FATIGUE FAILURE AND TESTING METHODS

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ABSTRACT

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ABSTRACT

The aim of this thesis work is to discuss the principle of fatigue failure, research the state of the art fatigue testing methods and finally design a verification fatigue test set-up to evaluate the performance of the newly developed dynamic testing machine in the mechatronics laboratory of HAMK University of applied sciences.

A comprehensive study of the underlying principle, stages and numerous factors that makes fatigue such a complex phenomenon was carried out. This was closely followed by research work on the standard fatigue testing methods and statistical analysis of fatigue test results.

Based on the knowledge gained from the research work stated above, a four-point fully reversed bending set-up design was developed to put into test the functionality of the dynamic testing machine once it is ready to run and also a planned fatigue test suitable for laboratory exercise in a material science or engineering design class was developed.

Keywords Fatigue Failure, Fatigue Testing Methods and 4-point bending set-up.

Pages 32 p. + appendix

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1 INTRODUCTION

A perusal of the broken parts in almost any scrap will show that a high number of failures occur at stresses below the yield strength of the part`s materials. This complex phenomenon is known as “Fatigue”. Fatigue is responsible for up to 90% of the in-service part failure which occur in industry.

In the 19th century, it was considered mysterious that a fatigue fracture did not show visible plastic deformation, this lead to an erroneous believe that fatigue was merely an engineering problem. Well, they were not so wrong since the power of microscopic equipment of that time was quite limited, also during this century few fatigue tests were carried out by notable researchers; most popular was the work of August Wöhler, who later come up with the idea of stress-lifetime curve (S-N Curve).

A major breakthrough in the understanding of the process of fatigue failure happened in the 20th century. Thanks to more powerful tools such as computer, powerful microscopic instrument, advance numerical analysis methods and much more research work (as much as 100,000 references was cited by John Mann in one of his works), fatigue began to be viewed not as an engineering problem but as both material and design phenomenon.

Despite the large amount of research carried out on fatigue failure, its true nature still remains unknown and damage, cracks or even complete failure due to cycling loads are constantly been reported. If the problem still exists after 100 years of research in the previous century, there is something to be explained.

The idea behind this thesis work is not to provide answers to the unanswered questions, but to tackle the problem from a different perspective. This includes explaining the complex nature of fatigue failure, introduce basic idea of engineering design against fatigue failure, explain the known techniques of fatigue testing, set-up a verification test for the servo-hydraulic dynamic testing machine (still under construction) in the mechatronics laboratory of HAMK University of Applied Sciences and also plan a laboratory fatigue test exercise suitable for a machine design or material science courseware.

2 FATIGUE AS A PHENOMENON IN THE MATERIAL

2.1 General

Fatigue is the condition whereby a material cracks or fails because of repeated (cyclic) stresses applied below the ultimate strength of the material. Fatigue failure often occurs quite suddenly with catastrophic result.

When a structure is loaded, a crack will be nucleated (crack nucleation) on a microscopically small scale, this crack then grows (crack growth), then finally complete failure of the specimen. The whole process constitutes the fatigue life of the component in question. According to Jaap Schijve, Reasonable fatigue prediction for design or analysis can only be done if fatigue is viewed not only as an engineering problem but also a material phenomenon that is a process involving an invisible micro scale crack initiation till a macro scale fatigue failure.

To this ends, the underlying stages of fatigue life of a component will be discussed as well as important fatigue properties of common materials and also the basic principle of design against fatigue failure.

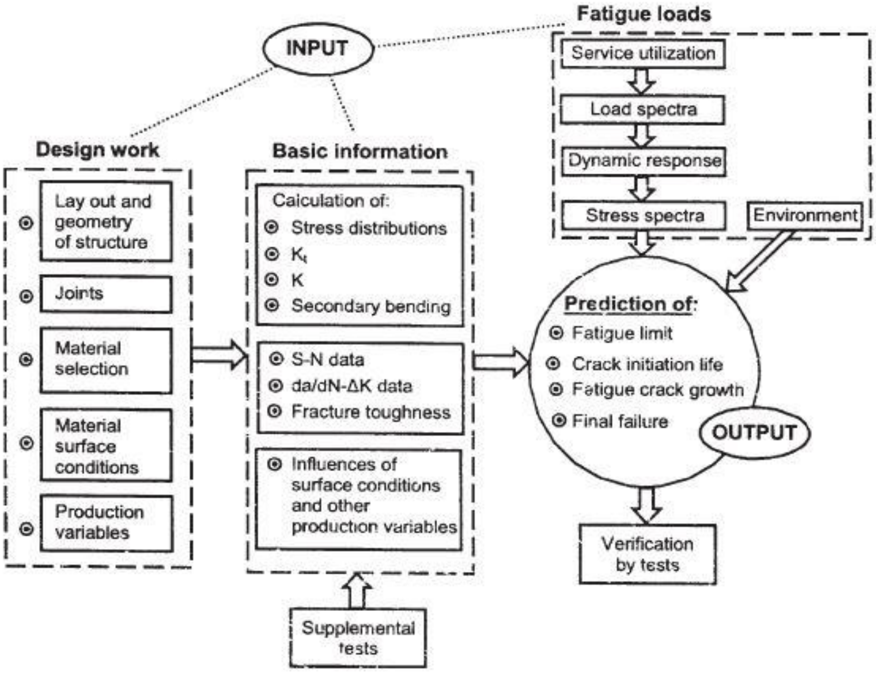


Figure 1 Survey of the various aspects of fatigue of structures [3].

2.2 Different phases of fatigue life

Microscopic investigation in the 20th century has revealed that the nucleation of fatigue cracks occurs at a very early stage of fatigue life. The crack starts as a slip band within a grain. The cyclic slip occurs as a result of cyclic shear stress, this slip leads to formation of slip steps, in the present of oxygen, the freshly exposed surface of the material in slip steps get oxidized, which prevents slip reversal. The slip reversal in this case occurs in some adjacent slip plane, thereby leading to formation of extrusions and intrusions on the surface of the material as shown in the figure below.

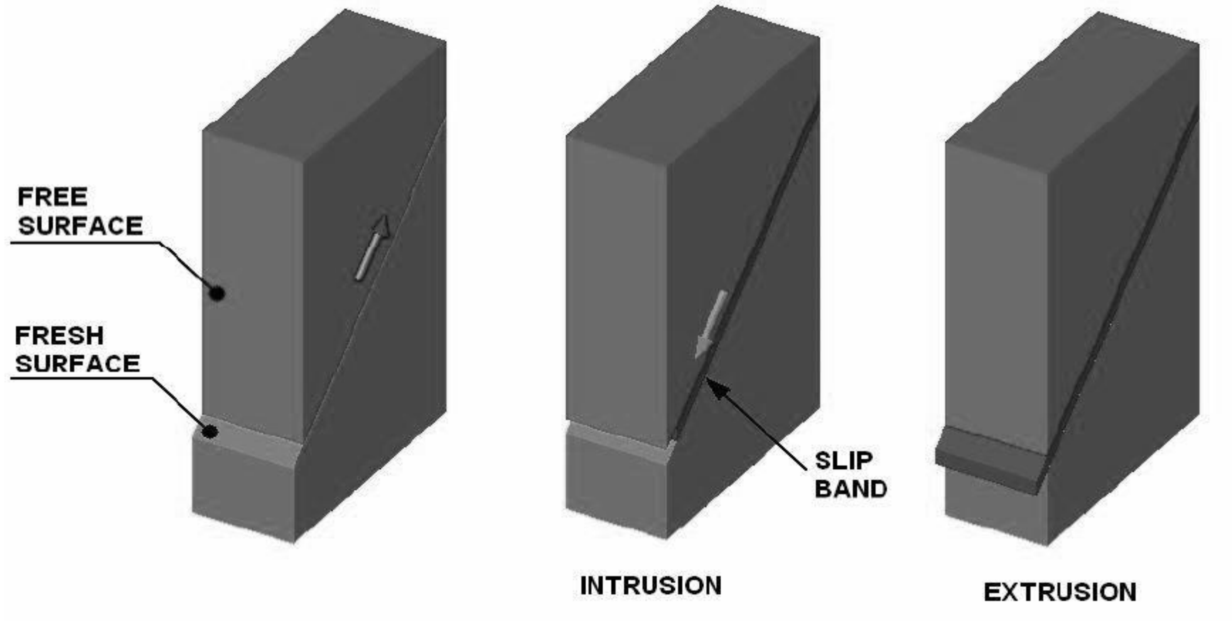


Figure 2 Formation of intrusion and extrusion marks on the material surface

The fatigue life is generally divided into three stages/periods

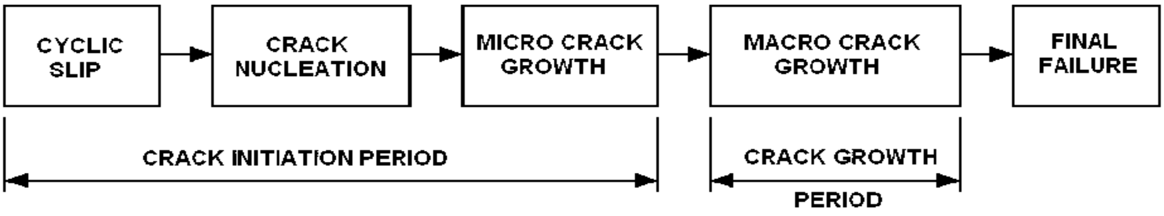


Figure 3 Different phases of the fatigue life

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:

$$N_f = N_i + N_p \quad (1)$$

2.2.1 Crack initiation (N_i)

This is the number of cycles required to initiate a crack. It generally results from dislocation pile-ups and imperfections such as surface roughness, voids, scratch etc. hence; in this period fatigue is a material surface phenomenon.

The stress concentration factor, K_t is another factor to be considered in crack initiation prediction.

2.2.2 Crack growth N_p

This is the number of cycles required to grow the crack in a stable manner to a critical size, generally controlled by stress level. Since most common material contains flaws, the prediction of crack growth is the most studied aspect of fatigue. Crack growth resistance, when the crack penetrates into the material, depends on the material as a bulk property. It is no longer a surface phenomenon. The stress intensity factor is an important factor for fatigue growth prediction.

2.2.3 Rapid fracture

Very rapid critical crack growth occurs when the crack length reaches a critical value. Since rapid fracture occurs quickly, there is no rapid fracture term in the fatigue life expression.

The fracture toughness K_{IC} of the material is the primary factor for rapid fracture prediction or design against fracture.

2.3 Fatigue Properties of Materials

Fatigue is generally understood as the gradual deterioration of a material which is subjected to cyclic loads. In fatigue testing, a specimen is subjected to periodically varying constant amplitude stress. The applied stresses may alternate between equal positive and negative value from zero to maximum positive or negative value, or between equal positive and negative values or between unequal positive and negative values.

A series of fatigue tests are made on a number of specimens of the material at different stress levels. The stress endured is then plotted against the number of cycle sustained. By choosing lower and lower stresses, a value may be found which will not produce failure, regardless of the number of applied cycle. This stress value is called the fatigue limit of the material or the endurance limit. The plot of the two terms is called stress-cycle diagram or S-N diagram. The fatigue limit may be established for most steels between 2 and 10 million cycles. Non-ferrous metals such as aluminum usually show no clearly defined fatigue limit. (Mark´s Standard-Handbook/Strength of Materials).

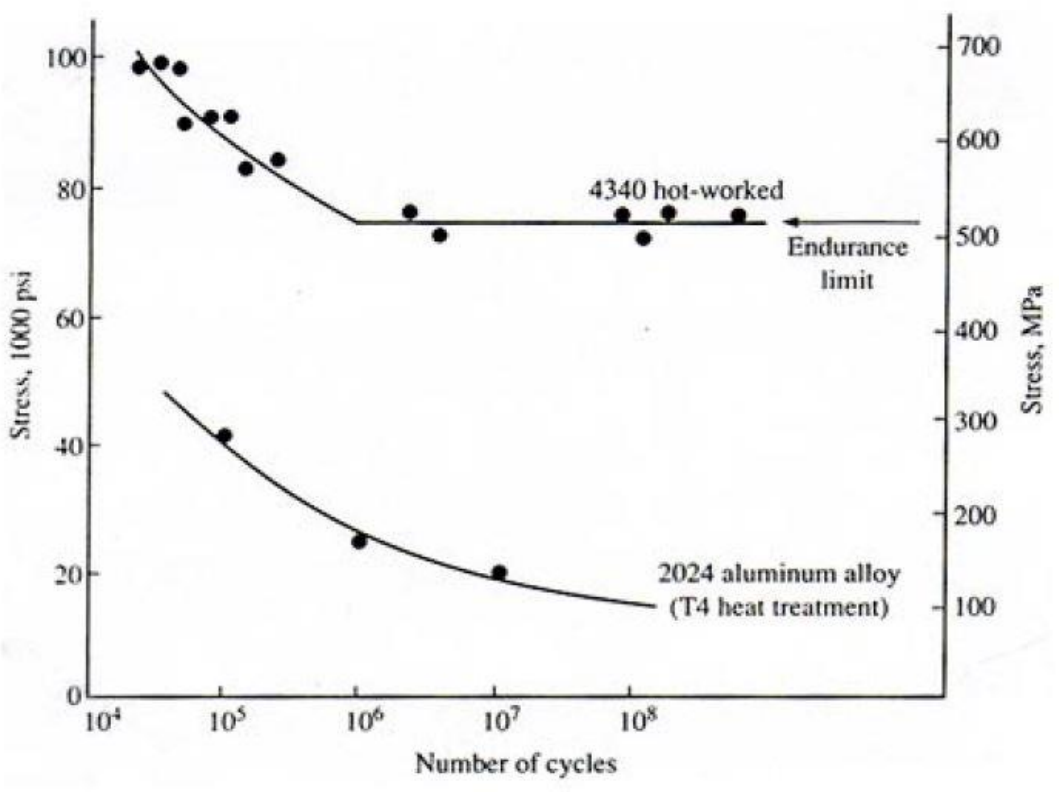
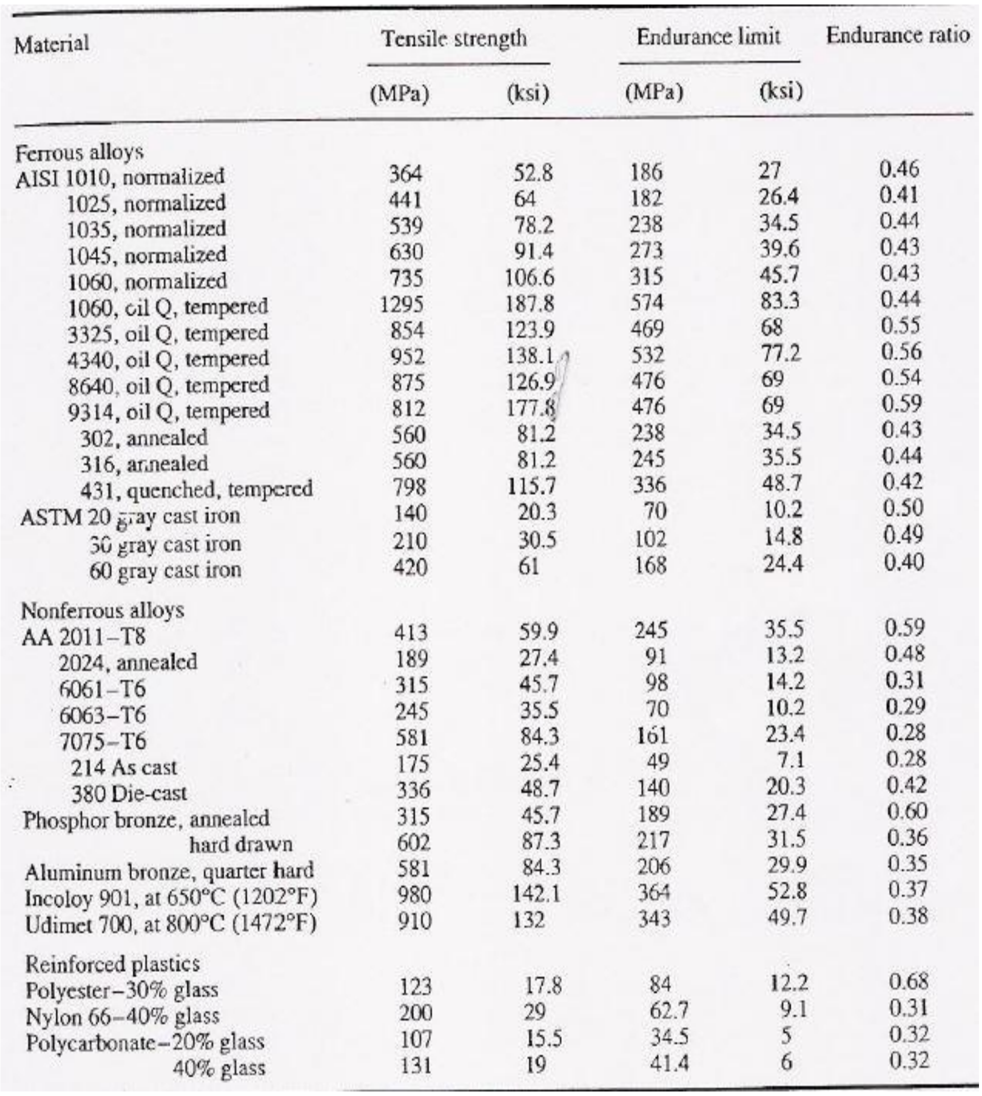


Figure 4 S-N Curve of a ferrous and non-ferrous metal

Surface defects, such as roughness or scratches and notches or shoulders all reduce the fatigue strength of a part. Various metals differ widely in their susceptibility to the effect of roughness and concentrations or notch sensitivity. For a given material subjected to a prescribed state of stress and type of loading, notch sensitivity can be viewed as the ability of that material to resist the concentration of stress incidental to the presence of a notch.

Corrosion and galling (due to rubbing of mating surfaces) can cause great reduction of fatigue strength, sometimes amounting to as much as 90% of the original endurance limit. Although any corroding agent will promote severe corrosion fatigue, there is so much difference between the effects of sea water or tap water from different localities. This among others explains the complex nature of fatigue phenomenon. Shot-penning, nitriding and cold work usually improve fatigue properties.

No very good overall correlation exists between fatigue properties and any other mechanical property of a material. The best correlation is between the fatigue limit under completely reversed stress and the ordinary tensile strength. For many ferrous metals, the fatigue limit is approximately 0.40 to 0.60 times the tensile strength. For non-ferrous metal, it is approximately 0.20 to 0.50 times the tensile strength.



Material	Tensile strength (MPa)	Tensile strength (ksi)	Endurance limit (MPa)	Endurance limit (ksi)	Endurance ratio
Ferrous alloys					
AISI 1010, normalized	364	52.8	186	27	0.46
1025, normalized	441	64	182	26.4	0.41
1035, normalized	539	78.2	238	34.5	0.44
1045, normalized	630	91.4	273	39.6	0.43
1060, normalized	735	106.6	315	45.7	0.43
1060, oil Q, tempered	1295	187.8	574	83.3	0.44
3325, oil Q, tempered	854	123.9	469	68	0.55
4340, oil Q, tempered	952	138.1	532	77.2	0.56
8640, oil Q, tempered	875	126.9	476	69	0.54
9314, oil Q, tempered	812	177.8	476	69	0.59
302, annealed	560	81.2	238	34.5	0.43
316, annealed	560	81.2	245	35.5	0.44
431, quenched, tempered	798	115.7	336	48.7	0.42
ASTM 20 gray cast iron	140	20.3	70	10.2	0.50
30 gray cast iron	210	30.5	102	14.8	0.49
60 gray cast iron	420	61	168	24.4	0.40
Nonferrous alloys					
AA 2011–T8	413	59.9	245	35.5	0.59
2024, annealed	189	27.4	91	13.2	0.48
6061–T6	315	45.7	98	14.2	0.31
6063–T6	245	35.5	70	10.2	0.29
7075–T6	581	84.3	161	23.4	0.28
214 As cast	175	25.4	49	7.1	0.28
380 Die-cast	336	48.7	140	20.3	0.42
Phosphor bronze, annealed	315	45.7	189	27.4	0.60
hard drawn	602	87.3	217	31.5	0.36
Aluminum bronze, quarter hard	581	84.3	206	29.9	0.35
Incoloy 901, at 650°C (1202°F)	980	142.1	364	52.8	0.37
Udimet 700, at 800°C (1472°F)	910	132	343	49.7	0.38
Reinforced plastics					
Polyester–30% glass	123	17.8	84	12.2	0.68
Nylon 66–40% glass	200	29	62.7	9.1	0.31
Polycarbonate–20% glass	107	15.5	34.5	5	0.32
40% glass	131	19	41.4	6	0.32

Figure 5 Fatigue strength and tensile strength of common materials

2.4 Design for fatigue failure

2.4.1 Corrected fatigue strength

It can be said that since fatigue properties of a material is easily influenced by many factors (size, surface, test method, environment and probability). The S-N curve obtained from laboratory tests has to be related to real-life design condition by modifying it with some factors and least the laboratory results should not be used directly with no question.

Laboratory endurance strength (S_e') of the materials obtain from S-N diagram (or the likes) are therefore corrected for actual conditions by using correction factors like;

$$S_e = K_a \text{ x } K_b \text{ x } K_c \text{ x } K_d \text{ x } K_e \text{ x } K_f \text{ x } S_e' \qquad (2)$$

Where,

K_a = Surface Correction factor

K_b = Size Correction factor

K_c =Reliability Correction factor

K_d = Temperature Correction factor

K_e = Stress concentration Correction factor

K_f = Miscellaneous Correction factor

$S_e^{'}$ = Endurance Strength of material specimen under laboratory condition

S_e = Endurance Strength of material specimen under actual running condition

2.4.2 Selection of materials for fatigue resistance

In many applications, the behavior of a component in service is influence by several other factors besides the properties of the material used in its manufacture. This is particularly true for the cases where the component or structure is subjected to fatigue loading, the fatigue resistance can be greatly influenced by the service environment, surface condition of the part, method of fabrication and design details. In some cases, the role of the material in achieving satisfactory fatigue life is secondary to the above parameters, as long as the material is free from major flaws. Commonly used material type for design against fatigue is elaborated below with their basic characteristics.

Steel and cast iron

1. Steels are widely used as structural materials for fatigue application as they offer high fatigue strength and good process-ability at relatively low cost.

2. The optimum steel structure for fatigue is tempered martensite, since it provides maximum homogeneity.

3. Steel with high hardenability gives high strength with relatively mild quenching and hence, low residual stresses, which is desired in fatigue applications.

4. Normalized structure, with their finer structure give better fatigue resistance than coarse pearlite structure obtained by annealing.

Nonferrous alloys

1. Unlike ferrous alloys, the nonferrous alloys, with the exception of titanium, do not normally have clear endurance limit.

2. Aluminum alloys usually combine corrosion resistance, light weight, and reasonable fatigue resistance

3. Fine grained inclusion-free alloys are most suited for fatigue applications.

Plastics

1. The viscoelasticity of plastics makes their fatigue behavior more complex than that of metals.

2. Fatigue behavior of plastics is affected by the type of loading, small changes in temperature and environment and method of fabrication

3. Because of their low thermal conductivity, hysteretic heating can build up in plastics causing them to fail in thermal fatigue or to function at reduces stiffness level.

4. The amount of heat generated increases with increasing stress and test frequency.

Composite materials

1. The failure modes of reinforced materials in fatigue are complex and can be affected by the fabrication process when difference in shrinkage between fibers and matrix induce internal stresses.

2. However from practical experiences, some fiber reinforced plastics are known to perform better in fatigue than some metal

3. The advantage of fiber-reinforced plastics is even more apparent when compared to a per weight basis.

4. As with static strength, fiber orientation affects the fatigue strength of fiber reinforced composite.

5. In unidirectional composites, the fatigue strength is significantly lower in directions other than the fiber orientation.

6. Reinforcing with continuous unidirectional fibers is more effective than reinforcing with short random fibers.

3 FATIGUE TESTING METHODS

The objective of a fatigue test is generally speaking to determine the fatigue life and/or the danger point, i.e. the location of failure of a test-piece subjected to a prescribed sequence of stress amplitude.

By simplifying and idealizing the test conditions, it would be possible to vary one or a few of the factors, which influence the fatigue life and to state their effects.

Even if these conditions are fulfilled, there will always remain a number of unknown and uncontrollable factors which produce a large scatter in fatigue life even of test-piece which are considered to be identical.

There are 2 basics for a classification of the different methods of fatigue testing.

1. The sequence of stress amplitude.

2. The nature of the test-piece.

3.1 Classification based on the sequence of stress amplitudes

3.1.1 Constant-amplitude test

This is the simplest sequence of amplitude obtained by applying reversals of stress of constant-amplitude to the test-piece until failure occurs. Different specimens of the test series may be subjected to different stress amplitude but for each individual item, the amplitude will never be varied.

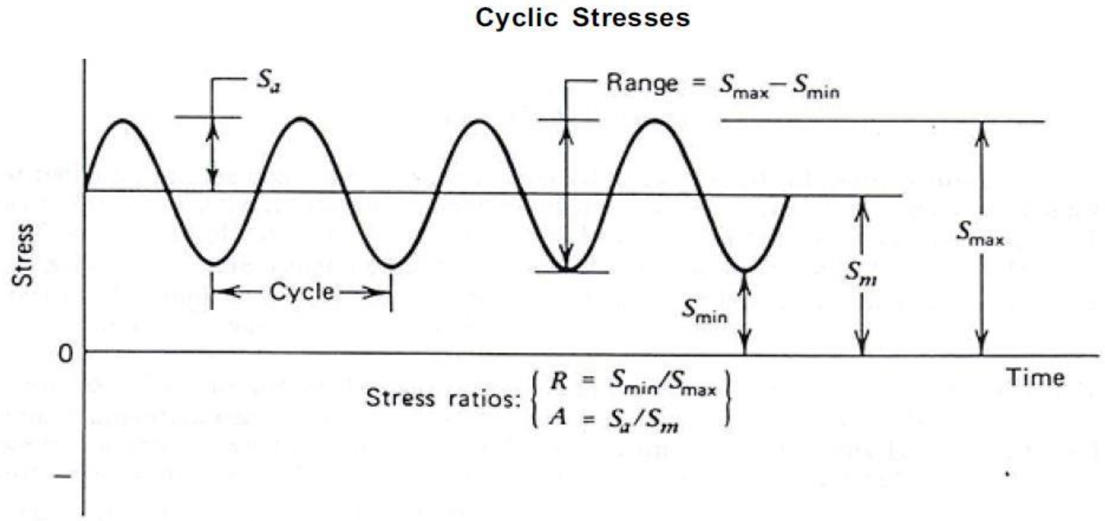


Figure 6 Schematic Illustrating Cyclic Loading Parameters [Fuch & Stephens, 1980].

The following parameters are utilized to identify fluctuating stress cycles:

Mean Stress,S_m

$$S_m = \frac{S_{\max} + S_{\min}}{2} \tag{3}$$

Stress Range, S_r

$$S_r = S_{\max} - S_{\min} \tag{4}$$

Stress Amplitude, S_a

$$S_a = \frac{S_{\max} - S_{\min}}{2} \tag{5}$$

Stress Ratio, R

$$R = \frac{S_{\min}}{S_{\max}} \tag{6}$$

Depending upon the choice of stress levels, constant-amplitude tests may be classified into three types

Routine test

In routine test, the applied stresses are chosen in such a way that all specimens are expected to fail after a moderate number of cycles say 10^4 to 10^7, a few run-outs, although not intended may be allowed.

Short-life test

The stress levels are suited above the yield stress and some of the specimens are expected to fail statically at the application of the load.

Long-life test

In this type of testing method, the stress levels are suited below or just above the fatigue limit and a fraction of the specimen does not fail after a pre-assigned number of cycles about 10^6 to 10^7 cycles.

3.1.2 Variable-amplitude tests

More complicated sequences of amplitude are required in order to simulate the stresses to which a specimen is subjected in actual service. A realistic simulation is very complicated.

In order to discover laws in relation to the accumulation of fatigue damage in a specimen subjected to stress reversals of different amplitudes, the sequence of stress amplitudes may be simplified. Independent of the pattern used, such tests is known as variable-amplitude tests.

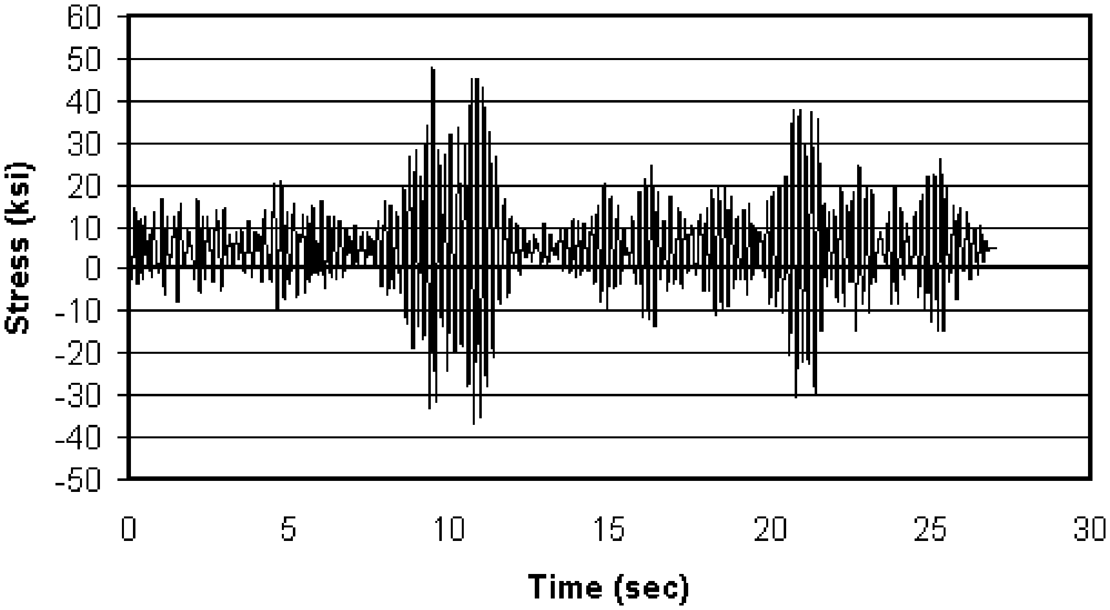


Figure 7 Variable amplitude fatigue stress loading

Variable-amplitude tests can be further divided into:

Cumulative damage test

These are tests where the objective is to investigate cumulative damage theory, in which case the sequences are frequently simplified.

Service simulating test

These are tests which uses a more elaborate pattern (close to real service loading) for simulating purpose.

3.2 Classification based on the nature of the test-piece

It will suffice to divide the test-piece into two categories

3.2.1 Specimens

The term “specimen” is generally used in the sense of a test-piece of simple shape, frequently standardized, of small size and prepared carefully and with good surface finish. The purpose of the simplification is not to make it less expensive but more to reduce the variability of the product and to keep different influential factors under control.

Test-pieces of this type are generally intended for testing the material and for stating its fatigue properties; they are also used extensively for research purposes.

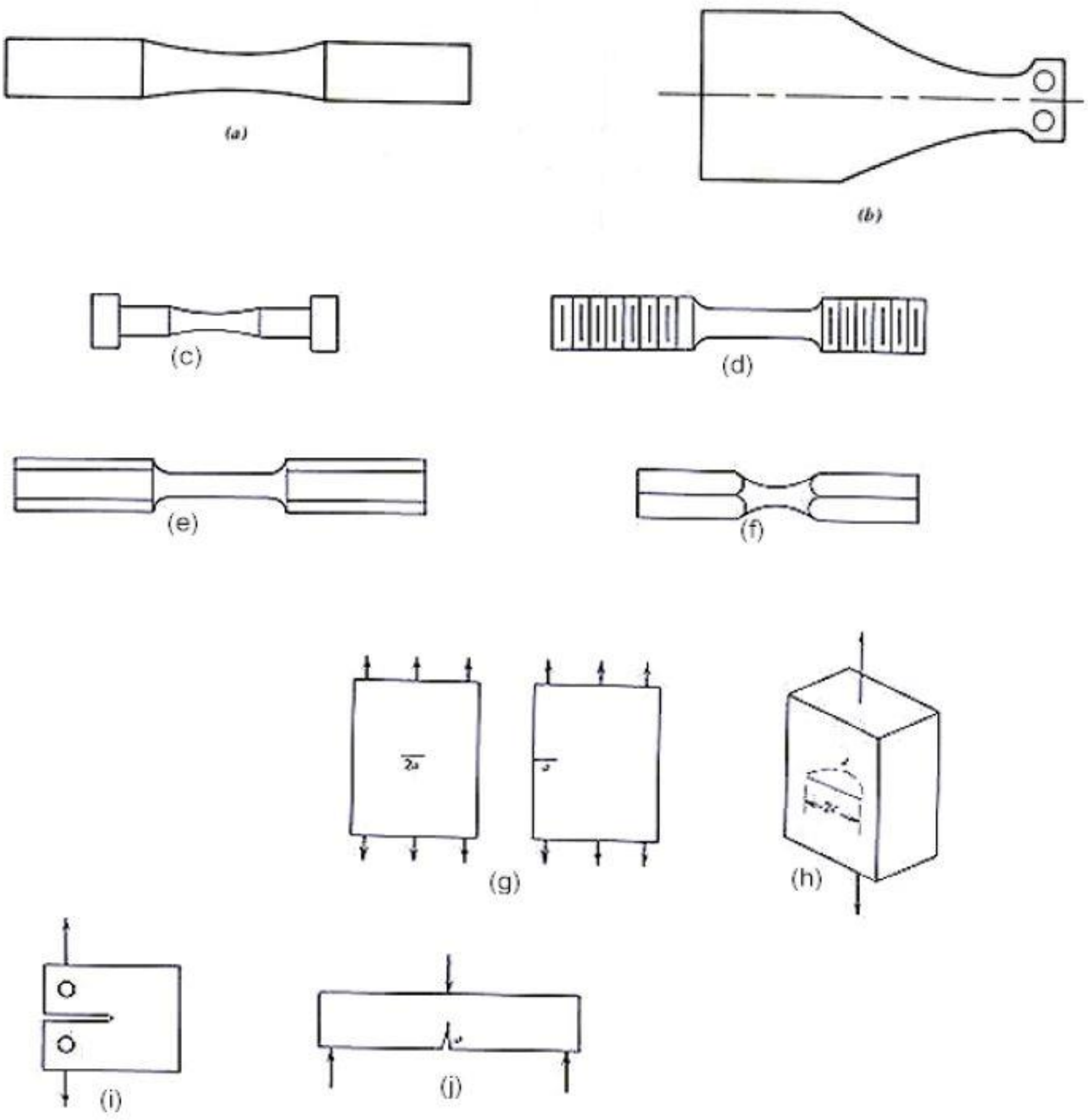


Figure 8 Fatigue Test Specimens: (a) Rotating Bending, (b) Cantilever Flat Sheet (c) buttoned axial dog-bone, (d) threaded axial dog-bone, (e) torsion, (f) combined stress, (g) axial Cracked sheet, (h) part-through crack,(i) Compact tension and (j) three point bend specimen [Fuch & Stephens, 1980].

Even if the simplified specimen may simulate many of the properties of actual machine parts, there are two factors pertaining to the component which are not represented in the specimen i.e. design and fabrication. For this reason, it is indispensable to carry out actual tests with components in exactly the same condition as used in actual service.

3.2.2 Component

It is used to signify any machine part, actual structure, machine and assembly including elements simulating actual components.

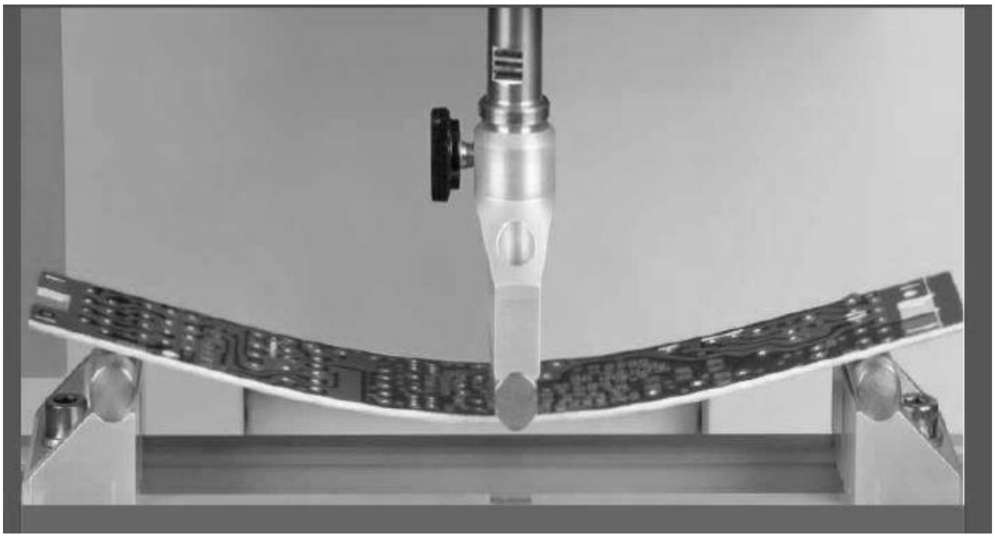


Figure 9 3-point bending test of a circuit board [2]

Figure 10 Service testing of a whole car model

3.3 General Classification of Fatigue Testing

Based on the three categories above, fatigue testing maybe divided base on the objective of the test, the three categories are:

3.3.1 Material type test

Test of the material type are useful for a comparison of the behavior of different materials subjected to repeated stresses, of the effects of various manufacturing processes, of the behavior of material in various environment, of various simple geometrical factors such as different sizes and shapes, of notches and different surface finishes.

It could also be used for elaborating the effect of surface treatment such as case-hardening, decarburization, nitriding, shot-peening and plating on the fatigue properties of different materials.

3.3.2 Structural type test

This type of test may be useful for a comparison of components made from different materials, of different design and of structure fabricated by different procedures. They may also be used for revealing stress concentration and for developing better designs or better fabrication procedures.

3.3.3 Actual service type test

They are tests usually used as reliability test or quality test, mainly for fault finding or verifying a new component in the machine or structure.

Fatigue tests completely different in type from the above mentioned tests are those which have as an objective a study of the initiation and propagation of fatigue cracks, this requires complex knowledge of fracture mechanics and microscopic view of material structure and it is beyond the scope of this thesis work.

4 FATIGUE TESTING MACHINE

A fatigue testing machine may be classified from different viewpoints such as purpose of the test, type of stressing, means of producing the load, operation characteristics, type of load etc.

The purpose of the investigation is the most important item for thee research and of course, this is known when starting the investigation. Hence, it makes sense to base the classification on the purpose of the test.

4.1 Classification of fatigue testing machine

Base on the purpose of the test, fatigue testing machine can be divided into the following:

1. General purpose fatigue testing machine
2. Special purpose fatigue testing machine
3. Equipment for testing parts and assemblies

In this work, the general purpose class will be expanded further as this is the widely used type, most especially in academic environment.

4.2 General purpose testing machine

The general purpose testing machine can be further divided into two broad categories. They are the following:

4.2.1 Classification based on type of stressing method

Rotating bending testing machine

The type of S-N curve created by this machine is identified as a rotating-bending, stress-controlled fatigue data curve. The rotating bending test machine is used to create an S-N curve by turning the motor at a constant revolution per minutes, or frequency. To create a failure on the specimen, a constant-stationary force is applied on the specimen, which creates a constant bending moment. A stationary moment applied to a rotating specimen causes the stress at any point on the outer surface of the specimen to go from zero to a maximum tension stress, back to zero and finally to a compressive stress. Thus, the stress state is one that is completely reversed in nature.

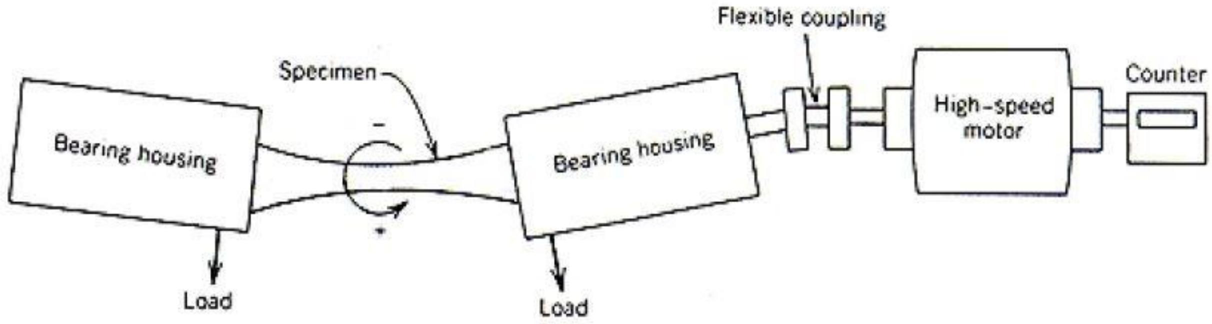


Figure 11 Rotating Bending Testing Machine [Callister, 1994].

Reciprocating bending test machine

The type of S-N curve produced is identified as a tension-compression, strain controlled fatigue data curve. This machine type is capable of zero mean cyclic stresses by positioning the specimen clamping vice with respect to the mean displacement position of the crank drive.

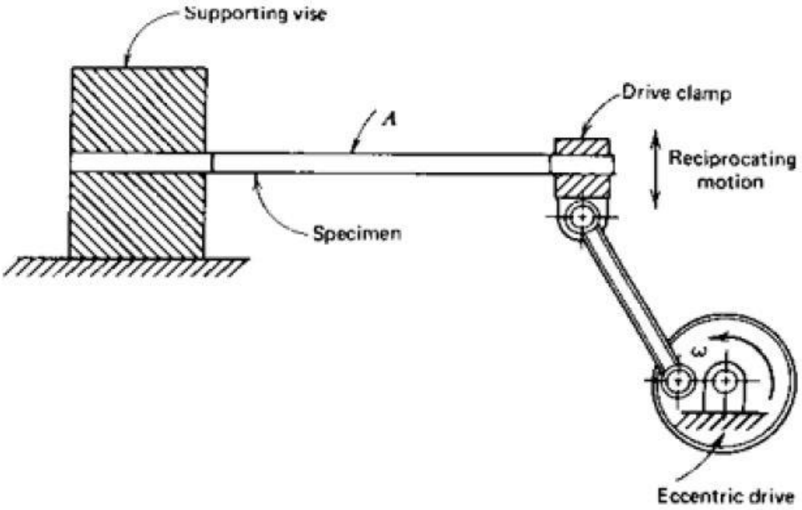


Figure 12 Reciprocating Bending Testing Machine [Collins, 1981].

Axial loading (push-pull) type fatigue tester

In this type the specimen is not exposed to bending but to pure axial (tensile or compressive) loading. Specimen is held at two ends and loaded cyclically between two extreme (maximum and minimum) values.

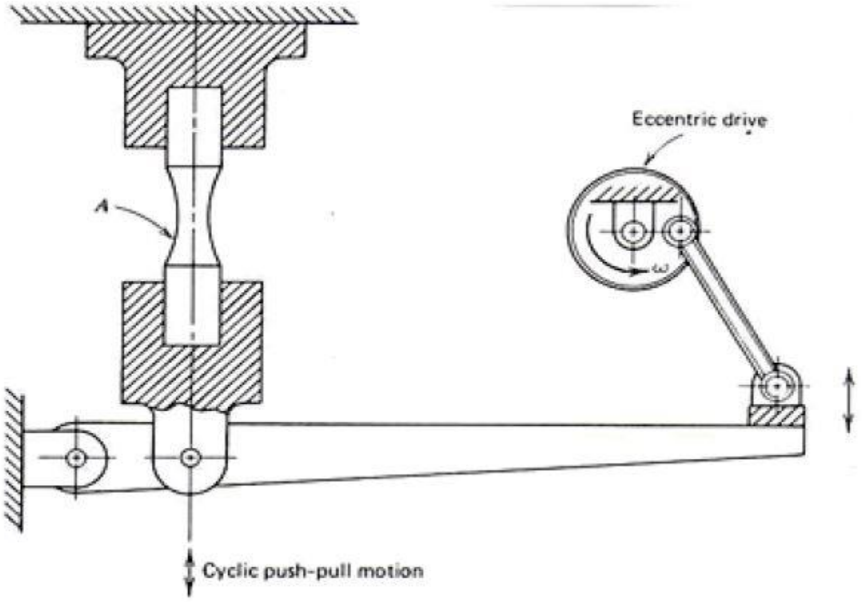


Figure 13 Direct-Force Fatigue Testing Machine [Collins, 1981].

The axial loading (push-pull) tester employing conversion attachments are also capable of bending and torsion fatigue testing when necessary, most commercial universal fatigue testing machines have this feature.

Figure 14 Universal-tester [http://testersupply.com/8-fatigue-testing-machine.html]

Other possible types, though not commonly used for simplified testing are:

1. Torsion loading fatigue tester.

2. Combined bending and torsion fatigue tester.

3. Bi-axial and tri-axial loading fatigue tester.

Classification based on source of stressing

The following classification of fatigue testing machine is based on the principle behind the source of the test-force. Load produced by:

1. Mechanical deflection
2. Dead weight or constant spring force
3. Centrifugal force
4. Electromagnetic force
5. Hydraulic force
6. Pneumatic force

The choice of load source depends on numerous factors such as the needed frequency, amount of forces required, available control system, cost, and how close the test is to be simplified to the actual working loading in service.

4.3 Components of a fatigue testing machine

All type of fatigue testing machine is composed of the following structural components:

1. Load-producing mechanism

This generates the alternating load (displacement) to which in some cases a steady load is added.

2. Load-transmitting member

This includes grips, guide fixtures, flexure joints etc. by which the load produced is transmitted in such a way as to produce the desired stress distribution within the specimen.

3. Measuring devices

This permit the setting of the nominal upper and lower load limits.

4. Control devices

This component controls the load throughout the test and sometimes automatically corrects changes in force or displacement arising during the test using feedback techniques.

5. Counter and shut-off apparatus

This counts the number of stress reversals imposed on the specimen and stop the testing machine after a given number of cycles, at complete fracture of the specimen or at some pre-assigned change in deformation or frequency.

6. Framework

It supports the various parts of the machine and if necessary is arranged to reduce the vibratory energy transmitted to the foundation.

In conclusion, the purpose of a fatigue testing machine is to apply to the specimen an alternating load producing a well-defined stress distribution. The distribution should be reproducible within narrow limits, a requirement which includes that the load should be reproduced with sufficient accuracy and it should be transmitted to the test-piece without undue scatters. Hence a careful and correct calibration and checking of the testing machine is an indispensable condition for obtaining reliable results from any fatigue testing machine.

4.4 The testing machine of HAMK University, mechatronic laboratory

The testing machine (still under construction) is a universal testing machine which can be used for tensile test, compressive test and fatigue testing. The hydraulic can produce forces up to 16KN and a frequency of maximum 10Hz.

The machine is a servo-controlled hydraulic testing machine. It is controlled with phoenix programmable logic controller and can support wide ranges of load cell both for axial force test and bending tests.

A full description of the capability of the tester and its components specification including its user manual is available as a separate document.

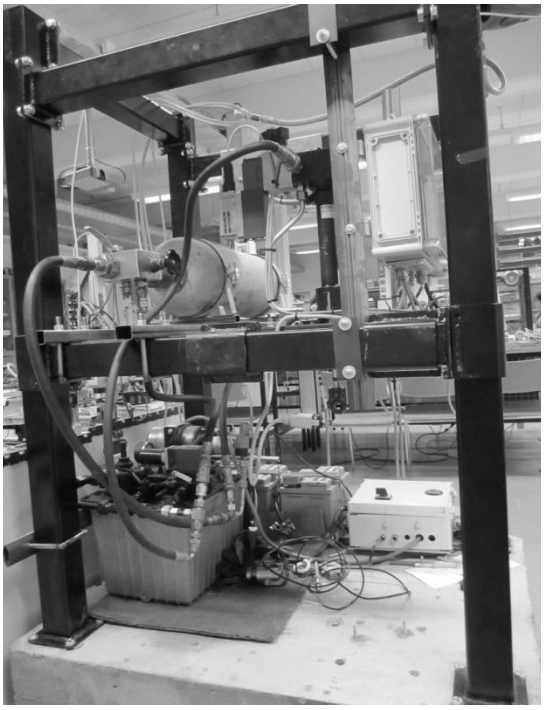


Figure 15 Dynamic testing machine in HAMK Mechatronics laboratory (under-construction)

4.5 Design of the testing support structure

The initial idea was to design a set-up for tensile test as the verification test for the dynamic fatigue tester, a major reason for this is that the machine was intended to be used to test the behavior of welded TRIP Steel for Innosteel Oy, Hämeenlinna when the welded parts is subjected to tensile force of 2-3 KN dynamic loading. To come up with this design, several commercial universal fatigue testers were analyzed and also international standards on basic design of mechanical testing. It was later discovered that tensile fatigue testing will not be possible with the machine because the hydraulic cylinder of the dynamic tester cannot provide the needed linear movement amplitude for tensile fatigue testing, hence a new design (require smaller linear amplitude) is needed.

A bending setup was then considered, aside the fact that the first documented laboratory fatigue test done by August Wöhler was actually a rotating bending fatigue up, bending set-up offers much more advantages than other possible forms of set up, some of this advantages are stated below:

1. Easy way to characterize some of the mechanical properties of a material
2. No special gripping is required
3. Mounting and dismounting of test-pies is very straight forward
4. The specimen is usually of very simple shape (rectangular cross section)

There are two options for the fatigue bending set-up

1. Three points fatigue bending set-up.
2. Four points fatigue bending set-up.

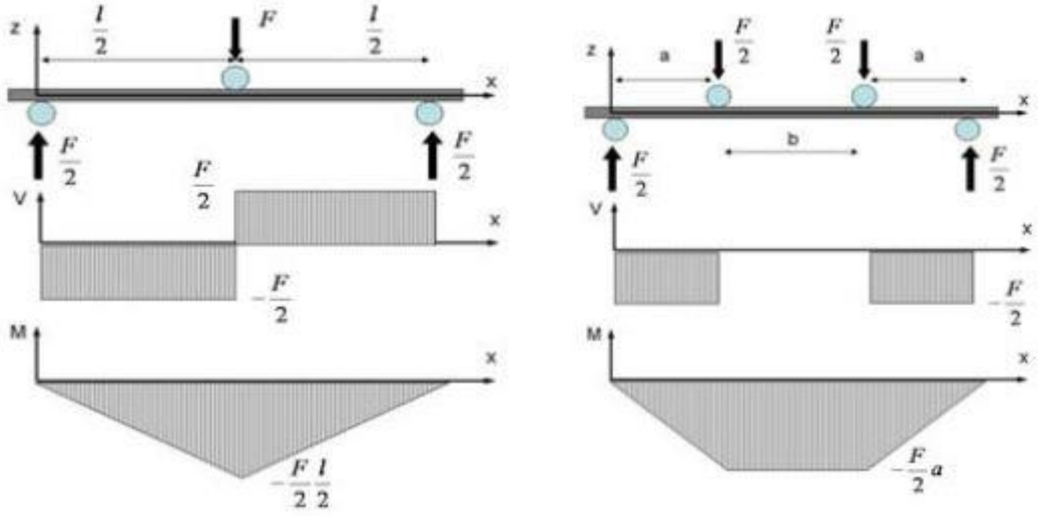


Figure 16 Transverse force and moment for the two bending setups.

In three points bending set-up, each section of the beam has a transverse force, resulting in an interlaminar shear tension, which can cause delamination. But in four points bending, there is a section of the beam which is constant and the transverse force (thus the interlaminar shear stress) is zero. This section experiences only normal stress.

In fatigue testing, the specimen shows permanent deflection after a few thousand cycles. As a result, the indenter loses contact when its displacement is smaller than the permanent deflection. In the next cycle, the indenter has an impact on the surface of the specimen, causing impact damage, and as a result corrupts the fatigue data.
This problem can be solved if the permanent deflection is kept symmetrically, which means at zero deflection. This can be easily obtained by fully reversed bending, where the displacement varies between $–U_{min}$ and $+U_{max}$.

In addition, since the specimen rotates at its ends, the outer supports need to allow this rotation; otherwise, this would induce unwanted reaction forces in the specimen, corrupting the fatigue data.

To carry out a four points fully reversed fatigue-bending test, a 4 points set-up is required. The figure below is the initial proposed design for bending set up support structure taking care of all the points stated above so as to achieve reasonable fatigue data.

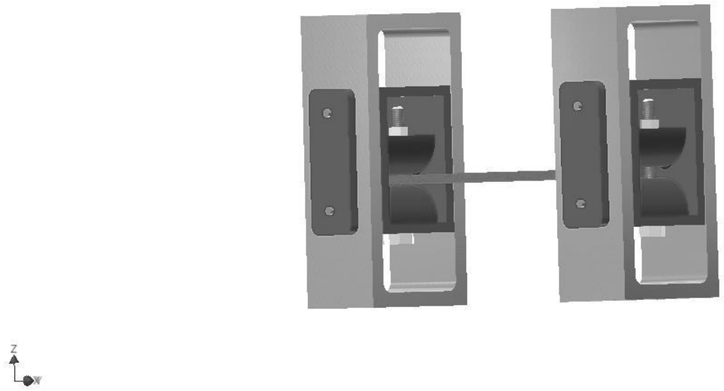


Figure 17 Initial proposed design of a 4-point fully reversed bending set-up with rotating side supports.

Although the design above took care of the necessary points stated above, is major disadvantages are:

1. Complexity: it is quite complex and its mode of operation is not easy to comprehend.

2. Manufacturability: Several manufacturing process such as welding, drilling, milling, turning, cutting will be required to make this design hence, it will be expensive to make.

Due to the reasons stated above and some minor ones, this design could not be approved, so, a cheaper, intuitive and easy to produce design is required.

> "*It is more difficult to make a simple design than a complex one….anonymous*"

To solve the problem of cost, it was decided that all materials needed to manufacture the support structure and set-up will be from the stock of HAMK Mechanical Engineering Laboratory and also major machining operations such as turning, milling will be eliminated. The new design must be easy to assemble and dissemble with little or no manual required and finally it must allow test of wide range sizes/dimensions i.e. it must be adjustable in length and height.

Figure below is the final design of the testing support structure. The beam structure is far stronger than the maximum capacity of load that the hydraulic unit of the tester can produce and it requires less manufacturing process (basically cutting, drilling and welding) than the earlier design.

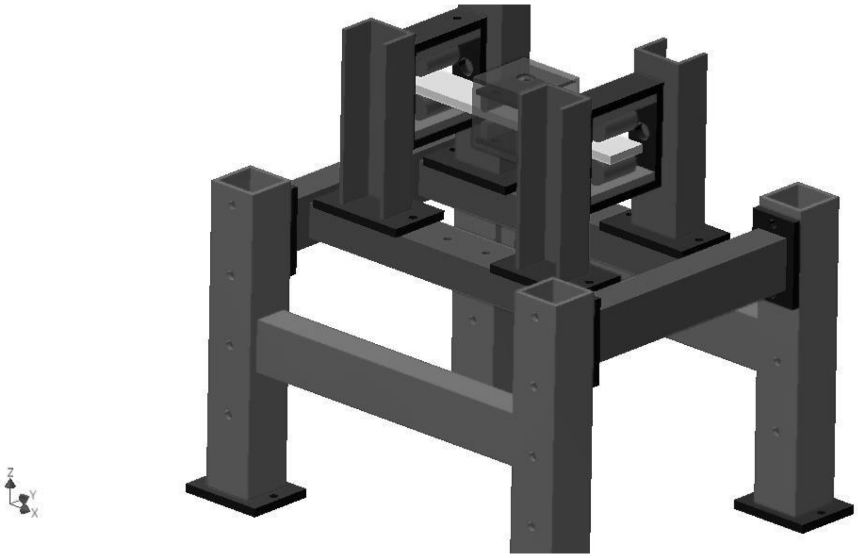


Figure 18 Final design of the support structure for bending set up.

5 COLLECTION, ANALYSIS AND PRESENTATION OF FATIGUE DATA

In order to generate realistic data for fatigue analysis, the fatigue tests are carried out on several specimens at different levels of maximum alternating stresses. The fatigue data is plotted on a semi-log or log-log scale in the form of S-N curve (i.e. stress vs. number of cycles to failure curve), also known as the Wöhler curve. The portion of curve with negative slope constitutes the finite life region and represents fatigue strength of the material for given number of stress cycles, while the horizontal portion represents infinite life region.

The stress level corresponding to horizontal portion (i.e. infinite life) is known as fatigue Limit of the material. The changeover point, or the knee, signifies the phenomenon where Crack nucleation is essentially arrested by some microstructural features.

5.1 Analysis and determination of finite life

Owing to inherent microstructural inhomogeneity in the material properties, differences in surface finish and test condition, fatigue data exhibit scatter. The variance of log life generally increases with decreasing stress levels, particularly for un-notched specimens; hence, it is necessary to take into account the statistical nature of the fatigue data.

Various techniques are available to construct a median S-N curve and associate lower and upper bound curves that characterize the minimum and maximum fatigue lives at a given level of stress amplitude.

The JSME S 002 standard is one of them and much simpler in principle to other techniques. It involves testing of two fatigue specimens at four stress levels for finite life regions; while 6 specimens are used for determining the fatigue limit through the staircase method (will be discussed in the next paragraph). The recommended test sequence is shown in figure xxx, where the numbers next to the data points represent the order for conducting the fatigue tests. The fatigue is determined by taking the average of the stress levels employed during the staircase test.

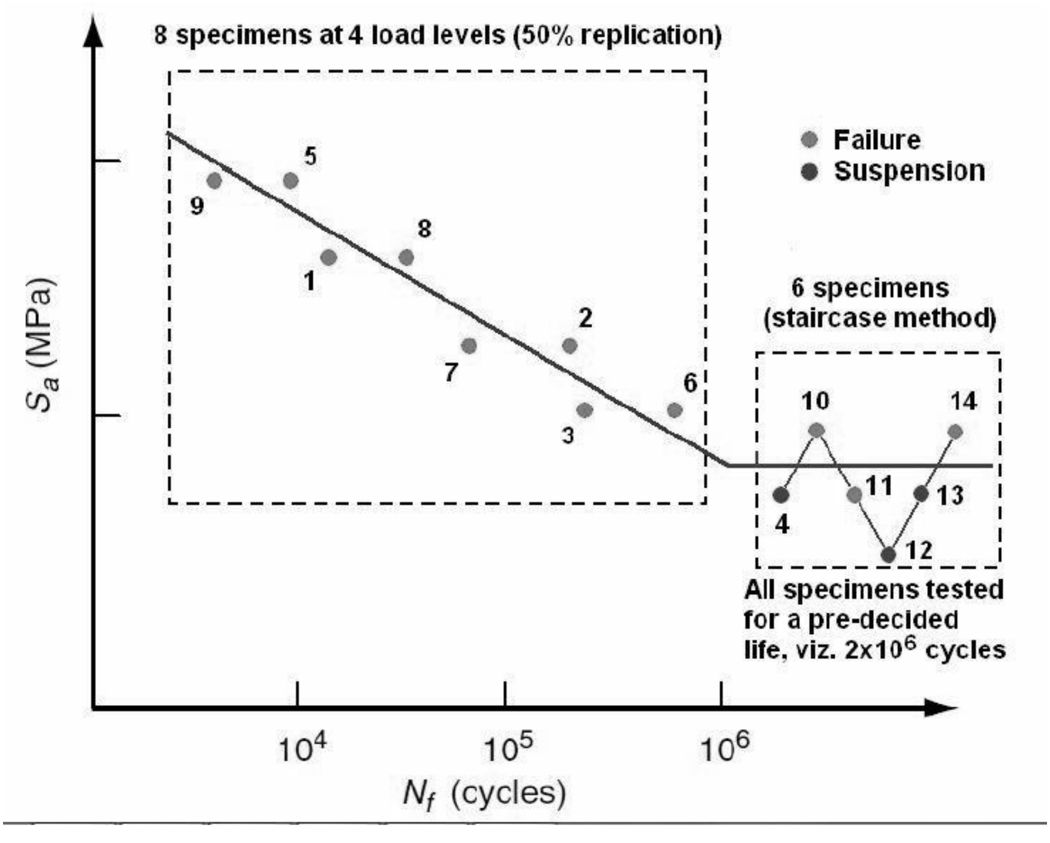


Figure 19 *S-N* testing according to JSME standard

5.2 Staircase method

The staircase method provides an estimate of the endurance limit by taking into account its statistical nature. It is also known as up and down method. It is more efficient than other methods such as the probit method because it can reduce the number of needed for the whole text by forty percent.

In this test method, first of all, the mean endurance limit is estimated. Following this, a specimen is tested at stress amplitude S_a slightly (about 5%) higher than the expected endurance limit. If the specimen fails before completion of stipulated number of cycles (about 2 million cycle), then the next specimen is tested at lower stress amplitude. However, in the event of survival of a specimen, the test is suspended after completion of stipulated number of cycles and the next specimen is tested at higher amplitude of maximum alternating stress. Thus, the stress amplitude of each successive test is based on the outcome of its previous test.

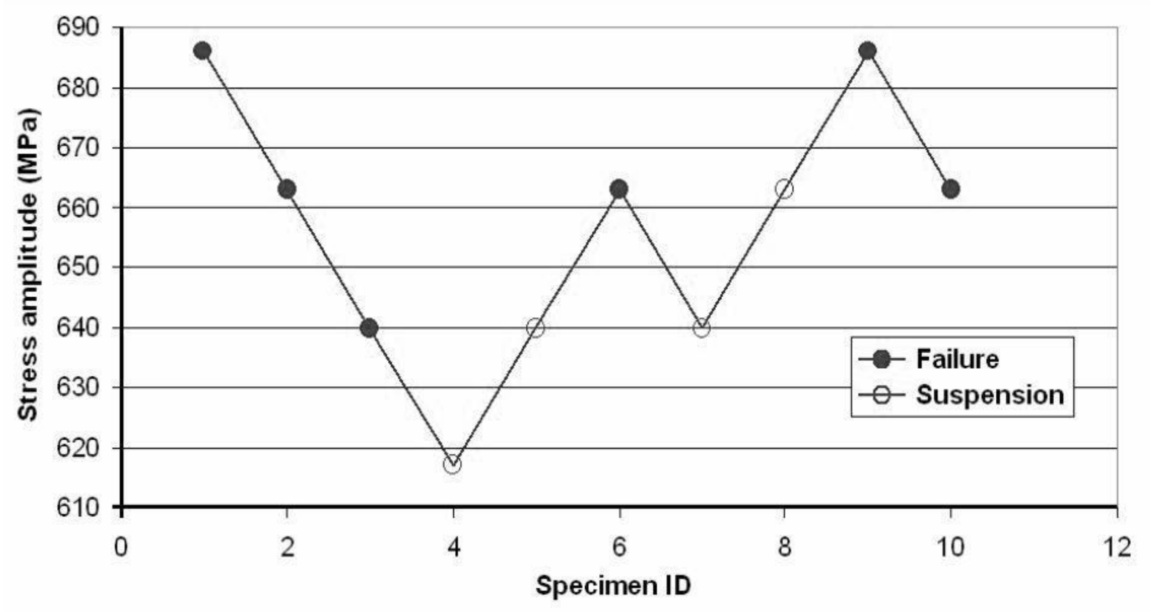


Figure 20 Staircase method for determining endurance limit.

In order to use the Dixon-mood method for statistical analysis of the test data from the staircase method, the stress-steps must be uniform. The Dixon-mood method provides formulae for estimating the mean, μ_s and standard deviation, σ_s of the endurance limit, S_e, this is estimated by using the data of less frequent event out of the two possible events i.e. survivals or failures. The individual stress amplitude, S_a which are spaced uniformly at an interval of (d) are numbers as I, where i = 0 is used to denote the lowest stress amplitude, S_0. The method also requires that:

$$\frac{\sigma_s}{2} \leq d \leq \sigma_s$$

The estimate of mean endurance limit is given by;

If survival is less frequent event,

$$\mu_s = S_0 + d \cdot \left(\frac{A_{DM}}{\sum n_{DM,i}} + \frac{1}{2} \right) \qquad (7)$$

If failure is less frequent event,

$$\mu_s = S_0 + d \cdot \left(\frac{A_{DM}}{\sum n_{DM,i}} - \frac{1}{2} \right) \qquad (8)$$

Where,

$A_{DM} = \Sigma(i)(n_{DM,i})$

$n_{DM,i}$ is the count of less frequent event corresponding to the ith stress amplitude.

The standard deviation is estimated from either of the following two expressions:

$$\sigma_s = 1.62d \left[\frac{B_{DM} \sum n_{DM,i} - A^2}{\left(\sum n_{DM,i}\right)^2} + 0.029 \right] \qquad (9)$$

If $\frac{B_{DM} \sum n_{DM,i} - A_{DM}{}^2}{\left(\sum n_{DM,i}\right)^2} \geq 0.3$

Or,

$$\sigma_s = 0.53d \qquad (10)$$

If $\frac{B_{DM} \sum n_{DM,i} - A_{DM}{}^2}{\left(\sum n_{DM,i}\right)^2} \leq 0.3$

Where $B_{DM} = \Sigma\left(i^2\right)\left(n_{DM,i}\right)$.

6 A PLANNED FATIGUE TEST

6.1 General

The test machine under construction could be used for fatigue testing for student of engineering design and material sciences. To demonstrate this, a sample fatigue test exercise will be discuss in the next section, in addition, other test could be easily planned by the instructor by varying one of the factors that affect the fatigue behavior of material such as surface roughness, sizes. It is also a good idea to subject a component, such as a circuit board to a constant cyclic stress and ask the student to determine how much cycle the component can withstand.

It is important that the students are introduced to the theory of fatigue and if possible use this thesis work as references before they perform the laboratory task and also study the manual of the dynamic testing machine in order to be able to conduct the experiment independently.

6.2 Fatigue test exercise

Objective

The main objectives of this experiment are.

1. Perform the fatigue test on the given specimen using the dynamic testing machine in the laboratory to predict the fatigue life

2. Determine the safe stress level for the specimens if the fatigue life of 1,000,000 reversals had to be withstood.

Apparatus required

Dynamic testing machine, vernier caliper, aluminum specimens.

Experimental procedures

As fatigue experiments may run for hours, the usual procedure is to divide the class into groups; each group will experiment with four aluminums specimens or more depending on the size of the class. Each group will have a unique load set; two specimens will be experimented with each of the load set. The load set for each group will be provided once the group is made.at the end of the exercise, results will be shared among the groups. The following procedures are to be followed:

1. Measure the dimension of the test piece and inspect the surface roughness.

2. Fix the test piece to the testing machine, set the test parameters and begin the test. Instructions on how to operate the testing machine is available on the machine manual.

The test parameters are given below.

Material: Aluminum

Dimensions: 160mm x 30mm x 2.5mm

Frequency: 2 Hz

Amplitude: 6 mm

Force range: 1 – 7 KN.

3. Test two specimens for each load value.

4. Collate the results and record the testing parameters and testing conditions

Results

After obtaining the results for your load cases and getting the results of the remaining cases from other groups, plot stress against logN on a suitable graph paper and look for best fit lines and also determine the safe stress level if a fatigue life of 1,000,000 reversals had to be withstood. Also discuss the fractured cross section of your specimens and identify the cause of the fracture and also analyze the factor which could have affect the result of your test.

Finally, compare your graph with standard S-N graph of aluminum and state reasons for difference, if any.

7 CONCLUSION

Due to the wealth of materials on fatigue available on fatigue failure for research works, it was quite challenging to sieve through these useful materials and come up with the most relevant ones to the task at hand. Despite this fact, tremendous effort was put into this work to select the most relevant information necessary for designers and researcher.

Perhaps, works such as this will inspire young engineers to design structures that can withstand fatigue loading. Although numerous work has been done on fatigue failure and testing methods, much still need to be done perhaps in a new dimension, I observed that engineering students are introduce to the principle of fatigue towards the end of their bachelor studies or early masters studies. I strongly suggest that students should be introduce to the principle of fatigue failure right from their first year alongside other testing (tensile test, hardness test and the rest) and also much more collaboration between engineers and materialist is needed so as to tackle the problem of fatigue failure.

Upon completion of the dynamic testing machine, this thesis work may serve as a guide for various laboratory exercises and structural design courses for the engineering student of HAMK University of Applied Sciences.

SOURCES

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[6] W. Weibull, Fatigue Testing and Analysis of Results; oxford. London. New York. Paris, Pergamon press, 1961.

APPENDIX

Technical Drawings of the Proposed design of Support Structure.
(Available as attachment in the hard-copy version at HAMK Riihimäki library).