Our real concern is how to design a component so that failure by fatigue could be precluded. We have noted earlier that

-Materials response to fatigue loading is characterized by its S-N behavior obtained through a standard test

-The most important factors that affect the fatigue performance (strength) are also noted in the previous lecture.

-Standard test conditions do not account for all these factors.

-Components in real use will be subjected to different or varied conditions.

In order to design for satisfactory fatigue life (prior to testing actual components), good practice requires that the "laboratory" Endurance Limit value be reduced by several adjustment factors. These reductions are necessary to account for:

   (a) the differences between the application and the testing environments, and
   (b) the known statistical variations of the material.

This procedure is to insure that both the known and the unpredictable factors in the application (including *surface condition, actual load, actual temperature, tolerances, impurities, alloy variations, heat-treatment variations, stress concentrations*, etc. etc. etc.) will not reduce the life of a part below the required value. Please read that paragraph again, and understand it well.

An accepted contemporary practice to estimate the maximum fatigue loading which a specific design can survive is the *Marin* method, in which the laboratory test-determined EL of the particular material (tested on optimized samples) is adjusted to estimate the maximum cyclic stress a particular part can survive.

This adjustment of the EL is the result of six fractional factors. Each of these six factors is calculated from known data which describe the influence of a specific condition on fatigue life.

Those factors are:

(a) Surface Condition (k_a): such as: polished, ground, machined, as-forged, corroded, etc. Surface is perhaps the most important influence on fatigue life;

(b) Size (k_b): This factor accounts for changes which occur when the actual size of the part or the cross-section differs from that of the test specimens;

(c) Load (K_c): This factor accounts for differences in loading (bending, axial, torsional) between the actual part and the test specimens;

(d) Temperature (k_d): This factor accounts for reductions in fatigue life which occur when the operating temperature of the part differs from room temperature (the testing temperature);

(e) Reliability (k_e): This factor accounts for the scatter of test data. For example, an 8% standard deviation in the test data requires a ke value of 0.868 for 95% reliability, and 0.753 for 99.9% reliability.

(f) Miscellaneous (K_f): This factor accounts for reductions from all other effects, including residual stresses, corrosion, plating, metal spraying, fretting, and others.

These six fractional factors are applied to the laboratory value of the material endurance limit to determine the allowable cyclic stress for an actual part: Real-World Allowable Cyclic Stress = $k_a * k_b * K_c * k_d * k_e * k_f * EL$

Thus designers are now able to tackle this situation by applying as many modification factors as possible so that most important deviations of the real design condition from the standard test conditions are accounted. So the next part of the discussion will deal with the endurance strength modification factors.

Endurance Strength Modification Factors

The most important deviations that occur in design situation compared to standard test conditions are

- *Size variations*

- *Surface finish differences*

- *load variations*

- *temperature differences*

- *Other miscellaneous-effects*

Differences-load variations-temperature differences-other miscellaneous-effects To account for these conditions a variety of modifying factors, each of which is intended to account for a single effect, is applied to the endurance limit value of test specimen obtained under laboratory conditions. Consequently we may write

$S_e = S_e^* \ k_a \ k_b \ k_c \ k_d \ k_e$ S = endurance limit of mechanical element (to be designed) S_e^* = endurance limit of test specimen. k_a = surface factor k_b = size factor k_c = load factor k_d = temperature factor k_e = miscellaneous-effects factor

Modification Factors

Surface Factor k_a

the surface of the rotating-beam specimen is highly polished, with final polishing in the axial direction to smooth out any circumferential scratches. For other conditions the modification factor depends upon the quality of the finish and upon the tensile strength. Sufficient data is available in the literature relating the basic strength of the material and its surface finish or surface condition to the modification factor which is nothing but the percentage of standard endurance that could be realized under this condition. Typical charts are given below. A more practical approach can be to use an empirical relation of the type $k_a = a S_{ut}^b$

is available in literature to account for the various surface condition values of constant a and b are shown in the table below.

SURFACE FINISH	FACTOR a		EXPONENT b
	Kpsi	MPa	
Ground	1.34	1.58	-0.085
Meachined or cold rolled	2.70	4.51	-0.265
Hot Rolled	14.4	57.7	-0.718
As- forged	39.9	272	-0.995
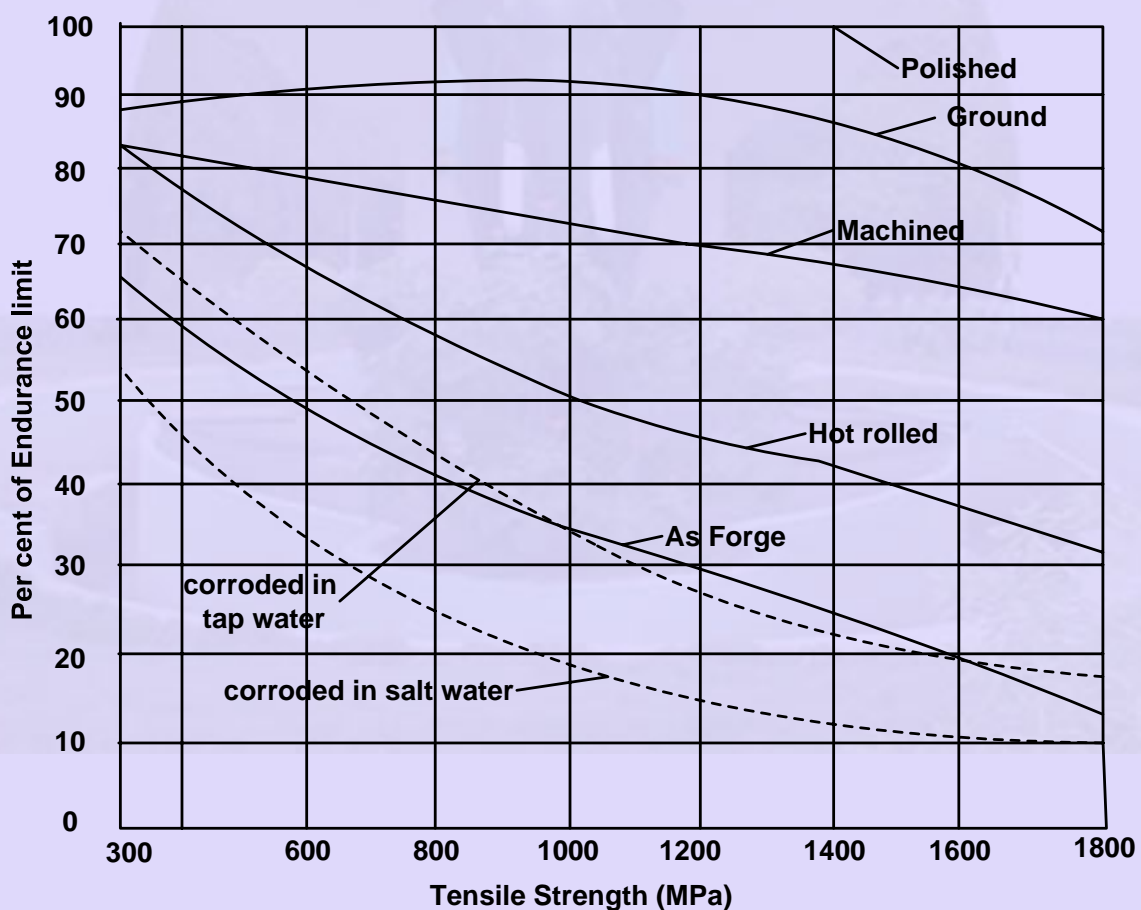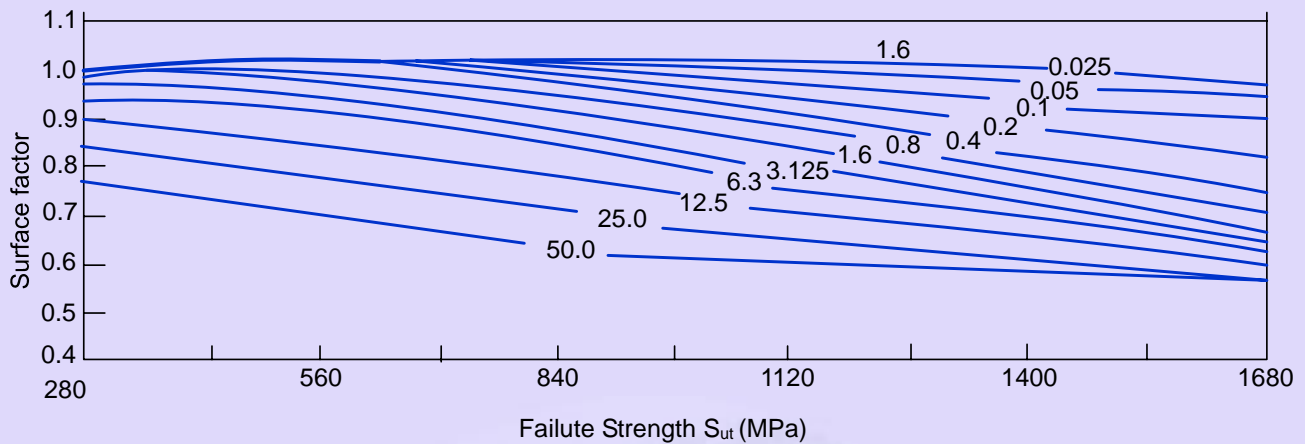
Size Factor K$_b$

The size factor accounts for the variations in the size of the component when compared to the test specimen. The size factor has been evaluated using sets of data points, from available literature. The larger the size higher the probability of internal defects, hence lower the fatigue strength. An empirical relation for the case of bending and torsion can be expressed as given below

$$k_b = \begin{cases} (d/7.62)^{-0.107} = 1.24d^{-0.107} & 2.79 \le d \le 51mm \\ 0.859 - 0.000837d & 51 \le d \le 254mm \end{cases}$$

Size Factor

For large sizes, k$_b$ further reduces to 0.60 and lower Note that for axial loading there is no size effect, therefore use k$_b$ = +1.0 in this case

Load Factor-Axial Loading

Though there is no apparent size effect for specimens tested in axial or push–pull fatigue, there is definite difference between the axial fatigue limit and that in reserved bending. A very extensive collection of data has been made by R.W.Landgraf (Ford motor

company), on axial fatigue. These results were analyzed, resulting in the modification values for axial loading as shown in the table.

Load Factor-Torsional Loading

A collection of 52 data points comparing the torsional endurance limit with the bending endurance limit yielded a load factor for torsion of 0.565. Using a different set of data points, Mischke obtained the result k_c =0.585. Both of these are very close to the value of 0.577 shown in the table. Note that this value incidentally happen to be the relation between torsional and tensile yield strengths according to the distortion energy theory.

Load Factor

Hence for the three basic types of loading normally encountered in most practical applications, namely axial, bending and torsional stressing the effect could be accounted by the load factor as shown in the table

$$k_c = \begin{cases} 0.923 & \text{Axial Loading} & \text{S<1520MPa(220Kpsi)} \\ 1 & \text{Axial Loading} & \text{S<1520MPa(220Kpsi)} \\ 1 & \text{Bending} \\ 0.577 & \text{Torsion and shear} \end{cases}$$

Temperature factor

The limited amount of data available show that the endurance limit for steels in creases slightly as the temperature rises and then begins to fall off in the 400 to 700 $^{\circ}$F range, not unlike the behaviour of the tensile strength shown figure below
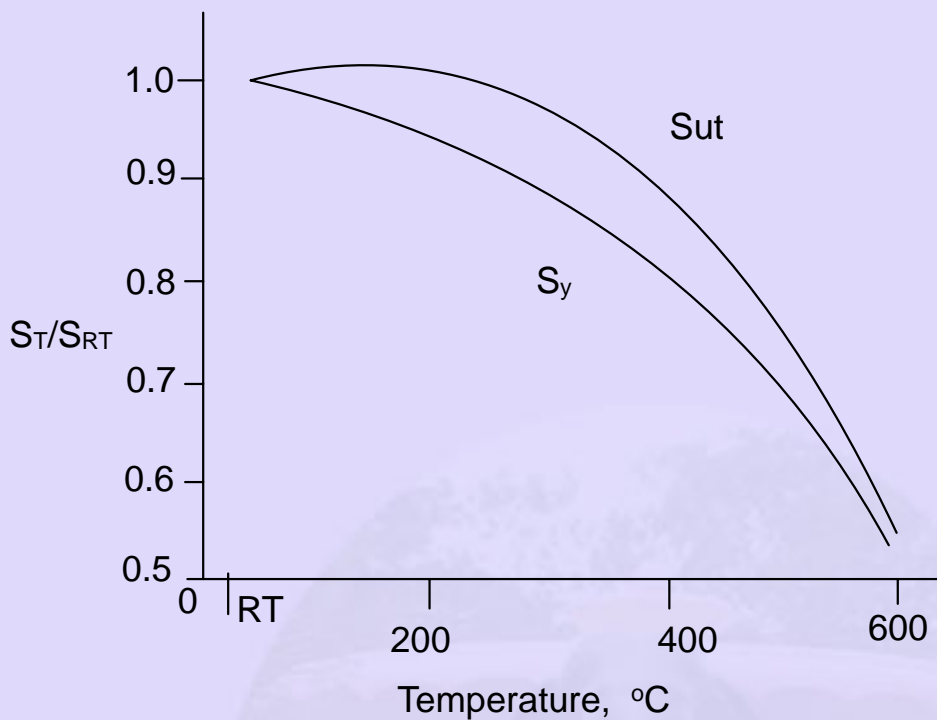
For this reason it is probably true that the endurance limit is related to tensile strength at clevated temperatures in the same manner as at room temperature. It seems quite logical, therefore, to employ the same relations to predict endurance limit at elevated temperatures as are used at room temperature, at least, this practice will provide a useful standard against which the performance of various materials can be compared.

Two types of problems arise when temperature is a consideration. If the rotating- beam endurance limit is known at room temperature, then use

$$k_d = \frac{S_T}{S_{RT}}$$

Miscellaneous – Effects Factor K_e

Similarly the other factors take into account the deviations of actual condition of use from the standard testing. Though the factor ke is intended to account for the reduction in

endurance limit due to all other effects, it is really intended as a reminder that these must be accounted for, because actual conditions of use vary from standard test condition; values of ke are not always available.

Endurance - Limit - Preliminary Observations

The determination of endurance limit by fatigue testing is now a routine, though a lengthy procedure. Generally stress testing is preferred to strain testing for endurance limits. For preliminary and prototype design and for some failure analysis as well, a quick method of estimating endurance limit is needed. There are great quantities of data in the literature on the results of rotating-beam tests and simple (static) tension tests of specimen taken from the same bar or in got. By plotting the resulting tensile and endurance strength values as in shown in Figure, it is possible to see whether there is any correlation between the sets of results. The graph appears to suggest that the endurance limit ranges from about 40 to 60 percent of the tensile strength for steels up to about 1400 MPa (200 kpsi). Beginning at about S_{ut} = 1400 MPa (200 kpsi), the scatter appears to increase, but the trend seems to level off, as suggested by the dashed horizontal line at S'_e=700MPa (100 kpsi).

Hence for preliminary design purposes the standard laboratory endurance strength of can be derived from its ultimate tensile strength values using the following relations
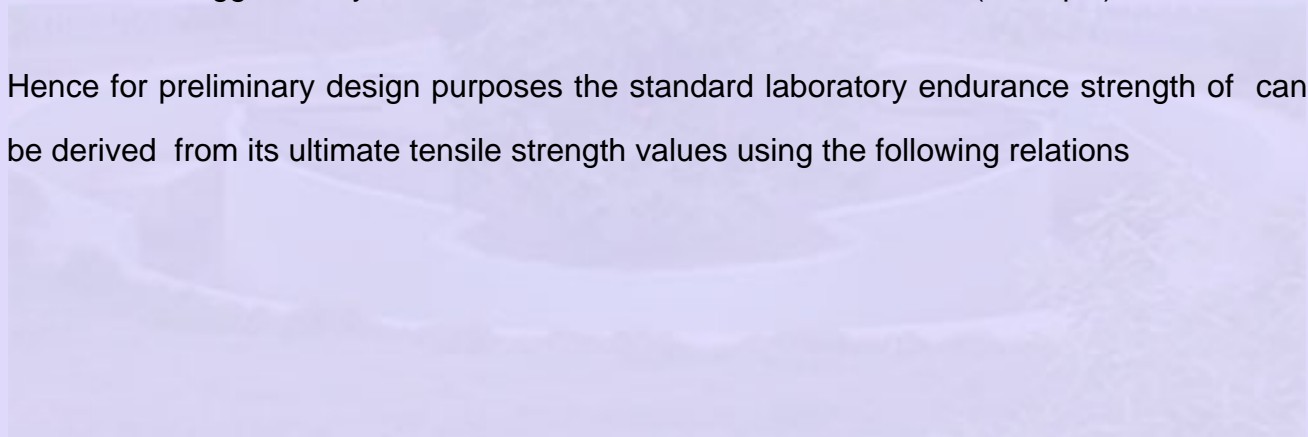
Stress Concentration Effect

Fatigue Stress Concentration

The existence of irregularities or discontinuities, such as holes, grooves, or notches, in a part increase the magnitude of stresses significantly in the immediate vicinity of the discontinuity. Fatigue failure mostly originates from such places. Hence its effect must be accounted and normally a fatigue stress-concentration factor K_f is applied when designing against fatigue, even if the materials behavior is ductile.

Fatigue Stress Concentration Factor

Recall that a stress concentration factor need not be used with ductile materials when they are subjected to only static loads, because (local) yielding will relieve the stress concentration. However under fatigue loading, the response of material may not be adequate to nullify the effect and hence has to be accounted. The factor K_f commonly called a fatigue stress concentration factor is used for this. Normally, this factor is used to indicate the increase in the stress; hence this factor is defined in the following manner. Fatigue stress concentration factor can be defined as

$$k_f = \frac{\text{Fatigue strength (limit) of unnotched specimen}}{\text{Fatigue strength (limit) of notched free specimen}}$$

The other form of use, where necessary is the miscellaneous-effects factor k_e applied as a strength reduction factor on the fatigue limit value. With this approach we define

$$k_e = \frac{1}{K_f}$$