Objectives

- To demonstrate the use of the Instron servohydraulic testing machine for testing specimens subjected to cyclic (fatigue) loadings.

- To analytically approximate the fatigue damage accumulated in a part which is subjected to a known fatigue spectrum.

Introduction

A perusal of the broken parts in almost any scrap yard will reveal that the majority of failures occur at stresses below the yield strength. This is a result of the phenomenon called fatigue which has been estimated to be responsible for up to 90% of the in-service part failures which occur in industry. If a bar of steel is repeatedly loaded and unloaded at say 85% of its' yield strength, it will ultimately fail in fatigue if it is loaded through enough cycles. Also, even though steel ordinarily elongates approximately 30% in a typical tensile test, almost no elongation is evident in the appearance of fatigue fractures.

Basic fatigue testing involves the preparation of carefully polished test specimens (surface flaws are stress concentrators) which are cycled to failure at various values of constant amplitude alternating stress levels. The data are condensed into an alternating Stress, S, verses Number of cycles to failure, N, curve which is generally referred to as a material's S-N curve. As one would expect, the curves clearly show that a low number of cycles are needed to cause fatigue failures at high stress levels while low stress levels can result in sudden, unexpected failures after a large number of cycles.

Background

Definition: **Fatigue** is the condition whereby a material cracks or fails as a result of repeated (cyclic) stresses applied below the ultimate strength of the material.

Fatigue failures generally involve three stages:

       1.) Crack Initiation,

       2.) Crack Propagation, and

       3.) Fast Fracture

Fatigue failures often occur quite suddenly with catastrophic (disastrous) results and although most insidious for metals, polymers and ceramics (except for glasses) are also susceptible to sudden fatigue failures. Fatigue causes brittlelike failures even in normally ductile materials with little gross plastic deformation occurring prior to fracture. The process occurs by the initiation and propagation of cracks and, ordinarily, the fracture surface is close to perpendicular to the direction of maximum tensile stress.

Applied stresses may be axial (tension-compression), flexural (bending) or torsional (twisting) in nature. In general there are three possible fluctuating stress-time modes possible. The simplest is completely reversed constant amplitude where the alternating stress varies from a maximum tensile stress to a minimum compressive stress of equal magnitude. The second type, termed repeated constant amplitude, occurs when the maxima and minima are asymmetrical relative to the zero stress level. Lastly, the stress level may vary randomly in amplitude and frequency which is merely termed random cycling.
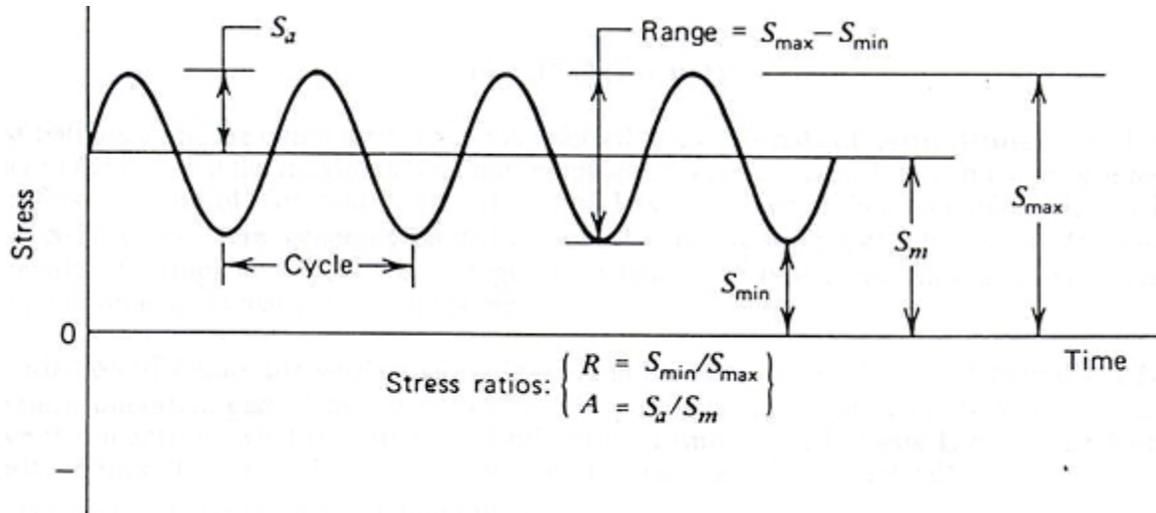
Cyclic Stresses

Figure 1 Schematic Illustrating Cyclic Loading Parameters [Fuch & Stephens, 1980].

The following parameters are utilized to identify fluctuating stress cycles:

Mean Stress (σ_m):

$$\sigma_m = \frac{S_{max} + S_{min}}{2}$$

Stress Range (σ_r):

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

Stress Amplitude (σ_a):

$$\sigma_a = \frac{S_{max} - S_{min}}{2}$$

Stress Ratio (R):

$$R = \frac{S_{min}}{S_{max}}$$

Tensile stresses are normally considered positive and compressive stresses are considered negative.

The **Fatigue Life (N_f)** of a component is defined by the total number of stress cycles required to cause failure. Fatigue Life can be separated into three stages where

$$N_f = N_i + N_p$$

1.) **Crack Initiation (N_i)** - Cycles required to initiate a crack. Generally results from dislocation pile-ups and/or imperfections such as surface scratches, voids, etc.

2.) **Crack Growth (N_p)** - Cycles required to grow the crack in a stable manner to a critical size. Generally controlled by stress level. Since most common materials contain flaws, the prediction of crack growth is the most studied aspect of fatigue.

3.) **Rapid Fracture** - Very rapid critical crack growth occurs when the crack length reaches a critical value, a_c. Since Rapid Fracture occurs quickly, there is no Rapid Fracture term in the Fatigue Life expression.

(S-N_f) Curve

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Most Fatigue Tests are conducted at what is referred to as "**Constant Amplitude**" which merely refers to the fact that the maximum and minimum stresses are constant for each cycle of a test. **S-Nf** refers to a plot of Constant Amplitude Stress Level (**S**) verses Number of Cycles to Failure (**Nf**). **S-Nf** Curves are generally plotted on semi-log or log-log paper where each dot represents the results of a single test specimen. Fatigue tests tend to be time consuming and expensive; each data point represents many hours of testing.

A prediction of failure for various stress levels can be made by studying a material's S-Nf curve. The most important part of the curve is often the portion to the right of the bend (or "knee") in the curve that identifies what is termed the **Endurance Limit** or the **Fatigue Limit**. The **Endurance Limit** defines the stress level below which the material will theoretically withstand an infinite number (~10^8) of stress cycles without fracture.
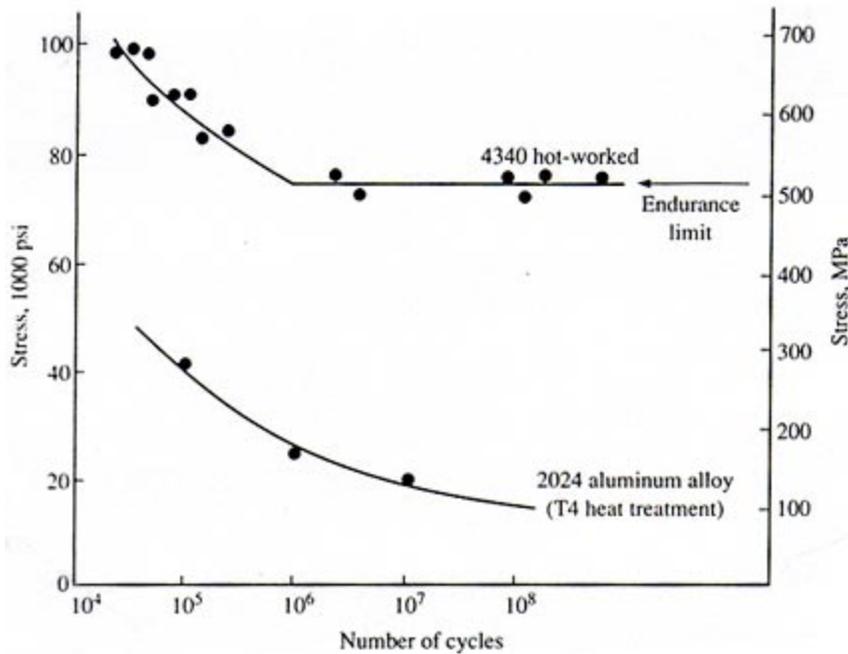

Figure 2 Stress Amplitude versus Number of Cycles to Failure Curves [Flinn & Trojan, 1990].

Fatigue Testing

Materials Testing to obtain S-Nf Curves is common; several ASTM standards address stress-based fatigue testing. The "Rotating Bending Testing Machine" is similar to the original railroad axle-type Wohler used where the bending moment is constant along the beam length. Each point on the Surface of the Rotating Bend Specimen is subjected to fully-reversed cycling ($\sigma_m = 0$) and the tests are generally Constant Amplitude.
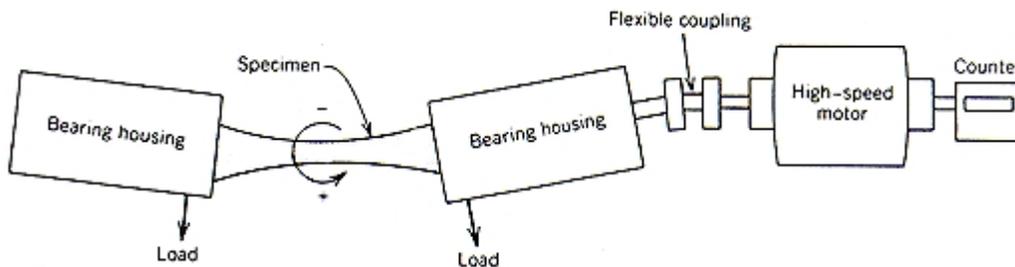

Figure 3 Rotating Bending Testing Machine [Callister, 1994].

"Reciprocating Bending Testing Machines" utilize a rotating crank to achieve a non-zero mean stress through positioning of the specimen with respect to the motor as shown in Figure 4.
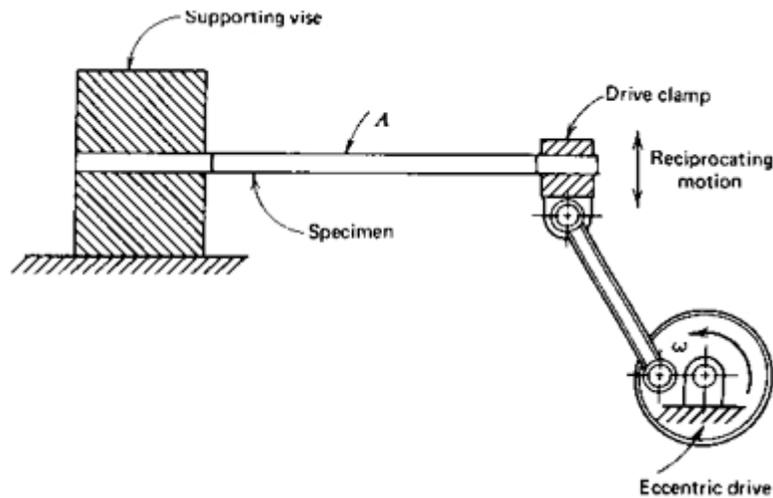

Figure 4- Reciprocating Bending Testing Machine [Collins, 1981].

Similar to the Reciprocating Bending set-up, the "Direct Force Fatigue Testing Machines" apply axial loads as is illustrated in Figure 5.
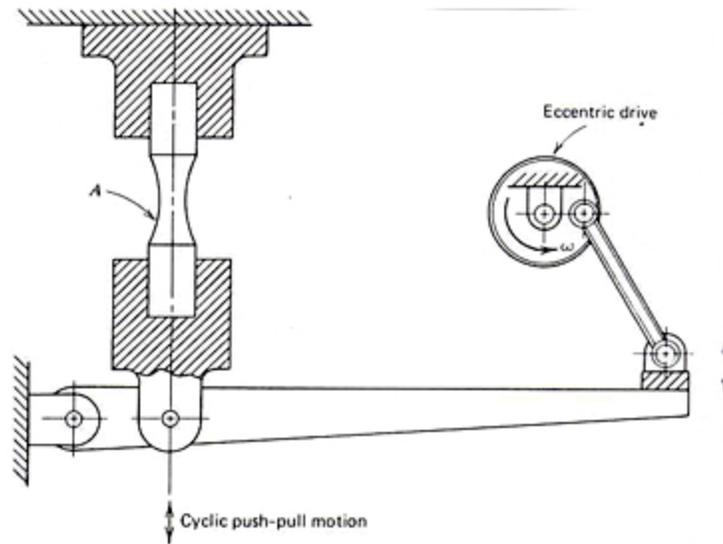

Figure 5- Direct-Force Fatigue Testing Machine [Collins, 1981].

None-the-less, computer controlled "Servohydraulic Systems" are the most common in operation today; the newest Instron Machine at LSU-ME is of this type. Computerized Servohydraulics are capable of both Monitoring and Controlling a desired cyclic pattern in any of the following:

Load-Time   Strain-Time   Displacement-Time

This level of control allows the operator to program real-time fatigue spectrums including underloads and overloads.

"Component Testing" and/or "Full-Scale Prototype Tests" are still carried out on Fatigue-Critical structures. Most fatigue testing is conducted at the basic material level; differences between laboratory and service conditions must be considered by mechanical designers. Common test specimen types for obtaining fatigue data are shown in Figure 6.
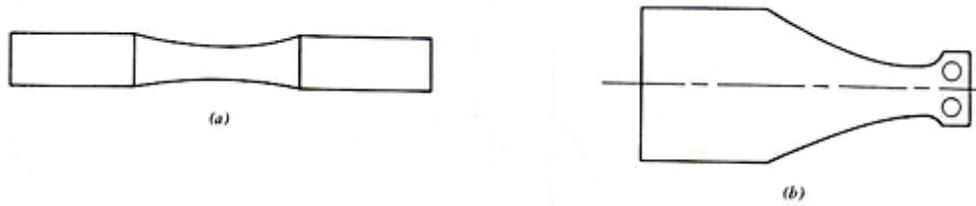

Figure 6 Fatigue Test Specimens: (a) Rotating Bending, (b) Cantilever Flat Sheet (cont.)
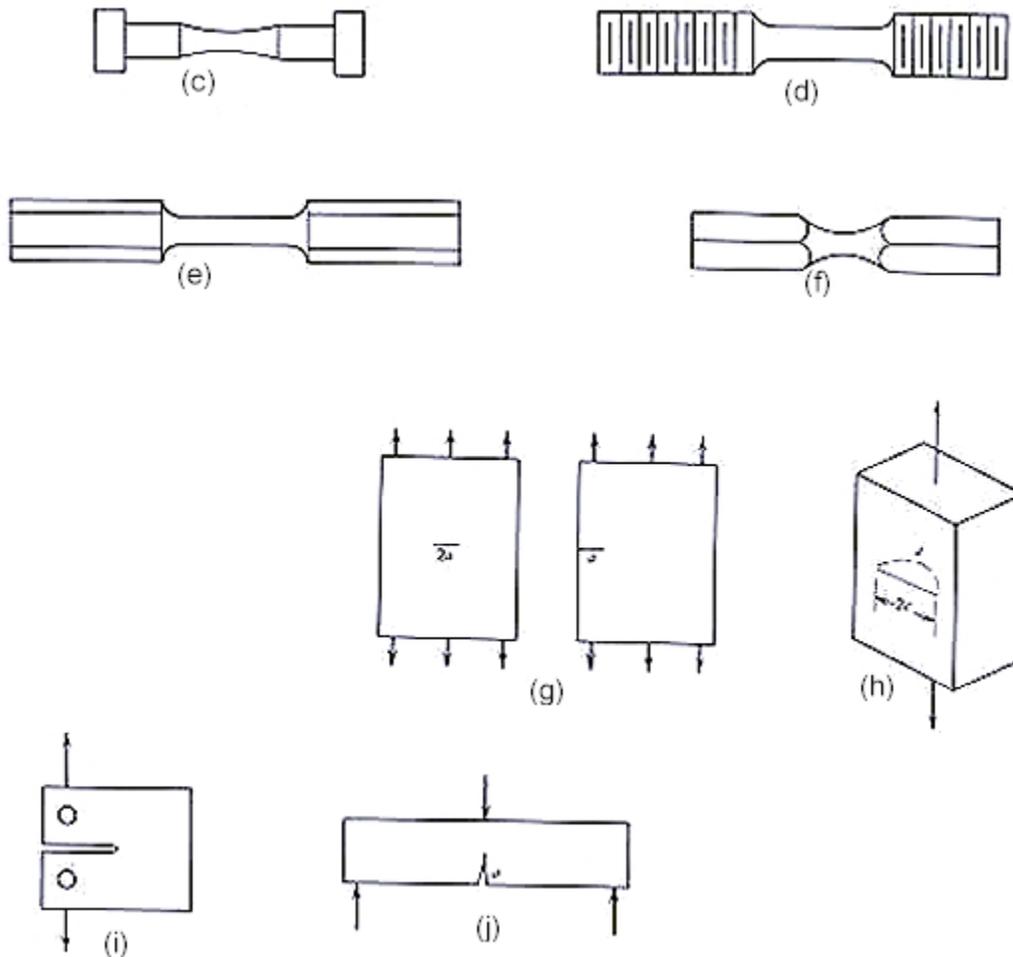

Figure 6 Fatigue Test Specimens: (c) buttoned axial dog-bone, (d) threaded axial dog-bone, (e) torsion, (f) combined stress, (g) axial cracked sheet, (h) part-through crack,(i) Compact tension and (j) three point bend specimen [Fuch & Stephens, 1980].

Fatigue Testing Procedures

A number of fatigue testing procedures have been developed to satisfy specific objectives:
- Life distribution at a constant stress level.
- Strength distribution at a constant life.

- Design data at a minimal cost and time, etc.

The specific procedure followed should be carefully chosen based on the data requirements. The "Standard Method" of fatigue testing is the most common and is utilized when only a few test specimens are available. A low number of tests (1 to 3) are conducted at a set of stress amplitudes that span the expected stress range of the material; σ_a and N_f are recorded for each specimen. Run-Outs (specimens which do not fail after 10^8 cycles) are noted (o––>, see Figure 7) and rerun at a higher stress level to maximize the data obtained from the limited specimen set.

Two S-N_f Curves are generally constructed: (1) an "Eyeballed Mean Curve" which passes near the mean of each tested stress amplitude, and (2) an "Eyeballed Conservative Curve" which is slightly below all of the data points. Note that Probability Estimates for this method would be unreliable due to the scarcity of data"
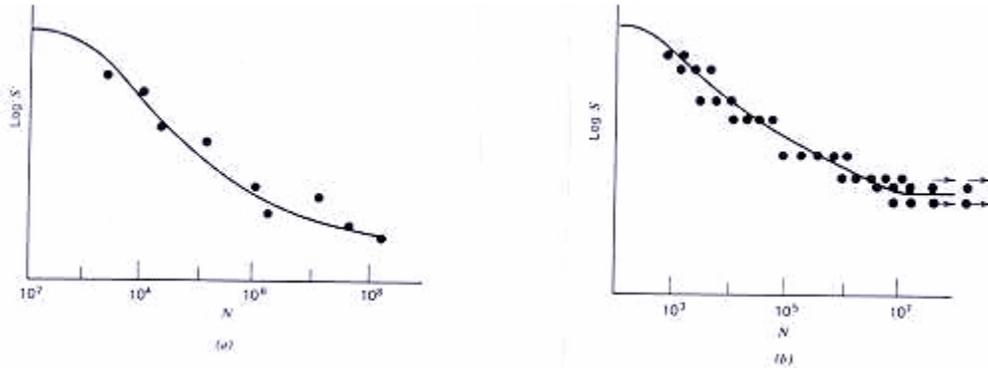

Figure 7 Standard Method S-N_f Curves [Fuch & Stephens, 1980]

Analysis Method

Realize that most fatigue is NOT actually constant amplitude, but methods have been developed for utilizing constant amplitude S-N_f results to predict failure under varying load histories. This area of fatigue is referred to as "**Cumulative Damage**".
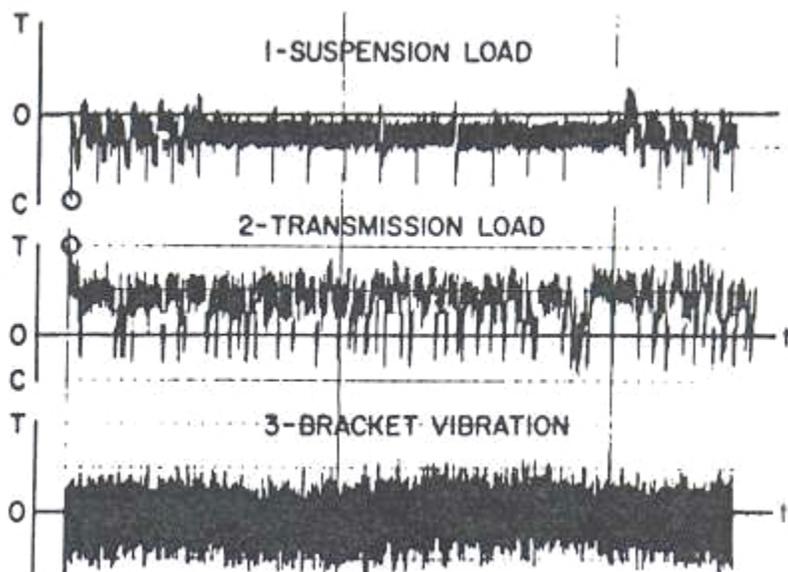

Figure 8 Sample Actual Fatigue Spectrums [Fuch & Stephens, 1980].

The most basic cumulative damage approach, and the most often utilized, is referred to as Miner's Law which is based on the man who developed the approach. Under this approach, the damage (D) caused by one cycle is merely defined as

$$D = 1/N_f$$

The damage produced by "n" cycles at a given stress level is given by

$$D = n/N_f$$

Thus the cumulative damage for a set of cycles over a range of stress levels can be expressed as

$$D = \sum D_i = \sum n_i/N_{fi}$$

where n_i represents the number of cycles at stress level "i" and N_{fi} represents the number of cycles that will cause failure at stress level "i".

Procedure

This lab consists of an in-class demonstration of using a Universal Testing Machine (Instron) to conduct fatigue tests, a single test on a dog-bone specimen, and a fatigue failure prediction problem applying Miner's Law.

1. Fatigue Demonstration: The lab TA will demonstrate the versatility of the Instron Machine for conducting fatigue tests by showing how waveform, amplitude and frequency can be easily varied in Position Control (similar flexibility can be achieved in Load Control) without any specimen mounted on the machine.

2. Fatigue Test: The lab TA will conduct a constant amplitude, tension-tension fatigue test on a dogbone sample up to fracture. Measure the sample prior to testing and record its' dimensions; document the testing parameters used (waveform, maximum & minimum load, frequency, etc.).

3. Miner's Law Problem - see Lab Requirements

Lab Requirements

This is an In-Class Lab; all student work must be submitted prior to leaving the lab session.

1. Present the test parameters (waveform, D, S_{max}, S_{min}, S_m, S_r, S_a, R, f) and test results (N_f) for the fatigue sample tested. Comment on the results of the test.

2. Problem (Miner's Law): The S-N_f curve shown on the next page is for a low-carbon steel. If an automobile strut made of this steel is subjected to the stress spectrum listed below over a 4 month period:

    a. How much damage will the part accumulate in 2 years based on Miner's Law?

    b. What's the expected life for the part?

    > 1 Cycle at 55 ksi
    >
    > 35 Cycles at 45 ksi
    >
    > 147 Cycles at 35 ksi
    >
    > 21,271 Cycles at 25 ksi
    >
    > 1,920,174 Cycles at 15 ksi

Applied Stress (ksi) vs Number of Cycles