Evaluation of creep strain concrete specimens subjected to stress reversal

by

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Abstract

In the repair and rehabilitation of concrete structures, it is important to know how concrete could behave in different scenarios. In some cases, such as in prestressed bridges or prestressed concrete containment vessels, structures may be exposed to a stress that is outside of the designed use for that structure. The purpose of this research is to understand how creep affects the flexural response of concrete given a sudden stress reversal. A series of normal strength 4”x4”x36” concrete beams were cast and tested for this research. The specimens were loaded axially at 30%f’c and 50%f’c for 70-days and then subjected to a four point loading flexural test. Brass inserts were cast into the beam so that a Whittemore gauge could be used to measure the creep during the axially loading phase and later a surface mounted strain gauge was used to measure the creep recovery at unloading and the strain experienced during the flexural test. From these tests it was discovered that beams that have experienced more creep have a similar but slightly lower flexural strength and a lower flexural modulus of elasticity. It was also found that after specimens have undergone creep, a one-month relaxation period lessened the reduction in strength and stiffness.

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Chapter 1 - Introduction

Background

Creep is the deformation exhibited during sustained loading over time [5]. Concrete creep is particularly unique because it occurs at any temperature and load. Since the early 1900s, researchers have studied concrete creep to better predict the material's behavior. [10] Prestressed concrete members rely on these predictions to accurately design the prestressing forces required. During the lifespan of these members, detensioning a tendon can change the distribution of stress within the structure which could lead to a failure of the structure. This event could occur in prestressed bridges during redecking, when removing the driving surface [9], the sustained dead load is removed which causes the girders to shift from a positive moment to a negative moment. Similarly, prestressed concrete containment vessels in nuclear reactors can be detensioned during routine maintenance causing a significant difference in the stresses where the tendons were previously stressed. A nuclear reactor at the Crystal River facility experienced large delamination cracks in the area where tendons were being detensioned for the replacement of a steam generator [8]. In the effort of understanding what happened at the Crystal River site the US Nuclear Regulatory Commission created a task force which identified concrete creep as an “important mechanism” that could affect the structural integrity of containment vessels in the future [13]. Although these events exist, little research has been done to see how creep affects the behavior of concrete during a stress reversal event.

Scope and Aim

The scope of this research is to better understand how creep affects concrete strength regarding a sudden stress reversal by observing how concrete behaves during continuous compressive loading for 70 days then suddenly unloaded and loaded to failure in a four point loading flexural test. The deformation of the specimens was measured using a Whittemore gauge on brass inserts embedded into the concrete. The data was used to understand the time history creep of each specimen. A surface mounted strain gauge was applied to observe the creep recovery as the specimens were unloaded and then also to capture the strain observed during a four point loading flexural test. The behavior of concrete during a stress reversal can then be better understood by analyzing the strain data and results of the flexural test.

Thesis Outline

This thesis is broken down into five chapters. Chapter one provides background information along with the scope and aims of the thesis. Chapter two presents a brief literature review about the mechanics of creep in concrete. Chapter three shows the mix design used in the experiments along with the procedure of how the test was completed. Chapter four presents the results of the research and lastly chapter five concludes the report.

Chapter 2 - Literature Review and Theory

With creep being studied for over 100 years, there is a lot of information regarding concrete creep. Mindess et al. [5] collected data and information from researchers and put it together in a textbook titled “Concrete”. Within the creep section it discusses parameters that influence creep, the mechanisms behind creep and how creep is predicted. This literature review will cover these topics from “Concrete” to provide a better understanding of creep.

According to *Concrete*, there are nine parameters that affect creep, as follows:

- Applied stress
- Water/cement ratio
- Curing conditions
- Temperature
- Moisture
- Cement composition
- Chemical admixtures
- Aggregate
- Specimen geometry

These parameters do not only affect creep but also affect drying shrinkage which adds to the difficulty of interpreting test data. [5]. It is also difficult to test how a single parameter may affect the creep of concrete such as the water/cement ratio.

By changing the w/c ratio there is a change in cement content and thus in concrete strength. ACI 209.1R-05 [1] points out how direct comparison of different cement mixtures is difficult because creep “is largely dependent on applied stress level relative to the concrete strength”. Despite these difficulties researchers considered these factors and were able to find that generally “specific creep increases with increasing w/c ratio” [5]. Taking this information and knowing that as w/c ratio increases the compressive strength decreases, it can be concluded that as the compressive strength of concrete increases, the specific creep decreases.

Researchers have spent time discovering how the applied stress effects creep. [1] discusses that it is generally accepted that up to 0.4f’c the creep strain relationship to load applied is linear, but some researchers found that it only applies to stresses from 0.3f’c to 0.6f’c “dependent on the particular concrete”. However, [5] discusses how some researchers found that this relationship is more defined as a nonlinear one. This nonlinear relationship is represented by a “thermally activated process” [5] but for application use a linear relationship is used because of simplicity.

Not only does the water content of the concrete mixture affect creep but also the moisture during curing and the humidity in the environment. Researchers have found that the length of moist curing also affects the amount of creep concrete exhibits. [5] discusses how a longer moist cure reduces the overall creep. This is because younger concrete has a higher porosity in the paste and an overall lower degree of hydration. This effect of lower creep at longer moist cures may also be “attributed to the aging effect” of the paste and its ability to resist the stress the older it is. [5] also points out how the reduction in creep due to longer moist cures is in the irreversible portion of creep. They also point out how increasing the temperature during curing reduces overall creep but when the concrete is loaded and being subjected to higher temperatures, up to 175 °F, the creep increases linearly. [1] states how the relative humidity that the concrete is in directly influences creep. A. M. Neville [15] found in their tests that mortar specimens that were kept at 32RH experienced more creep than specimens kept at 95RH. [1] says that in an environment where drying cannot happen, such as in water or high humidity environments, the creep is a quarter of what drying concrete is. In general, the movement of water within concrete from the C-S-H to the capillary pores is likely what causes creep [15]. Concrete in a high humidity environment will have less movement of that internal water than in a low humidity environment. In *Concrete* the authors discuss how after moist curing, drying out the concrete to 40% RH before applying a load decreases the overall creep. It is especially noted that moisture related creep happens in both the drying and wetting of the concrete.

Some researchers have tried to find how cracking affects the irreversible part of creep strain. Rossi et al. [7] performed compressive, tensile and bending creep tests on concrete loaded at varying stress-strength ratios. From their studies they found that the microcracking that happens at loading creates voids where liquid water tends to concentrate and cause extra drying shrinkage which in turn causes more unrecoverable strain. They also concluded that after the specimens were unloaded the amount of residual strain is a "linear function of the creep strain" and is independent on the level of loading and age of loading.

Another behavior of concrete is when a sustained load is released there is an instantaneous recovery due to the viscoelastic properties, but then the concrete will continue to recover slowly over time, this is called creep recovery [11]. Not all the creep that the specimens are subjected to is fully reversable. [11] performed creep tests of concrete specimens with varying ratios of cement to aggregate by weight with different applied load to f'c ratios to help develop a mathematical model for creep. In his testing they found that for typical concrete mixes, only 10%-20% of creep was able to be recoverable and that a higher applied stress resulted in less recovery. They also found that the time for creep recovery to end seems to be independent of applied stress but more related to cement content of mixes. For a mix of 1:6 cement to aggregate it took around 210 days to finish whereas a 1:1 mix took nearly 520 days. [11]

[15] performed creep tests on different types of cement mortar specimens in both a high and low humidity environment and observed the corresponding creep recovery of each paste. They concluded that “creep recovery is not a function of the strength of the mortar either at the time of the original application of the load or the time of its release”, and that creep recovery does not depend on the relative humidity of its environment. They came to this conclusion because the recovery of both the wet and dry specimens was nearly the same even though at the time of application and at release the strengths of mortars were different. It should be noted that the application force was different for each specimen, the wet specimens were subjected to 150 kg/cm^2 and the dry specimens were at 100 kg/cm^2. The reason for the different loads was so the specimens were each loaded to 50%f’c which in theory results in similar amounts of creep if they were in the same environment. Although the strength of mortar does not affect the creep recovery, they found in their tests that the strength of mortar at time of release was inversely related to the instantaneous recovery. In the end [15] concludes that creep recovery is related to the “movement of the cement paste” as it tries to reach the new equilibrium once the stress is released. It is likely not fully recoverable due to the rigidity of the cement paste as the specimen ages. This conclusion follows what Yue and Taerwe [6] found in their creep tests. They subjected different concrete mixes to an axial compressive load at different ages to determine how age at loading and age at release affects creep recovery. From these tests they found that when the load is applied before 28 days or if the load is applied for a shorter duration the creep recovery value is significantly higher. At the earlier ages the cement paste is less rigid as it is still rapidly curing which results in more recovery. Bazant and Kim [12] found when concrete is subjected to sustained compressive loading it seems to accelerate the aging of concrete which

possibly explains why [6] found that at longer loading ages there was less creep recovery because the cement paste has become more rigid.

Most research about creep and creep recovery has been dedicated to long load application times and sudden release of stress whereas, Li Su et al. [10] performed research to discover how short-term load application times affect creep and its recovery. They used concrete prisms and applied the load at 3, 7, and 28 days and for each different age of specimen they were subjected to a consistent compressive load for a time of 0, 60, 300, 600, 1800 seconds. The conclusion from this work was like [6] in that the longer the load was applied there was less recovery of strain. They also found that higher stress-strength ratios are able to recover more but have a longer recovery rate. It was also discovered that as the age of concrete when load was applied increased there was a decrease in the rate at which creep strain developed. This is backed up by other researchers which found the age of the specimen greatly affects the amount of creep and recovery [6]. Mei et al. [14] also researched creep and its recovery in the short term but at different loading and unloading rates. They found that as the loading and unloading rates were increased so did the creep strain, but the amount of recoverable strain decreased. They discuss how this is likely due to more damage occurring to the concrete creating microcracks during the sudden loading. Both of the researchers goals were to better understand creep in the short term as it is traditionally thought of only being a long-term behavior and to develop mathematical models to predict the short-term behavior.

Galitz and Grasley [9] discuss how prestressed beams at an early age may be exposed to stress reversals such as when they are moved from their casting location to the truck or during the placement of concrete decking for bridge girders. They point out how there is not much knowledge on cementitious materials during this phenomenon and created their research using a three-point bending test. The study was carried out by subjecting concrete beams to bending in three loading steps. The beams were all subjected to the same loading during the first step but on the second step the stress reversal beams were unloaded and flipped, during this step it was found that the beams that undergone the reversal experienced less relaxation than its counterparts. After the third loading step all beams experienced the same amount of relaxation. They believe that this “lines up with the theory of relaxation being a function... of microcracking”, in that during the first loading step, microcracks are formed on the tension side of the beam and are subsequently closed during the reversed loading step. Although this theory may seem to explain the phenomenon, they note that the relaxation theory also should show a change in the modulus of elasticity but in their test results there was no difference between the reversal beams and normal beams meaning that there is more at play than just relaxation. In any case they believe that this phenomenon could lead to “unpredictable long-term performance” for structures that experience a stress reversal at an early age.

Chapter 3 - Methods and Materials

Concrete Mix Design

The concrete was designed using a volumetric approach. The mix was designed to reach a compressive strength of 6 ksi after 28 days of curing. A w/c of .45 in conjunction with a water reducer was used to achieve the desired strength. Type IL Portland cement was used, and oven dried river sand and crushed stone were used for the aggregates. The table below shows the mixing proportions per cubic yard of concrete needed.

Table 1. Mix Proportions of concrete specimens per cubic yard batched

Material	Amount/yd^3
Cement	562.68 lb
Water	253.53 lb
Fine aggregate	1978.02 lb
Coarse Aggregate	1076 lb
Adva 140M - Water Reducer	737.64 ml

After the 28-day moist cure the cylinders were placed into a Forney hydraulic compressive testing machine fitted with a Forney Link to report the data. In addition to the compressive tests six 3”x4”x16” specimens were made to perform four point loading flexural tests conforming to ASTM C78 except for lack of steel bars or balls required for the supports. This test was performed using a Shimadzu material testing machine fitted with a custom steel load applicator to apply the load at the third points. The flexural specimens were placed on top of semi-circle steel supports ensuring that the specimens are centered on it. Lastly neoprene rubber pads were placed under the load application points to prevent premature cracking and an even load distribution along the top of the specimen. The flexural test was performed 70 days after the 28-day moist cure to match the age of the concrete specimens subjected to creep. The results of the compressive tests and four point flexural tests are in the table below.

Table 2. Properties of the concrete mix

Test	Value
28-day Compressive Test	5400 psi
Four point flexural test	680 psi

Experimental Setup

The following sections discuss how each step of the test is performed along with how the data is gathered. The entire research can be broken down into five steps, mixing and casting, a 28-day moist cure, a 70-day creep analysis, an unloading step and finally a four point loading flexural test to failure. Below shows a timeline depicting these five steps along with a graph that depicts an example of what the stress history of a specimen would look like.

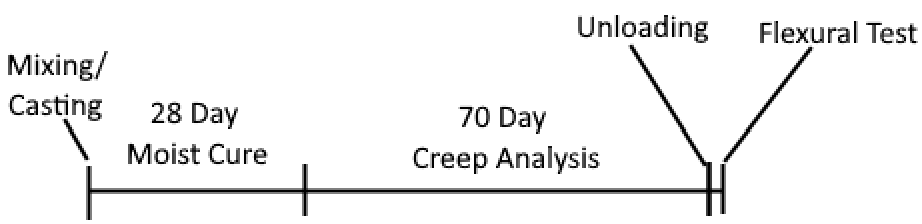

Figure 1. Timeline of tests

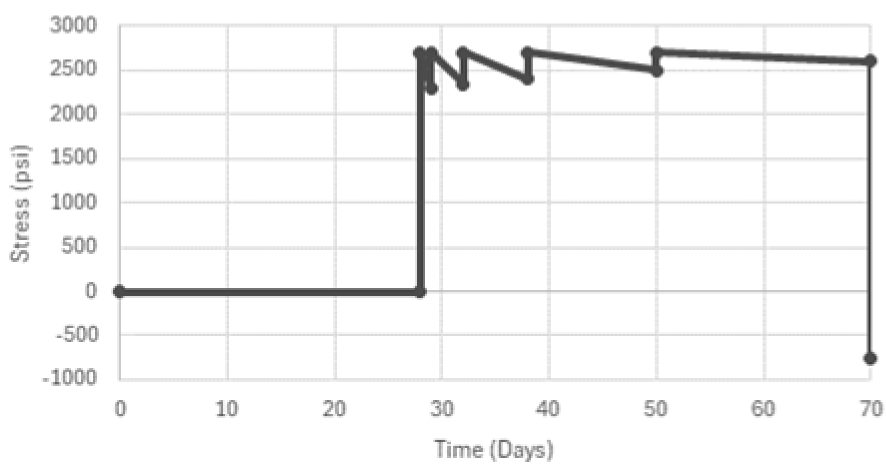

Figure 2. Approximate stress levels during lifetime of specimens

Concrete Casting

Being limited by the number of molds available, only four beams could be batched at a time. The concrete was batched and mixed following ASTM C192. Two pairs of brass inserts were cast in the beam on each face 2.5” from the ends and spaced 8” between the points so that the strain could be measured by observing the change in length between the brass points by use of a Whittemore gauge. The brass Whittemore points were hot glued onto steel bars with an 8” spacing then placed into slots in the mold to hold the points in place as the concrete cures.

Figure 3. Wooden concrete mold

Figure 4 Steel spacer for brass inserts placed in mold slot

Before the concrete is poured into the molds form release oil was sprayed onto the surface to aid in the demolding process. The concrete was poured in two lifts, being rodded and vibrated using a vibrating table between lifts. This was done to ensure proper distribution of the concrete in the mold. The first 24 hours of curing for the 36” specimens were done by covering the molds with plastic to retain moisture. This was done instead of putting the molds directly into a moist room to help preserve the molds for reuse. After the first 24 hours the specimens were de-molded and placed into a moist room at 95% RH and 23°C for the rest of the 28-day cure. After the 28-day period the specimens were moved out of the moist room and into a room that is held at 50% RH and 23°C for the remaining tests. A total of thirteen test specimens were created with ten of them being subjected to the creep testing and three being used as control specimens. The control specimens did not have Whittemore points because they would not undergo compressive creep.

Concrete Testing

The creep test was performed using a hydraulic driven hand jack with a creep frame apparatus. On the hydraulic pump a pressure gauge was installed to read the pressure being applied to the specimen. To keep the load applied by the hydraulic jack on the specimen, hex nuts were tightened snug against the plate in contact with the specimen.

Figure 5. Creep loading apparatus

The specimens were placed into the creep frames in a way so all sides could still be reached with the Whittemore gauge. Each specimen was then loaded to the prescribed 50% or 30% of the ultimate compressive strength found earlier from the compressive tests. The loads were held constant for 70 days and would be checked every hour for the first day since there is more load loss in the beginning of loading and then gradually increased to checking twice a week at the end of the 70-day period. In addition to checking the load on the specimens the distance between Whittemore points was also measured. This was done so the amount of creep strain the specimens were subjected to could be captured. This was carried out by using a Whittemore gauge and a Mitutoyo ABS Digimatic indicator and USB input tool attached to the Whittemore gauge to record the measurements with an error of .0001”. Before being measured the gauge was zeroed out with a control gauge length of 7.965”. Once zeroed the inserts were then measured starting with the top pairs and then the bottom pairs for each side. Each pair was measured three times ensuring that the gauge was properly in the brass inserts, and the average of those measurements was used for the remainder of the analysis.

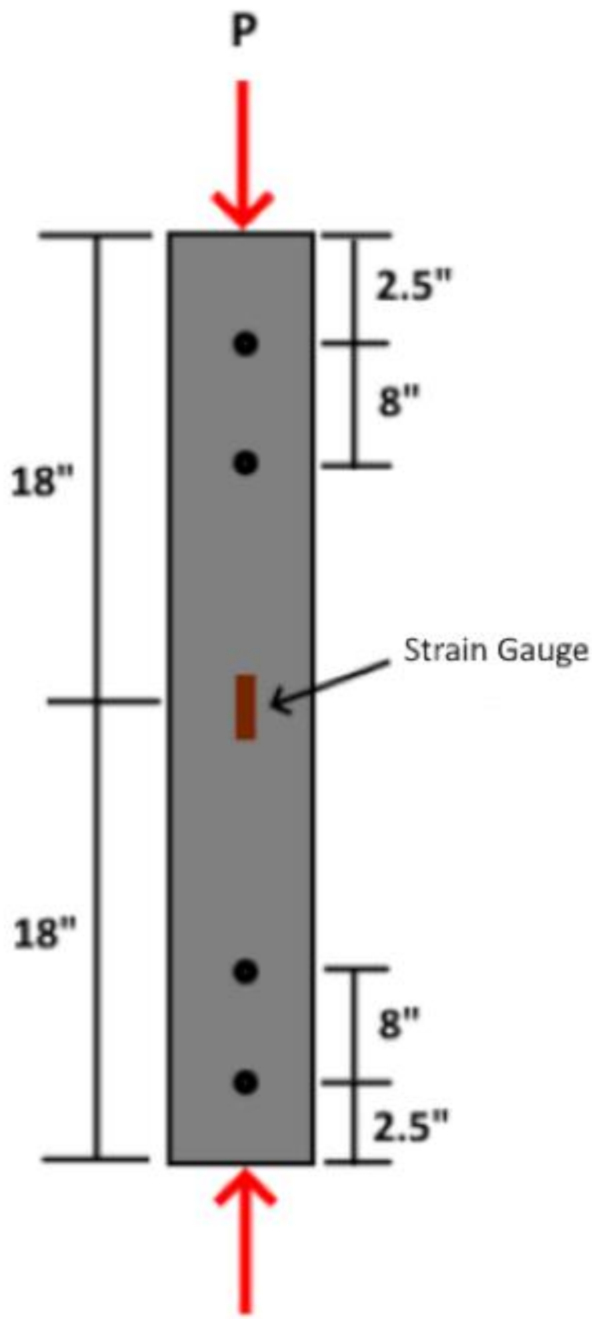

Figure 6. Creep loading diagram

After the 70-day period before unloading, a surface mount strain gauge was applied to the center of the concrete surface to capture the creep recovery and later the strain during the flexural test. A thin layer of epoxy was used to create a smooth mounting surface for the gauge. This surface was sanded smooth and treated with acid to clean the surface and a base to neutralize the acid. Cyanoacrylate glue was used to mount the strain gauge to the prepared surface. The strain gauge was then connected to a P-3500 strain indicator and calibrated, so the reading measurement was zero at the time of application. The P-3500 strain indicator was then connected to a Keithley Multimeter/Switch System and using a custom LabVIEW based software, the strain data was continuously recorded to a file during the unloading step. After being carefully unloaded the specimen was then placed into a four point loading flexural test and loaded to failure. The specimens were unloaded and subjected to flexural testing one at a time to ensure a quick transition between the two steps.

Figure 7. Control creep specimens connected to the P3500 strain indicator box

A Shimadzu material testing machine was used to conduct the 4-point bending test with custom fabricated spreader bar to place the load at the third points of the beam. The beam is supported 2” from the edges of the beam by semi-circle steel bars. Between the load applicator and the specimen surface a neoprene rubber pad is placed to help prevent premature cracking and ensure there is an even loading across the top of the specimen. The beams were loaded to failure at a rate of .01in/min. The Shimadzu was also connected to the Keithley so the strain and load readings could be recorded simultaneously.

Figure 8. Four point stress reversal test

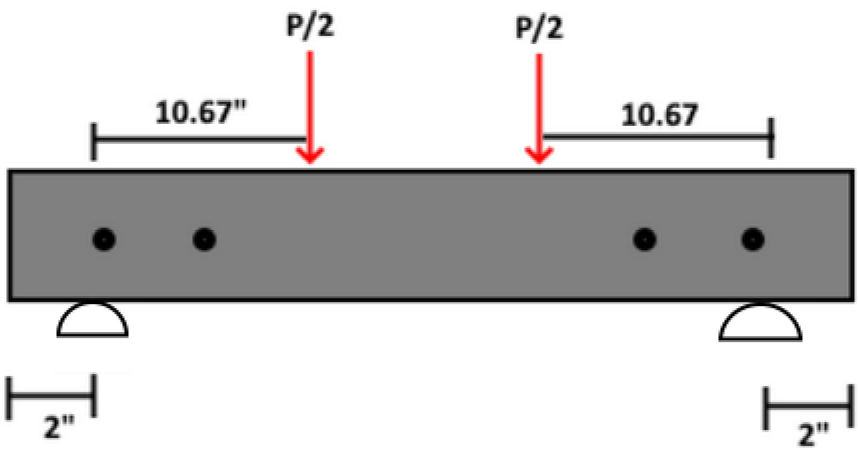

Figure 9. Four point stress reversal diagram

Lastly the broken beams were cut into 8” sections by using a large wet concrete saw. The sections were then tested in the Forney compressive testing machine to determine the compressive strength of the specimens at the time of flexural testing.

Data Processing

After the data was collected the strain data from the Whittemore points needed to be processed to separate the drying shrinkage strain from the mechanical strain. First the control gauge length of 7.965” was added to the measurements to get the distance between points. The strain for each point was then calculated by dividing the change in length by the gauge length. The data was then looked through to eliminate outliers from the set before finding the average strain in the specimen at each time interval. Next using Rogowski’s [16] shrinkage equations the shrinkage strain was found and subtracted from the overall strain of the specimens. The result gives you the mechanical creep gained for each time interval. To show the entire strain history of each specimen the mechanical creep at the end of the 70-day period was added to the strain gauge reading so it was easier to interpret the results. The stress during the flexural tests was found by taking the load at failure and plugging that into equation given by ASTM C78 shown below where R is the stress, P is the load, L is the span between supports, b is width, and d is depth.

$$R = \frac{PL}{bd^2}$$

Chapter 4 - Results and Discussion

Mechanical Creep Strain

After the moist curing time the concrete specimens were placed into the creep apparatus and subjected to a compressive forces of 50%f'c and 30%f'c. The graph below shows the average mechanical creep strain of the beams.

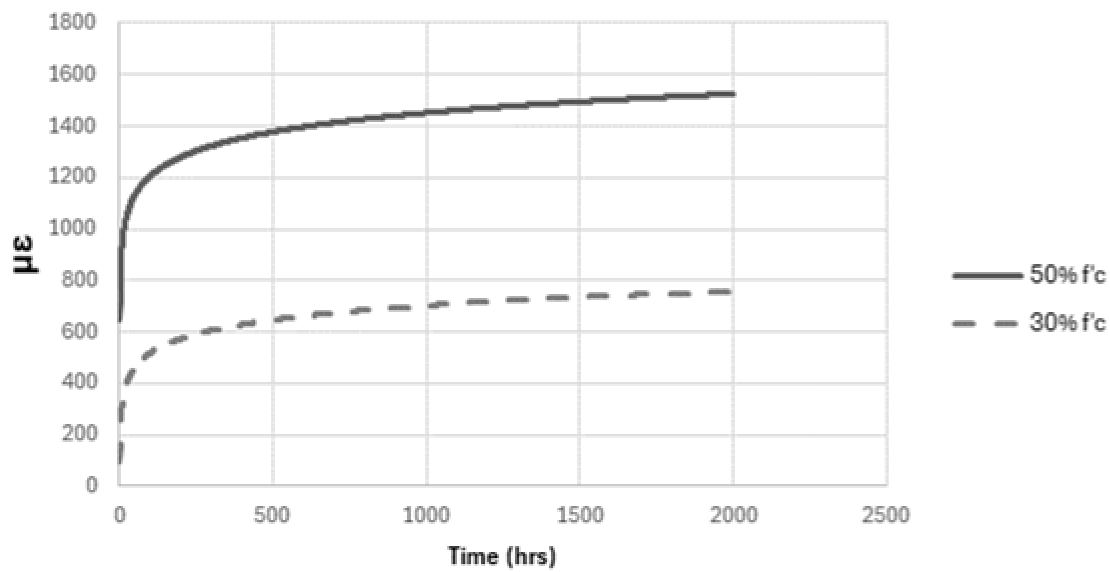

Figure 10. Average mechanical creep gained for 50%f'c and 30%f'c

The mix design and beam sizes matched Rogowski's [16] so that the shrinkage equation found in their research could be used to isolate the mechanical creep strains for our research. The mechanical creep strain was found by subtracting the shrinkage strain from the overall strain found from the Whittemore gauges. The best fit line was found using Microsoft Excel's exponential trendline tool. Seeing that the beams at a higher stress developed more creep matches what is seen in literature.

Strain Recovery

After the specimens had been loaded for 70 days the specimens were equipped with a surface mount strain gauge to measure the strain as the specimens were being unloaded. The graph below shows the strain recovery for beam six which was loaded at 50%f'c.

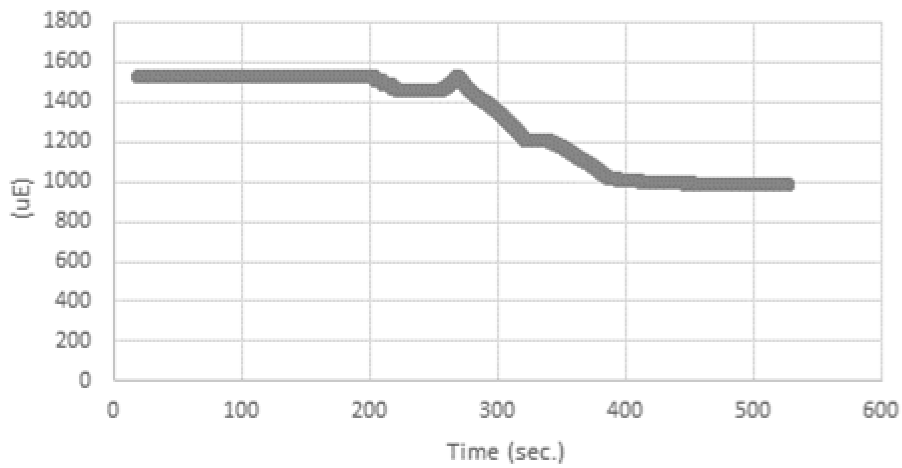

Figure 11 Beam six creep recovery

This graph shows the difficulty of working with a hydraulic hand jack for this research. It is difficult to unload these specimens at a consistent rate as can be seen by the spikes and plateaus in the graph. The average amount of recovery for the .50f'c specimens was 604.73 uE and for the .30f'c specimens it was 537.97 uE The total recovery of each specimen is shown in the table below.

Table 3. Strain recovery of specimens

	.50f'c							.30f'c		
Specimen	1	2	3	4	5	6	7	8	9	10
Strain (uE)	568.84	910.509	504.88	305.83	449.65	544.29	949.08	415.88	662.98	535.05
Average (uE)	604.73							537.97		

Table 4. Strain recovery of specimens relaxed for one month

	.50f'c			.30f'c
Specimen	4	5	6	10
Strain (uE)	286.32	103.24	163.05	179.65

Stress Reversal Response

After being unloaded the beams were placed in a four point loading flexural test to observe how the creep may affect the flexural strength of the concrete. The graph below shows the averages of the control, 30%f’c, and 50%f’c beams. This graph shows that the beams that have experienced creep have a similar but slightly lower modulus of elasticity than the beams that have not. The 50%f’c beams experienced nearly double the amount of strain before fracture than the control beams. The one result that was expected was that the beams that have experienced creep had a lower flexural strength than the control beams.

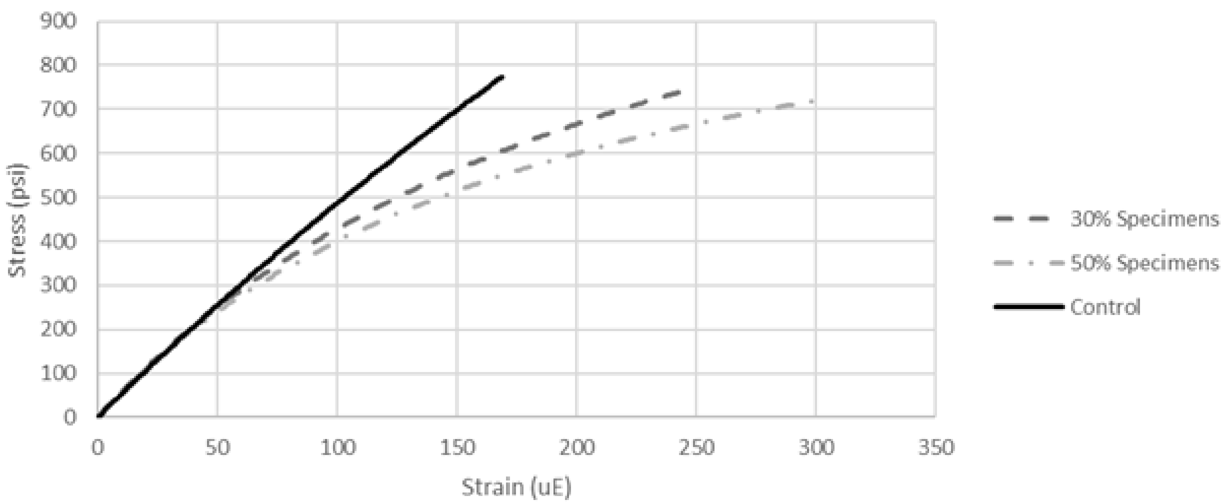

Figure 12. Average four point stress reversal results

It is important to note that the strain shown in these graphs is not the true strain in the specimen, but the strain gained during the flexural test.

An additional round of testing was done where after being subjected to creep some specimens were left to relax for one month before flexural testing. The two graphs below show the individual beams responses during the four point loading flexural tests.

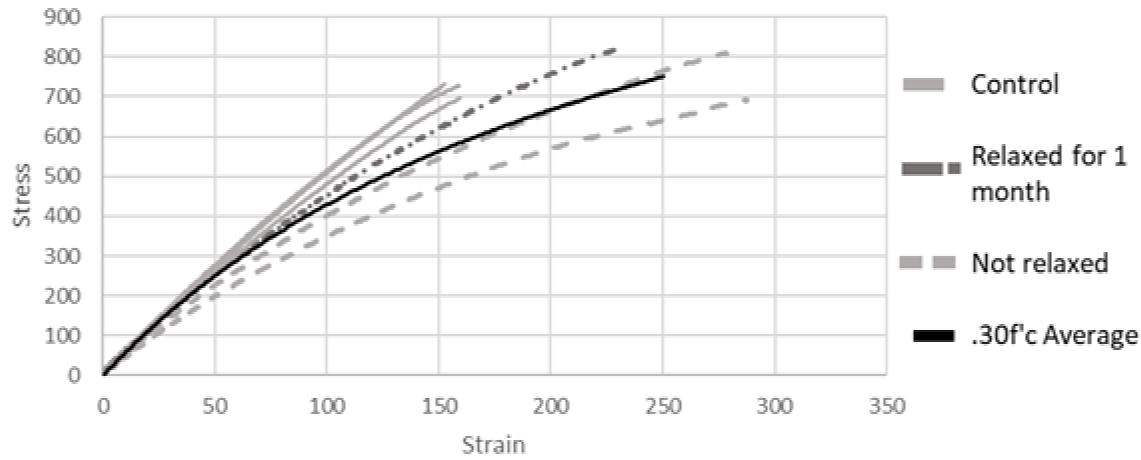

Figure 13. Stress reversal results of 30%f'c

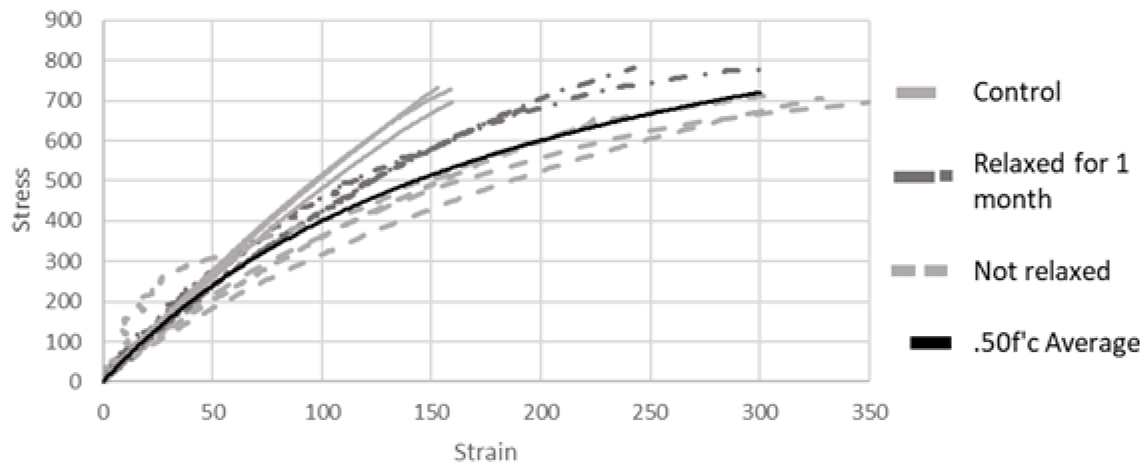

Figure 14. Stress reversal results of 50%f'c

These results indicate that the one-month relaxation period in a way reduced the effect that creep had on the concrete in flexure. This could be attributed to the longer creep recovery time that the concrete was subjected to.

Lastly the compressive strength of the specimens was found by cutting them into 8" sections and loading them to failure. The table below shows the average compressive strength of each specimen.

Table 5. Compressive strength at time of stress reversal

	50%f'c							30%f'c		
Specimen	1	2	3	4	5	6	7	8	9	10
Strength (psi)	5951	4012	6781	5472	6200	5109	6517	7094	5171	4596

There is a large variation in strength between all specimens. For the 50%f'c specimens the average strength was 5720 psi and for the 30%f'c the strength was 5620 psi. From the literature review the expected strength of the concrete specimens should be higher than the 28-day compressive strength due to the aging effect. [12] The lower strength values could be caused by microcracks and other damage that happened during testing and the cutting of the specimens after failure

Chapter 5 - Conclusion

Knowing how materials behave in different scenarios helps make our structures safe and helps engineers to design adequate solutions to complex problems. The results of this research show that beams that have undergone more creep are able to experience more deformation before breaking than beams with less creep. More samples should be gathered at different stress levels and time intervals to better understand the phenomena that was observed during the testing. Through more testing it would be possible to determine how much of a decrease in flexural strength and modulus of elasticity concrete experiences due to creep. This could be useful in the design of structures experiencing sudden changes in forces like during earthquakes where structures are quickly subjected to variable compressive and tensile stresses or in the repair of PCCVs when the prestressing is detensioned. Understanding that concrete may experience more deflection than previously believed could aid designers in creating structures that can better withstand these stress reversal scenarios.

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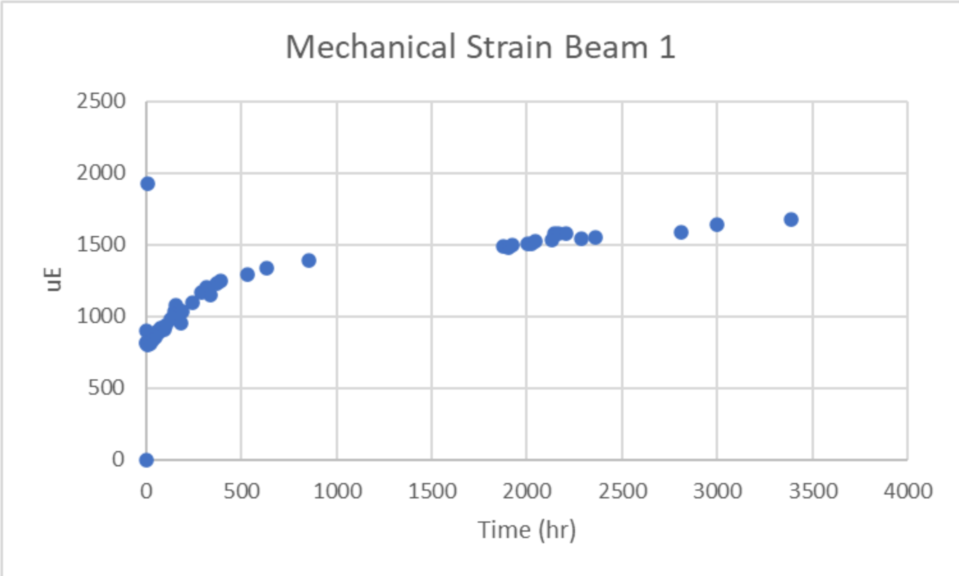
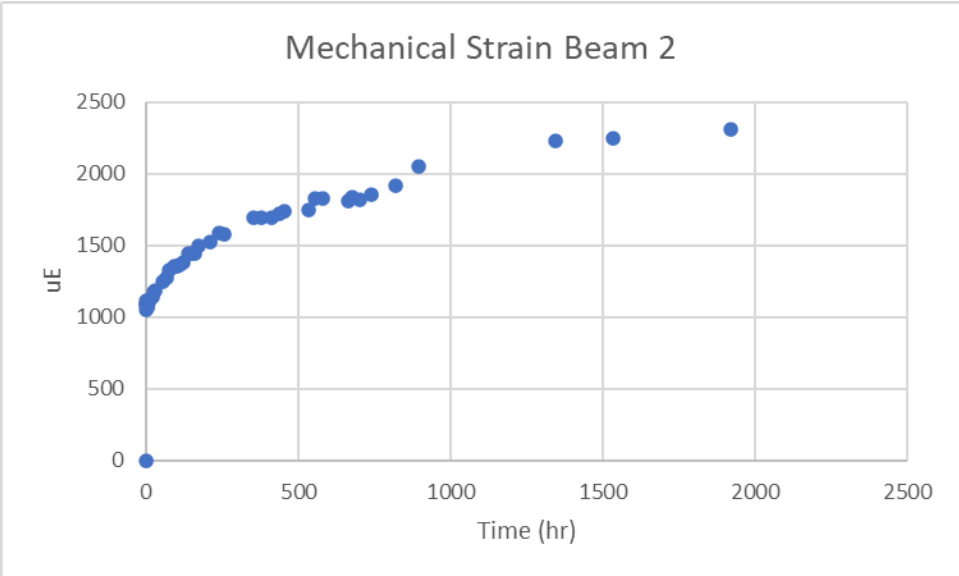
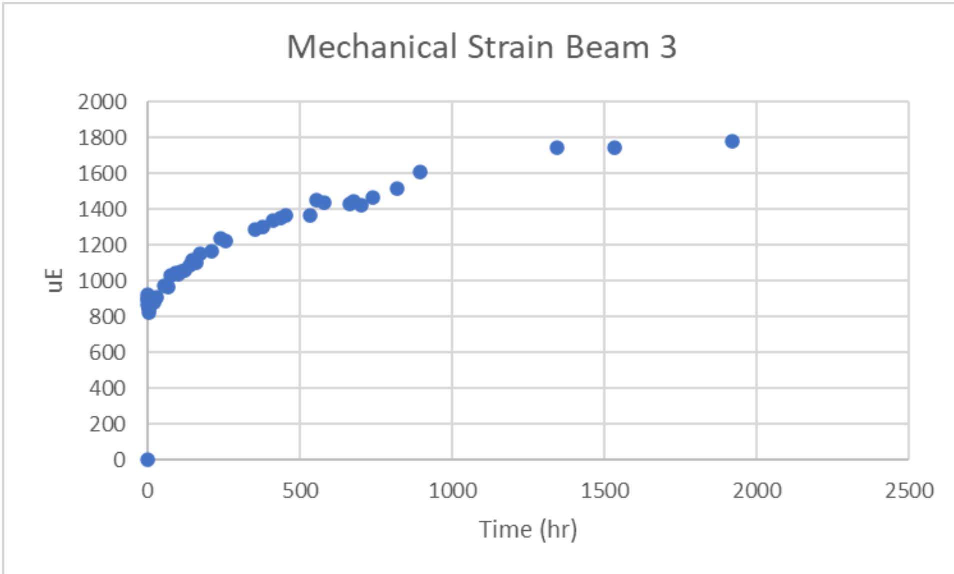
Appendix A - Testing Data



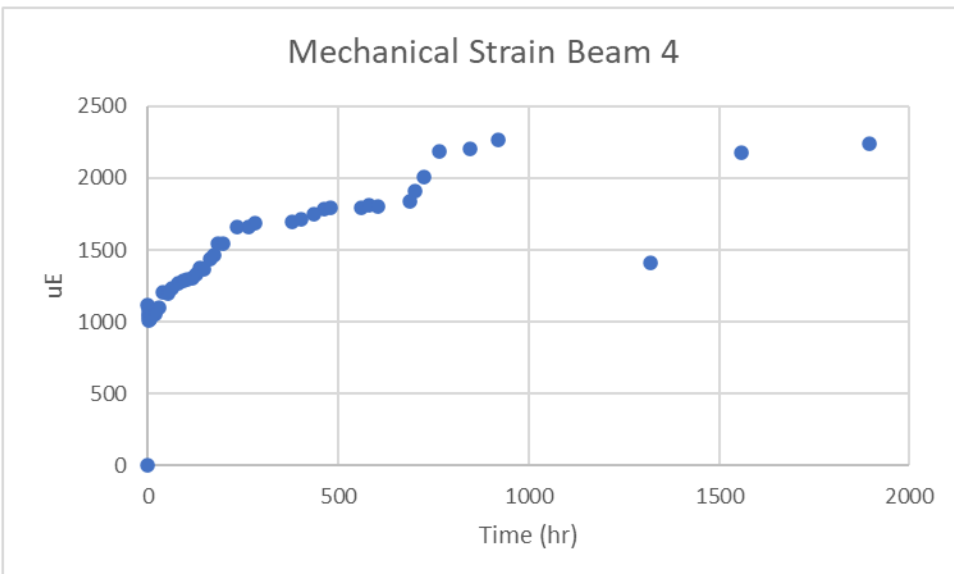
Appendix Figure A.1 Mechanical strain beam 1



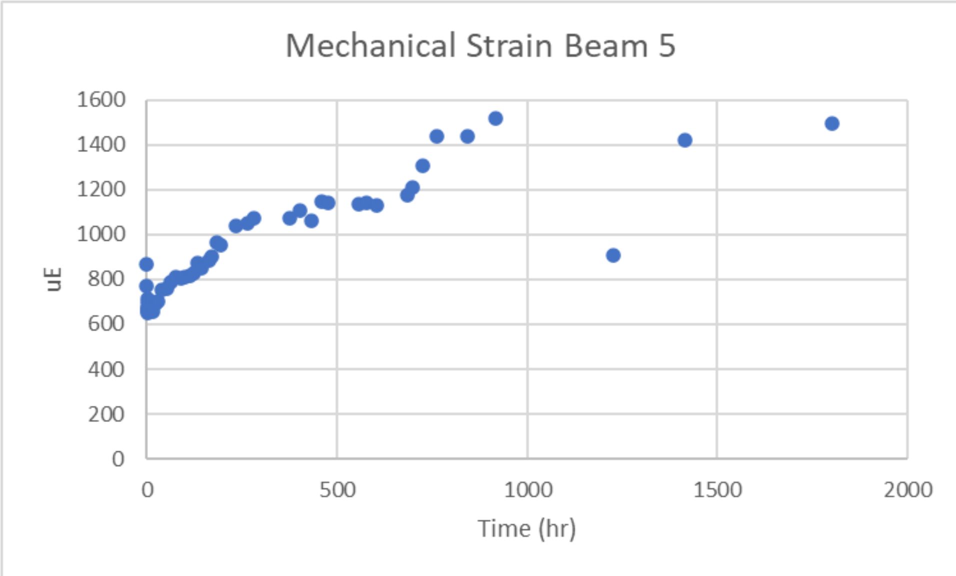
Appendix Figure A.2 Mechanical strain beam 2



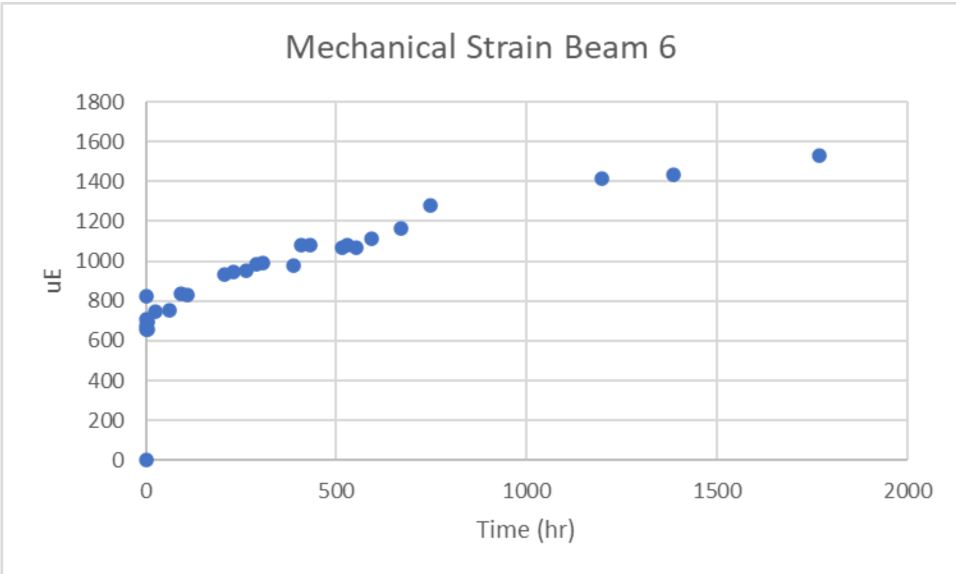
Appendix Figure A.3 Mechanical strain beam 3



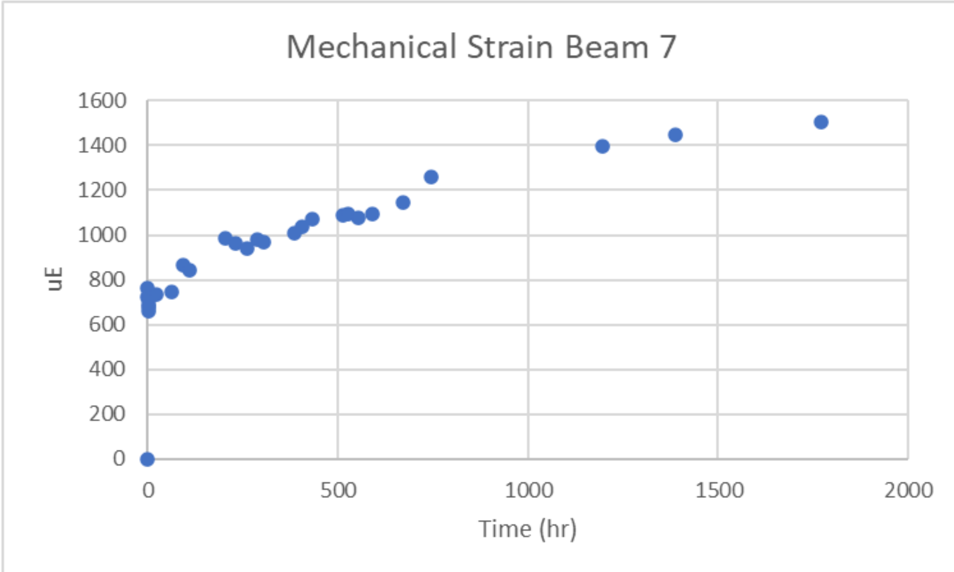
Appendix Figure A.4 Mechanical strain beam 4



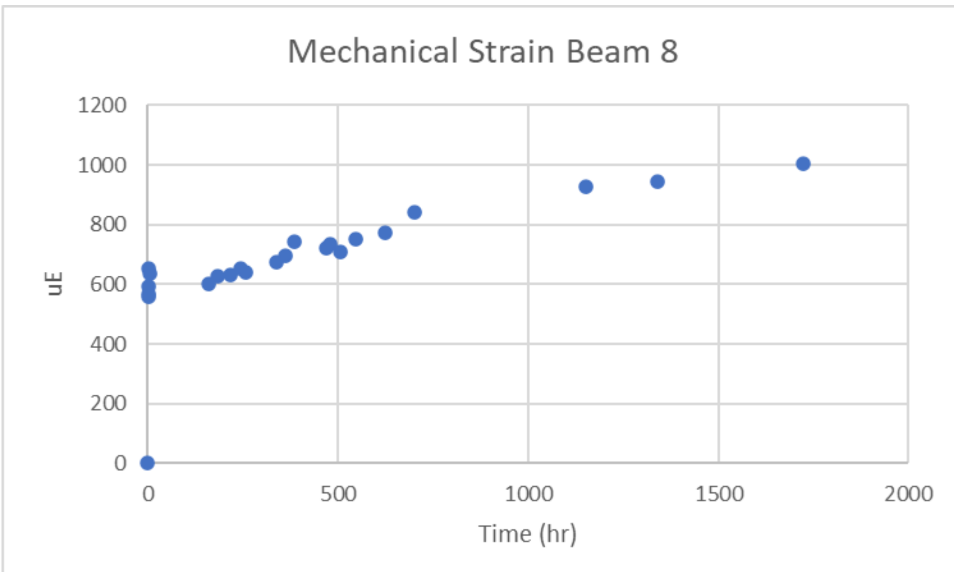
Appendix Figure A.5 Mechanical strain beam 5



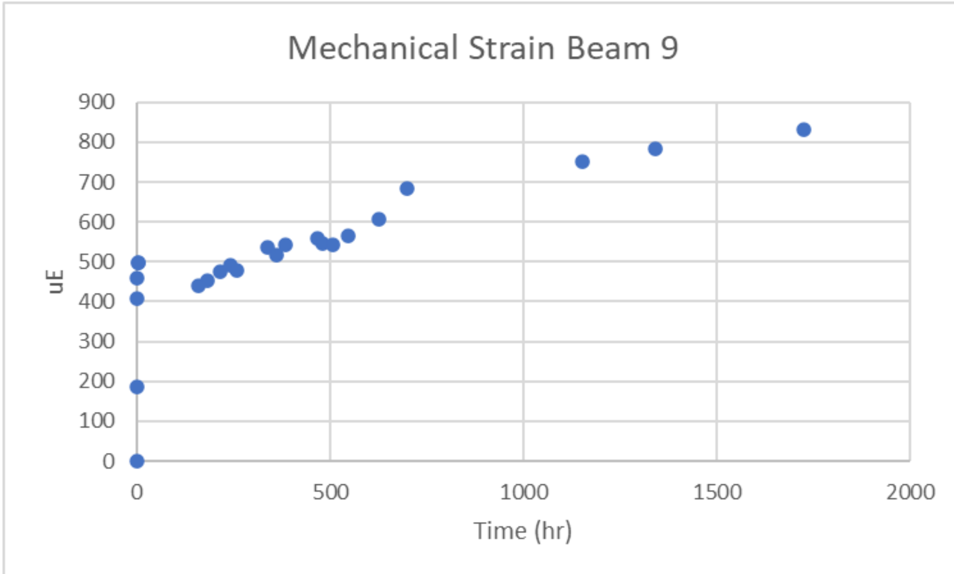
Appendix Figure A.6 Mechanical strain beam 6



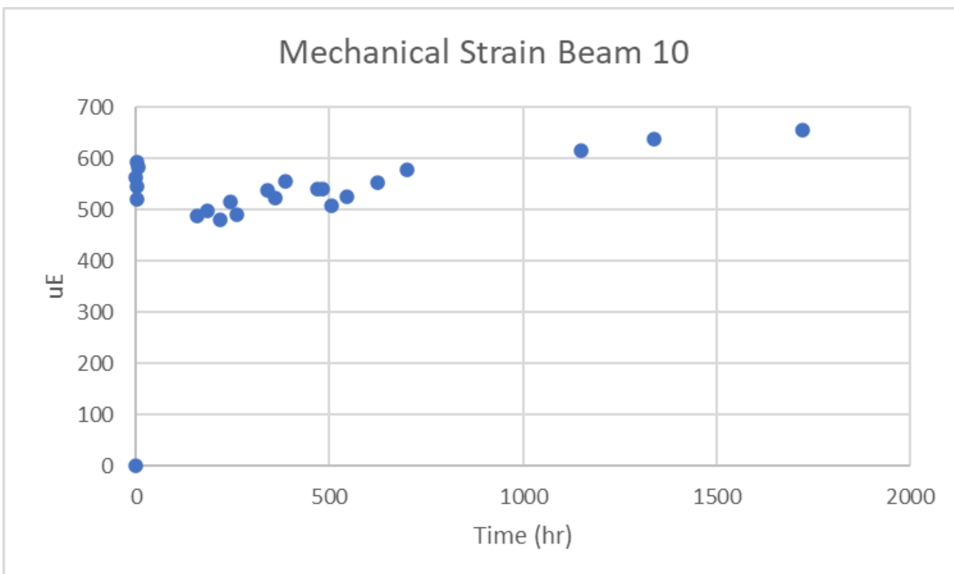
Appendix Figure A.7 Mechanical strain beam 7



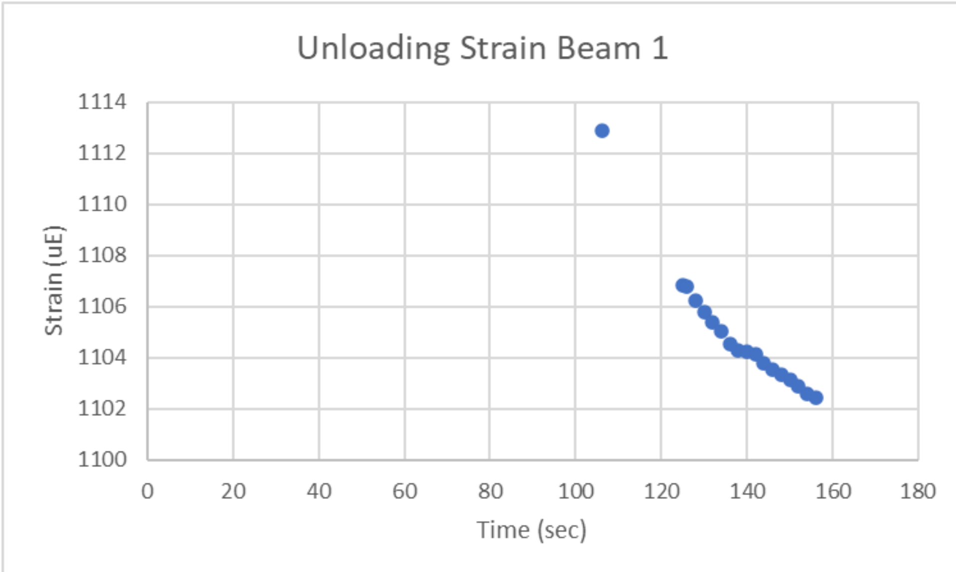
Appendix Figure A.8 Mechanical strain beam 8



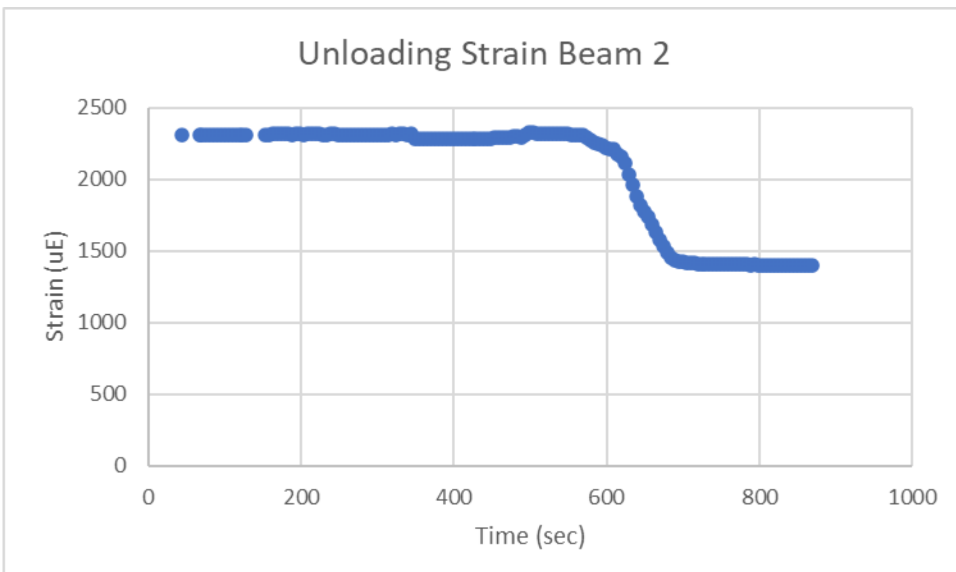
Appendix Figure A.9 Mechanical strain beam 9



Appendix Figure A.10 Mechanical strain beam 10



Appendix Figure A.11 Unloading strain beam 1



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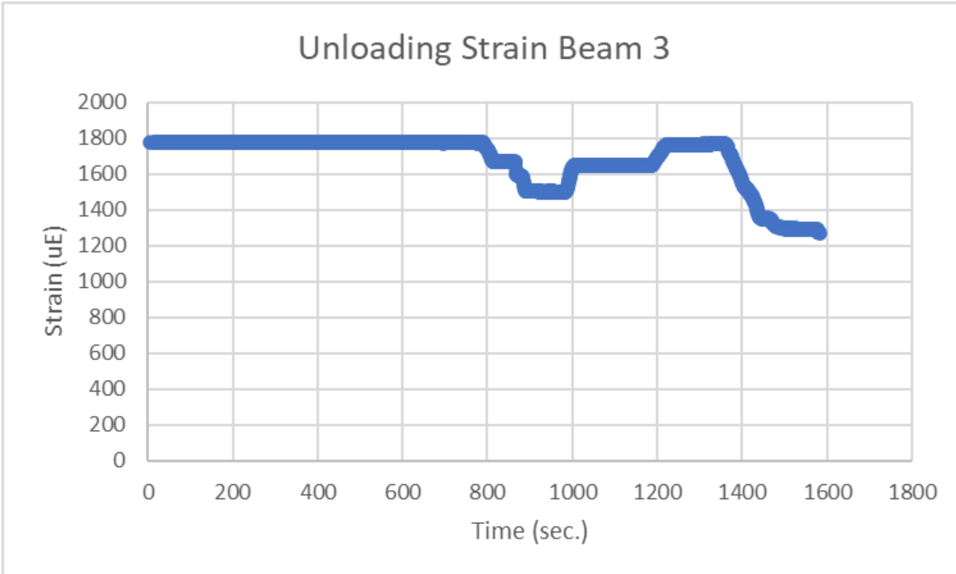
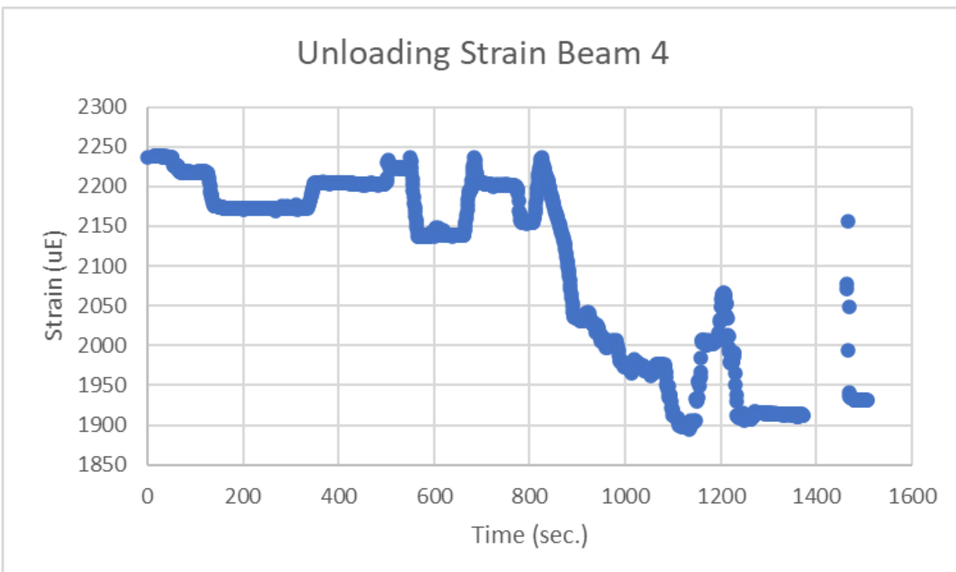
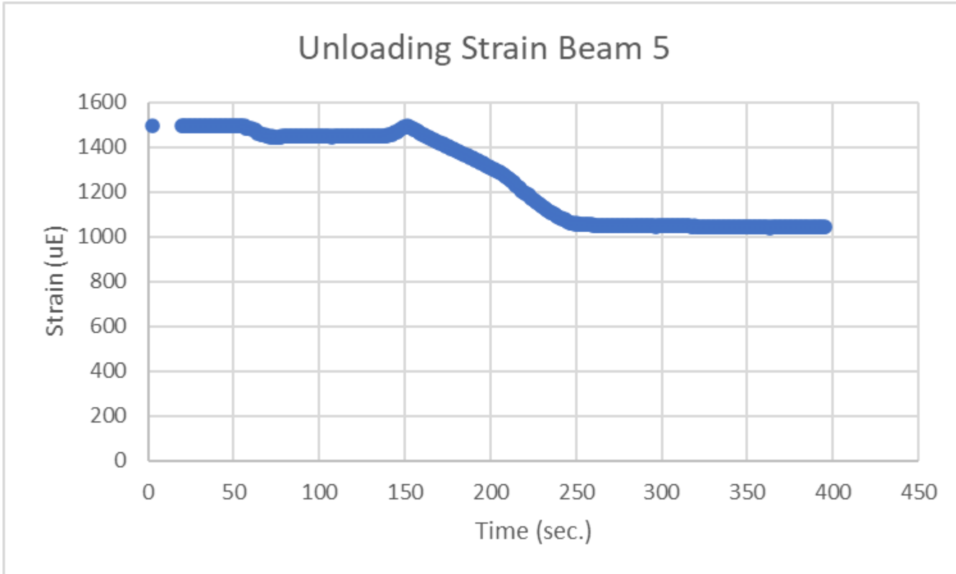


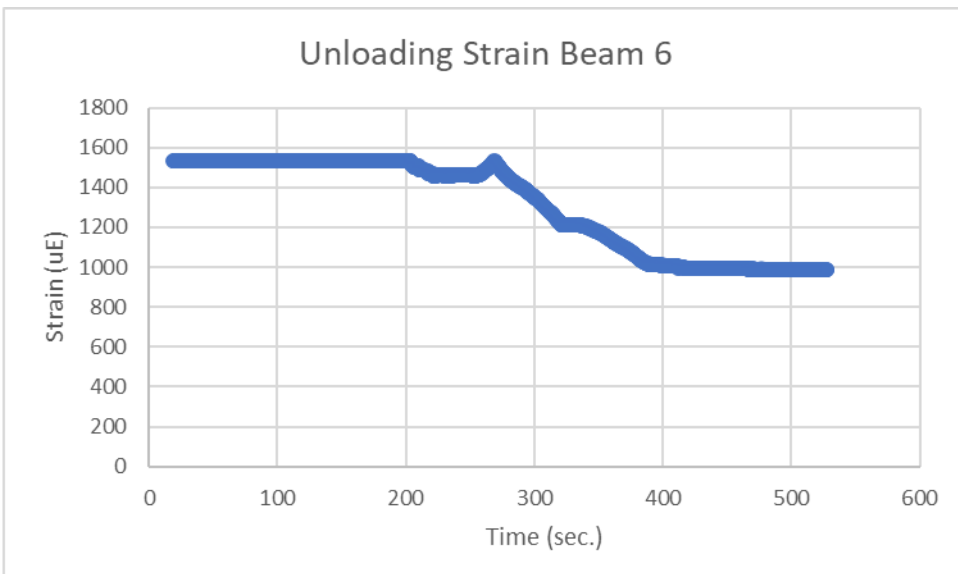
Appendix Figure A.13 Unloading strain beam 3



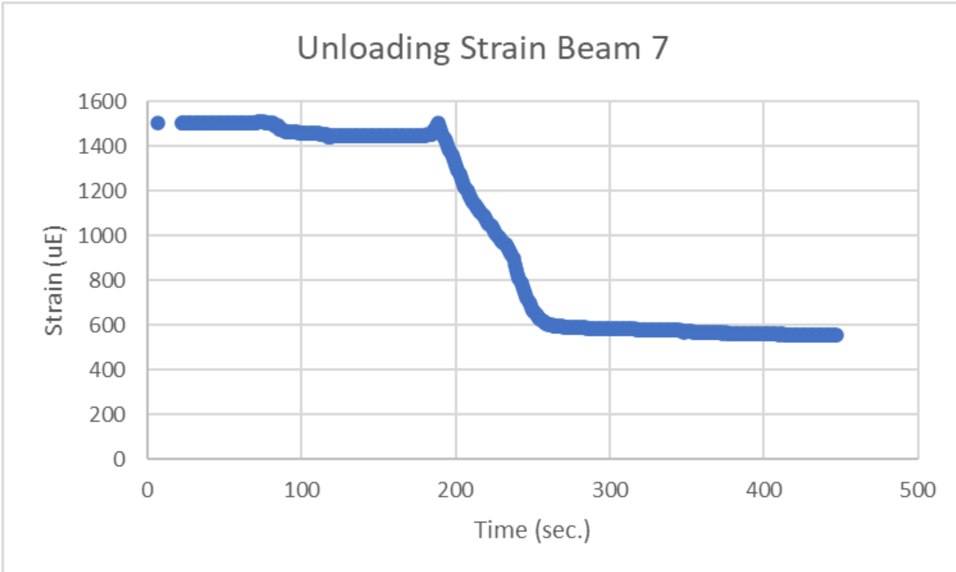
Appendix Figure A.14 Unloading strain beam 4



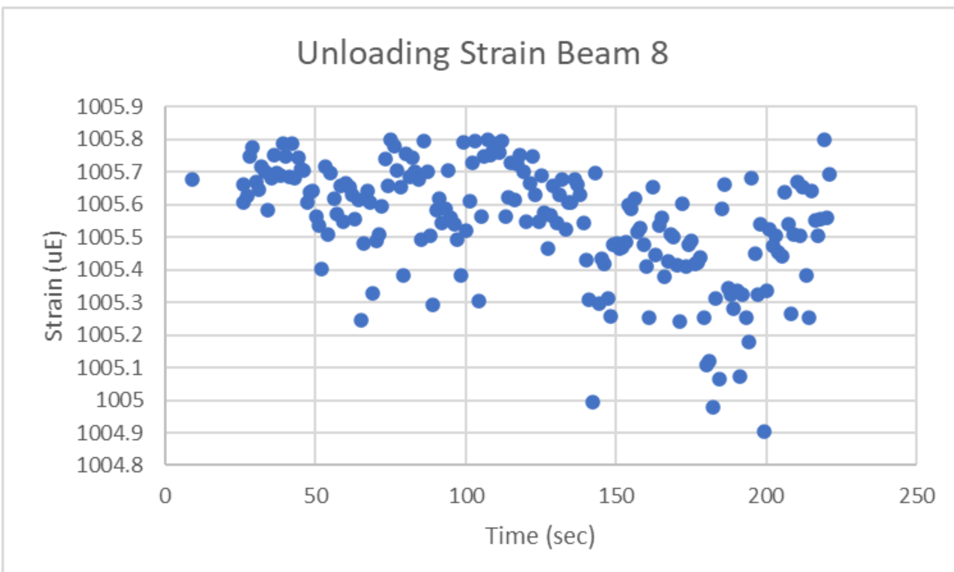
Appendix Figure A.15 Unloading strain beam 5



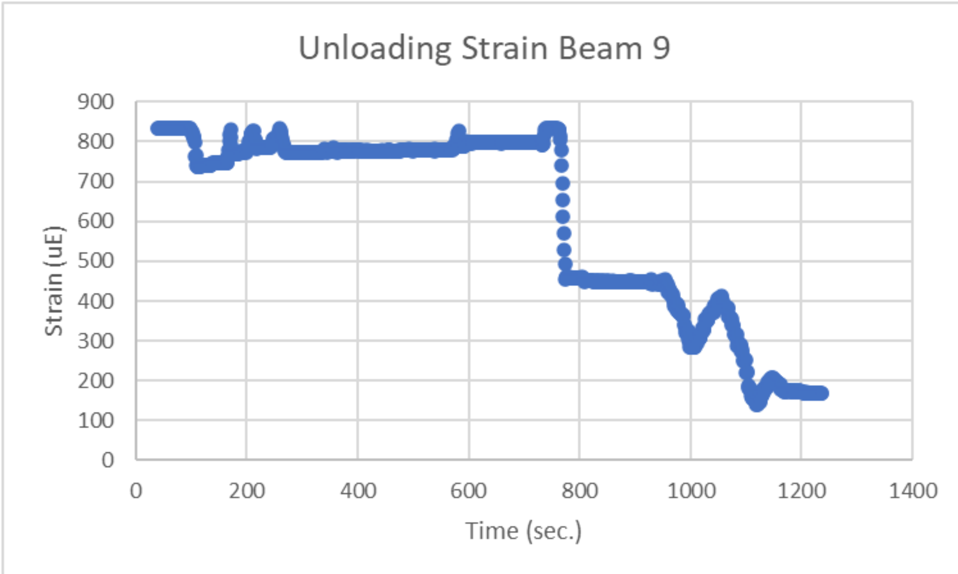
Appendix Figure A.16 Unloading strain beam 6



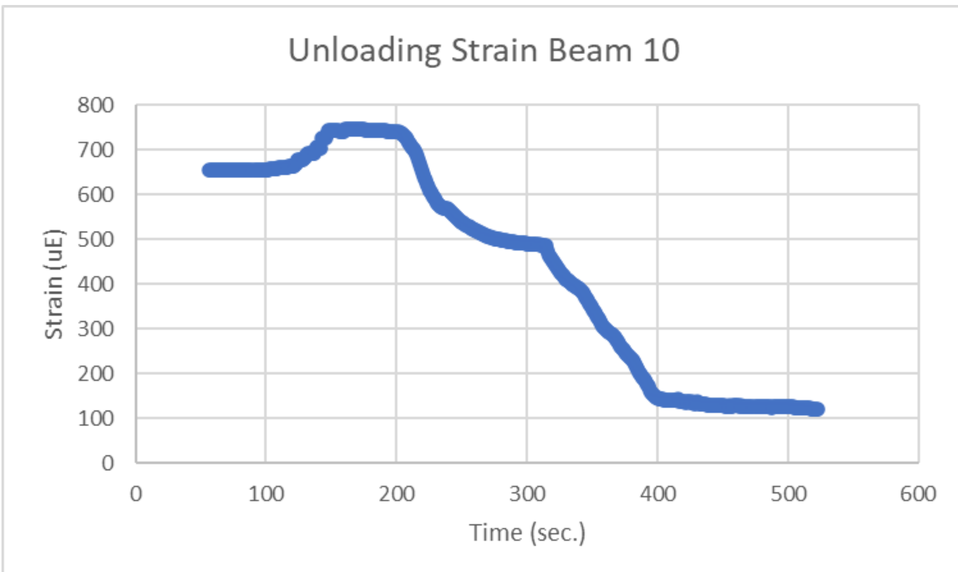
Appendix Figure A.17 Unloading strain beam 7



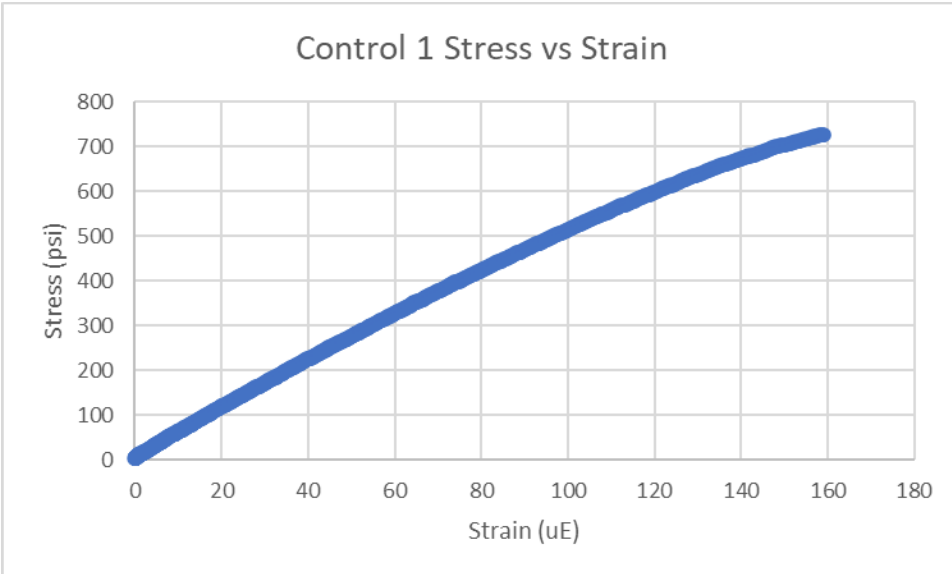
Appendix Figure A.18 Unloading strain beam 8



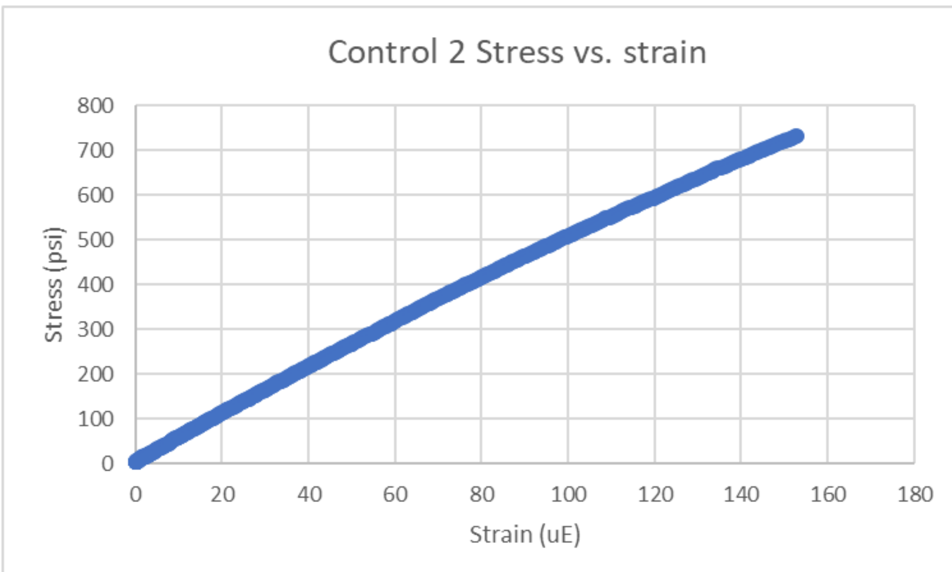
Appendix Figure A.19 Unloading strain beam 9



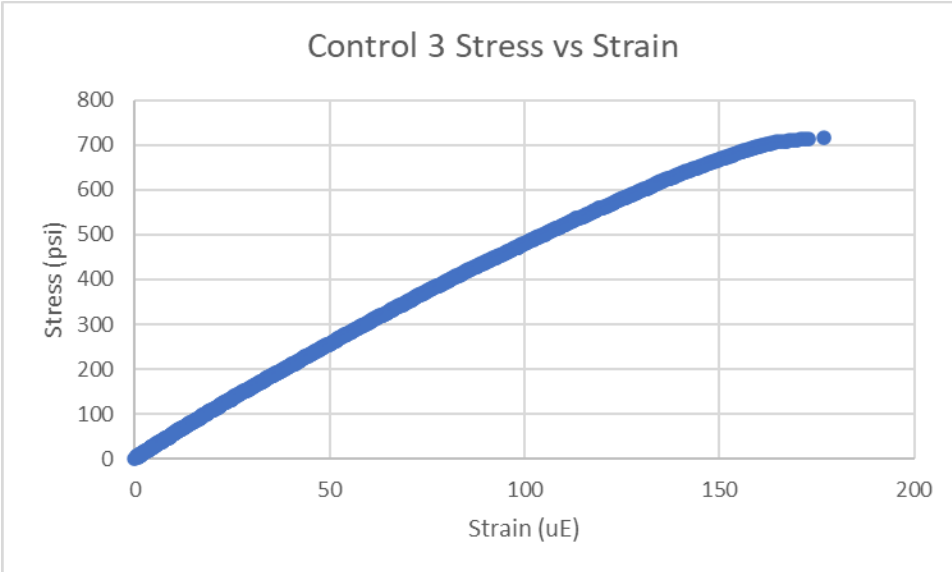
Appendix Figure A.20 Unloading strain beam 10



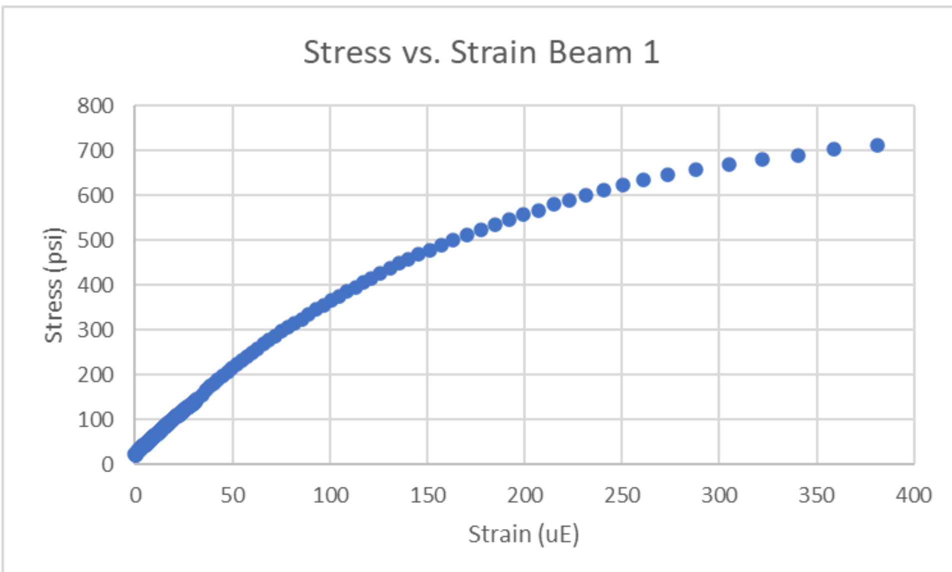
Appendix Figure A.21 Stress reversal control 1



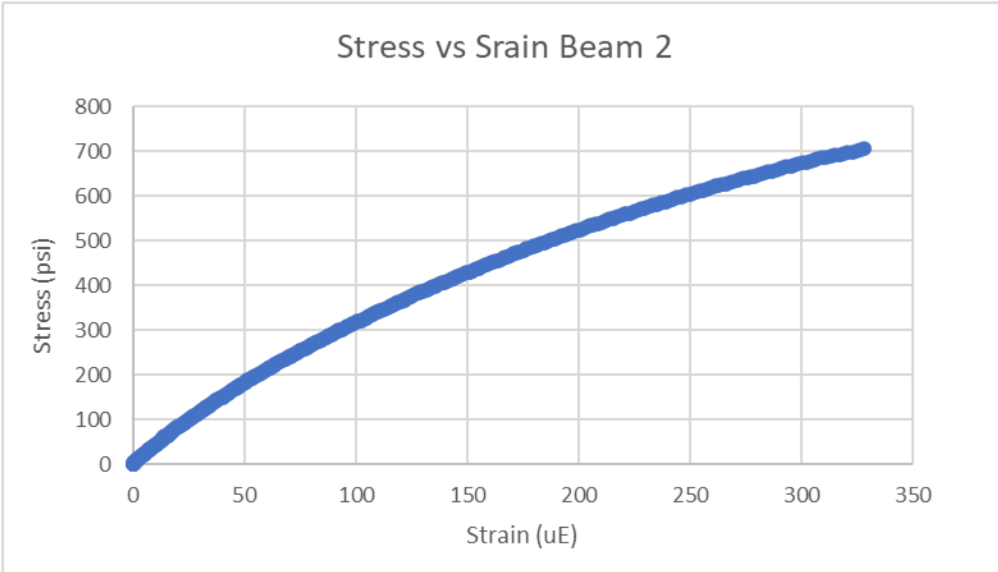
Appendix Figure A.22 Stress reversal control 2



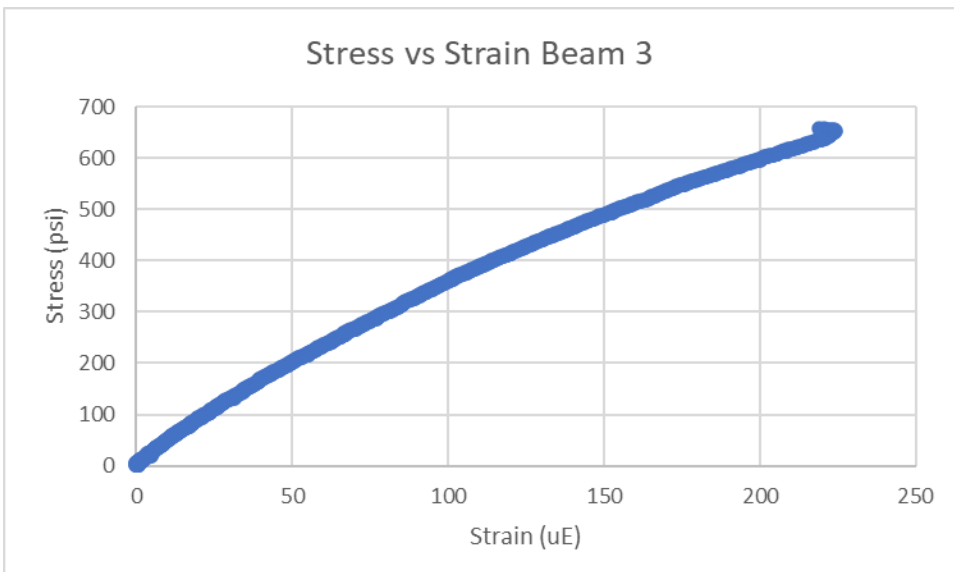
Appendix Figure A.23 Stress reversal control 3



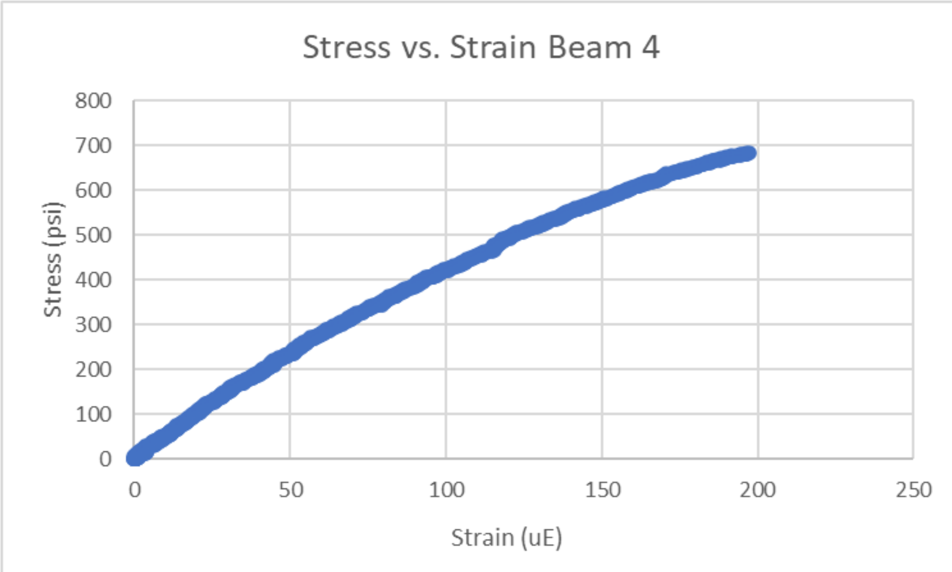
Appendix Figure A.24 Stress reversal beam 1



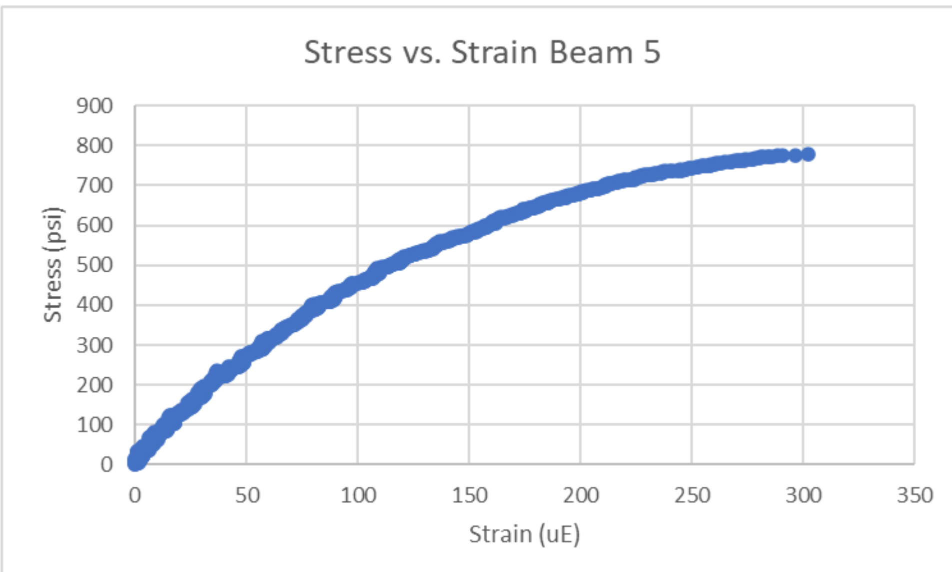
Appendix Figure A.25 Stress reversal beam 2



Appendix Figure A.26 Stress reversal beam 3



Appendix Figure A.27 Stress reversal beam 4



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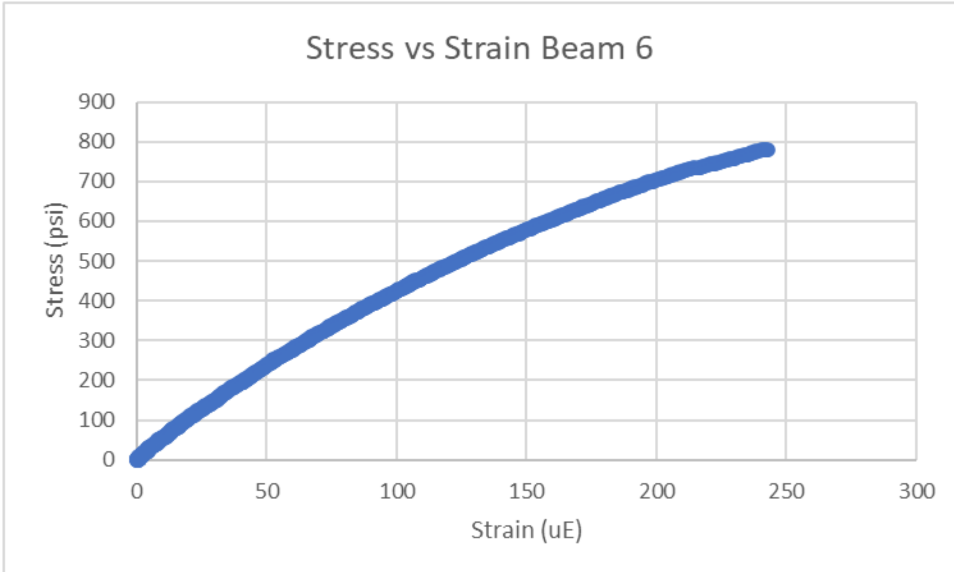

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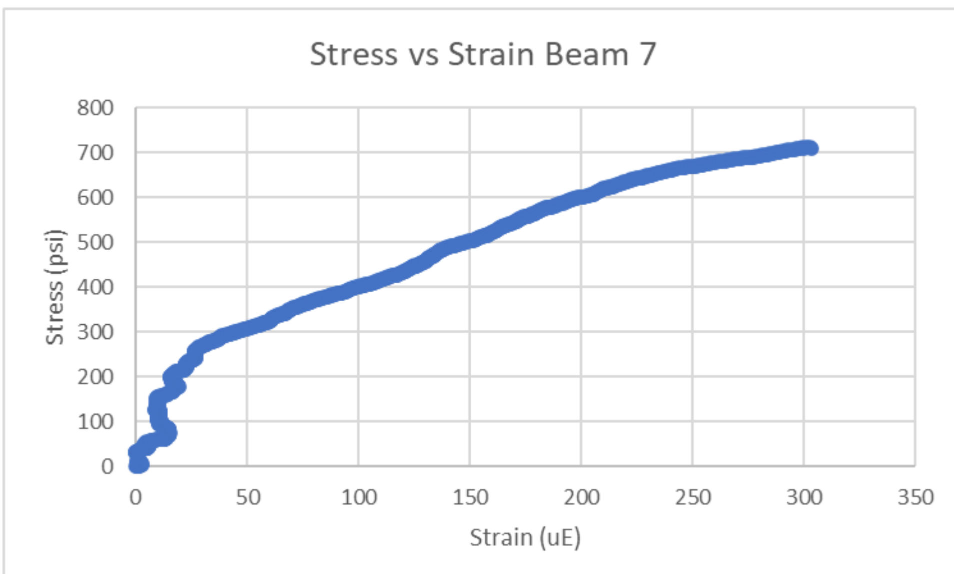
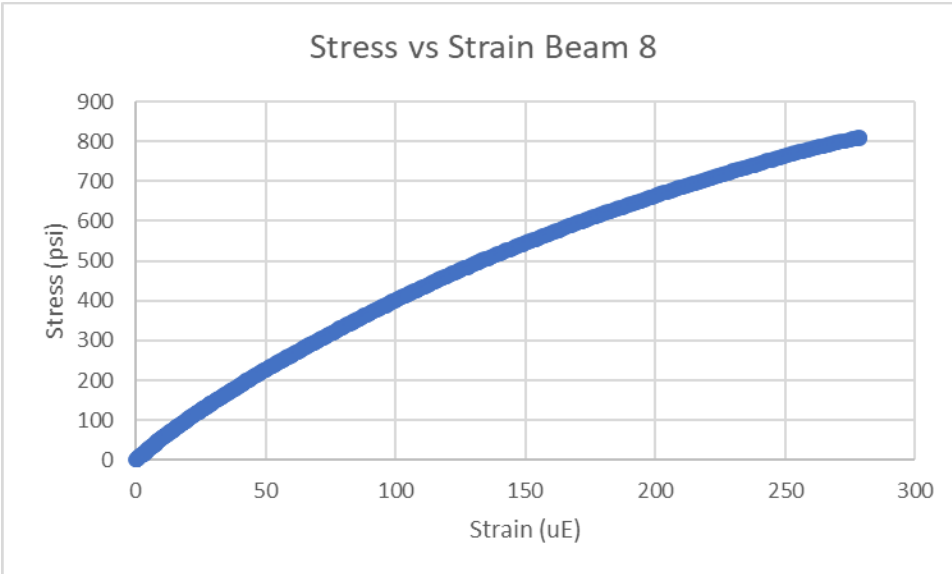
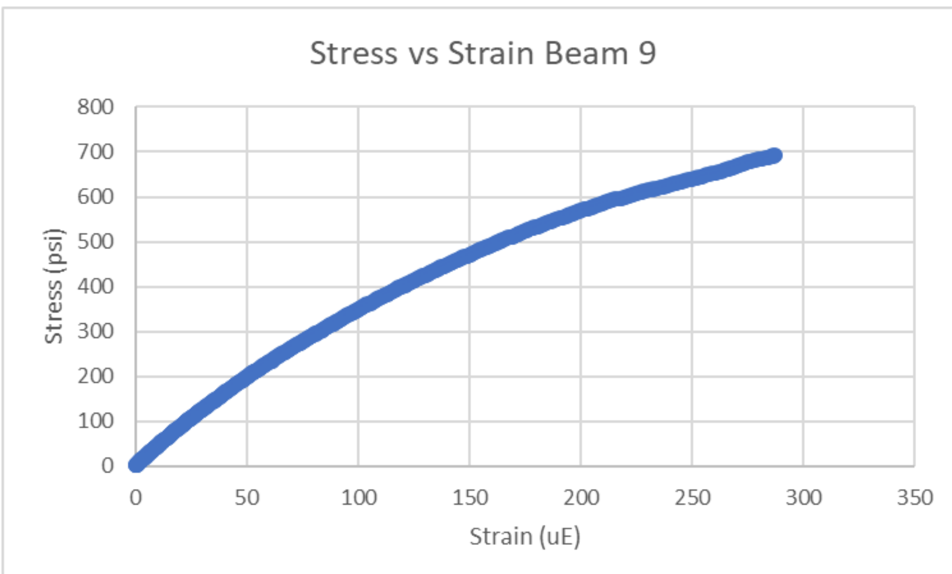


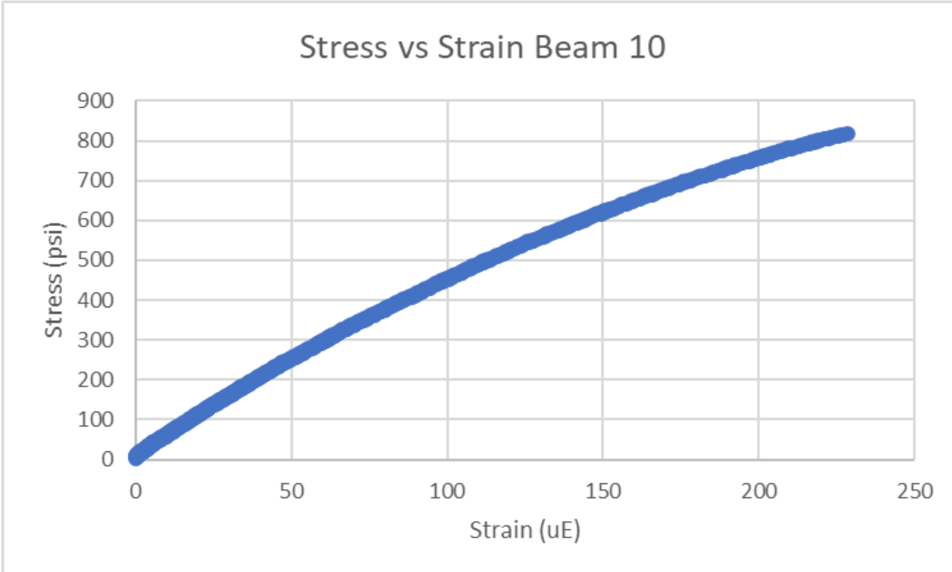
Appendix Figure A.30 Stress reversal beam 7



Appendix Figure A.31 Stress reversal beam 8



Appendix Figure A.32 Stress reversal beam 9



Appendix Figure A.33 Stress reversal beam 10