DEFORMATION DUE TO CYCLIC LOADING

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ME108: Mechanical Behavior of Materials

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Introduction:

For many materials, their applications involve conditions that are not in a steady state, meaning that the material will not be under a constant load at all times. The material must withstand the microstructural changes that come from being loaded and unloaded multiple times. During loading cycles, small cracks can form due to fatigue and in subsequent cycles these crack can propagate [2]. These microstructural changes can cause catastrophic failures. Cyclic loading tests are important for materials that will experience variable loads. Monotonic loading tests will not give enough information for their applications. One example is the cables used on a suspension bridge: as vehicles pass over and weather conditions change, the amount of stress being applied to each cables is constantly changing. The material used needs to be able to withstand these changes for the life of the bridge.

To figure out if a material will withstand these changes, we must gather information on its mechanical behavior while it is under multiple loading and unloading cycles. This is known as cyclic loading. There are four main responses to cyclic loading. The first is the purely elastic region, which occurs when the load is not enough to pass the yield condition [2]. As the load increases, the response enters the elastic shakedown region. As the strain increases past the elastic shakedown limit of the material, the behavior changes to a state of plastic shakedown. In this region constant plastic strain accumulates with each cycle. During plastic shakedown, the material undergoes a steady state response of cyclic plasticity. The hysteresis loop created by this test represents the energy dissipated in each loading cycle. Once you reach the plastic shakedown limit, the material exhibits a ratcheting response where the sample experiences a continuous accumulation of plastic strain [1].

The purpose of this lab was to see how AISI 1045 steel preformed under a cyclic loading in different controlled environments. For this lab, we performed both strain and load controlled tests with a INSTRON and observed the samples in plastic shakedown and ratcheting. The first round of tests were displacement controlled where we observed the samples in the plastic shakedown region. The next were load controlled, where we observed ratcheting behavior. The results were then analysed for cyclic hardening/softening and energy dissipation.

Theory:

To understand the effects of fatigue on AISI 1045 steel, we analyze its mechanical behaviors under cyclic loading tests. When an elastic-plastic material such as steel is cyclically loaded, its response can result in 4 regions. These are classified as purely elastic, elastic shakedown, plastic shakedown, and ratcheting. The occurrence of each depends on the amount of stress applied to the sample [1]. The purely elastic region occurs at low stresses at which the yield condition is not satisfied. Once the stress is high enough to cause yielding while also having a purely elastic steady-state response in the continuing cycles, we reach the point of elastic shakedown. The highest load point in this region is known as the elastic shakedown limit; past this point we move into the region of plastic shakedown. In the plastic shakedown region, we begin to experience plastic deformation. At this point, the steel experiences cyclic plasticity that occurs until the load passes the plastic shakedown limit. When applying a load past this point, the cyclic loading causes increasing unidirectional plastic strain on the sample known as ratcheting. In this region, the cycles move further on the strain axis as cycling continues. This effect is seen the most in the beginning of cycling and the effect stabilizes over time. These four different types of loading can be seen in Figure 1.

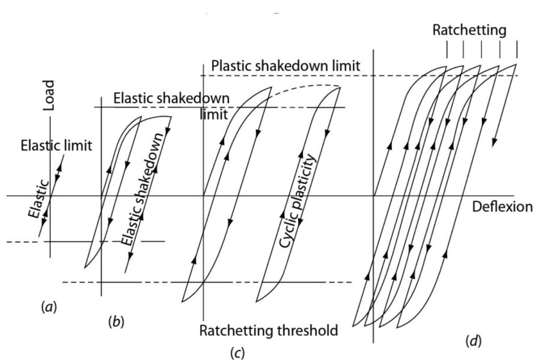


Figure 1: Material response due to cyclic loading

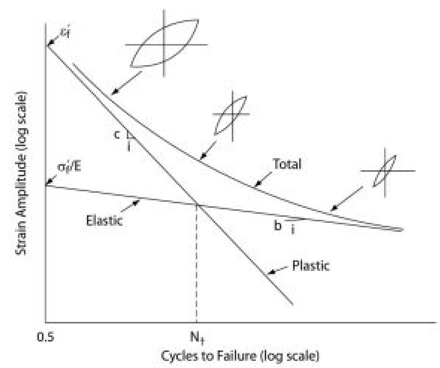


Figure 2: Hysteresis loops for various strain amplitudes

Cyclic loading is first done by choosing the strain ratio you wish to apply to your sample, the formula for which is given by eq.1. After this, the strain amplitude can be found using eq.2 [3]. In both equations, ε_{max} and ε_{min} represent the maximum and minimum strains to be applied during the cycle.

$$R = \frac{\varepsilon_{mac}}{\varepsilon_{min}},\ \varepsilon_a = (\varepsilon_{max} - \varepsilon_{min})/2 \qquad (1), (2)$$

Examining the stress-strain response curve we find hysteresis loops for the plastic shakedown and ratcheting regions. In the hysteresis loop during unloading, the stress-strain curve has a constant slope, which is very close to that of the elastic modulus [2]. As the steel reaches the point of plastic deformation in the reverse direction, the slope becomes nonlinear due to strain hardening. By obtaining the area of the loop, we find the energy that is lost due to each cycle [1]. As more cycles occur, more energy is lost, and ultimately, the steel will fail. In this lab, no samples were brought to the failure point. Hysteresis loops can also exhibit cyclic hardening and softening from the stress-strain curves. Cyclic hardening occurs if the stress for a strain state increases after each cycle and cyclic softening behavior if the stress goes down. This stress change occurs quickly for early cycles but as the the number of cyclic loads increases, the stress change decreases to a stable value [1].

Experimental Procedures:

We began our experiment by obtaining 6 samples of 1045 AISI steel which were formed into a dog bone shape for testing. The samples were loaded into an INSTRON 5500 machine in order to apply a monotonic tensile load to the samples. An extensometer and a force gauge was attached on each of our samples. The extensometer was used to ensure accurate measurements of the samples cross-sectional area during the cyclic loading. The force gauge was used to measure the force applied to the sample.

Before testing each sample, we measured the width and thickness of each of our samples and entered the data into the INSTRON program. After measuring each sample, we loaded our samples into the INSTRON machine and began to run tests. For this lab, the testing parameters we changed in each test were the strain range and force range as well as the maximum value of the strain and force which was applied to the sample. For all 6 samples, we ran 25 cycles of loading and unloading. For first and third test, the strain range was the same but loaded to different maximum strain values. Then for the second, third, and fourth tests, we kept the minimum strain at the same value, but allowed the strain range to increase. In the last two tests, the maximum force values were the same, but the minimum force was lowered giving them different force ranges. The different loading conditions conducted in this lab are tabulated in Table 1. The energy dissipated per cycle was then computed for each test by finding the area between loading and unloading curves.

Test #	**Max. Strain (%)**	**Min. Strain (%)**	**Strain Range (%)**	**Mean Strain (%)**	**# of Cycles**
1	3.25	3.00	0.25	0.03125	25
2	6.85	6.75	0.10	0.068	25
3	7.00	6.75	0.25	0.06875	25
4	7.15	6.75	0.40	0.0695	25
Test #	**Max. Force (kN)**	**Min. Force (kN)**	**Force Range (kN)**	**Mean Force (kN)**	**# of Cycles**
5	45	40	5	42.5	25
6	45	20	25	32.5	25

Table 1: Loading conditions for each test

Results:

The material response for each test was determined by plotting its stress-strain curve and matching them with the four response types as shown in Figure 1. Tests 1-4 exhibited plastic shakedown responses while tests 5 and 6 exhibited ratcheting. The energy dissipated per cycle for tests exhibiting plastic shakedown responses were found in MATLAB using the trapezoidal method and are tabulated in Table 2. For tests exhibiting ratcheting responses, the associated strain increments per cycle were found by calculating the change in strain for each cycle.

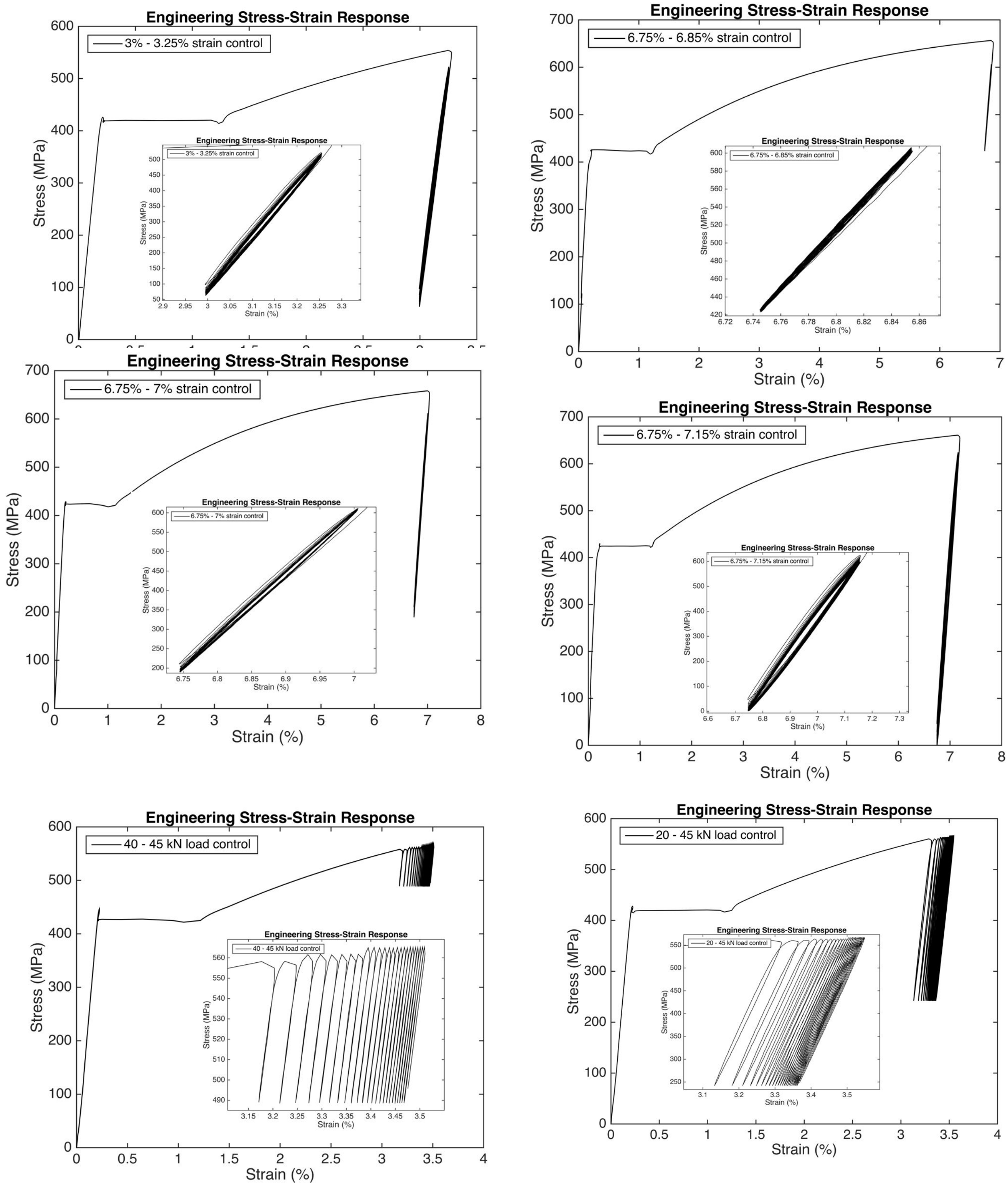


Figure 3: Stress-Strain responses for each test

Test 3 was loaded to about twice the mean strain as test 1 is, and after calculating the energy dissipation per cycle for each test, we see test 1 dissipated 255% more energy per cycle than test 3 did. Test 4 dissipated 840% more energy than test 3 did and test 3 dissipated about 900% more energy than test 2 did (i.e. an increment of 0.15% in strain range yields ~900% more energy lost).

Test #	Response	Energy Dissipated per Cycle (J/m^3)
1	Plastic Shakedown	4.39
2	Plastic Shakedown	0.185
3	Plastic Shakedown	1.72
4	Plastic Shakedown	14.5

Test #	Response	Strain Energy Density (J/m^3)	Strain Increment per Cycle (%)
5	Ratcheting	2.57	0.033
6	Ratcheting	2.58	0.177

Table 2: Response types and associated energies

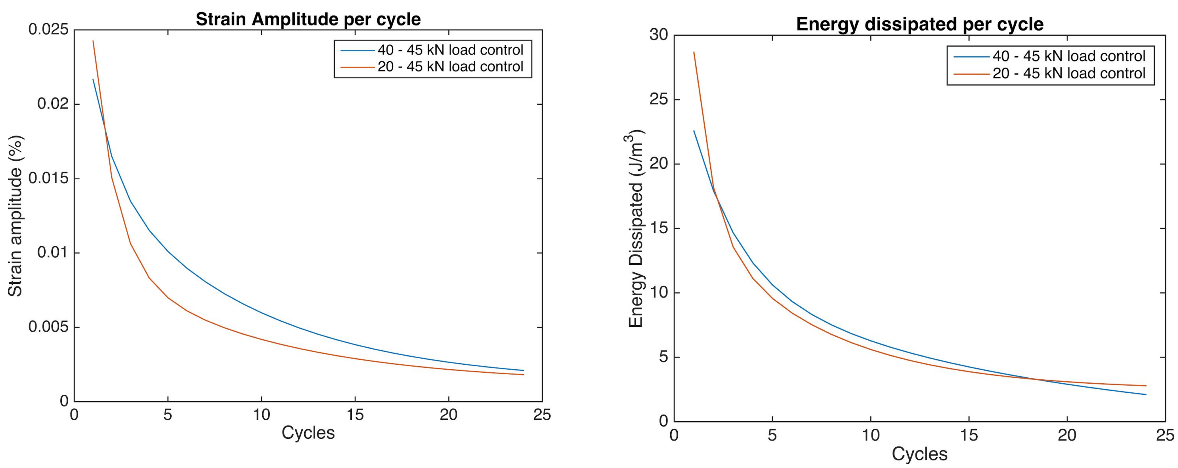


Figure 4: Strain amplitude and energy dissipation per cycle for ratcheting responses

Test 6 increments 536% more than test 5 does per cycle (comparing 0.177 and 0.033). In other words, a change in load range by a factor of 5 yields about a 500% increase in strain increment per cycle. From Figure 4, we see that test 5 stabilizes to a slightly smaller energy dissipation value and strain amplitude value than test 6 does after numerous cycles. Lastly, effects of cyclic hardening and softening are nearly negligible as shown in App. B.

Discussion:

The results are expected because in tests 1-4, strain was controlled, which prevented the samples from deforming more on subsequent cycles. In tests 5 and 6, load was controlled, which resulted in the samples plastically deforming more on each cycle to meet the prescribed load. If we compare the stress-strain responses for test 1 and 3, we note that both samples exhibit similar plastic shakedown behavior, with sample 3 reaching a higher max stress. This result is expected because of the higher mean strain in test 3 (0.06875% vs. 0.03125%). However, this higher mean strain alone does not correspond to a higher energy dissipated on each cycle. If we examine the behavior of samples 2, 3, and 4, we note that the energy dissipated per cycle in sample 4 is the highest, while energy dissipated in sample 2 is the lowest despite all 3 tests having similar mean strains. This suggests that there is also a positive correlation between strain amplitude and energy dissipated per cycle. This is why sample 1 dissipated more energy per cycle than sample 3, despite having a lower mean strain. However, if we compare tests 1 and 4, we note that sample 4 dissipated more energy per cycle than sample 1 despite having a lower strain amplitude. This indicates that energy dissipated on each cycle is a function of both mean strain, and strain amplitude. These results are in agreement with the theoretical model. If we examine Figure 2, we see that the characteristic hysteresis loop for high strain amplitudes has a much larger area than the loop for low strain amplitudes. This larger area of the hysteresis loop indicates larger amounts of energy being dissipated per cycle. Finally, if we compare tests 5 and 6, we can see that the strain energy density for test 6 is marginally higher than that of test 5, while its strain increment per cycle is significantly larger. Since sample 6 has a larger hysteresis loop per cycle than sample 5, it follows that more energy is more energy inputted on each cycle. Thus, sample 6 plastically deforms more per cycle given that higher load amplitude.

Because of the simple, repeatable nature of our experimental setup, there were not many sources of systematic error. Since all loading was done by an INSTRON machine, the only systematic variability came from varying who physically loaded the sample into the testing machine. While this may have had a small effect on our results, it is unlikely that this variability caused significant error. Beyond this, the samples were prepared by an outside source, and as such, there may have been small differences in the samples from machining. Random error is also always present in the form of random voids or defects in the samples. Furthermore, our experiment only tested one sample for each test case. The investigation could be improved by testing multiple samples and averaging results to minimize the impact of the aforementioned defects.

Conclusion:

In this investigation, we determined that ratcheting behavior is a larger risk during load controlled cyclic loading than during strain controlled cyclic loading due to the larger accumulation of plastic strain.. Furthermore, we found that the amount of energy dissipated on each cycle is a function of both strain amplitude and mean strain, with the former seeming to have a greater effect than the latter. Finally, we found that an increase in load amplitude during load controlled cyclic loading will result in an increase in strain increment per cycle. Overall, this lab demonstrated the impact of strain amplitude, mean strain, and load amplitude on the response of 1045 steel during cyclic loading.

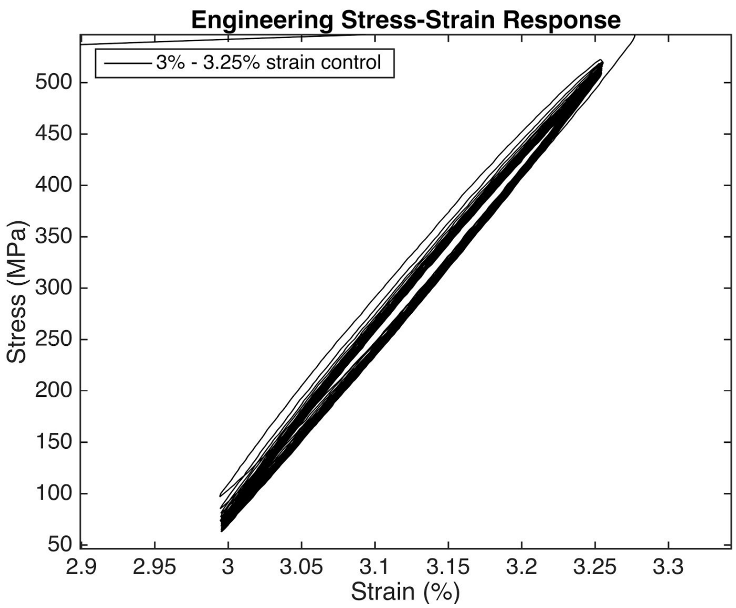
Appendix A: References

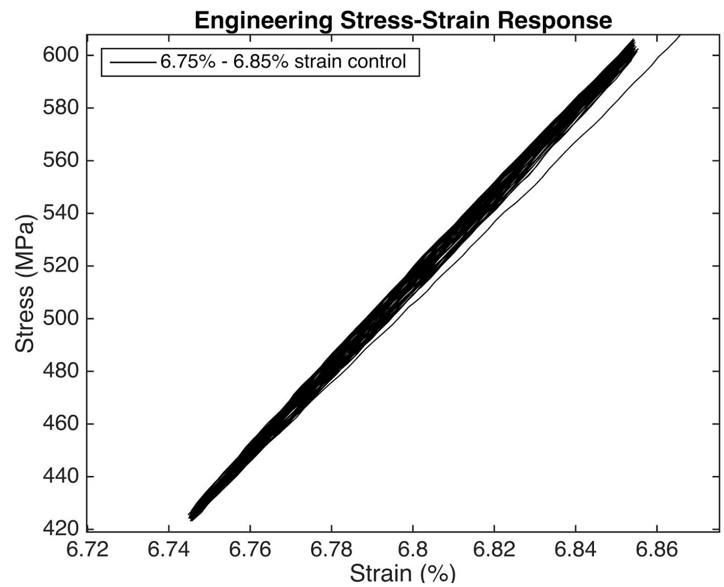
[1] K Komvopoulos, Mechanical Testing of Engineering Materials, 1st edn (University Readers, 2011).

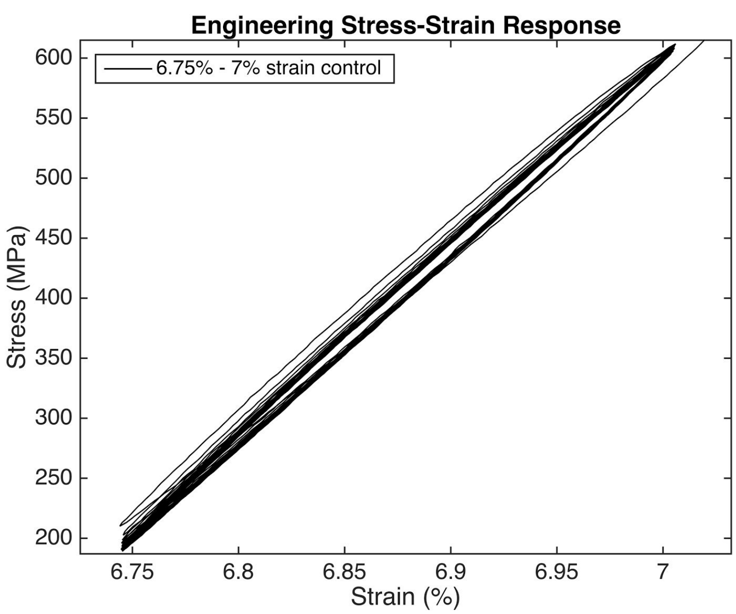
[2] N.E Dowling, Mechanical Behavior of Materials. 4th edition (Pearson,2012)

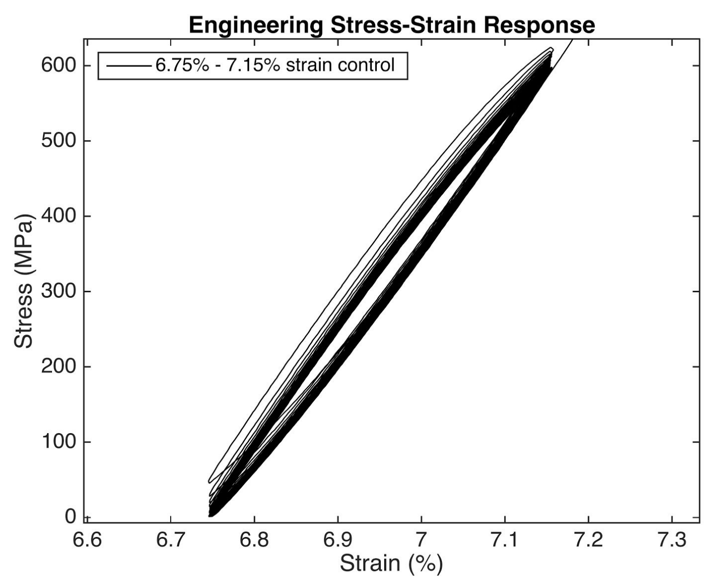
[3]W. D. Callister, Materials Science and Engineering, an Introduction, 7th edn (John Wiley and Sons, 2007)

Appendix B: Plots









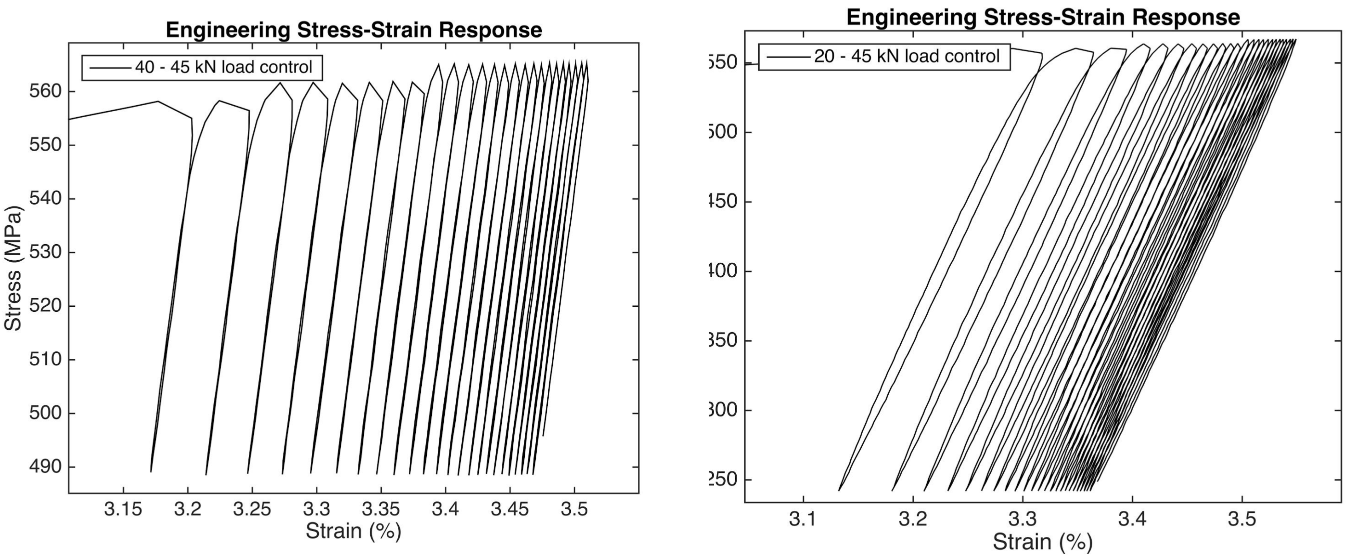


Figure B1: Zoomed in plots of stress-strain responses

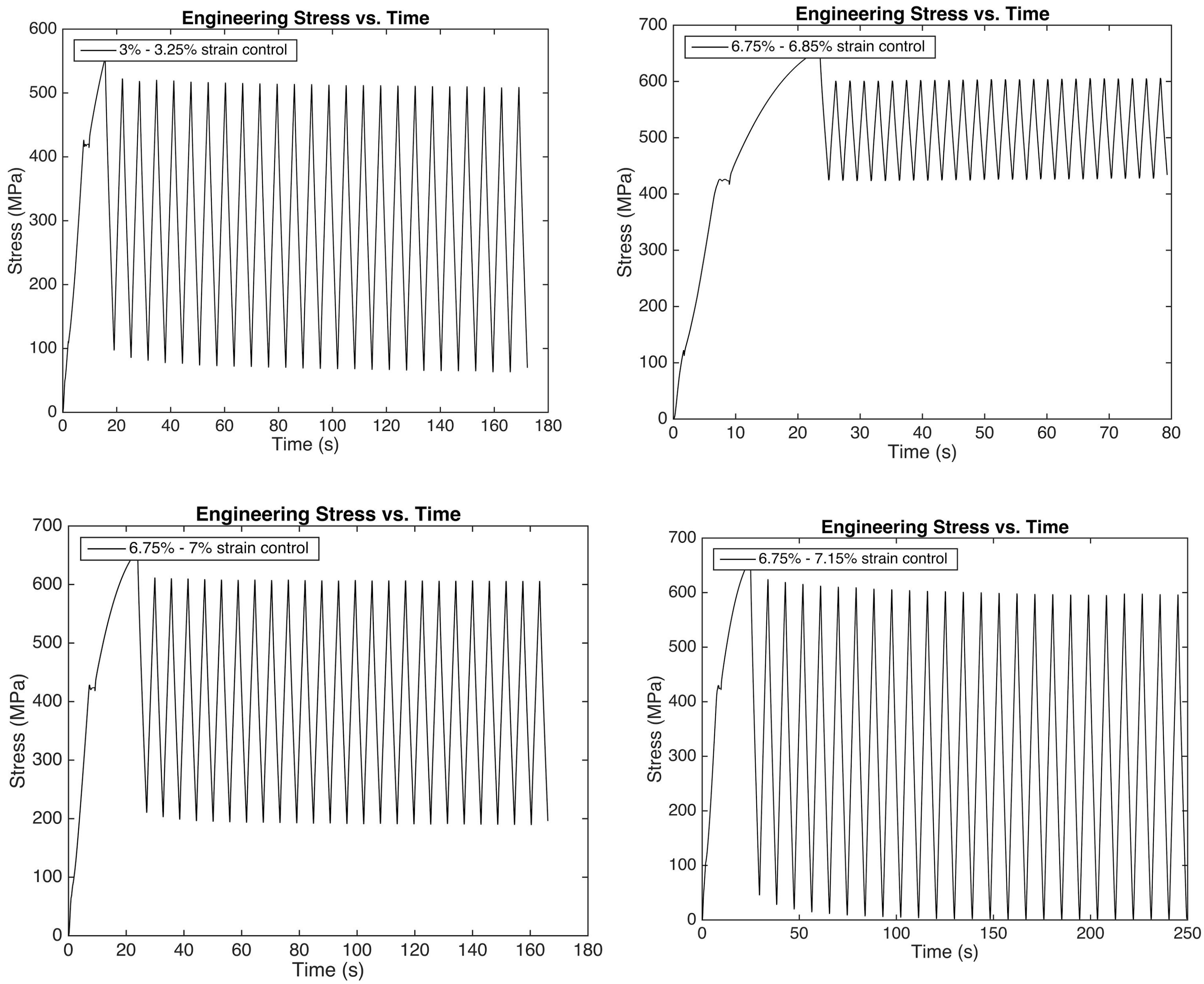


Figure B2: Stress-time plots for tests under strain control

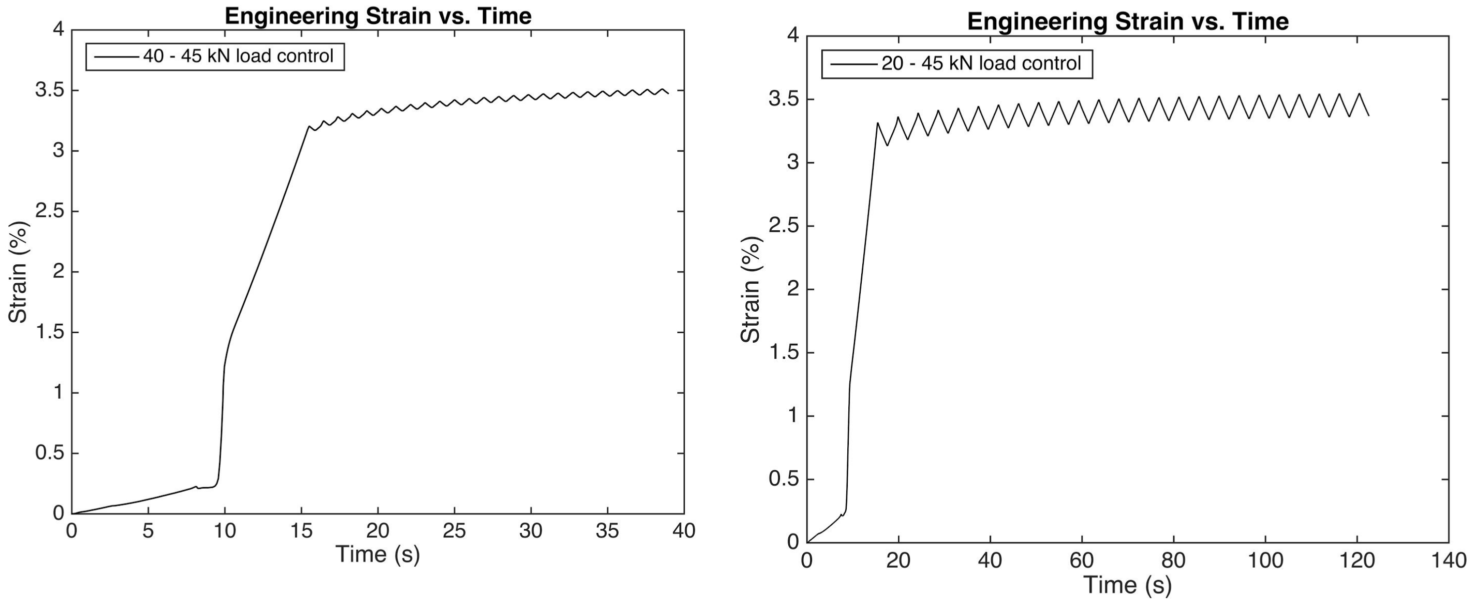
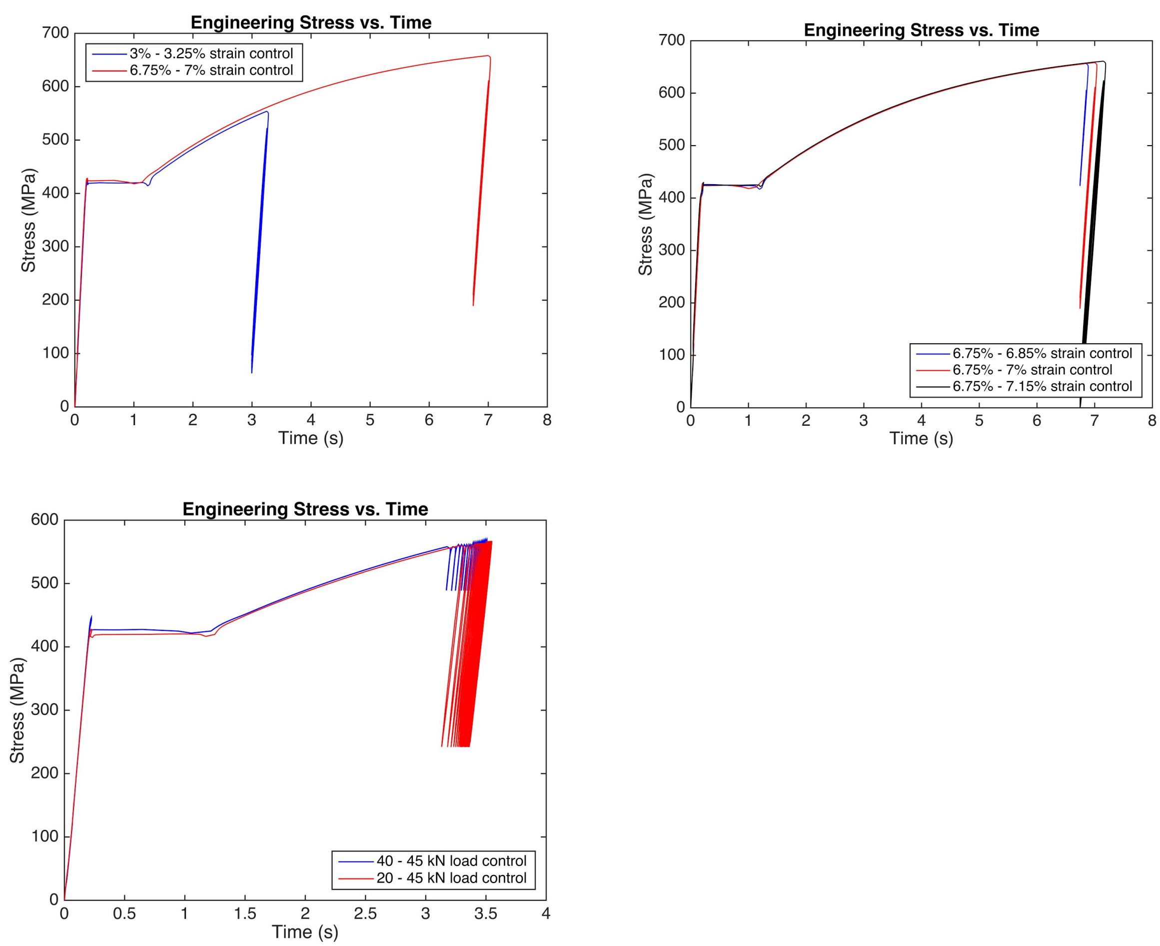


Figure B3: Strain-time plots for tests under load control



Appendix C: MATLAB Code

```
%% Load and Save Data
% ALWAYS RUN THIS FIRST TO GET DATA

% Column 1: time (s)
% Column 2: Extension (mm)
% Column 3: Load (N)
% Column 4: Tensile Strain (%)
% Column 5: Total Cycle Count
% (1,6): Specimen length (mm)
% (1,7): Specimen Thickness (mm)
% (1,8): Specimen Width (mm)
% (1,9): Specimen Area (mm^2)
for i = 1:6
        data(i).data = csvread(['RawData_' num2str(i) '.csv']);
        data(i).time(:,1) = data(i).data(:,1); %s
        data(i).stress(:,1) = data(i).data(:,3)/data(i).data(1,9); %kN
        data(i).strain(:,1) = data(i).data(:,4); % percent
        data(i).cycles(:,1) = data(i).data(:,5); %
end

legendInfo{1} = '3% - 3.25% strain control';
legendInfo{2} = '6.75% - 6.85% strain control';
legendInfo{3} = '6.75% - 7% strain control';
legendInfo{4} = '6.75% - 7.15% strain control';
legendInfo{5} = '40 - 45 kN load control';
legendInfo{6} = '20 - 45 kN load control';
```

```
%% Strain amplitude and energy per cycles
 for j = 1:6
   for i = 1:24
        x1 = find(data(j).cycles==i+0.5,1) - 1;
        x2 = find(data(j).cycles ==i-1, 1);
        strainamp(i,j) = ((data(j).strain(x1))-(data(j).strain (x2)))/(2);

        x3 = find(data(j).cycles == i); %Find where top portion of hysteresis loop 23 is
        x4 = find(data(j).cycles == i+0.5); %Find where bottom portion is
        top = trapz(data(j).strain(x3), data(j).stress(x3));
        bottom = trapz(data(j).strain(x4), data(j).stress(x4)); % Find area under bottom of loop
        energy(i,j) = top + bottom; %MJ/m^3

   end
    figure
    plot(cycles, strainamp(:,j))
    xlabel('Cycles'); ylabel('Strain amplitude'); title('Strain amplitude per cycle');
    legend(legendInfo{j});
    set(gca, 'FontSize', 15);

    figure
    s = exp2fit(cycles, energy(:,j),2);
```

```
    fun = @(s,t) s(1) + s(2)*exp(-cycles/s(3))+s(4)*exp(-cycles/s(5));
    tt = linspace(0,24,200);
    ff = fun(s,tt);
    plot(cycles, ff);
    xlabel('Cycles'); ylabel('Energy Dissipated'); title('Energy dissipated per cycle');
    legend(legendInfo{j});
    set(gca, 'FontSize', 15);
end

clear;
```

```
%% Stress Strain Response for Strain Control
for i = 1:4
  figure
  plot(data(i).strain, data(i).stress, 'k')
  xlabel('Strain (%)'); ylabel('Stress (MPa)'); title('Engineering Stress-Strain Response');
  legend(legendInfo{i}, 'Location', 'NorthWest')
  set(gca, 'FontSize', 15);

  figure
  plot(data(i).time, data(i).stress, 'k');
  xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');
  legend(legendInfo{i}, 'Location', 'NorthWest')
  set(gca, 'FontSize', 15);
end
```

```
%% Stress Strain Response for Load Control
for i = 5:6
  figure
  plot(data(i).strain, data(i).stress, 'k')
  xlabel('Strain (%)'); ylabel('Stress (MPa)'); title('Engineering Stress-Strain Response');
  legend(legendInfo{i}, 'Location', 'NorthWest')
  set(gca, 'FontSize', 15);

  figure
  plot(data(i).time, data(i).strain, 'k');
  xlabel('Time (s)'); ylabel('Strain (%)'); title('Engineering Strain vs. Time');
  legend(legendInfo{i}, 'Location', 'NorthWest')
  set(gca, 'FontSize', 15);
end
```

```
%% Finding the energy dissipation for all tests
for i = 1:6
  x1 = find(data(i).cycles == 23); %Find where top portion of hysteresis loop 23 is
  x2 = find(data(i).cycles == 23.5); %Find where bottom portion is
```

```
    top = trapz(data(i).strain(x1), data(i).stress(x1)); %Find area under top portion of loop
    bottom = trapz(data(i).strain(x2), data(i).stress(x2)); % Find area under bottom of loop

    energy(i) = top + bottom; %MJ/m^3
end
energy
```

```
%% Finding the strain increment for tests exhibiting ratcheting (5 and 6)
for i = 1:2
    x1 = find(data(i+4).cycles == 23); %Find where cycle 23 occurs

    increment(i) = data(i+4).strain(x1(end)) - data(i+4).strain(x1(1));

end
increment
```

```
%% Comparison between tests 1 and 3
figure
plot(data(1).strain, data(1).stress, 'b'); hold on;
plot(data(3).strain, data(3).stress, 'r');
xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');
legend(legendInfo{1}, legendInfo{3}, 'Location', 'NorthWest')
set(gca, 'FontSize', 15);

figure
plot(data(1).time, data(1).stress, 'b'); hold on;
plot(data(3).time, data(3).stress, 'r');
xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');
legend(legendInfo{1}, legendInfo{3}, 'Location', 'NorthWest')
set(gca, 'FontSize', 15);
```

```
%% Comparison between tests 2, 3, and 4
figure
plot(data(2).strain, data(2).stress, 'b'); hold on;
plot(data(3).strain, data(3).stress, 'r');
plot(data(4).strain, data(4).stress, 'k');
xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');
legend(legendInfo{2}, legendInfo{3}, legendInfo{4}, 'Location', 'SouthEast')
set(gca, 'FontSize', 15);

figure
plot(data(2).time, data(2).stress, 'b'); hold on;
plot(data(3).time, data(3).stress, 'r');
plot(data(4).time, data(4).stress, 'k');
xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');e
legend(legendInfo{2}, legendInfo{3}, legendInfo{4}, 'Location', 'SouthEast')
set(gca, 'FontSize', 15);
```

```
figure
plot(data(2).time, data(2).strain, 'b'); hold on;
plot(data(3).time, data(3).strain, 'r');
plot(data(4).time, data(4).strain, 'k');
xlabel('Time (s)'); ylabel('Strain (%)'); title('Engineering Strain vs. Time');
legend(legendInfo{2}, legendInfo{3}, legendInfo{4}, 'Location', 'SouthEast')
set(gca, 'FontSize', 15);
```

```
%% Comparison between test 5 and 6
figure
plot(data(5).strain, data(5).stress, 'b'); hold on;
plot(data(6).strain, data(6).stress, 'r');
xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');
legend(legendInfo{5}, legendInfo{6}, 'Location', 'SouthEast')
set(gca, 'FontSize', 15);

figure
plot(data(5).time, data(5).stress, 'b'); hold on;
plot(data(6).time, data(6).stress, 'r');
xlabel('Time (s)'); ylabel('Stress (MPa)'); title('Engineering Stress vs. Time');
legend(legendInfo{5}, legendInfo{6}, 'Location', 'SouthEast')
set(gca, 'FontSize', 15);
```

Acknowledgements

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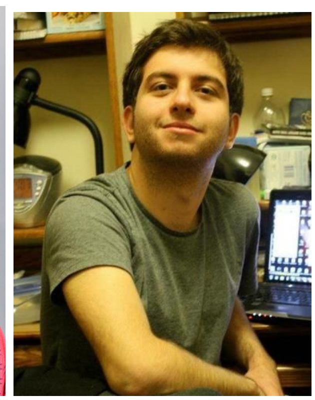

I, Sonja Davison, confirm that Darren Kong wrote Theory of the lab report. Sonja Davison

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