A CRITICAL EVALUATION OF CYCLIC MEAN STRESS EFFECTS IN A STRUCTURAL STEEL

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The influence of mean stress on fatigue life is well known and various rules have been applied to account for its effect. However, in low strength ductile materials the existence of a mean stress only occurs as a result of significant plasticity. Hence it is necessary to consider these two phenomena (i.e., mean stress and overstrain) together rather than in isolation.

This work deals with mean stress effects in a low carbon structural steel and evaluates fatigue life prediction methods. It is shown that when overstrains are taken into account the additional effects of either tensile or compressive mean stresses are small. Many of the conventional rules for mean stress correction are shown to be too conservative and misleading. If a correction is to be made, then that of Gerber is preferred.

INTRODUCTION

The detrimental effect of tensile mean stress on fatigue life has been known to exist for over a century. The original fatigue tests of Wohler (1) and Bauschinger (2) provided the information with which the early researcher used to formulate mean stress criteria. Of these, the most notable have survived to this day. Examples are the Gerber (3) and Goodman (4) rules. Over this period numerous other rules and hypotheses have been presented. However, they have contributed little to our understanding of the underlying physical phenomena. In fact, since the outstanding paper by Gerber, there appears to have been few attempts to relate the empirical rules to fatigue mechanisms.

This work examines mean stress effects in a low carbon structural steel and the general intent is to improve variable amplitude life prediction methods. This is accomplished by examining the various rules and hypotheses, exploring their limitations and attempting to understand the fatigue damage accumulation process.

Mean Stress

Much of our understanding of metal fatigue stems from significant work of the nineteenth century. The major contributor was Wohler (1819-1914) who

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conducted the first systematic study of the fatigue of iron and steel. The test data he reported was then used in very different ways by both Gerber and Goodman to establish their hypotheses.

Gerber attempted to relate applied loads to the microscopic structure of metals. His careful study resulted in his 'Parabolic Law':

$$\sigma_a = (\sigma_{uts}/3)[1 - \sigma^2{}_o/\sigma^2{}_{uts}] \qquad [1]$$

or in the more general case

$$\sigma_a = \sigma_{f1}[1 - \sigma^2{}_o/\sigma^2{}_{uts}] \qquad [2]$$

Goodman took an entirely empirical approach and, based on his 'dynamic theory', established his 'Rule':

$$\sigma_a = (\sigma_{uts}/3)[1 - \sigma_o/\sigma_{uts}] \qquad [3]$$

or more generally

$$\sigma_a = \sigma_{f1}[1 - \sigma_o/\sigma_{uts}] \qquad [4]$$

Goodman explained his 'dynamic theory' as follows: "When a load is suddenly applied to a bar or structure the stress produced is twice as great as if the load was gradually applied." Goodman's major justification for suggesting that his hypothesis had more to offer than the work of Gerber was its simplicity. He stated, "The dynamic theory equation however fairly fits the results and is very easy of application and is moreover very simple to remember; but whether the assumptions of the theory are justifiable or not is quite an open question, which we shall not discuss."

Since those early days other attempts have been made to establish rules governing the effect of mean stress on fatigue. Kommers (5) in 1930 reported more than ten different approaches, most of which were simple adjustments of Goodman's Law. The first original idea to be introduced was from Soderberg (6) who thought that yielding must be considered. He suggested the following equation:

$$\sigma_a = \sigma_{f1}[1 - \sigma_o/\sigma_{ys}] \qquad [5]$$

During the 1950's and 1960's two noteworthy efforts were made to adapt the Gerber and Goodman models to contemporary knowledge. Marin (7) suggested the following modification to Gerber's Parabola:

$$\sigma_a = \sigma_{f1}[1 - \sigma^2{}_o/\sigma^2{}_{uts}]^{1/2} \qquad [6]$$

Morrow (8) reasoned that if the intercept at one reversal on a log stress-log life curve was approximately equal to the true fracture stress, then that parameter should replace the ultimate tensile strength in Goodman's simple law, i.e.:

$$\sigma_a = \sigma_{f1}[1 - \sigma_o/\sigma_f] \qquad [7]$$

As a result of extensive research during the 1960's and 70's on the fatigue of notched components and the development of Neuber's Rule, a new approach to mean stress was suggested by Smith (9) and Smith, Watson and Topper (10). Smith and co-workers postulated that there was a unique relationship between the product of maximum stress and strain amplitude on the one hand and fatigue life on the other. His rule was based on the well established total strain-fatigue life equation:

$$\Delta\varepsilon/2 = (\sigma'_f/E)(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad [8]$$

which may be rewritten:

$$\sigma_{max}\varepsilon_a = (\sigma'_f/E^2)2N_f{}^{2b} + \sigma'_f\varepsilon'_f(2N_f)^{b+c} \qquad [9]$$

During the past decade as fatigue and fracture evolutions became more complex, Fuchs (11) reversed this trend by putting forward a very simple mean stress rule:

$$\sigma_a = \sigma_{f1} + \sigma_o/2 \qquad [10]$$

All of the mean stress formulae above (equations [1] through [10]) may be rewritten in a more general form which identifies the equivalent completely reversed stress amplitude which will result in an identical fatigue life for each combination of stress amplitude and mean stress. For example, Goodman's law becomes:

$$\sigma_{cr} = \sigma_a\,[\sigma_{uts}/(\sigma_{uts} - \sigma_o)] \quad \text{since } \sigma_{f1} = \sigma_{cr} \qquad [11]$$

where σ_{cr} is the equivalent completely reversed stress which should result in the same fatigue life as that achieved with the given values of σ_a and σ_o. Using a similar approach, the other criteria are:

Gerber	$\sigma_{cr} = \sigma_a\,[\sigma_{uts}{}^2/(\sigma_{uts}{}^2 \pm \sigma_o{}^2)]$	[12]
Soderberg	$\sigma_{cr} = \sigma_a\,[\sigma_{ys}/(\sigma_{ys} - \sigma_o)]$	[13]
Marin	$\sigma_{cr} = \sigma_a\,[\sigma_{uts}{}^2/(\sigma_{uts}{}^2 \pm \sigma_o{}^2)]^{1/2}$	[14]
Morrow	$\sigma_{cr} = \sigma_a\,[\sigma_f/(\sigma_f - \sigma_o)]$	[15]
Fuchs	$\sigma_{cr} = \sigma_a - \sigma_o/2$	[16]

The Smith equation was originally proposed in this general form hence no adjustment is required.

It is important to note that in these equations the tensile value of σ_o is positive and the compressive value is negative. If σ_o is squared, the above sign convention applies to the squared value.

Overstrain

The complexities of service loading and fabrication processes for many engineering components are such that the occurrence of an occasional high strain cycle amidst numerous low strain cycles is common, e.g., see reference (12). Application of a few high strain cycles has been shown to significantly reduce subsequent fatigue life (12, 13, 14, and 15). The most common explanation for such reductions is based on a rapid acceleration of the crack initiation or stage 1 crack growth phase. It is now firmly established that the 'overstrain effect' should be considered in any fatigue evaluation.

Fatigue Life Prediction

The prediction of fatigue life has become an important part of design and development of components and structures. Such evaluations become exceedingly complex when analyzing notched components under variable amplitude load histories because of significant notch plasticity which can be induced by nominally elastic loads. Furthermore it is generally accepted that a mean stress correction is required. This necessitates the construction of a cycle by cycle stress-strain history from the load history using notch geometry, Neuber's Rule and a material deformation model. In most cases, when the load history consists of many cycles, such an analysis is only possible using computer based routines. There are many routines available, (e.g., references 16,17) which rely on one of the mean stress criteria just mentioned. Overstrain effects can be accounted for by using basic material data from overstrained specimens.

Major questions concerning mean stress effects under variable amplitude conditions in service are: how are the mean stresses introduced? how long do they remain and how do they effect damage accumulation? It is important to point out that significant mean stresses can only be introduced as a result of considerable deformation. High mean stresses will occur in stress histories, due to high strains which are plastic in many instances. Hence the effect of such mean stresses must be considered together with the effect of the overstrains which induce them.

The intent of this investigation is to evaluate the suitability of the various mean stress criteria using a low carbon structural steel. The extreme ductility of this type of steel has two important ramifications. First of all, significant mean stresses can only be induced by large plastic strains. Hence, the mean stress and overstrain phenomena are inseparable. Secondly, large values of mean stress cannot occur in most practical situations because most fatigue failures occur at notches where the deformation is restrained by the surrounding material. Hence, the very large plastic strains which are required for high values of mean stress cannot occur. Therefore, the appropriate mean stress criteria for use in life prediction should be that which is successful in the region close to zero mean stress. This is displayed on a modified Goodman diagram in Figure 1. Presentation of mean stress criteria in this manner also displays the beneficial effects of compressive mean stresses.

EXPERIMENTAL PROCEDURE

All test specimens were made from CSA G40.21-50A structural steel. The chemical composition is presented in Table 1. The monotonic tensile stress properties for this material were: σ_{ys} = 365 MPa, σ_{uts} = MPa and σ_f = 1020 MPa. The basic strain-life and stress-life curves are shown in Figures 2 and 3, respectively.

All specimens were unnotched having a minimum diameter of 5.1 mm and a parallel sided gauge length of 12.7 mm. The specimens were cut from plate with their axis orientated transverse to the rolling direction. Great care was taken during final machining to minimize the residual stress induced. Final polishing was performed by hand in the longitudinal direction beginning with 220 grit emery cloth and progressing down to 600 grit emery cloth.

TABLE 1

CHEMICAL COMPOSITION FOR G40.21-50A STEEL

ELEMENT	PERCENTAGE
Carbon	0.12
Manganese	1.07
Phosphorus	0.008
Sulfur	0.028
Silicon	0.25
Copper	0.29
Nickel	0.31
Chromium	0.37
Vanadium	0.02

All specimens were unnotched having a minimum diameter of 5.1 mm and a parallel sided gauge length of 12.7 mm. The specimens were cut from plate with their axis orientated transverse to the rolling direction. Great care was taken during final machining to minimize the residual stress induced. Final polishing was performed by hand in the longitudinal direction beginning with 220 grit emery cloth and progressing down to 600 grit emery cloth.

All testing was performed in strain control on a M.T.S. servocontrolled closed loop hydraulic testing machine. Load was monitored continuously by a 44 kN load cell mounted in series with the specimen. Strain was controlled by means of an extensometer, having a gauge length of 7.6 mm. To prevent fatigue cracks starting at the knife edges, plastic tape or epoxy was first applied to the specimen before the extensometer was attached. The overstrain sequence and initial stress-strain hysteresis loops were recorded on an X-Y plotter. After initial start-up, strain and load were monitored by means of a tracking voltmeter. Load response was recorded with a high speed strip chart recorder. Failure of the specimen was defined as complete separation.

Four different types of tests were performed. Their loading histories or cases are described below and illustrated in Figure 4.

1) Fully reversed constant amplitude cycling to failure for comparison with Conle's Data (20) to validate the method used and for basic data.

2) A single ± 1% overstrain followed by fully reversed cycling to failure.

3) A single ± 1% overstrain followed by cycling from a maximum tensile strain of 1% with a range of strain amplitudes investigated. This provided the maximum tensile mean stress which was still within the overstrain hysteresis loop.

4) A single ± 1% overstrain followed by cycling from a minimum compressive strain of 1% with a range of strain amplitudes investigated. This provided the maximum compressive mean stress which was still within the overstrain hysteresis loop.

The cyclic strain amplitudes (0.14% to 0.20%) were carefully chosen in order to concentrate on the long life region.

EXPERIMENTAL RESULTS

During each overstrain sequence an X-Y plot of the initial hysteresis loop illustrated the large amount of plasticity occurring during the overstrain cycle, as well as the low cyclic work hardening rate. The experimental results for all four test series are included in Figures 5, 6 and 7 which are plots of strain range, stress range and Smith parameter versus cyclic life, respectively.

The range of obtainable mean stresses for the test material is indicated by the dashed region illustrated on the modified Goodman diagram, Figure 1. It is clearly seen that under strain control the obtainable mean stress is very limited for load responses slightly greater or equal to the endurance limit. For example, the maximum tensile mean stress obtained at 50% life was 95 MPa and the maximum compressive mean stress was -81 MPa.

DISCUSSION

Life Plots

Commissioning of the test equipment and determination of operator effectiveness was performed for the zero mean stress condition with no overstrain (loading history or case 1). Previous results on G40.21-50A, of identical specimen specimen geometry, by Conle (20) provided a useful basis for comparison. This work has been reproduced in terms of the strain-life and stress-life plots, Figures 2 and 3, respectively. Conle's results are included in these figures. It is apparent that the present testing procedure and results are fully compatible.

For loading history or case 2 it was initially thought that a single overstrain cycle in these overstrained tests would result in minor differences between the present tests and those of Conle (20) who used 10 overstrain cycles and a ramping down procedure. However, as Figures 2 and 3 show, no apparent difference exists between the two sets of data. This observation is supported by Dowling (21) who showed that for prestrains larger than ± 0.5%, the effect on the subsequent fatigue life was not dependent on the number of cycles or amplitude of prestrain.

It is evident that there is a clear distinction between the various test series of the present work when the results are plotted on a strain-life curve, Figure 5. In particular the beneficial effect of compressive mean stress (case 4) on fatigue life should be noted. Yet, when the results are plotted on a stress-life curve, Figure 6, this distinction is lost. It must be remembered that the tests were strain controlled and hence the strain measurements were more precise. The stress values, by comparison, were uncontrolled and were changing in magnitude and mean, therefore making them relatively imprecise. An additional complication was that due to the low cyclic work hardening rate, the fatigue lives changed more rapidly with stress level fluctuations rather than strain level fluctuations. For example, the difference in the stress amplitude due to a major change in strain amplitude from +0.25% to +0.50% was only 12.6 MPa.

Cyclic Softening and Stress Relaxation

It is well known that most metals harden or soften when cycled between constant strain limits. Generally this depends on their initial heat treatment and the cyclic strain amplitude. These changes occur rapidly at

first and are essentially stabilized by 20% of life (22). Variation of stress range with cycles for the three types of overstrained tests used in the present work followed a similar trend. Rapid softening occurred at the beginning of cyclic straining followed by stable stress response after about 100 reversals. Any effects of mean stress on the stable stress response were not observed with the degree of scatter present. After approximately 100,000 reversals the stress response again started to decrease as a result of stable crack propagation.

Mean stress relaxation, where the initially applied mean stress shifts towards zero stress, is expected to occur on cycling between fixed strain limits. It is generally acknowledged that the mean stress relaxes to zero at an exponential rate although when the plastic strain is small, relaxation to some finite value takes place (23,24,25). Jhansale (23) demonstrated that the following empirical equation adequately represented mean stress relaxation behaviour in normalized mild steel.

$$\sigma_{oi} = \sigma_{on}^{B} \qquad [17]$$

Applicability of the above equation was investigated for tensile mean stress tests at strain ranges of 0.30% and 0.32% and compressive mean stress tests at a single strain range of 0.35%. The values used for the initial mean stress were read off the X-Y plots. It was apparent that Equation 17 did not satisfactorily describe the present experimental data. In comparison, the work by Jhansale (27) showed very little scatter and excellent agreement with Equation 17. Despite the poor fit of the present data to this equation, it was evident that the rate of relaxation was significantly less. This may be due to two factors. First, the materials used were different. Secondly, the loading histories used by Conle and Jhansale consisted of precycling at a strain range of approximately 0.9% until the stress response stabilized compared to a single overstrain cycle of ± 1.0%.

Mean Stress Parameters

All the mean stress criteria discussed in the introduction have been applied to the test data and the results are presented in Table 2. For each criterion the equivalent reversed form is used. Additionally, Table 2 contains the completely reversed stress amplitude and the completely reversed Smith parameter for the test lives obtained. In order to compare the Smith parameter, which is of the form $(E\,\varepsilon_a \sigma_{max})^{1/2}$, with the other parameters, all the results have been normalized by calculating the percent error between the predicted and actual completely reversed values. The average error for each parameter has been plotted in Figure 8 for tensile and compressive mean stress separately. The uncorrected results (termed 'no correction') are included for comparison.

When considering the tensile mean stress test, the Gerber equation was found to be the most accurate (0.65% average error) by a factor of approximately two over the Marin equation. For the compressive mean tests, the Gerber equation gave results similar to the Marin equation. i.e., an average error of 0.10%. It is evident that the high placing of both of these equations is the result of the low magnitude of correction they exhibit in the region of obtainable mean stresses, see Figure 1. Hence, the third place ranking of the 'no correction' values should be of no surprise. The average errors were 2.60% and 0.31% for the tensile and compressive mean stress tests, respectively.

The Morrow, Goodman and Soderberg equations exhibit ranking which is inversely proportional to the magnitude of their material parameters

TABLE 2. MEAN STRESS CRITERIA RESULTS (MPa)

TEST NO.	σ_{cr}	GERBER	MARIN	MORROW	SMITH (ACTUAL)	SMITH (CALC.)	FUCHS	GOODMAN	SODERBERG
TENSILE MEAN STRESS									
4	284	282	280	295	317	332	305	310	327
5	279	276	274	289	309	329	300	303	321
6	285	284	282	299	317	336	310	316	336
8	287	291	288	311	324	347	325	334	365
12	286	278	275	296	321	340	311	317	345
13	284	289	287	305	317	340	316	323	345
18	278	273	271	291	307	337	306	312	336
22	276	275	271	295	303	345	313	322	359
24	275	269	265	289	303	343	308	316	353
25	274	275	271	294	302	343	311	319	352
COMPRESSION MEAN STRESS									
31	278	277	278	265	305	285	252	253	243
32	291	293	293	287	345	334	282	281	276
35	271	272	273	261	302	285	249	251	239
36	292	293	292	282	338	326	274	274	266

(i.e., σ_f, σ_{uts} and σ_{ys}, respectively). The Morrow equation had the lowest error of these three equations and the Soderberg equation the highest. Again, this is to be expected, since the only difference between their respective equations is the material parameter and the least correction is obtained with the largest material parameter (see Figure 1).

The Fuchs criterion gave results which were essentially the same as those obtained by applying the Goodman equation. The rankings of these two equations were reversed between the tensile and compressive mean stress tests.

The Smith parameter showed reasonable accuracy placing fifth in both tests, lying between the Goodman and Morrow results. This performance is not nearly as good as indicated in references (8) and (9). But it should be remembered that only a limited range of "R" values ($R = \sigma_{min}/\sigma_{max}$) have been examined.

The Soderberg equation was the worst mean stress parameter in both the tensile and compressive results and exhibited average errors of 22.51% and 9.98% for tensile and compressive mean stresses respectively. Although this is a conservative error with tensile mean stress, it becomes non-conservative in the compressive mean stress region, as described in the introduction. The poor showing of this equation is a direct result of its formulation which attempts to provide a safeguard against general plastic deformation as well as predicting fatigue life.

From a practical viewpoint, a 5.0% error in a mean stress parameter should be considered insignificant in view of other major sources of error. However, it must be pointed out that a 5% error in stress results in a 80% change in fatigue life. With this thought in mind, employment of the Gerber, Marin, 'No correction', and Morrow equations would give satisfactory results.

In the introduction, the procedure for fatigue analysis of a notch under variable amplitude loading, with mean stress correction was described. From that brief summary it was apparent that the process may be time consuming as well as requiring detailed material data. However, for such an analysis on structural steel it is now apparent that by disregarding mean stress, with the employment of overstrained fatigue data, excellent results may be obtained. Hence, the analytical procedure could be performed on the strain history directly. This would result in substantial savings in time for the engineer as well as equipment savings when computerized data reduction is contemplated for field testing.

Although 'no correction' is the most practical approach for calculating the fatigue lives of structural steels, the employment of a correction may still be desired in the interest of standardizing the analytical procedure. This would be of concern where a general purpose computerized model is required for evaluating a wide range of materials and loading conditions. For this situation the use of the Gerber equation would have to be recommended as the best choice. This view is also supported by Watson and Plumtree (28) for high mean stress fatigue. Thus it is possible that the Gerber equation is the best all round mean stress parameter.

CONCLUSIONS

1. No mean stress correction is required to obtain accurate life predictions for structural steel in the range of mean stresses obtainable in practice.
2. If a mean stress correction is to be used, the Gerber equation would give the most satisfactory results.
3. Tensile mean stresses may reduce fatigue life in a way which is similar to the effect of a few high strain cycles hence it is conservative to account for both phenomena in a cumulative manner.
4. Several mean stress parameters showed excessive conservatism for the tensile mean stresses and excessive optimism for the compressive mean stresses.
5. The Soderberg mean stress parameter has little if any connection with realistic fatigue life prediction.

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NOMENCLATURE

σ_{uts} - ultimate tensile strength
σ_{ys} - yield strength
σ_{fl} - fully reversed fatigue limit (amplitude)
σ_a - stress amplitude
$\Delta\sigma$ - stress range
σ_o - mean stress
σ_{cr} - equivalent completely reversed stress amplitude
σ_f - true fracture stress
σ_{max} - maximum stress level
σ'_f - fatigue strength coefficient
σ_{oi} - absolute initial mean stress
σ_{on} - absolute mean stress after N cycles
ε_a - strain amplitude
$\Delta\varepsilon$ - strain range
ε'_f - fatigue ductility coefficient
N - number of cycles
2N - number of reversals
N_f - number of cycles to failure
$2N_f$ - number of reversals to failure
b - fatigue strength exponent
c - fatigue ductility exponent
E - Young's modulus
B - relaxation exponent (a function of the strain range)

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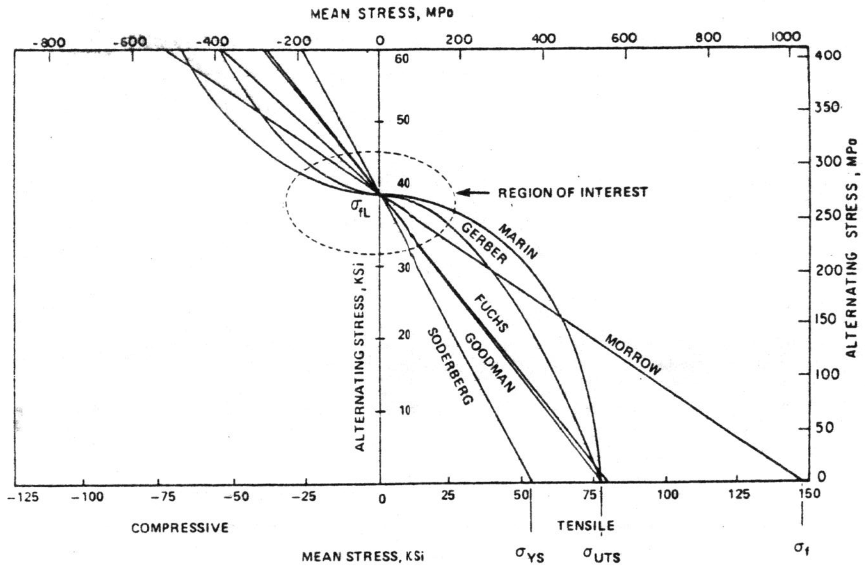


Figure 1 Region of Interest for G40.21-50A Steel

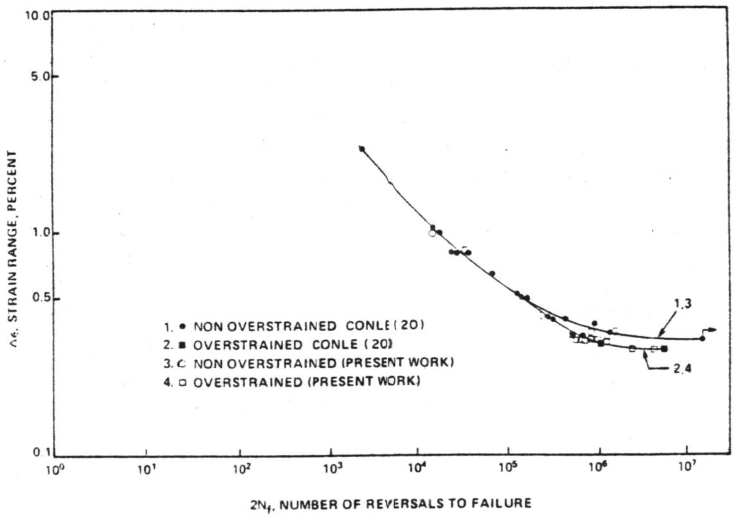


Figure 2 Reference Strain-Life Curve

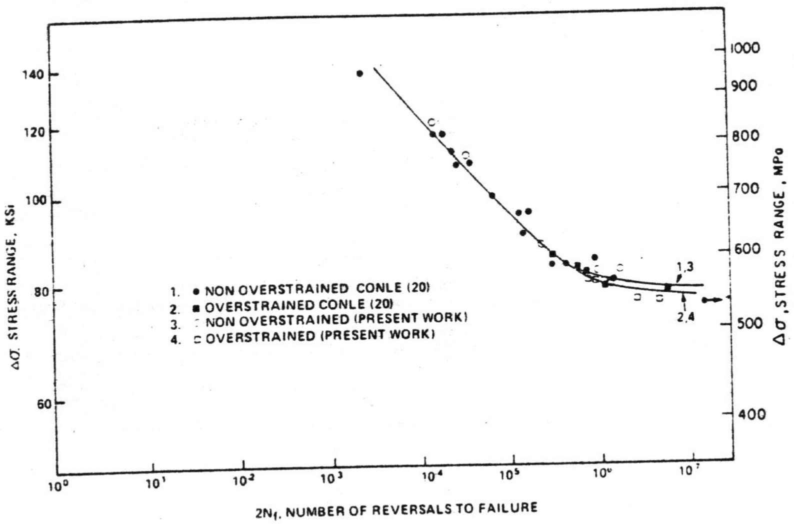


Figure 3 Reference Stress-Life Curve

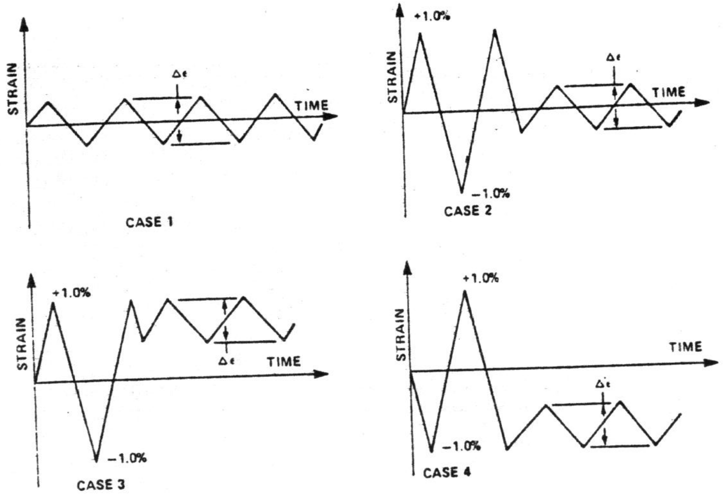


Figure 4 Loading Histories

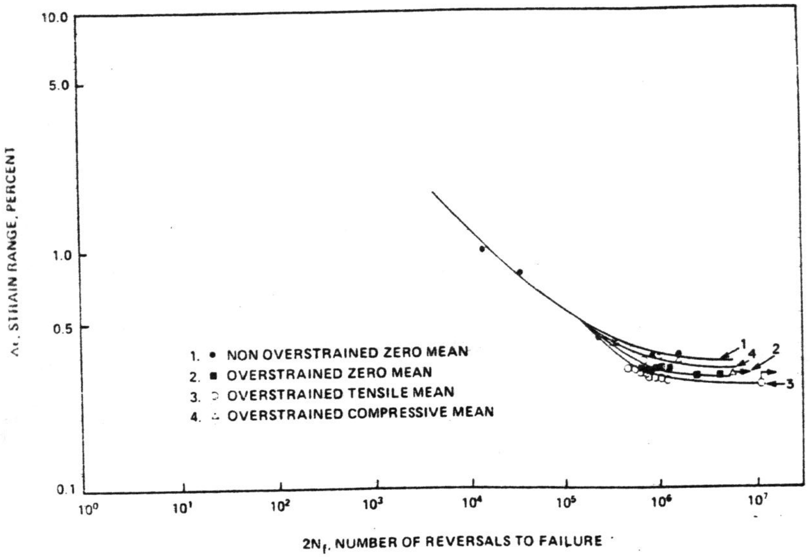


Figure 5 Experimental Strain-Life Curve

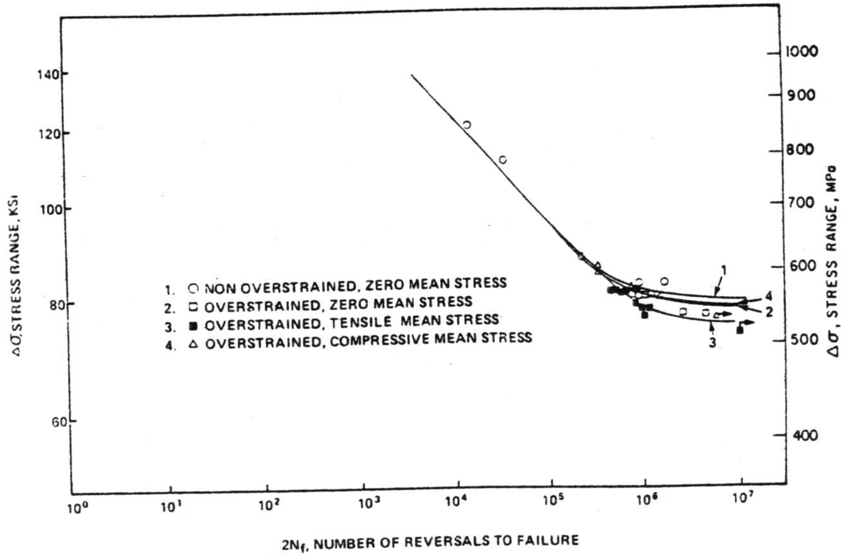


Figure 6 Experimental Stress-Life Curve

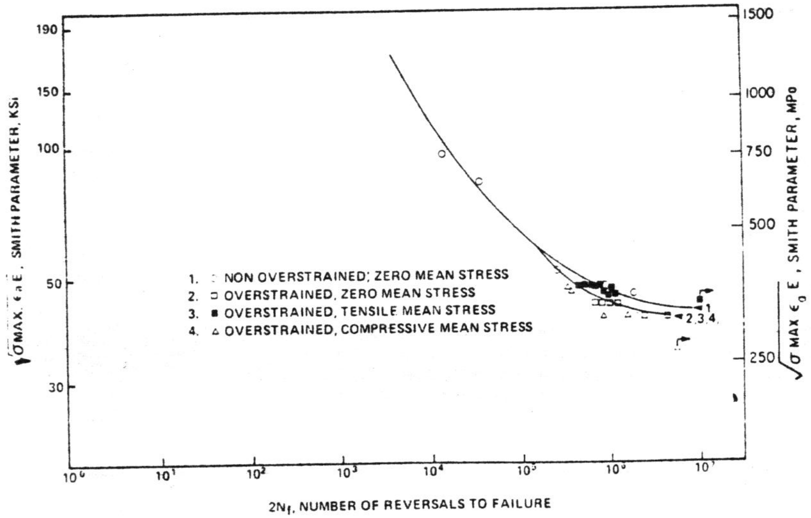
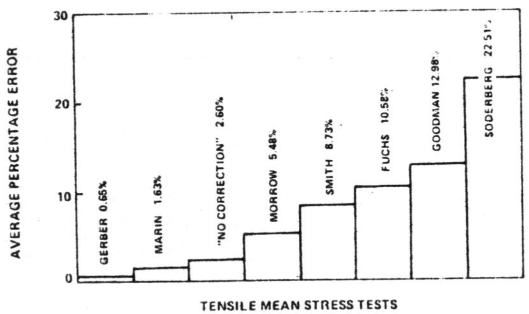


Figure 7 Experimental Smith Parameter Curve



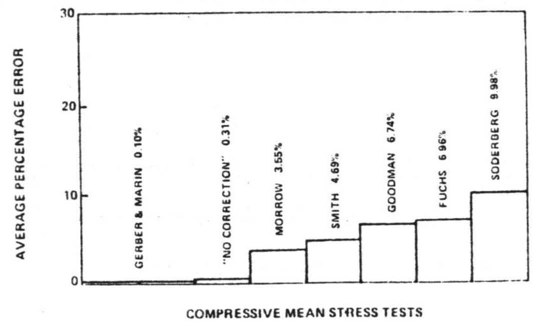


Figure 8 Comparison of Mean Stress Criteria for Tensile and Compressive Mean Stresses