Apparent Effects of Geometry on Fatigue and Strength Behavior of Aluminum and Steel

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Key Words: notch effects, stress concentration factor, fatigue, fracture, strength, fatigue life, life prediction.

Prerequisite Knowledge: basic knowledge on strength of materials, stress analysis, deflection of cantilever beams.

Objective: to understand that the strength and fatigue behaviour of metallic components is influenced by their geometry. To determine the differences in fatigue behavior of components with geometric discontinuities.

Equipment and Materials:

Equipment

1. A universal tensile testing machine, Instron.
2. A rotating-bending fatigue machine powered by an AC motor*.
3. Separate sets of metal fatigue samples with a 90 mm radius, a semi-angle 36° notch, and a set of parallel-sided tensile samples.
4. A measuring device to determine the number of cycles to failure of the metal samples.

*The fatigue machine design is based on that developed by R R Moore and uses the cantilever bending rotating beam principle (Collins 1993; Instron 2002). The specimen functions as a simple cantilever beam loaded at one end. When the specimen is rotated one half cycle, the stresses in the metal just below the neutral axis are reversed from tension to compression and vice versa. At the end of one revolution the stresses are once more reversed so that during one revolution the test specimen goes through a complete cycle of flexural stresses. The machine accepts parallel circular shaped specimens which are locked into a jaw chuck within a set of collets, the spacing between clamped ends is 62mm. Stress is applied to the specimen at free end by applying a deflection to the end of the beam not attached to the motor. The machine operates at a speed of 1380rpm. At the nominal rate of 1380rpm the machine is capable of 82,800 cycles per hour. A pulley is attached to the end of the specimen which is then attached by a belt to the counter. The mechanical digital counter provides an accurate indication of the number of cycles attained by each specimen. When the sample fails, the counter stops. At no stage are stress calculations required. Observation of the effect of end deflection is an indicator of the relative stress loading.
Materials:
There are 3 samples of either aluminum or steel, with one of the geometries given in Table 1. A total of 6 samples for fatigue testing. A further 3 samples of parallel-sided tensile samples of aluminum or steel are also provided [Figure 3]. Due to time restrictions, only one type of metal is tested. Results for the other type of metal are collected from other experiments and distributed to the student groups. At the end of the semester all the results for all the test samples are collected and a statistical analysis of the data is performed.

Table 1. Typical geometries of fatigue and tensile test specimens.

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>36 semi-angle° notch</td>
<td>36 semi-angle° notch</td>
</tr>
<tr>
<td>(b)</td>
<td>90 mm radius</td>
<td>90 mm radius</td>
</tr>
<tr>
<td>(c)</td>
<td>Parallel sided</td>
<td>Parallel sided</td>
</tr>
</tbody>
</table>

Introduction:
By far, the majority of mechanical failures happen from fatigue. According to independent studies by Battelle in 1982, between 80-90% of all structural failures occur through a fatigue mechanism (Halfpenny). Fatigue may be defined as failure under a repeated or otherwise varying load which never reaches a level sufficient to cause failure in a single application. An understanding of the effects of fatigue is critical to the design of devices and structures subjected to cyclic loading. Failure can result in fracture, customer dissatisfaction, financial losses, or endangerment.

A stress concentration is a physical or metallurgical condition that increases the local stress in the part by some factor. Geometric discontinuities which are unavoidable in design, such as holes, fillets, groove and keyways, cause the stress to be locally elevated and so are called stress raisers or notches (Dowling 1999). Their presence may reduce the resistance of a metal component to fatigue failure. A good example is the shaft with a keyway. The stress in the area of the corner of the keyway varies depending on the size of the corner radius. A small radius can increase the stress dramatically. This may simply be a consequence of the locally higher stresses, causing fatigue failure cracks to initiate and propagate at such locations. Stress concentrations, indicated by the symbol Kt, can be caused by changes in metallurgy, internal defects, or changes in shape. The resultant values depends on both the type of stress, i.e., bending, torsion, etc., and the general shape of the part. Stress concentrations have a great effect on crack initiation because of their effect on increasing the local stress. The crack can start solely as the effect of the operating loads or it can be multiplied by the stress concentration factor (Hyler, Lewis and Grover 1954).

In many engineering applications a shaft is a metal bar usually cylindrical in shape and solid, but sometimes hollow, that is used to support rotating components or to transmit
power or motion by rotary or axial movement. Shafts may be subjected to a variety of loads in general, tension, torsion, compression, bending or a combination of these.

When smooth specimens of metal shafts are fatigue tested at a range of stress levels a variation in fatigue life (stress at failure) is found (Dowling 1999; Callister 2001), resulting in the common S-N curves. When tested in tension the result is one value which is indicative of the material strength. Aluminum and steel display such a range of fatigue lives and tensile strengths. Moreover, due to the effect of different stress concentrators, there may also be a distinct difference in fatigue life and tensile strength of these metals. In applications involving relatively low stresses applied for large numbers of cycles design against fatigue may require only that the fatigue strength at long lives of the order $10^6$ to $10^8$ cycles be known. Rotating-bending fatigue tests are often used for these calculations.

Many modification factors may be incorporated into the analysis of fatigue life (Callister 2001). A quantifiable effect is that of the presence of a notch. If a notch is present, the fatigue life is reduced by a fatigue notch factor $k_f$ which may be simply defined by the ratio of fatigue strength of the metal component with the notch, divided by the fatigue strength of the metal component without the notch (Dieter 2000). The S-N type fatigue behaviour may often not be seen for these samples with a notch, or the fatigue life may be dramatically reduced (Hyler, Lewis and Grover 1954). The mathematical applications of the effect of stress concentration factors can become quite complex and has been detailed in a number of extensive publications (Neuber 1946). These applications and approaches are not investigated in this exercise. They are left as a major exercise in the junior year of the course for mechanical engineers.

Normally, long life fatigue testing is performed in rotating bending or cantilever bending where a stress gradient is imposed on the material (Collins 1993) (Instron 2002). However, the effect of notches and geometrical changes on the tensile and fatigue strength and life of metal components can be illustrated by simple experiments which do not require an understanding of the mathematics of notches. The experiments are phenomenological in that the results illustrate the outcome of rotating bending fatigue conditions on metal samples with varying loading and geometric conditions.

In these experiments a selection of either steel or aluminum test pieces which contain either a severe stress concentrator, semi-angle semi-angle $36°$ notch, or a mild stress concentrator in the form of a 90 mm radius groove (essentially a specimen without a notch) are tested in both a rotating-bending fatigue mode, and tensile mode. In addition, all the sample geometries together with standard test pieces are tested in a Universal tensile testing machine, to illustrate the effect of stress concentrators on the tensile strength of metals.

The fatigue equipment used in this experiment is a typical bending-fatigue rig that is applying a constant load to one end of a rotating shaft causing a cyclic tensile and compressive stress to operate [Figures 1a, 1b and 1c]. An indication of the loads applied as the deflection is increased is given in Figures 2a, 2b, 2c, and 2d. This data was obtained from simulation modeling using Mathematica®.
Procedure:

**Tensile testing (Figure 4)**
1. Measure the minimum diameter of each sample
2. Use the Instron Universal tensile testing machine on the 20 kN range.
   - Run the chart at 2 cm per minute to obtain graphs for each test.
3. Tensile test THREE samples of each of test specimens [Figure 4].
4. Record and calculate the tensile strength, and the fracture strength, including the mean value and standard deviation.
   - in either Table 2 or 3 as appropriate for your specimens

**Fatigue Testing (Figure 1a, 1b, and 1c)**
1. Conduct fatigue test at four deflections,
   - i.e., 1, 1.25, 1.54 and 175 mm
   - each representing a different loading condition.
   - The value of the loading condition is not required.
   - An indication of the load applied to the specimens is shown in the graphs of Figure 1a, 1b, 1c, and 1d.
2. Fatigue test THREE samples at each deflection.
3. Refer to Figure 4 for a view of the experimental equipment.
4. Raise the bearing moulding until the dial gauge just stops turning
   - Place the test piece in the chuck and tighten the chuck with the tools provided.
   - It is absolutely vital at this point that the bearing centre and the chuck are at the same height and collinear otherwise the act of tightening the chuck will bend the specimen before the test load is applied.
5. Simultaneously turn the chuck by hand and lower the bearing housing. Continue until the bearings just begin to rotate and have just touched the test piece.
6. Set zero on the dial gauge.
7. Continue lowering the bearing housing until the pre-determined deflection is shown on the dial gauge.
8. Fasten a pulley onto the test piece. Make sure that the groove of the pulley is in the same vertical plane as the groove of the pulley on the counter.
9. Set the counter to read zero.
10. Install a rubber band as a belt between the pulleys.
11. Switch the motor on.
12. Record in the table provided, the number of revolutions to failure at each deflection
   - in either Table 2 or 3 below. The loads at each deflection have been previously measured and are inserted in the tables. If a fatigue specimen remains unbroken after 25000 cycles, remove it and record the number of cycles as >25000

**Comments:**

The overall fatigue results should show a decrease in the number of cycles to failure as the applied load (deformation) is increased. Since only four deflections are used, a curve of ‘best fit’ is drawn through the data. The curve indeed does show that there is a decrease in fatigue life as the applied stress increases. This situation occurs for both the 90 mm radius
samples and the semi-angle 36° notch samples. When the effect of severity of notch is compared, the semi-angle 36° notch samples have a marked decrease in fatigue life when compared with the 90 mm radius samples.

Shown in Figure 5 are the failed steel tensile samples. All samples appeared to fail in a ductile manner. A similar result occurred for the aluminum tensile samples. When comparing results from the tensile test, it is again seen that the semi-angle 36° notch samples fail at a higher stress than the other samples. The local stress at the root of the notch is higher than the ‘far field’ stress for either the 90 mm radius samples or the standard parallel-sided samples.

This phenomenological approach is implemented for the conduct of these experiments for freshman students of engineering. Over half the cohort is comprised of electrical engineering/computer science students and only require a basic knowledge of fatigue behavior. The remainder of the cohort is comprised of civil and mechanical and biotechnology engineering students – they will have the principles of fatigue behavior elaborated upon in later years. At this stage it is sufficient that they also have a basic understanding of the effect of various stress concentrators on the fatigue behavior of metals.

Typical Results:

A set of typical results for the tensile testing of specimens is given in the last row of results from Tables 2 and 3. Here it is seen that the effect of stress concentrators is to modify the load at which the various specimens fail. Before the fatigue tests take place, a class discussion ensues as to the effect of the stress concentrators and various loads on the final life of the specimens. The students then undertake the experiment.

Bibliography

Fig. 1a. Typical arrangement of the bend rotating fatigue rig with a fatigue sample eg with semi-angle 36° notch test pieces of steel.

Fig. 1b. Typical arrangement of the bend rotating fatigue rig with three fatigue samples running at once.
### Table 2: 90 mm radius test pieces of Aluminum and Steel (average of 30 tests) *

<table>
<thead>
<tr>
<th>DEFORMATION</th>
<th>STEEL</th>
<th>ALUMINUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (newton)</td>
<td>Number of Cycles</td>
</tr>
<tr>
<td>1.00 mm</td>
<td>32</td>
<td>&gt;25000</td>
</tr>
<tr>
<td>1.25 mm</td>
<td>38</td>
<td>10454</td>
</tr>
<tr>
<td>1.50 mm</td>
<td>48</td>
<td>3763</td>
</tr>
<tr>
<td>1.75 mm</td>
<td>55</td>
<td>770</td>
</tr>
<tr>
<td>Stress at offset yield of 90 mm radius test pieces</td>
<td>659 MPa</td>
<td>212 MPa</td>
</tr>
<tr>
<td>Stress at offset yield of parallel sided tensile samples</td>
<td>523 MPa</td>
<td>332 MPa</td>
</tr>
</tbody>
</table>

### Table 3: Semi-angle 36° notch test pieces of Aluminum and Steel (average of 30 tests) *

<table>
<thead>
<tr>
<th>DEFORMATION</th>
<th>STEEL</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Force (newton)</td>
<td>Number of Cycles</td>
</tr>
<tr>
<td>1.00 mm</td>
<td>248</td>
<td>1002</td>
</tr>
<tr>
<td>1.25 mm</td>
<td>310</td>
<td>535</td>
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<tr>
<td>1.50 mm</td>
<td>420</td>
<td>238</td>
</tr>
<tr>
<td>1.75 mm</td>
<td>490</td>
<td>46</td>
</tr>
<tr>
<td>Stress at offset yield of semi-angle 36° notch samples</td>
<td>1178 MPa</td>
<td>422 MPa</td>
</tr>
<tr>
<td>Stress at offset yield of parallel sided tensile samples</td>
<td>523 MPa</td>
<td>332 MPa</td>
</tr>
</tbody>
</table>
Fig. 1c. Front view of the bending-rotating fatigue showing the dial indicator employed to establish a deflection of the cantilever beam.

Figure 2a. Deflection Force (Newton) Vs Deflection (metre) for Steel: 90 mm radius test pieces. (data obtained from simulation modeling using Mathematica©)
Figure 2b. Deflection Force (Newton) Vs Deflection (metre) for Aluminum: 90 mm radius test pieces. (data obtained from simulation modeling using Mathematica©)

Figure 2c. Deflection Force (Newton) Vs Deflection (metre) for Steel: semi-angle 36° notch test pieces. (data obtained from simulation modeling using Mathematica©)
Figure 4. Sample in the tensile testing machine [Instron]

Figure 5. Example of failed specimens; (a) semi-angle 36° notch, (b) 90 mm radius, and (c) parallel sided tensile sample.
Figure 2d. Deflection Force (Newton) Vs Deflection (metre) for Aluminum: semi-angle 36° notch test pieces. (data obtained from simulation modeling using Mathematica®)

Fig. 3. Layout of the fatigue and tensile sample (refer to Table 1)