130E-04	
3390.288.....3698.496	2.	0.3174855E-05	0.3991615E-04	
3698.496.....4006.703	0.	0.0000000E 00	0.3991615E-04	
4006.703.....4314.912	0.	0.0000000E 00	0.3991615E-04	
4314.912.....4623.120	0.	0.0000000E 00	0.3991615E-04	
4623.120.....4931.328	2.	0.1316748E-03	0.1715909E-03	
4931.328.....5239.536	0.	0.0000000E 00	0.1715909E-03	
5239.536.....5547.743	0.	0.0000000E 00	0.1715909E-03	
5547.743.....5855.952	0.	0.0000000E 00	0.1715909E-03	
5855.952.....6164.159	0.	0.0000000E 00	0.1715909E-03	
6164.159.....6472.367	0.	0.0000000E 00	0.1715909E-03	
6472.367.....6780.576	2.	0.2278043E-02	0.2449634E-02	
6780.576.....7088.783	0.	0.0000000E 00	0.2449634E-02	
TOTAL REVERSALS =		1804.	HOURS TO FAILURE = 1496.82	

Fig. 12—The damage profile

RANGE - MEAN - DAMAGE MATRIX

ENGINEERING UNITS - MICROSTRAIN	RANGES									
	0.0	800.0	1600.0	2400.0	3200.0	4000.0	4800.0	5600.0	6400.0	7200.0
MEANS	400.0	1200.0	2000.0	2800.0	3600.0	4400.0	5200.0	6000.0	6800.0	7600.0
-3800.0	0.00									
-3600.0	0.00	0.00								
-3400.0	0.00	0.00	0.00							
-3200.0	0.00	0.03	0.00	0.00						
-3000.0	0.00	0.00	0.00	0.00	0.00					
-2800.0	0.00	0.00	0.00	0.00	0.00	0.00				
-2600.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
-2400.0	0.00	0.00	0.00	0.00	0.12	0.00	0.00			
-2200.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
-2000.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
-1800.0	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	
-1600.0	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
-1400.0	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
-1200.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-1000.0	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
-800.0	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00
-600.0	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00
-400.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-200.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
200.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
400.0	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
600.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
800.0	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
1000.0	0.00	0.00	0.00	0.31	7.09	0.00	0.00	0.00	0.00	0.00
1200.0	0.00	0.00	0.06	4.40	0.00	0.00	0.00	0.00	0.00	0.00
1400.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1600.0	0.00	0.01	0.13	0.53	4.62	5.37	0.00	0.00	0.00	0.00
1800.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000.0	0.00	0.00	0.13	1.63	4.62	33.99	0.00	0.00	0.00	0.00
2200.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2400.0	0.00	0.00	0.00	0.41	3.30	0.00	0.00	0.00	0.00	0.00
2600.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2800.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3000.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3200.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3400.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3600.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3800.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

FATIGUE ANALYSIS OF TS-32 SPINDLE PRODUCTION CONFIGURATION 1
TAPE ID 100 CHANNEL 1 FOOTAGE-START 0 STOP 200

Fig. 13—The damage matrix

average life to failure of the spindles that failed in the field. The program could have calculated a concentration factor but, since the failure rates were known, trial and error was used to force the life prediction to equal the rate.

Figure 12 shows the amount of damage caused in each range of reversals, from the smallest ranges to the largest ranges. Note that there are more reversals

in the smaller ranges; yet, the greatest damage is done in the larger ranges, where there are fewer reversals. As shown in Fig. 2, the term reversal indicates the travel from a peak to the valley immediately following it, and vice versa. Consequently, there are two reversals in a cycle.

Figure 13 represents the damage done at each condition of a specific strain range occurring at a specific

RANGE - MEAN - OCCURRENCE MATRIX

ENGINEERING UNITS - MICROSTRAIN	RANGES									
	0.0	800.0	1600.0	2400.0	3200.0	4000.0	4800.0	5600.0	6400.0	7200.0
MEANS	400.0	1200.0	2000.0	2800.0	3600.0	4400.0	5200.0	6000.0	6800.0	7600.0
-3800.0	0									
-3600.0	6	0								
-3400.0	4	2	1							
-3200.0	1	2	1	0	0					
-3000.0	7	2	1	0	0	0				
-2800.0	11	5	1	1	0	0	0			
-2600.0	13	9	1	1	0	0	0	0		
-2400.0	18	13	4	1	0	0	0	0	0	
-2200.0	37	27	7	4	0	0	0	0	0	0
-2000.0	35	54	4	4	0	1	0	0	0	0
-1800.0	62	49	3	6	2	1	0	0	0	0
-1600.0	140	89	6	2	1	0	0	0	0	0
-1400.0	223	153	24	7	1	1	0	0	0	0
-1200.0	189	120	32	9	1	0	0	0	0	0
-1000.0	120	60	17	6	4	1	0	0	0	0
-800.0	77	31	12	6	3	4	0	0	0	0
-600.0	17	9	9	10	10	2	3	0	0	0
-400.0	10	2	0	1	0	0	0	0	0	0
0.0	0	0	0	0	0	0	0	0	0	0
200.0	0	0	0	0	0	0	0	0	0	0
400.0	0	0	0	0	0	0	0	0	0	0
600.0	0	0	0	0	0	0	0	0	0	0
800.0	0	0	0	0	0	0	0	0	0	0
1000.0	0	0	0	0	0	0	0	0	0	0
1200.0	0	0	0	0	0	0	0	0	0	0
1400.0	0	0	0	0	0	0	0	0	0	0
1600.0	0	0	0	0	0	0	0	0	0	0
1800.0	0	0	0	0	0	0	0	0	0	0
2000.0	0	0	0	0	0	0	0	0	0	0
2200.0	0	0	0	0	0	0	0	0	0	0
2400.0	0	0	0	0	0	0	0	0	0	0
2600.0	0	0	0	0	0	0	0	0	0	0
2800.0	0	0	0	0	0	0	0	0	0	0
3000.0	0	0	0	0	0	0	0	0	0	0
3200.0	0	0	0	0	0	0	0	0	0	0
3400.0	0	0	0	0	0	0	0	0	0	0
3600.0	0	0	0	0	0	0	0	0	0	0
3800.0	0	0	0	0	0	0	0	0	0	0

FATIGUE ANALYSIS OF TS-32 SPINDLE PRODUCTION CONFIGURATION 1
TAPE ID 100 CHANNEL 1 FOOTAGE-START 0 STOP 200

Fig. 14—The occurrence matrix

TABLE 2—EFFECTS OF GEOMETRY CHANGE

Configuration	Measured Strain	Indicated Stress		Scaling Factor
	$\mu\epsilon$	KSI	MPa	
Original No. 1	1845	59.04	407	1.000
Stress-relieved Groove No. 2	1495	47.84	330	.810
Increased Radius No. 3	1640	52.48	362	.889
Thicker Wall No. 4	1475	47.20	326	.799
Blended Radius No. 5	1625	52.00	359	.881
Blend and Thicker Wall No. 6	1425	45.60	315	.772

Loading: 60,000-lb force (267,000 N)
Applied at a moment arm of
30.39 in. (0.772 m)

TABLE 3—RESULTANT LIFE PREDICTIONS

Configuration	Scaling Factor	Percent Reduction	Life Prediction, h	Percent Increase, %
Original No. 1	1.000	—	1,496	—
Stress-relieved Groove No. 2	.810	20.9	12,791	755
Increased Radius No. 3	.889	11.1	4,521	202
Thicker Wall No. 4	.799	20.1	15,086	908
Blended Radius No. 5	.881	11.9	4,969	232
Blend and Thicker Wall No. 6	.772	22.8	23,536	1,473

strain mean. The ranges increase from left to right as shown across the top, and the means increase from center to either top or bottom as shown on the left. From this, it is evident that the most "stable" condition is that with a zero mean and a zero range. Any deviation from this would indicate that a less-stable condition is evident. As an analogy, if the damage matrix is considered as a 'tree,' then the most stable part of the tree would be at the base of the trunk. If a position is chosen either too far out on the limbs or too high up, then an unstable condition will exist. "The best place to build a tree house would be close to the trunk of the tree, not out on the limbs."

Figure 14 represents the number of occurrences at each condition of range and mean. Once again, if there are too many occurrences "out on the limbs," meaning at the larger ranges and means, there is room for design improvement.

After developing the above baseline, changes were made, and each effective change was evaluated to determine the increase or decrease in fatigue life. The input data as shown in Fig. 11 remained the same. The only item that was changed was the scaling of the response curve. The scaling factor was determined by physically applying a known load, in the

appropriate direction, to each modified spindle, and measuring the resulting strain at the bearing shoulder. That strain level was then compared to the baseline to determine the factor of increase or decrease. With a 60,000-lb load at the appropriate point on the spindle, the resultant factor changes due to the change in static strain were determined to be as in Table 2.

The results from each subsequent run of the program to predict life increase are shown in Table 3.

Note that percent reductions (determined by comparing the static-strain values) are not in direct proportion to the percent increases (based on the effective increase in fatigue life). If the six examples are plotted, static strain level vs. predicted life, a special S-N curve will be formed. The basic difference between this S-N curve and any given S-N curve for the casting material will be one of specifics. The S-N curve just created will take into account the specific component in question, not anything made of the basic material. It also takes into account the strain at the root of the notch as the effective strain. In addition, the random-load inputs determined through field testing are used to cause the failure, not some artificial load.

Taking a second look at Table 2, note that the difference between the static strains measured on configurations No. 4 and No. 6 is very small. Though the strain level in configuration No. 6 is only 3.5 percent less than that in configuration No. 4, the expected life in configuration No. 6 is 56 percent greater than that in configuration No. 4. When the differences are taken into account along with the requirement of at least 20,000 h of expected life, it is a simple decision to use configuration No. 6 as the final proposal.

Verification

In an effort to determine the accuracy of the predictions made, a physical test was made on the final configuration. Whereas the original spindles failed after 1500 h, a figure which can be related to 57,000 constant-amplitude, fully reversed lab cycles, the final spindles took many more lab cycles to cause failure. Specifically, two individual spindles were tested, and after an average of over one million cycles, failure occurred in the base casting instead of the bearing shoulder. Since a failure at the shoulder could not be created prior to a casting failure, it is assumed that the final-configuration life expectancy was at least equal to that predicted.

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