FATIGUE TESTING

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Introduction:

There are many aspects to consider when designing an engineering device such as a hip implant or any device that must withstand long periods of use without failure. When selecting a material for a medical implant it is important to know how long it can last under the the expected loads. The implant will be used constantly throughout every day of the patient's life, and must endure many loading and unloading cycles. After many cycles the implant can fail by means of fatigue damage. It is important to use testing to determine how many cycles can be expected out of each device. To do this we must perform fatigue testing.

Fatigue damage is cumulative and can occur at levels of stress below the yield stress. Fatigue happens in three stages: crack initiation, where microcracks form due to stress raisers or defects, crack growth, where the crack is propagating through the material, and fracture, which is failure. When adding the periods for each stage together we get a result that is called fatigue life. Data from fatigue testing is often displayed on a S-N diagram. This is a chart that displays the stress amplitude vs the number of cycles to failure. The S-N plot is used for cases where the the stress remains in the elastic limit and the number of cycles to failure is large. Using the data, we can determine the endurance limit, which is the stress amplitude that can be used for infinite fatigue life.

For this lab, we used fatigue testing to measure the stress controlled fatigue for 1045 notched steel samples under different loads. We will compare the fatigue life of specimens that have a notch with different stresses applied to it. The stress near the notched portion is greatly increased therefore changing the life of the specimen, so is important that we understand how significant notch size can impact the life of a material. Finally, this lab will compare our experimental results with our theoretical S-N curves with and without notches.

Theory:

Fatigue is a process dominated by cyclic plastic deformation, meaning failure occurs at stress and strain levels below the yield stress. Fatigue failure is composed of 3 distinct stages, the first of which is crack initiation. In this stage, microcracks develop in areas with defects such as notches, or other geometric irregularities. The next stage is crack growth, which consists of cracks propagating through different areas of the material this continues until the point of fracture. Fracture is a relatively short stage and is caused by failure from a dominant crack in the material [1]. Since the fracture region is so short, we can characterize the cycle life with Equation 1. Where N_f is the number of cycles to fracture, N_g is the number of cycles in the crack growth stage and N_i is the number of cycles in the crack initiation stage.For brittle material, N_f is approximately equal to N_i ,but for ductile materials, N_f is approximately equal to N_g.

$$N_f = N_i + N_g \tag{1}$$

In studying fatigue failure, there are 3 approaches that can be used: stress-based, strain-based, and fracture mechanics. The stress and strain approaches are termed as macroscopic due to N_f relating to a "global" driving force. Conversely, the fracture mechanics method uses a local driving force to find N_f. In this lab we analyze our samples with the stress-based method and the rest of the section will be dedicated to this method.

To understand the cycles required to reach failure we use a semi-log stress-life plot known as an S-N plot (Figure 1.) This plotting method is only used when the stress applied is within the material's elastic range which allows for a higher number of cycles to failure ($N_f>10^3$). Figure 1 shows two distinct regions in the the S-N curve: the finite fatigue life ($10^3<N_f<10^6$) and infinite fatigue life ($10^6<N_f$) region. In the finite region, the relationship of stress and cycles is given by Equation 2 where A and b are fatigue parameters intrinsic of the material, found by Equations 3 and 4 [1].

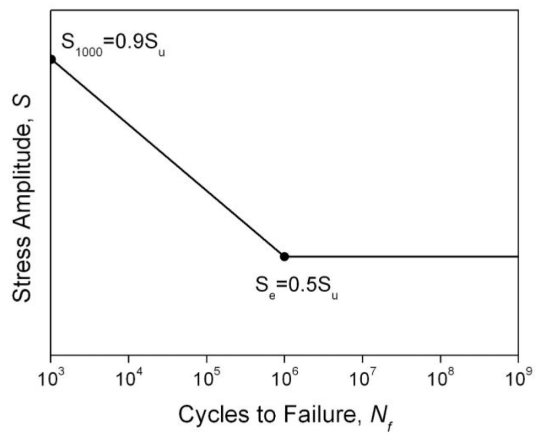


Figure 1: Schematic of stress-life (S-N) curve

$$S = AN_f^{\,b} \tag{2}$$

$$A = \frac{S_e}{(10^6)^{\,b}} \quad b = \frac{log(S_e)-log(S_f)}{log(10^6)-log(10^3)} \qquad (3), (4)$$

$$S_e = 0.5S_{uts} \ @\ 10^6\ cycles\,, S_f = .9S_{uts}@10^3\ cycles \qquad (5), (6)$$

A theoretical S-N curve can be found using Equations 5 and 6, where S_e is the endurance limit, S_{uts} is the ultimate tensile strength, and S_f is finite limit. We will also examine the the fracture cross-sections of our samples for each trial. Fatigue failures are preceded by nucleation on the surface of the material. So on our samples we expect to see things such as surface scratches, dents or threads [2]. Because our sample was notched, our analysis requires us to use Equation 7 which is the fatigue intensity factor for a notch. Here, q is the notch sensitivity and K_t is the stress concentration factor of the notch. In this experiment to complete our plot we also need the stress amplitude maximum found using Equation 8.

$$K_f = 1 + q(K_t - 1)\ ,\sigma = \frac{16WL}{\pi D^3 K_f} \qquad (7), (8)$$

Experimental Procedure:

In this lab, four samples of notched AISI 1045 steel were used, to control the fracture location during trials. The testing equipment used an INSTRON R. R. Moore apparatus as shown in Figure B.3. The machine provides high-speed rotation to the sample and includes a revolution counter attached to the controller of the machine for counting the number of cycles undergone before the sample fractured.

We started this lab by measuring the minimum diameter of the samples, which was used to calculate the maximum stress in the sample. Next, we carefully loaded the sample into the machine ensuring that the sample was not inadvertently bent during loading. The rotation speed of the INSTRON apparatus was set to 6000 rpm for each trial. Various weights were then loaded onto the loading harness and weight pan assemblies. Tests 1-4 were loaded to 10 lbs, 11 lbs, 12.5 lbs, and 14 lbs, respectively. For the first trial, the counter was reset immediately after we turned on the motor because the minimum weight was the weight of weight pan. However, for the second, third, and fourth trials, the counter was reset when the additional weight was gently loaded to the weight pan. Finally, we recorded the number of cycles and removed the fractured sample from the machine slowly to prevent additional damage to the fractured surface. A picture of each fractured surface sample was then taken under a microscope to compare the surfaces for different loads.

Results:

The plots of each S-N fatigue curve was found by curve fitting data points into the form $S = AN_f^b$. Figures 2 and 3 show theoretical S-N curves with and without the notch shown in Figure B1 taken into consideration. The notch was taken into consideration by finding q and K_t, from extrapolation of Figure B2. The fatigue intensity factor, K_f, was then found using Equation 7, where q = 0.77 and $k_t = 1.42$. Each equation that describe the S-N curves with and without the notch are given by: $S = 164.4N_f^{-0.08509}$ and $S = 217.6N_f^{-0.1257}$ respectively.

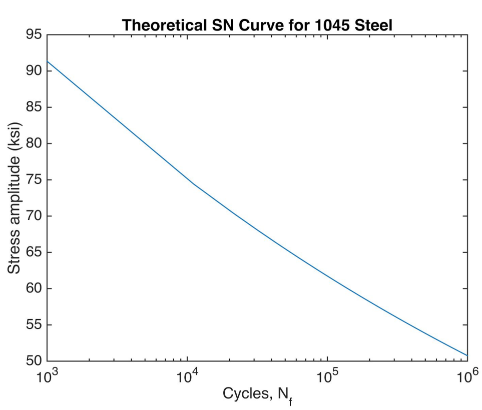


Figure 2: Theoretical SN curve for 1045 steel

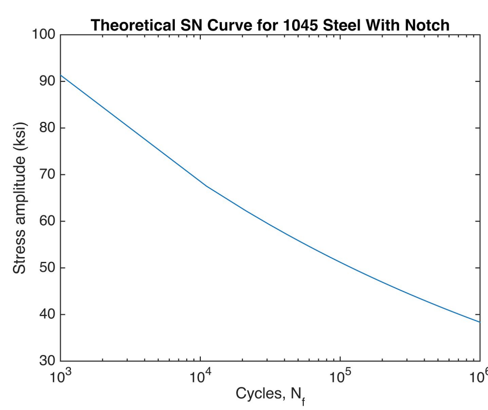


Figure 3: Modified SN curve for 1045 steel

The experimental S-N curve for 1045 steel was found by curve fitting our four data points into the form given in Equation 2. The equation for the experimental data is given by:

$$S = 372.6 N_f^{-0.1862} \tag{9}$$

Finally, the stress amplitudes were calculated using Equation 8. Table 1 shows a summary of our results showing specifically that our calculated fatigue life is slightly higher than the experimental values, but are still within reason (about a 50% error difference).

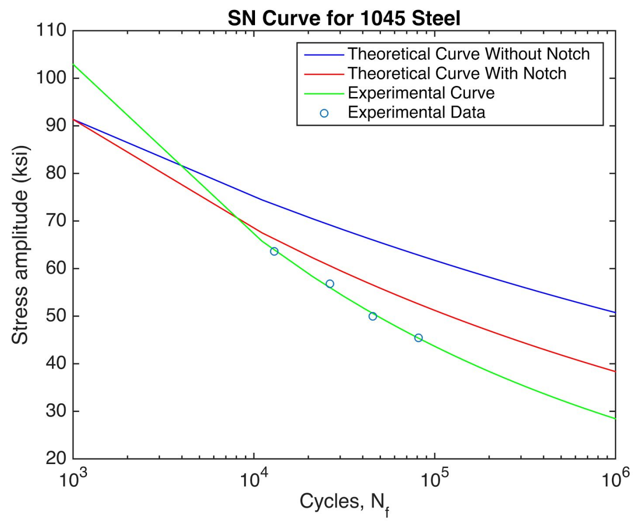


Figure 4: Fatigue life for AISI 1045 steel

Test #	Load (lbs)	Moment arm L (in.)	Specimen minimum diameter D (in.)	Stress amplitude (ksi)	Fatigue Life N_f (cycles)	
					Calculated [Eq. 9)]	Experimental
1	10	3.75	0.147	45.43	259000	81425
2	11	3.75	0.147	49.97	121000	45486
3	12.5	3.75	0.147	56.79	43900	26310
4	14	3.75	0.147	63.60	17800	12950

Table 1: Experimental and calculated results of fatigue life under different loads

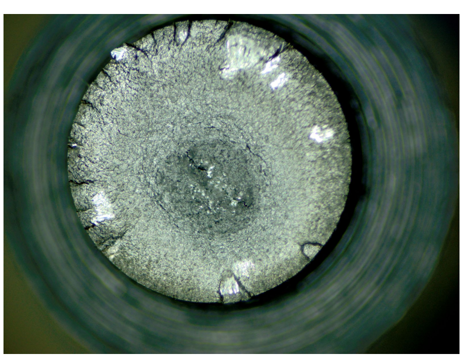


Figure 5: Cross section of test 1 specimen

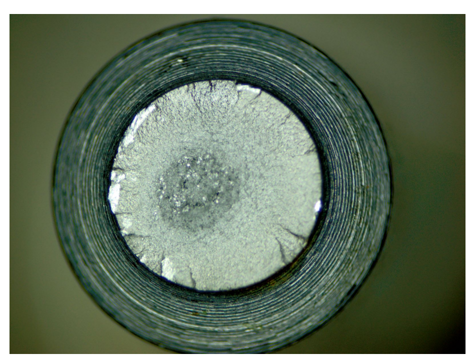


Figure 6: Cross section of test 2 specimen

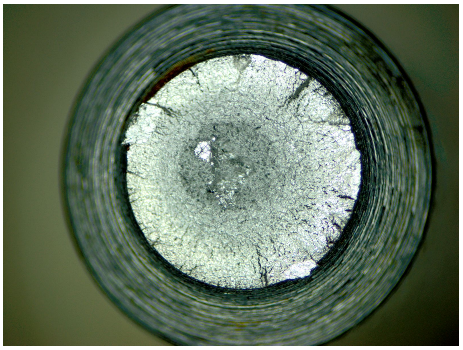


Figure 7: Cross section of test 3 specimen

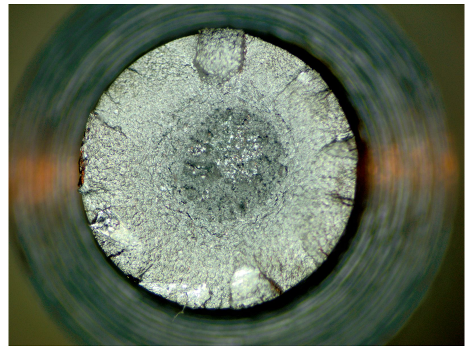


Figure 8: Cross section of test 4 specimen

Pictures of the cross section of each test is shown in Figures 5 through 8. The photographs verify what we expected to see: dents, scratches, and thread. We also see that as the load increases, the crack length increases accordingly.

Discussion:

In this investigation, as we increased the stress applied to the specimen, we observed a corresponding decrease in N_f. This due to the fact that during cyclic loading, increasing the magnitude of applied load increases the amount of plastic energy stored in a sample (as we discovered in our previous investigation). Therefore, since plastic energy accumulates faster, the sample fractures faster to release the stored energy.

Additionally, samples loaded to higher stress amplitudes had less clean break surfaces than those loaded to lower stress amplitudes. This result is expected and due to the faster crack growth, and possible unstable crack propagation present in these samples, particularly during later stages of crack growth. Because plastic energy accumulates at a higher rate in samples with higher stress amplitudes, cracks also develop and grow at a faster rate to release the built up energy. This results in the uneven fracture surfaces observed in samples loaded to higher stress amplitudes. Also of note is the fact that the fractured samples have rougher breaks near the outside edges than toward the center. This is because stress in samples under torsion is a function of distance from the axis of rotation ($\sigma_{z,\theta} = Tc/J$). Since stress is higher farther from the center of the sample, the stress concentration factor of the sample is also higher at the edges, and thus the fracture toughness is exceeded first. Examples of crack propagation in materials are also apparent in fractured samples in the form of beachmarks and striations. This can manifest as concentric ridges that form away from the point of crack initiation [2]. As these ridges continue, the local stress grows until it passes the yield strength of the material. It is important to note that although this is a sign of fatigue failures, beachmarks and striations are not always apparent in fatigue failures. Finally areas of the fracture surface that experienced a sudden failure have a more grainy and rough surface, which is common with brittle failures.

If we compare our experimental data with the theoretical SN curves for 1045 steel, we find that there are significant deviations because the theoretical SN curve for 1045 steel does not account for the notch present in the middle of our sample. This notch creates a non-uniformity in our sample geometry, and results in higher stress concentration factors near the edges of the notch. This in turn results in a lower number of cycles to failure for a given stress value than what would be expected from theory. If we compare the experimental data to the theoretical curve that has been modified to account for the presence of the notch, we find that this model approximates our data more accurately, and that as expected, the presence of the notch reduces expected life of the sample. Deviations between this theoretical curve and our experimental data can be attributed to the presence of random defects with the sample, or the relatively small size of the experimental data set. Furthermore, as the cycle count increases, the experimental data begins to deviate more from the theoretical curves. This is because the effect of the notch on stress concentration factor and the effect of random defects present in our sample become more pronounced as cycle count increases due to the cumulative accumulation of plastic strain in samples over time.

Our experiment was limited by the fact that we only used four data points to generate our experimental SN curve. Additionally, all points obtained were for stress amplitudes in the range of 45-65 ksi. To obtain more accurate results, we could conduct experiments at more stress amplitudes, over a wider range of stress values. The only source of systematic error in our lab came from varying the person who loaded the sample into the testing apparatus. Random error was present in the form of defects in the sample, or inconsistencies in the machining of the sample.

Conclusion:

In this lab, we found that increasing the stress amplitude during fatigue testing results in a lower number of cycles to failure. Additionally, increasing stress amplitude also results in a rougher fracture surface. Finally, we found that the presence of a notch or other geometric irregularity in the sample will also decrease the number of cycles to failure, due to an increase in stress concentration factor. Overall, this experiment illustrates the importance of stress amplitude and part geometry when trying to project the life of a part.

Appendix A: References

[1] K Komvopoulos, Mechanical Testing of Engineering Materials, 1st edn (University Readers, 2011).

[2] N.E Dowling, Mechanical Behavior of Materials. 4th edition (Pearson,2012)

[3] W. D. Callister, Materials Science and Engineering, an Introduction, 7th edn (John Wiley and Sons, 2007).

Appendix B: Supplemental Figures

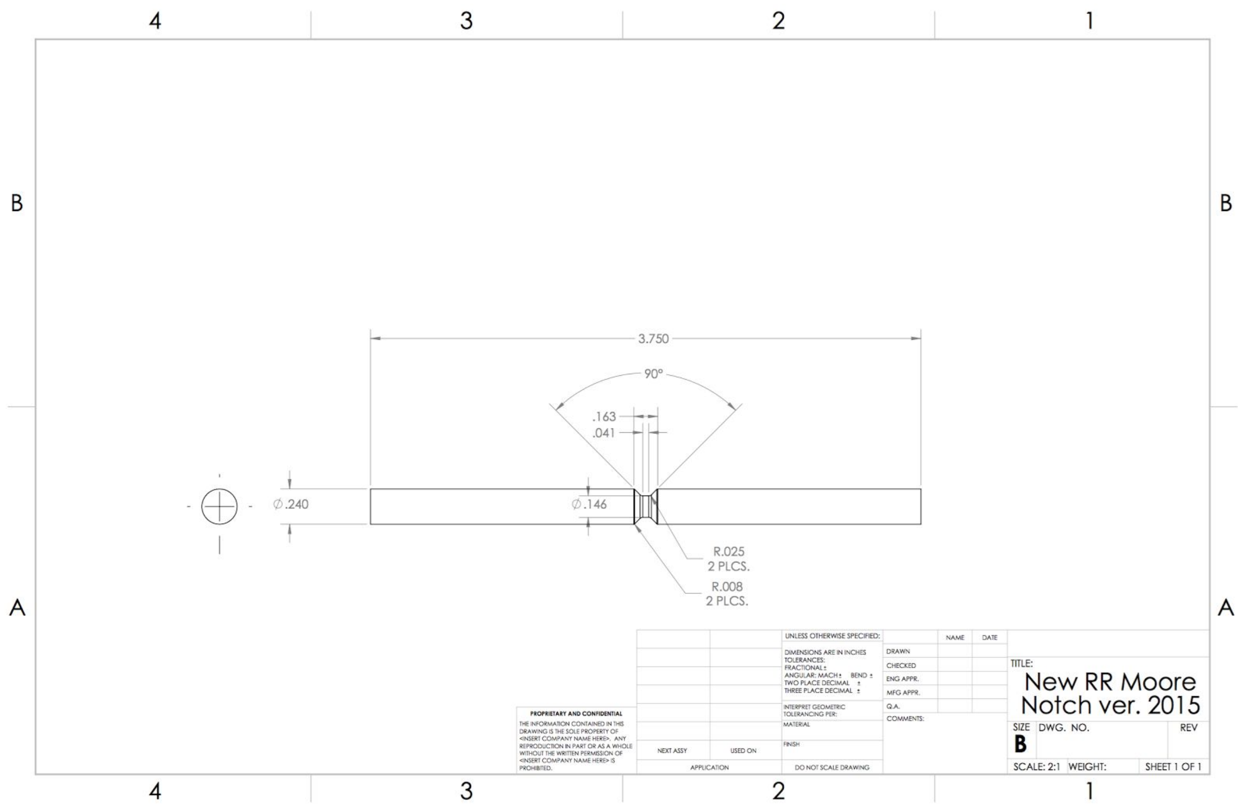
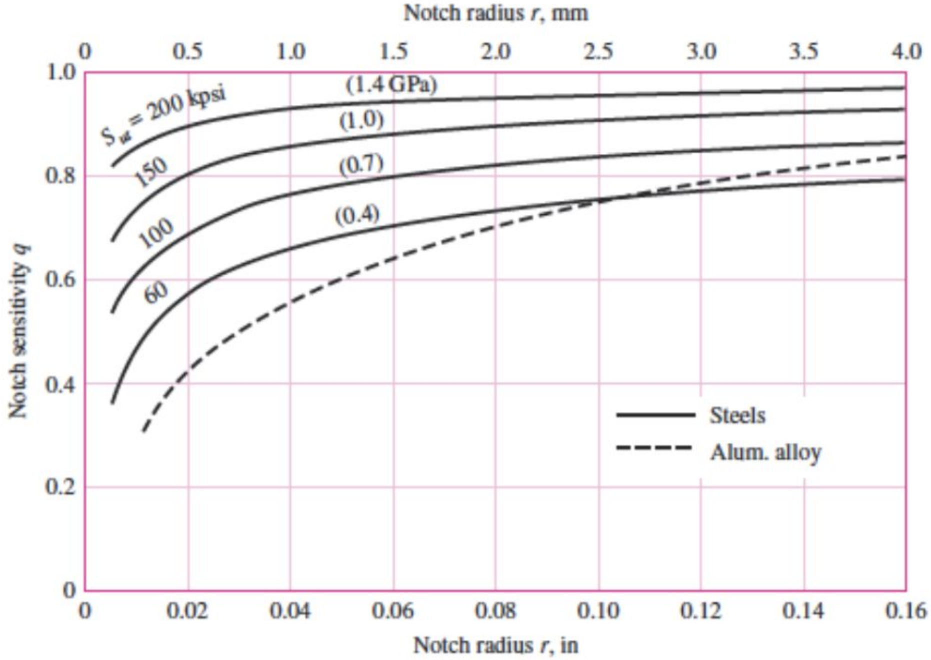


Figure B1: Dimensions of shank specimen for fatigue testing



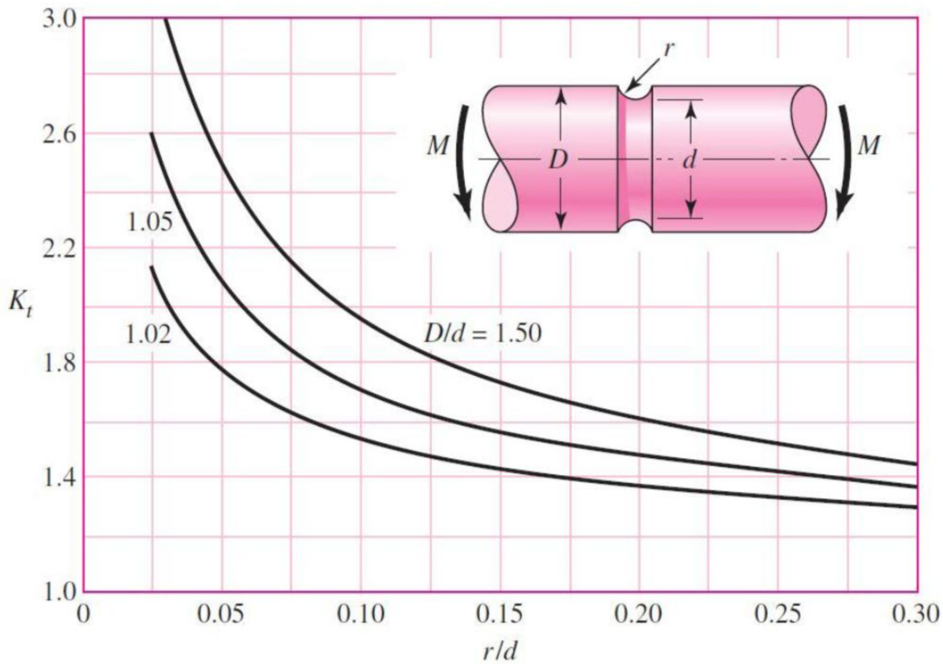


Figure B2: Specimen factors

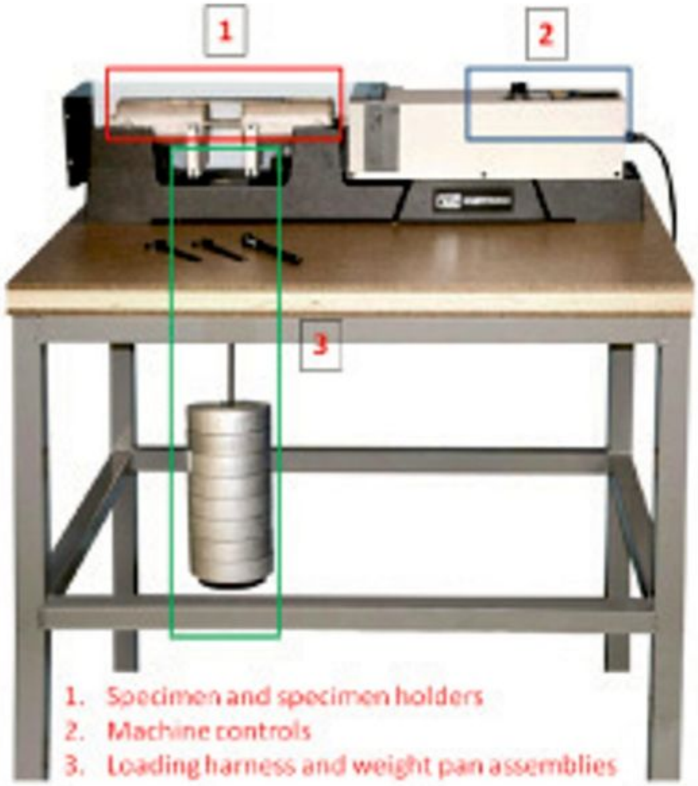


Figure B.3: Instron R.R. Moore apparatus for fatigue testing

Appendix C: MATLAB Code

```
%% Theoretical SN Curve
Suts = 700e6; %Pa
Se = 0.5*Suts; %10^6 cycles [Pa]
Sf = 0.9*Suts; %10^3 cycles [Pa]

b = (log10(Se) - log10(Sf))/(log10(10^6) - log10(10^3));
A = (Se)/((10^6)^b);

Nf = linspace(10^3, 10^6);
sigma_a = A*(Nf).^b;

sigma_a = sigma_a * (1.45e-7); %ksi

semilogx(Nf, sigma_a); hold on;
title('Theoretical SN Curve for 1045 Steel');
xlabel('Cycles, N_f'); ylabel('Stress amplitude (ksi)');

f = fit(Nf', sigma_a', 'power1')
```

```
%% Find constants
r = 0.047; d = 0.146; D = 0.240; %in

r/d;
D/d;

q = 0.77; % from extrapolate
Kt = 1.42; % from curve extrapolate

Kf = 1+q*(Kt - 1);
```

```
%% Theoretical Modified for notch
Se_m = Se/Kf;
b1 = (log10(Se_m)-log10(Sf))/(log10(10^6)-log10(10^3));
A1 = Se_m/((10^6)^b1);
sigma_a_m = A1*Nf.^b1; %Pa
sigma_a_m = sigma_a_m*(1.45e-7); %ksi

f1 = fit(Nf', sigma_a_m', 'power1')

figure
semilogx(Nf, sigma_a_m);
xlim([10^3, 10^6]);
```

```
title('Theoretical SN Curve for 1045 Steel With Notch');
xlabel('Cycles, N_f'); ylabel('Stress amplitude (ksi)');
```

```
%% Experimental Lab Data
L = 3.75; %in
D = 0.147; %in
W = [10, 11, 12.5, 14]; %lbs
cycles = [81425, 45486, 26310, 12950];

S = 16.*W*L./(pi*D^3.*Kf) * 10^-3 %ksi
Nf_theo = (S/f1.a).^(1/f1.b)

f2 = fit(cycles', S', 'power1')
S_exp = f2.a*(Nf).^(f2.b);

figure
plot(f2, cycles, S)
xlabel('Cycles, N_f'); ylabel('Stress amplitude (ksi)');
title('Experimental SN Curve');
```

```
%% Plot all 3 curves for comparison
figure
semilogx(Nf, sigma_a, 'b'); hold on;
semilogx(Nf, sigma_a_m, 'r');
semilogx(Nf, S_exp, 'g');
semilogx(cycles, S, 'o')

xlabel('Cycles, N_f'); ylabel('Stress amplitude (ksi)');
title('SN Curve for 1045 Steel');
legend('Theoretical Curve Without Notch', 'Theoretical Curve With Notch', 'Experimental Curve');
```

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1

I, Sonja Davison, confirm that Darren Kong wrote Theory of the lab report. Sonja Davison

I, Darren Kong, confirm that Jordan Francis wrote Discussion and Conclusion of the lab report. Darren Kong

I, Jordan Francis, confirm that Jinyu Ni wrote Experimental Procedure of the lab report. Jordan Francis

I, Jinyu Ni, confirm that Adolfo Tec wrote Results of the lab report.
Jinyu Ni

I, Adolfo Tec, confirm that Sonja Davison wrote Abstract and introduction of the lab report. Adolfo Tec