Objectives

- Students are required to understand principle of fatigue testing as well as practice how to operate the fatigue testing machine in a reverse loading manner.
- Students are required to construct an S-N curve (stress level - number of cycles to failure) of the test samples provided.
- Students can define the fatigue endurance limit or fatigue life and fatigue strength of the materials.
- Students are able to interpret the obtained experimental results and use them as a tool for material selection in engineering applications.
1. Literature Review

1.1 Characteristics of fatigue failure

Most engineering failures are mainly due to fatigue in which the components are subjected to fluctuating or cyclic loading such as suspended bridges, rails, or airplane wings. Though the fluctuating load is normally less than the yield strength of the materials, it results in fracture behaviour which is more severe than that achieved from static loading. Fatigue failures are therefore unpredictable, and provide high-risk situations, if the operators are not aware of material behaviour when subjected to fatigue loading.

Fatigue failures can be easily observed from its unique characteristics of fracture surfaces, revealing as a beach mark pattern as shown in figure 1 (a). Fatigue failures are also driven by severe environment. For example, corrosion fatigue is a combined situation of fatigue loading in a corrosive environment as illustrated in figure 1 (b).

![Fatigue surfaces](image)

**Figure 1:** Fatigue surfaces.

1.2 Stress cycles and the S-N curve

Cyclic loading in general has no repeated patterns or in situations where overloading occurs as seen in figure 2 (a). However, in order to investigate the fatigue behaviour according to engineering purposes, a simple relation between stress and number of cycles to failure (time) can be expressed in a sinusoidal curve as illustrated in figure 2 (b). Fatigue behaviour of materials can thus be practically described according to the parameters given as follows;
Laboratory 8: Fatigue testing

- Maximum stress ($\sigma_{\text{max}}$)
- Minimum stress ($\sigma_{\text{min}}$)
- Stress range ($\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$)
- Mean stress = $(\sigma_{\text{max}} + \sigma_{\text{min}})/2$
- Stress amplitude = $(\sigma_{\text{max}} - \sigma_{\text{min}})/2$
- Stress ratio = $\sigma_{\text{min}} / \sigma_{\text{max}}$

**Figure 2:** Relationships between stress and time or no. of cycles.

These parameters significantly affect the fatigue behaviours of the materials. This is for example, increasing in the maximum stress as well as mean stress and stress range leads to more severe fatigue conditions. If the maximum and minimum stresses are tensile, they are considered to be more dangerous than compressive stresses as the tensile stresses will open up the fatigue crack. Furthermore, if the maximum and minimum stresses are in similar amounts but having the opposite signs (tensile and compressive stresses), the stresses in this case is called completely reversed cyclic stresses in which the stress ratio equals -1. For instance, a rotating-beam fatigue machine as shown in figure 3, fitted with a fatigue specimen hung by a weight in the middle. Specimen rotating action is driven by a motor on the right results in tensile stress in the lower fibrous and compressive stress in the upper fibrous of the specimen gauge length. Therefore, along the gauge length, specimen will be subjected to alternating tensile and compressive stresses similar to the reversed cyclic loading. The specimen will be fatigue loaded until failure. The number of cycles to failure according to the cyclic stress applied will then be recorded.
Figure 3: Rotating-beam fatigue testing machine [2].

The fatigue testing can also be conducted using an instrument as shown in figure 4. The fatigue specimen is gripped on to a motor at one end to provide the rotational motion whereas the other end is attached to a bearing and also subjected to a load or stress. When the specimen is rotated about the longitudinal axis, the upper and the lower parts of the specimen gauge length are subjected to tensile and compressive stresses respectively. Therefore, stress varies sinusoidally at any point on the specimen surface. The test proceeds until specimen failure takes place. The revolution counter is used to obtain the number of cycles to failures corresponding to the stress applied.

Figure 4: Fatigue testing machine [3].

Increasing of the weight applied to the fatigue specimen results in a reduction in number of cycles to failure. We can then use the experimental results to construct an S-N curve as illustrated in figure 5. The fatigue test is normally conducted using at least 8-12 specimens in order to provide sufficient information for the interpretation of fatigue behaviour of the tested material. The S-N curve shows a relationship between the applied stress and the number of cycles to failure, which can be used to determine the fatigue life of the material subjected to cyclic loading. High applied cyclic stress results in a low number of cycles to failure. For example, the fatigue testing of a 1047 steel provides a small number of cycles to failure at a high cyclic stress. As the cyclic stress reduces, the number of
cycles to failure increases. At the fatigue endurance limit, there will be a certain value of the cyclic stress where specimen failure will not occur. This cyclic stress level is called the fatigue strength. According to figure 4, the fatigue strength of 1047 steel is approximately 320 MPa. However, nonferrous alloys such as some alloys of aluminium, magnesium and copper will not normally show the fatigue endurance limit. The slope can be found gradually downwards with increasing number of cycles to failure and shows no horizontal line. In such a case, the fatigue strength will be defined at a stress level where the number of cycles to failure reaches $10^7$ or $10^8$ cycles.

The fatigue strength of engineering materials is in general lower than their tensile strength. A ratio of the fatigue strength to the tensile strength as described in equation 1 is called the fatigue ratio. It is normally observed that, in the case of steels, the fatigue strength increases in proportional to the tensile stress. Therefore, improving the tensile strength by hardening or other heat treatments normally increases the fatigue strength of the material. However for nonferrous metals such as aluminium alloys, the fatigue ratio is found approximately 0.3 and the improvement of the tensile strength do not necessary increases the fatigue strength of the material.

\[
\text{Fatigue ratio} = \frac{\text{Fatigue strength}}{\text{Tensile strength}} \quad \ldots (1)
\]

\[\text{Figure 5: } S-N \text{ curves of 1047 steel and 2014-T6 aluminium alloy[2].}\]
The fatigue S-N curve are generally considered in 2 cases, which are high cycle fatigue and low cycle fatigue. The study of high cycle fatigue concerns about fatigue behaviour of the materials which is controlled by the applied load or stress and where the gross deformation taking place is elastic. However highly localized plastic deformation can also be observed for example at the crack tip. The number of cycles to failure in this case is normally determined at higher than $10^5$ cycles. The S-N curve in the high cycle fatigue region can be expressed using the Basquin equation as follow;

$$ N\sigma_a^p = C$$  \quad \text{...(2)}

where $\sigma_a$ is Stress amplitude $p$ and $C$ is Empirical constants

In the case of low cycle fatigue, the fatigue behaviour is controlled by elastic and plastic strains and the number of cycles leading to failure is lower than $10^3$ or $10^4$ cycles. Gross plastic deformation is due to high levels of the applied stresses and leads to difficulties for stress interpretation. The low cycle fatigue data is generally presented as a relationship between plastic strain ($\Delta \varepsilon_p$) and the number of cycles to failure ($N$) as illustrated in figure 6. When plotted in a log-log scale, the relationship can be expressed following the Coffin-Manson relationship

$$ \frac{\Delta \varepsilon_p}{2} = \varepsilon_f (2N)^C$$  \quad \text{...(3)}

where $\Delta \varepsilon_p/2$ is Plastic strain amplitude $\varepsilon_f$ is Fatigue ductility coefficient $2N$ is Strain reversal to failure, whereby 1 cycle equals 2 reversals $C$ is Fatigue ductility exponent, having the values ranging from -0.5 to -0.7.
Materials respond differently to static and cyclic loading as illustrated from stress-strain relationship. If we first consider figure 7 (a), which shows the stress-strain loop under controlled strain (at constant strain amplitude), the stress-strain relation follows the OAB line when subjected to tensile loading passing the yield point. On unloading, the stress-strain relation follows BC line and goes into the compressive region having a negative strain. It is noticed that the compressive yield is somewhat smaller than that obtained from the tensile yielding. This phenomenon is called the Baushinger effect. Reloading results in a hysteresis loop and gives a total strain \( \Delta \varepsilon = \Delta \varepsilon_e + \Delta \varepsilon_p \) where \( \Delta \varepsilon_e \) is the elastic strain range and \( \Delta \varepsilon_p \) is the plastic strain range as shown in figure 7 (a).

Furthermore, plastic deformation taking place during cyclic loading causes microstructural changes such as structure and density of dislocations. Therefore, after every cycle applied, the material responses slightly differently to the cyclic loading. The material will experience either cyclic hardening or cyclic softening, and both change the shape of the hysteresis loop as illustrated in figure 8. The hysteresis loop generally stabilizes after being cyclic loaded about 100 cycles. Figure 7 (b) demonstrates how materials response differently to static loading and cyclic loading. The former shows a monotonous \( \sigma-\varepsilon \) curve whereas the latter provides a cyclic \( \sigma-\varepsilon \) curve. This cyclic \( \sigma-\varepsilon \) curve is constructed by connecting the tip of the stabilized hysteresis loops obtained from a number of fatigue tests at different controlled strain amplitude. Moreover, the cyclic \( \sigma-\varepsilon \) curve can also be expressed in a power curve analogy to that obtained from static loading as shown in equation 4.

**Figure 6:** Low cycle fatigue curve (\( \Delta \varepsilon_p \) vs \( N \)) for 347 stainless steel [1].

### 1.3 Cyclic stress-strain curve
\[ \Delta \sigma = K' (\Delta \varepsilon_p)^{n'} \] ... (4)

where \( n' \) is the cyclic strain hardening exponent

\( K' \) is the cyclic strength coefficient

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**Figure 7:** a) Stress-strain loop for constant strain cycling and b) comparison of monotonic and cyclic stress-strain curve for a cyclic hardening material[1].

**Figure 8:** Responses of metals to cyclic strain cycles[1].
1.4 Characteristics of fatigue surfaces

Fatigue surfaces normally show no gross plastic deformation and exhibit relatively flat fracture surfaces as shown previously in figure 1 (a). The so called beach mark pattern is often well recognized on the fatigue surfaces on the macroscopic scale. However, if we examine the fatigue fracture surface using a high magnification scanning electron microscope (SEM), we can notice a number of minute striations as depicted in figure 9. These striations are normally observed in the stable fatigue crack growth region. Some metals might not show evident traces of these striations.

![Figure 9: Fatigue surface examined using a scanning electron microscope, showing the fatigue striations.](image)

The striations in the stable fatigue crack propagation are found to be related to the fatigue cycles applied. The occurrence of these striations is due to the plastic blunting process as illustrated in figure 10. If we consider the cross section of the fatigue crack, we will find that the crack is closed at the initial stage or when the minimum stress is applied. During the load increment, the fatigue crack will open according to the amount of the load applied. During crack opening, slips occur in the vicinity of both ends of the crack tips as seen from the arrows. This results in plastic deformation around the fatigue crack tip. When the load reaches the maximum values, plastic blunting process takes place, yielding the maximum crack opening distance as seen at stage 3 from figure 10. After unloading, crack closing takes place and the reversed slips now occur at the crack tips. Finally, the fatigue crack goes back to the initial stage of crack closer but with an increment of one striation as noticed from fatigue crack in stages 1 and 5 respectively.
1.5 Factors influencing fatigue properties of materials

As mentioned previously, characteristics of the applied stresses such as maximum stress, mean stress and stress ratio significantly affects the fatigue behavior of the materials. However, there are a range of factors which are also found to significantly influence the fatigue properties of engineering materials. These are for example, stress concentration, size effect, surface effect, combined stresses, cumulative fatigue and sequence effect, metallurgical variables, corrosion and temperature. Generally, the fatigue crack initiations are observed near the surface. Rough surfaces are therefore undesirable due to stress concentration which accounts for further fatigue crack propagation and eventually lead to global failure. Corrosive environment and high service temperatures are reckoned to have negative effects on fatigue properties of the materials as they accelerate faster rates of both fatigue initiation and propagation.
Figure 11: Fatigue testing machine in the laboratory [4].

Figure 12: Fatigue specimen [4].
2. Materials and equipment

2.1 Fatigue specimens

2.2 Micrometer or vernier caliper

2.3 Permanent pen

2.4 Fatigue testing machine

3. Experimental Procedure

3.1 Measure dimensions of brass and steel specimens provided and record in tables 1 and 2. If the distance from the load end to the minimum diameter of the specimen is 125.7 mm, the bending stress, $\sigma$, can be calculated the bending stress for a load $P$ (N) is shown in equation 5

$$\sigma = \frac{125.7P \times 32}{\pi \times D^3}$$

...(5)

3.2 Conduct the fatigue test at room temperature using the fatigue testing machine as shown in figure 11. Fit one end of the specimen to a motor and fit the other end to a bearing hung with a known weight, indicating the stress applied to the specimen. Start the motor to rotate the specimen at a constant speed. The revolution counter is used to record the number of cycles to which the specimen fails. Record the result in table 1 and 2.

3.3 Change the weights used and follow the experiment in 2.2. Again, record the results in tables 1 and 2.

3.4 Construct the S-N curves of the steel specimens.

3.5 Investigate fracture surfaces of broken fatigue specimen and sketch the result in tables 1 and 2.

3.6 Analyze, discuss the obtained results. Give conclusions.
### 4. Results

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<th>Details</th>
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<td>Fracture surfaces</td>
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*Table 1: Fatigue data of steel specimens.*
Figure 13: S-N curve of steel specimens.
5. Discussion
6. Conclusions
7. Questions

7.1 Explain the fatigue endurance limit. What is the obtained fatigue strength in steels?

7.2 Predict the fatigue strength of aluminium. Give reasons.
7.3 Explain the differences between fatigue failure and cleavage fracture.

8. References


