Deployable Concrete Bridge Arches Major Qualifying Project

Civil Engineering

A Major Qualifying Project
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
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Degree of Bachelor of Science
by

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Project Advisor:

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Project Registration Number: TEL-S209

0.1) Abstract

This project studied the feasibility of using flexible PVC pipe filled with different concrete and soil-concrete mixtures to form a support arch that can be used to support a bridge deck. Five (10 ft) model arches were designed, constructed, and tested. Computer modeling was used to determine the critical factors important in the structural response of the composite arches. Based on these results, recommendations for practical applications and structural capacity limits are suggested.

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0.5) Acknowledgements

Don Pellegrino for operating all of the laboratory equipment, assisting with testing and building restraints for testing.

Dean Daigneault for helping to build all of the formwork, helping to mix and pour all of the concrete and for helping with the arch bending.

Professor Mingjiang Tao for assisting with the finite element analysis.

Michal Parzych for help with the CAD model.

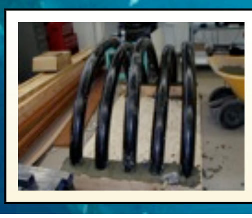
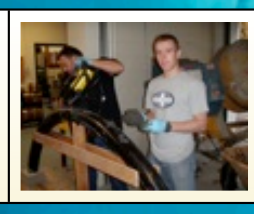
Andrew Crouse, Walter Woodington, and Wesley Simpson for assisting with some of the laboratory tests.

0.6) Executive Summary

DEPLOYABLE CONCRETE BRIDGE ARCHES

EXECUTIVE SUMMARY

Michael Pierri
Advisor: Professor Tahar El-Korchi, Ph.D.

Abstract:

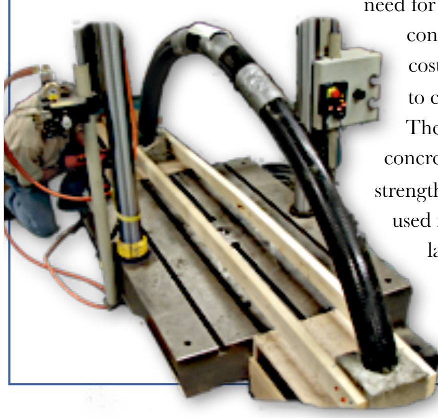
This project studied the feasibility of using flexible PVC pipe filled with different concrete and soil-concrete mixtures to form a support arch that can be used to support a bridge deck. Five (10 ft) model arches were designed, constructed, and tested. Computer modeling was used to determine the critical factors important in the structural response of the composite arches. Based on these results, recommendations for practical applications and structural capacity limits are suggested.

Background:

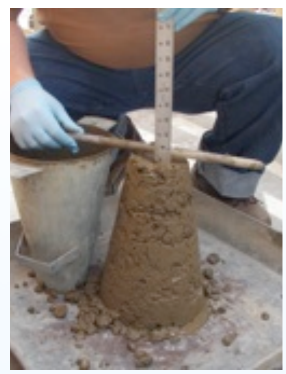
Deployable concrete bridging allows permanent bridges to be built in a short amount of time, utilizing limited labor and material. A system was developed by the University of Maine Advanced Structures & Composites Center that utilizes inflatable arches filled with concrete. It is currently in production on several bridges in Maine. The inflatable composite arches reduce the construction resources needed.

Concrete is strongest in compression by a large factor over its tensile strength. An arch takes advantage of this by keeping the concrete in compression throughout. This lowers the need for rebar, which typically caries the tensile forces in a concrete structure. Rebar significantly increases the cost. The project included the use of fiberglass fibers to carry some of the tensile forces.

The project included a focus on the use of soil-concretes. While there is a significant decrease in the strength of the concrete, there is a lower cost. It can be used in emerging countries or areas that do not require large capacities.



University of Maine: Advanced Structures & Composites Center. Bridge In a Backpack. http://www2.umaine.edu/aewc/content/view/185/71/ (accessed October 1, 2009).



Project Goals

- *Design, construct and load test scale arches*
- *Determine the feasibility of using soil-concrete in arches for bridge supports*
- *Conduct a finite element analysis*
- *Make recommendations for design guidelines based on the results*

DEPLOYABLE CONCRETE BRIDGE ARCHES

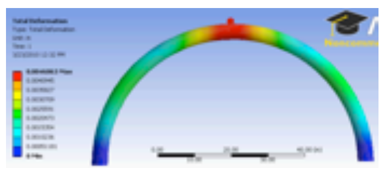
Methods/Process:

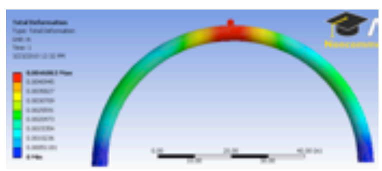
The project involved five major tasks. They were the design of the concrete mixtures, the construction of the five large arches and two smaller arches, the testing process, the computer modeling and the analysis.

The five concrete designs focused on the use of soil as a fine aggregate and the use of fiberglass fibers. The 5 arches were constructed out of 10' sections of flexible PVC Pipe. Concrete was poured into the top of the arches through three drilled holes. During the pouring process the arches were held in place by light bracing. The arches were tested using an Instron Servo-hydraulic testing machine in static mode. 6x12 concrete cylinder compression testing was conducted to determine the f'c of the samples. A finite element computer analysis was conducted using ANSYS Workbench 12. The analysis of the results was conducted using analytical methods.

Results/Outcomes:

The arches failed in tension at the load predicted by the computer analysis but with a much larger deflection. They deformed in the manner predicted by the computer model.

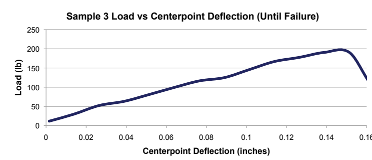




Finite Element Analysis for 250lb Point Load: Deformation (T). Stress (B)

Conclusions and Recommendations:

The arches were laterally unstable during structural loading, leading to the deformation of the geometric circular shape, causing the arches to fail in tension. Small amounts of rebar should be inserted into the top of arch to absorb the tensile forces, because this is the most likely place for tension to occur. A more robust bracing system should be used when pouring the concrete to maintain the geometry better.



Load vs Deflection

Project Acknowledgements:

Don Pellegrino, ***Dean Daigeault***, *Professor Mingjaing Tao, Michal Parzych, Andrew Crouse, Walter Woodington, Wesley Simpson*

1) Introduction

The focus of the project is the development of sustainable, deployable concrete arches that can be used for a variety of purposes such as bridging and building support structures. The goals of the project were to design, construct and load test scale arches to determine the feasibility of using soil-concrete in arches for bridge supports; to conduct a finite element analysis; and to make recommendations for design guidelines based on the results.

Tubes were made utilizing commercially available PVC piping. Multiple samples were tested, although experimentation was limited by budget and time. The arches were compared to a computer simulation and another product that has already been developed.

The project audience includes developers of currently available deployable concrete arches, people interested in bringing low cost bridging to areas with limited resources, and others interested in the subject.

The project is presented in a written report that meets the standards for a Major Qualifying Project at Worcester Polytechnic Institute, a presentation poster, along with accompanying video material from the testing project. The results were used to determine the feasibility of different materials that can be used to construct deployable arches.

2) Background

Deployable Bridging

Bridges are a major component of any transportation system that allows traffic to flow over different types of obstacles. Bridges, along with tunnels require a significantly greater expenditure of engineering knowledge and funding to develop and construct than ordinary sections of roadway. However many situations may occur when a bridge needs to be constructed rapidly such as when replacing a previous bridge would cause a large disruption in traffic, or after a bridge failure. Deployable bridging allows for obstacles to be crossed rapidly but they are usually only temporary solutions and require a significant amount of heavy equipment to deploy.

In recent years, rapidly deployable concrete bridging has gained a lot of attention because of their ease of construction, durability and cost. The systems allow for permanent bridging that can be constructed with limited resources including material, personnel or construction equipment.

The main component of theses bridges are concrete arches with limited reinforcement. The arches can be integrated into many different kinds of structures such as a bridge. The concept revolves around a lightweight composite tube that can be transported by a small crew. The tube is molded to the desired geometry and then placed in position. It is then filled with ordinary concrete. The tube holds the concrete while it sets as well as providing structural support and protection from the elements. Many of these arches are combined to build a support structure, and covered with decking.

Deployable concrete bridging has been extensively studied. The current state of the art design is the Rigidified Inflatable Arch system that was designed by the University of Maine Advanced Structures and Composites Center in conjunction with the United States Army Natick

Soldier RD & E Center. Over 55 Million dollars[1] have been invested in its development. The system has recently been used on a production bridge in Maine and there are plans to build many more with this system. The RICA system has been commercialized and the procedure used to manufacture the inner tubes is patent pending.

This project will be different from previous research because it will focus on utilizing low strength and soil-cement. It will utilize improvised inner tubes made of readily available materials and only a small amount of personnel.

Testing Equipment

The project utilized two major pieces of testing equipment in the lab. The machine depicted in the left of Figure 1 is a Satec (subsidiary of Instron) retrofit of an existing Tinius Olsen servo controlled hydraulic testing machine. The system is capable of tension, compression and flexural testing in accordance with ASTM standards. The retrofit included a computer based control system. It has a maximum load capacity of 400 kips[2].

The testing machine pictured to the right in Figure 1 is an Instron Axial Servo hydraulic dynamic two-column load frame. During testing it was used in static mode. It is computer controlled. It is capable of 110 kips[3]. The machine was able to accommodate the 10' long arch.

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[1] Christina Skiarz-Libby, "http://www.onekcwired.com/wiredacademy/maineFINAL.pdf," Maine's North Star Alliance (Augusta: Office of the Governor (ME), 2009).
[2] Satec, "Satec Quotation No. 029-9071-A," Satec (Worcester: Satec, 1999).
[3] Tim Baldwin and Maric Ghelfi, "Quotation," Instron (Canton: Instron, 2000).

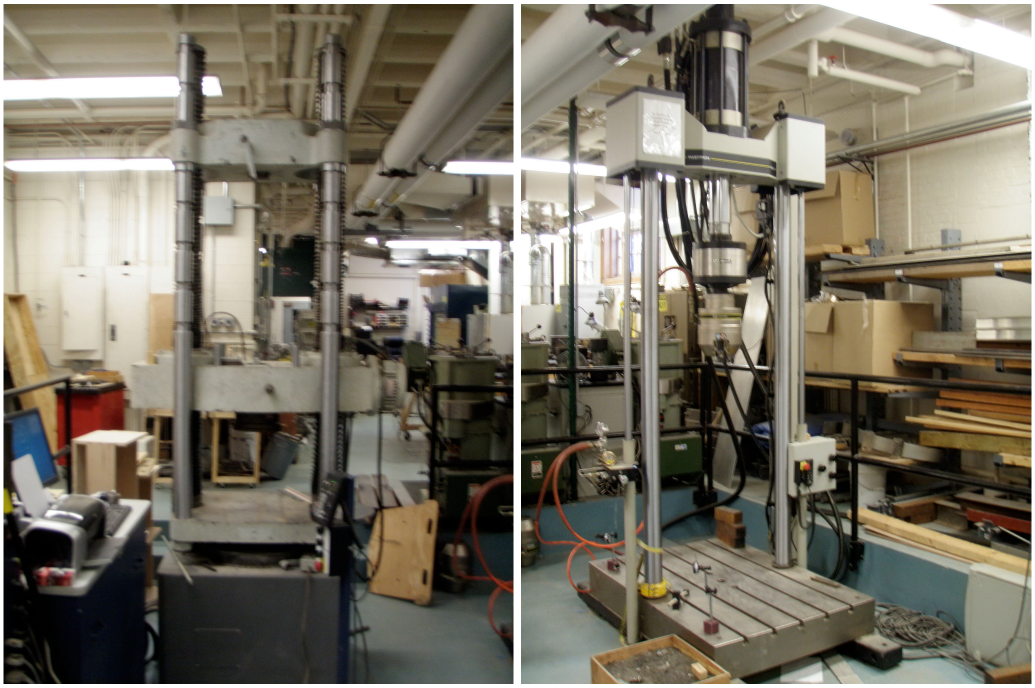
Figure 1 - 400,000 lb Tinius Olsen (L), 110,000 lb Instron (R)

Concrete Arches

Maintaining an accurate geometric arch shape will maintain the stresses in the arch in compression. This will take advantage of the high compressive strength capacity of the concrete. Concrete is a mixture of aggregate and paste. The aggregate usually consists of sand and gravel and the paste is a mixture of water and cement. The compressive strength (f'c) can vary greatly depending on the mix design. Most general use concretes have an f'c of 3000-6000 PSI. However, specialty high strength concretes can exceed 20000 PSI[4]. The tensile strength is only 8-12% of the compressive strength.

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[4] Steven H Kosmatka, Beatrix Kerkhoff and William C Panarese, Design and Control of Concrete Mixtures, 14th Edition (Skokie: Portland Cement Association, 2002), 8

3) Methodology

Project Planning

The original plan was designed to be flexible, depending on the availability of material, laboratory equipment and personal time. Although delayed by several weeks, the actual schedule was similar to the proposed timetable. The overage was acceptable because additional time was allocated in the original plan. The proposed and actual schedules are presented below.

Proposed Schedule:

Proposed Schedule and Tasks

- **A Term 09**
  - Complete Project Proposal
  - Obtain funding/approval
  - Develop Testing procedure
  - Perform Calculations
  - Order Materials early enough that they arrive before B-Term
  - Complete Background and skeleton of Project Report
  - Develop AutoCAD drawings of proposed arches
- **B Term 09**
  - Conduct Lab Work and collect data
    - Construct Inner Tubes
    - Mix and pour concrete
    - Static load testing of arches
  - Write Project Methodology section
- **C Term 09**
  - Analyze results
  - Submit full draft of project report and presentation
  - Complete Project Report
  - Complete Project Presentation
- **D Term 09**
  - Overflow time

Actual Schedule:

- **A Term 09**
  - Complete Project Proposal
  - Obtain funding/approval
  - Develop Testing procedure
  - Perform Calculations
  - Begin Background
- **B Term 09**
  - Attempt Pipe Bending
  - Purchase Flexible Pipe
  - Pour Footings
  - Pour Arch 1-5
- **C Term 10**
  - Test Arch 1-5
  - Test Cylinders 1-3
  - Continue Report
  - Begin Computer Analysis
- **D Term 10**

Complete Computer Analysis
Test Mini Arch 1-2
Design and Present Project Poster
Complete Project Report

Making Arches

Attempted Rigid PVC Bending

The second phase of the project focused the design and construction of the five arches. To save costs, attempts were made to use standard schedule-40 PVC pipe and bend it into the shape of an arch. A lot of laboratory time and material resources were committed to bending the PVC pipe. After four attempts, it was determined that bending non-flexible PVC pipe was unfeasible for the project. The PVC bending attempts set the project back about two weeks, but only cost about $100. Parts of the process are presented in Figure 2. (See Appendix C for more details about the PVC bending attempts)

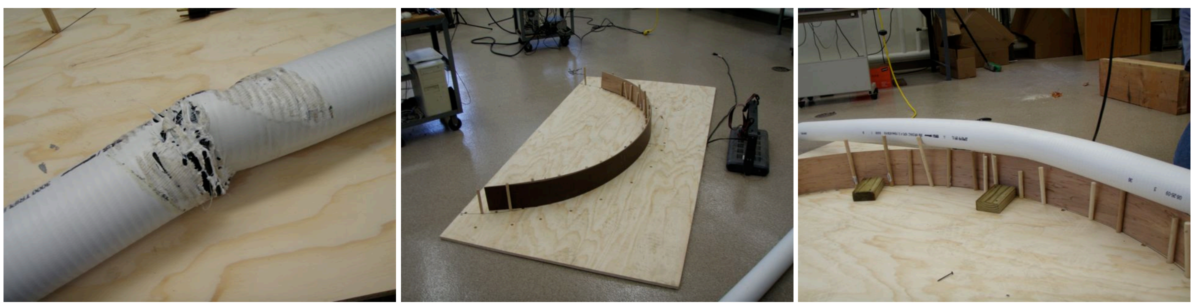


Figure 2 - Pipe Melting (L), Pipe Bending Jig (C), Bending in Progress (R)

Buying Flexible PVC Pipe

After the attempted bending, commercial pipe was purchased by the department from a pond supplier for around $600. The pipe was cut into 10’ sections and is presented in Figure 3.

Figure 3 – Purchased Flexible PVC Pipe

<u>Mix Design</u>

The mix designs were completed using the absolute volume method and they are detailed in <u>Appendix B</u>. The water content ratio varied between .45 and .55. Sample one was made from the same mix design as the footings. Sample two included silica fume and fiberglass fibers. Samples three and four were identical except that mix four included fiberglass fibers. Both mixes had a high proportion of silt. Sample five was mostly paste and included a lot of silt.

<u>Batching and Mixing Concrete</u>

The concrete was batched by weight and then mixed in a mechanical spinner on site. The wet concrete was poured into a wheelbarrow in preparation for pouring. Some images from the mixing process are presented in Figure 4.

Figure 4 - Mixing Concrete

Pouring Footings
Two wood forms with five slots each were built for the arch footings. The forms were filled half way with concrete and then the end of the tube was inserted. The rest of the footing was then filled. The footings were covered with plastic to assist with curing. Some images from the process are presented in Figure 5.

Figure 5 - Footing Form (L), Poured Footing (C, R)

Pouring Concrete
The concrete was inserted into the arches by hand through three 2" diameter holes that were cut along the top of each arch. A mechanical vibrator was used to help the concrete side to the bottom of the tube. The holes were then sealed with duct tape. The first arch was poured without using vertical or lateral supports while supports were used for the rest of the arches after the first method was found to be unfeasible. Slump tests were conducted for each mix. F'c testing cylinders were only made for three of the five samples due to limited supplies of excess concrete. More information about the pouring of the individual arches is presented in Appendix D and an image is presented in Figure 6.

Figure 6 - Inserting Concrete in to Top of Arch and Use of Mechanical Vibrator

<u>Setting</u>

The first two arches were removed from their supports and placed on the ground to free up supplies for the remaining arches. The remaining arches remained in the same supports that were used during pouring until final testing. The supports are presented in Figure 7.

Figure 7 - Arch Setting

Making Mini-Arches

Two smaller scale arches were made out of 2" diameter rigid PVC Pipe. The pipe was cut into two and three foot sections. The first two bending attempts were made by simply placing the section into the oven at around 130º F and then bending them using manual labor. The attempts were deemed unsuccessful because of excessive kinking. The next two sections had slots cut into the part that would form the inner edge of the arch and placed in the oven. This method was fairly successful, although there was still some kinking. The arches were then wrapped with clear duct tape to prevent leaking though the cuts and the ends. The process is presented in Figure 8.

Figure 8 - Mini Arch Bending Process

Concrete was batched and mixed in a small bucket using manual labor. The concrete was inserted into the arches through one of the tube ends and ridded throughout the process. The arch was then placed in the curing room for three days. The batching and pouring process is presented in Figure 9.

Figure 9 - Mini Arch Concrete Batching and Pouring

The arches were then tested in the small Instron machine. Two holes were drilled into a 2x4 to hold the ends of the arches. The 2x4 was clamped to the machine. The restraint is presented in Figure 10.

Figure 10 - Mini Arch Test Restraint

Testing

Cylinder Testing

The standard 6x12 cylinders from mixes 2, 3 and 4 were tested in compression using the small Instron machine. The loading rate was .7 in/min. The process is depicted in Figure 11 and Figure 12.

Figure 11 - Sample 2 Being Tested

Figure 12 - Sample 3 Being Tested

<u>Arch Testing</u>

The static load testing was conducted using the big Instron machine. A point load was applied in the center of each arch on to a cut piece of PVC pipe (depicted in white in Figure 13). The loading rate varied depending on the test between .5in/min and 1in/min.

An attempt was made to use strain gauges on some of the tests but the movement of the arch exceeded the capability of the gauge and the portion tested fluctuated in both directions throughout each test, making it hard to record data.

Throughout the testing process new restraint systems were developed. Since arch one and two were accidently broken before the testing process they were tested first in order to verify the testing process. The first test was conducted using minimal restraints. The setup is presented in Figure 13. Based on the first test, additional restraints were added as depicted in Figure 14. Based on the results, the final restraint system was implemented and is presented in Figure 15.

Figure 13 - Preparing for Test 1 (Arch 2)

Figure 14 - Preparing for Test 2 (Arch 1)

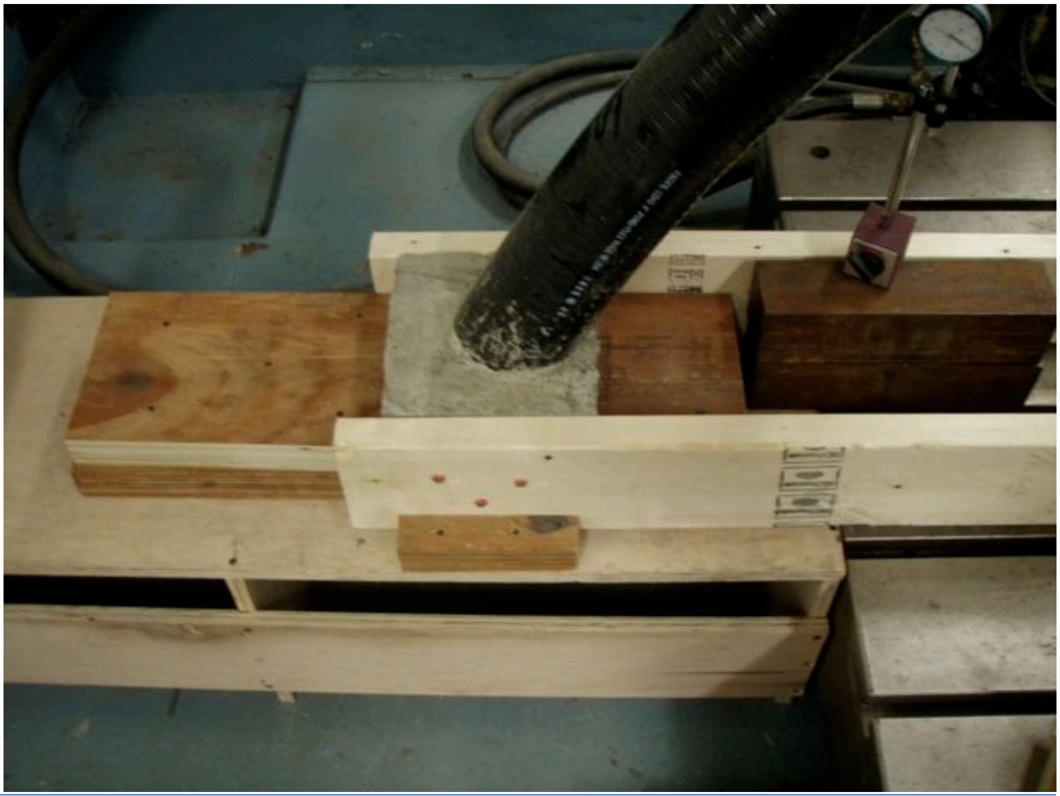


Figure 15 - Restraints Used for Test 3, 4 and 5

Mini Arch Testing

The static load testing was conducted using the small Instron machine. A point load was applied in the center of each arch. The loading rate varied from .5in/min to .75in/min depending on the test. The test setup is presented in Figure 16

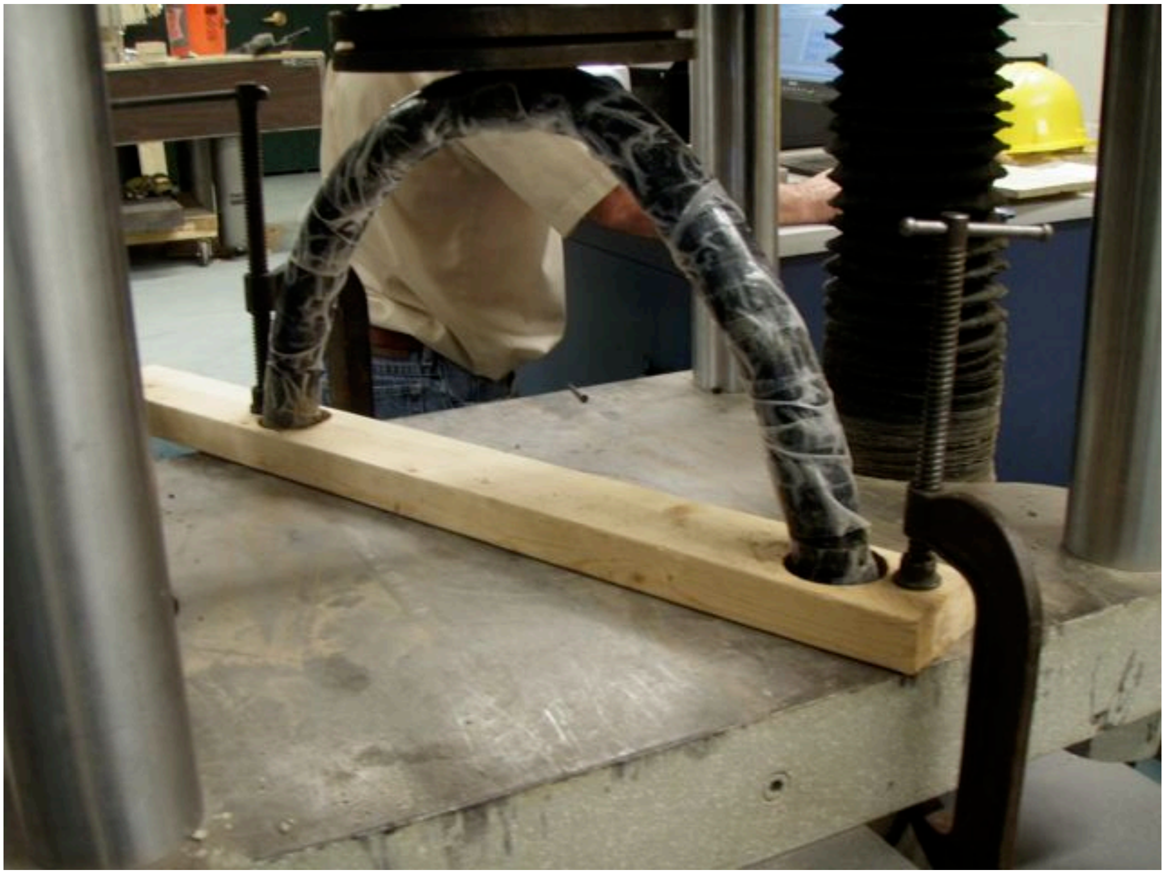


Figure 16 - Mini Arch Test Setup

Finite Element Computer Analysis

The computer analysis was conducted using ANSYS 12 Workbench through a remote desktop connection onto a terminal server. The first step was to develop the geometry. The model only considers the concrete portion of the arch. It does not include the plastic outer layer or the footings. A small object was included to simulate the object applying the load during the test. A screen shot from the geometry design is presented in Figure 17.

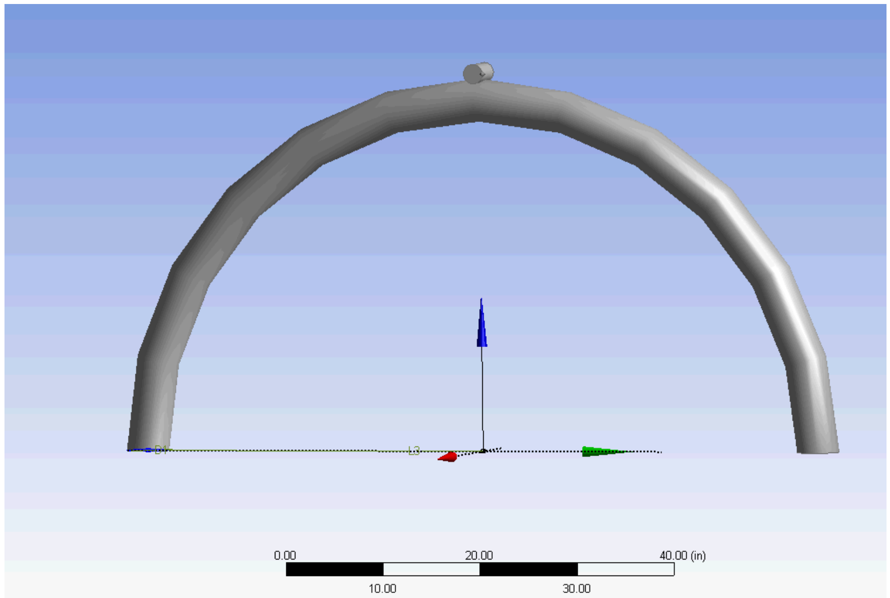


Figure 17 - ANSYS Geometry Development

The second step was to set up the simulation. This included defining material properties, defining supports, defining loads and specifying which analysis's to conduct. A screen shot from the analysis is presented in Figure 18.

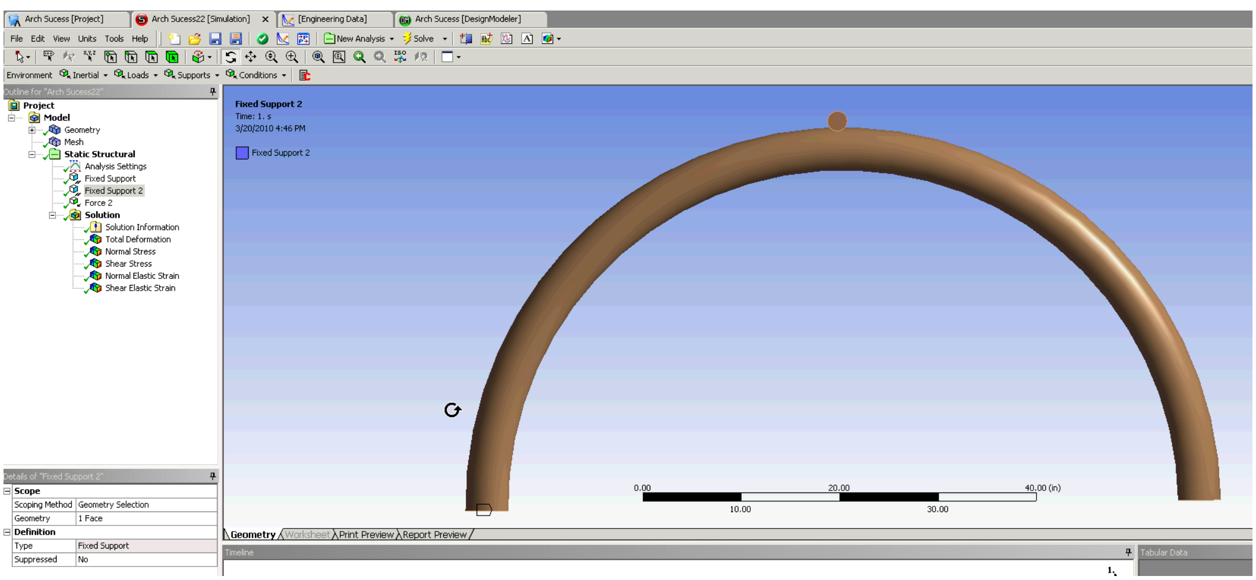


Figure 18 - ANSYS Simulation Screen Shot

All of the settings used are presented in Appendix G.

4) Results

Cylinder Tests

Compression tests were conducted on the three cylinders that were poured. The mix design for each cylinder is presented in Appendix E.

Sample 2

The results for sample 2 are presented in Figure 19, Figure 20 and Table 1.

Figure 19 - Results of Cylinder Sample 2 Compression Test

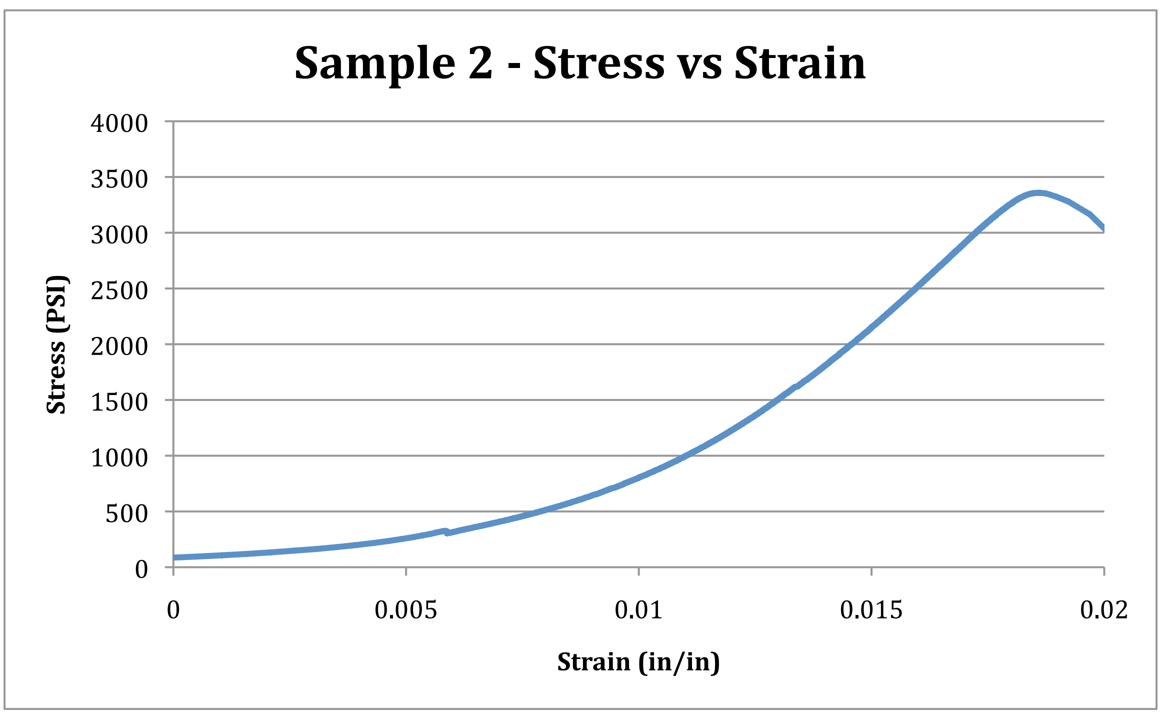


Figure 20 - Sample 2 Cylinder Compression Test Stress Strain Curve

Table 1 - Cylinder Sample 2 Compression Test Results

W/c	0.45	
Wt	25.7	Lb
F'c	3358	PSI
E	3136000	PSI
Density	131	PCF
F't ACI	371	PSI
F'b ACI	481	PSI
E ACI	2856538	PSI

Sample 3

The results for sample 3 are presented in Figure 21, Figure 22 and Table 2.

Figure 21 - Cylinder Sample 3 Compression Test Results

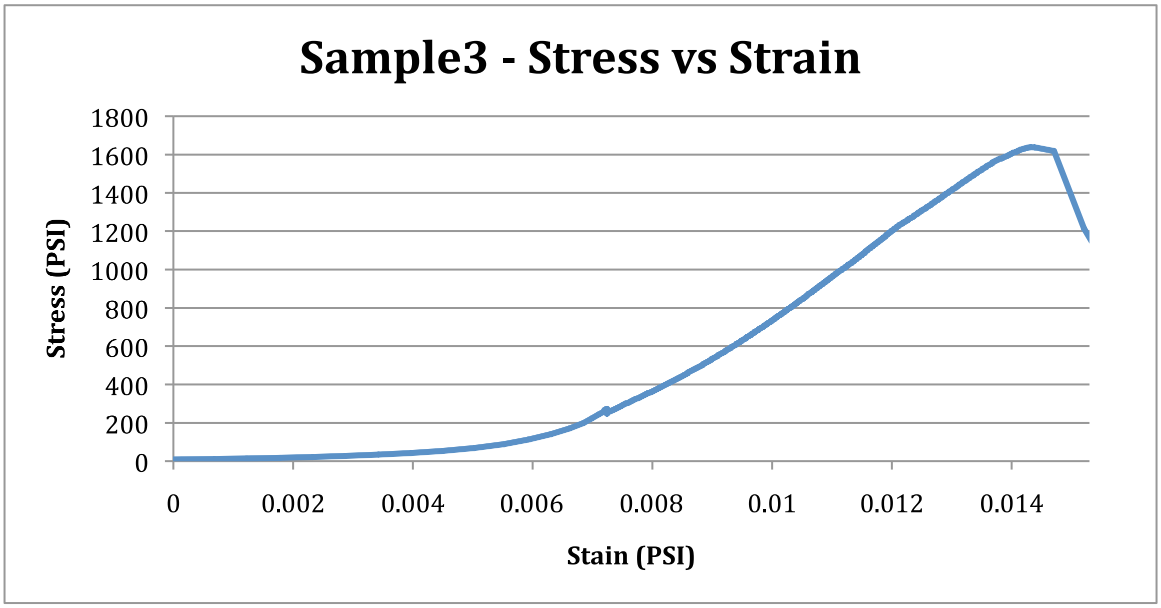


Figure 22 - Cylinder Sample 3 Compression Test Stress Strain Curve

Table 2 - Cylinder Sample 3 Compression Test Results

W/c	0.55	
Wt	26.9	Lb
F'c	1637	PSI
E	1916000	PSI
Density	137	PCF
F't ACI	259	PSI
F'b ACI	336	PSI
E ACI	2143725	PSI

Sample 4

The results for sample 4 are presented in Figure 23 and Table 3.

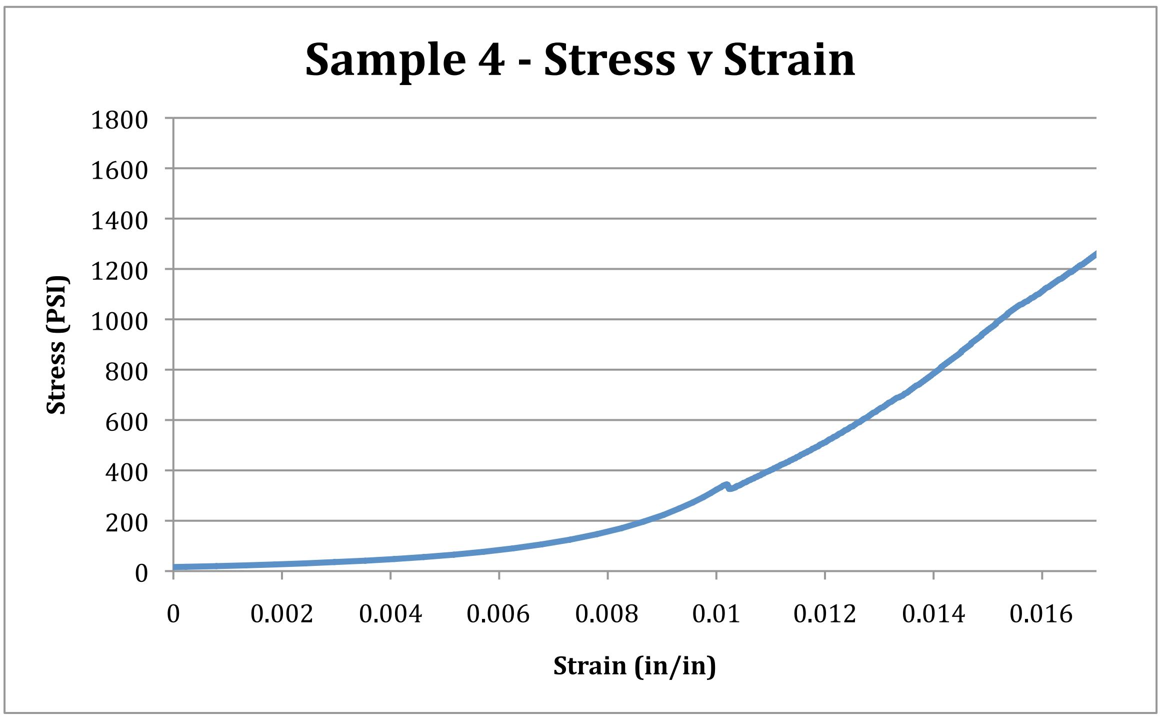


Figure 23 - Cylinder Sample 4 Compression Test Stress Strain Curve

Table 3 - Cylinder Sample 4 Compression Test Results

w/c	0.55	
Wt	27.3	Lb
F'c	1606	PSI
E	1171548	PSI
Density	139	PCF
F't ACI	256	PSI
F'b ACI	333	PSI
E ACI	2170340	PSI

The testing machine printouts are presented in Appendix E

Arch Tests

The main parameter tested during the arch tests was the center point deflection versus the load applied. The total deformation was captured in video and is presented in a series of frames. The machine printouts are presented in Appendix F.

Arch Sample 1

Arch one was broken (concrete fracture) during storage before the test was conducted. The main purpose of the test was to verify the testing method. Arch one was tested using the phase II restraint system as presented in the methodology section. The deflection results are presented in Figure 24 and Figure 25. The deformation results are presented in Figure 26. Images of the failure are presented in Figure 27.

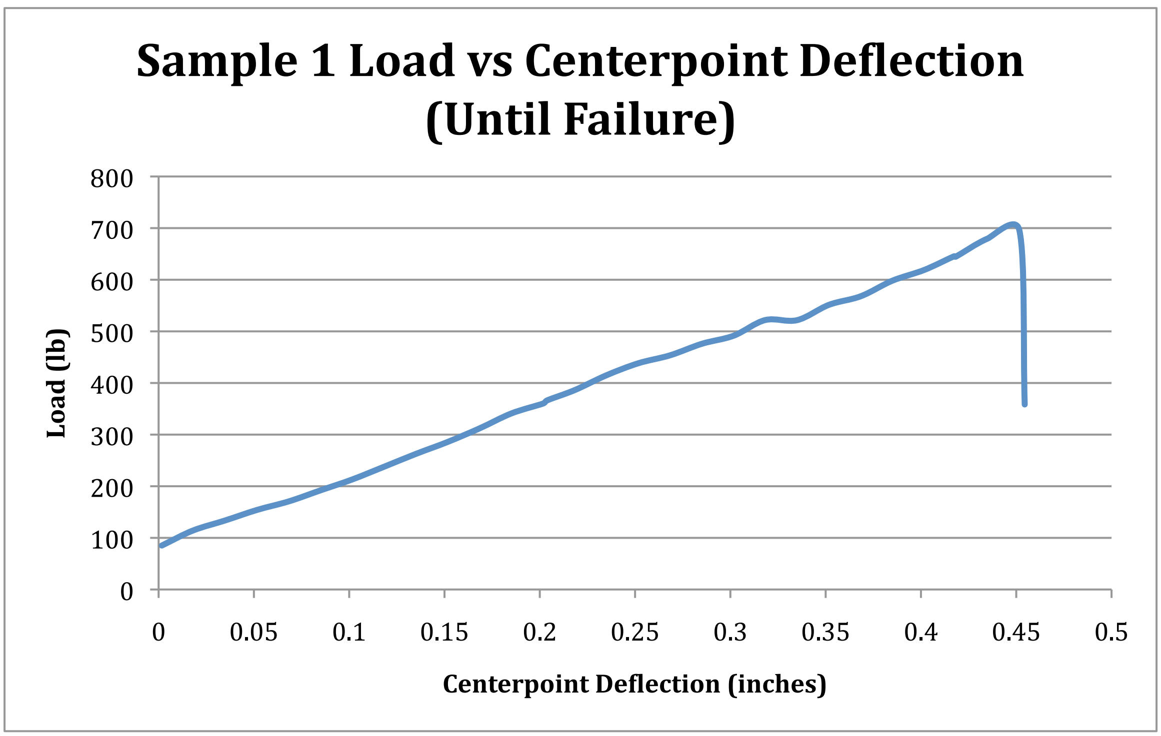


Figure 24 - Arch 1 Load vs. Deflection

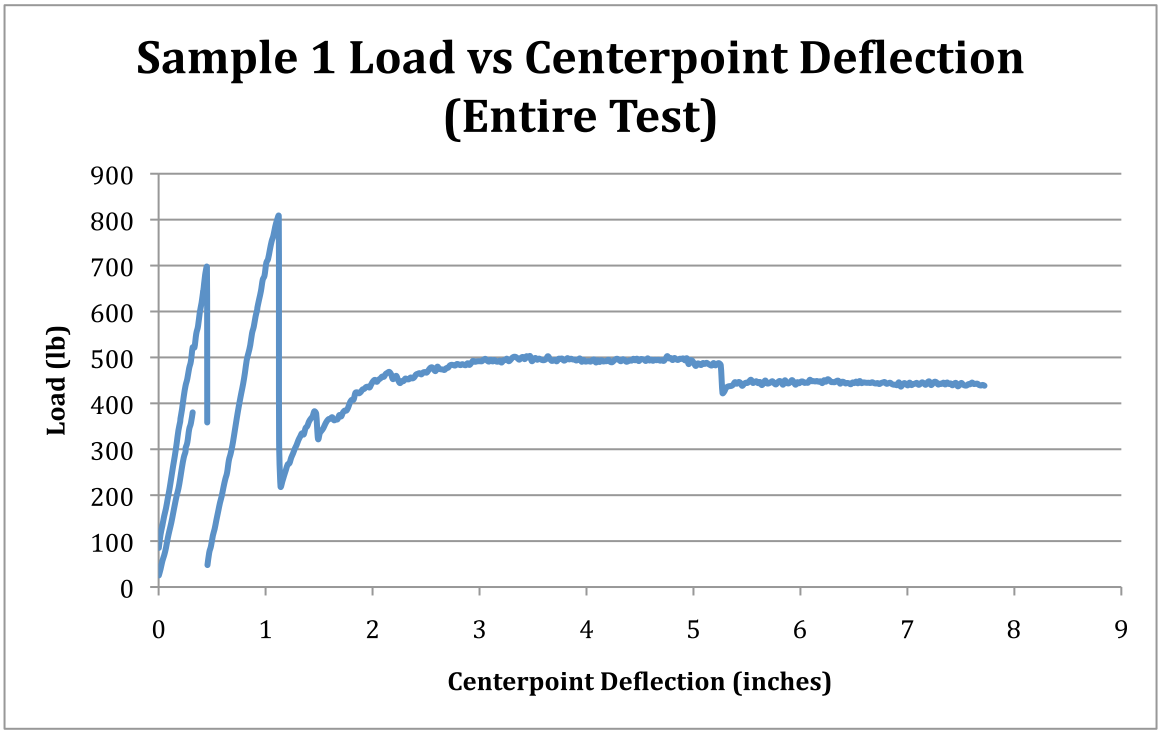
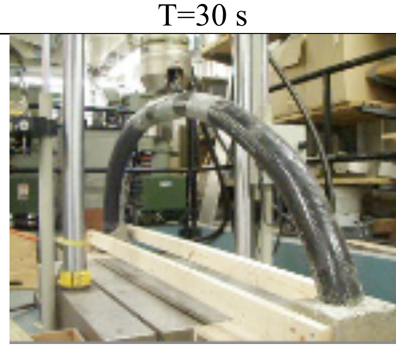


Figure 25 - Arch 1 Complete Load vs. Deflection

 T=0 s	 T=30 s	 T=60 s
 T=90 s	 T=120 s	 T=150 s

 T=180 s		

Figure 26 - Image Sequence of Arch Test 1

Figure 27 - Arch 1 Failure

<u>Arch Sample 2</u>

Arch two was broken (concrete fracture) during storage before the test was conducted. The main purpose of the test was to verify the testing method. Arch two was tested using the phase I restraint system as presented in the methodology. The deflection results are presented in Figure 30 and Figure 31. The deformation results are presented in Figure 28. Images of the failure are presented in Figure 29.

 T=0 s	 T=30 s	 T=60 s

 T=90 s	 T=120 s	 T=150 s
 T=180 s		

Figure 28 - Image Sequence of Arch Test 2

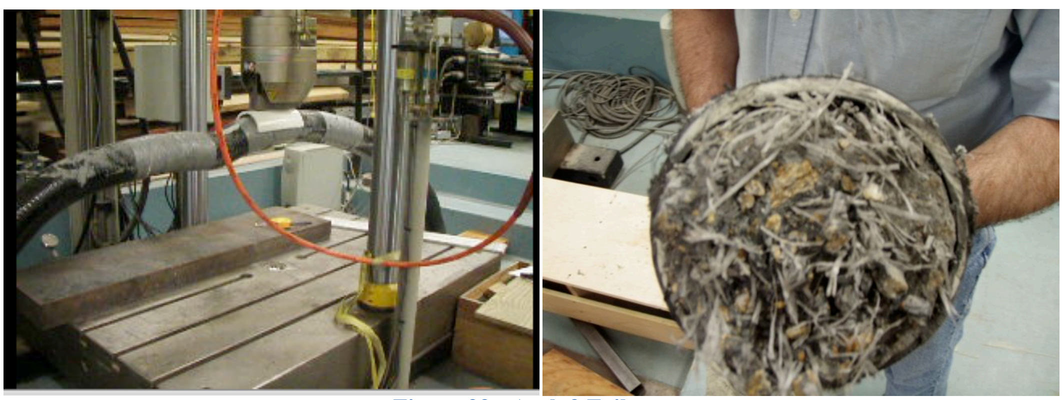


Figure 29 - Arch 2 Failure

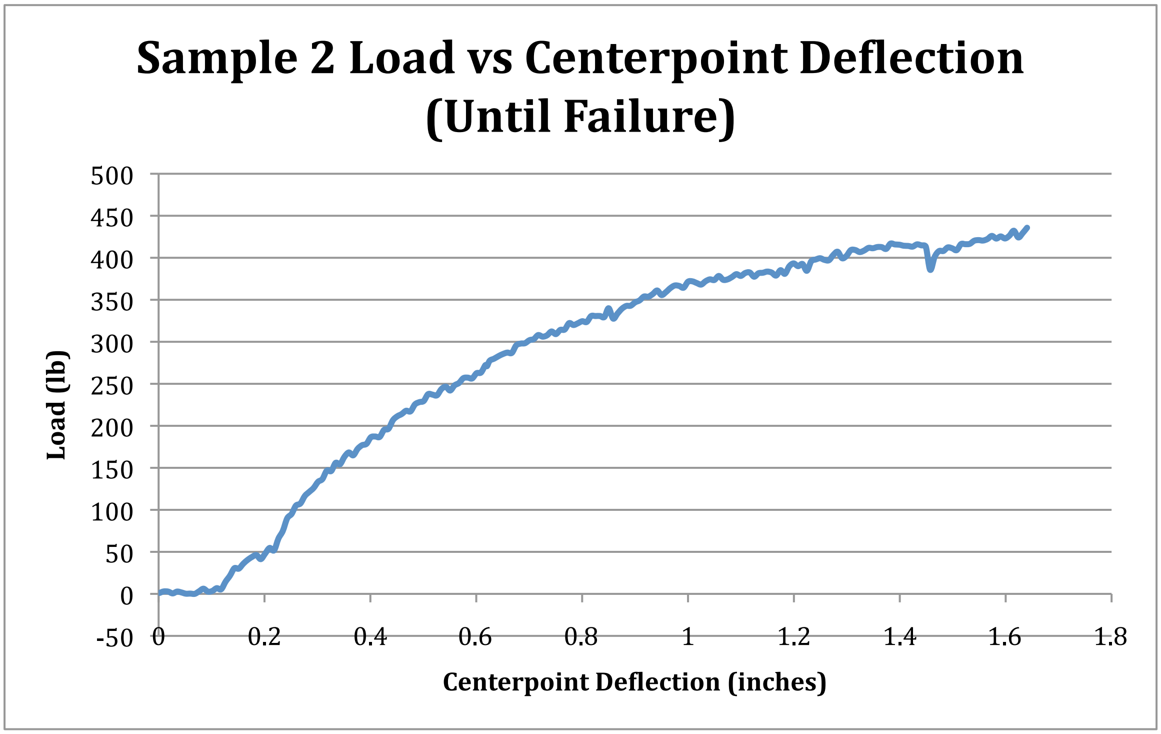


Figure 30 - Arch 2 Load vs. Deflection

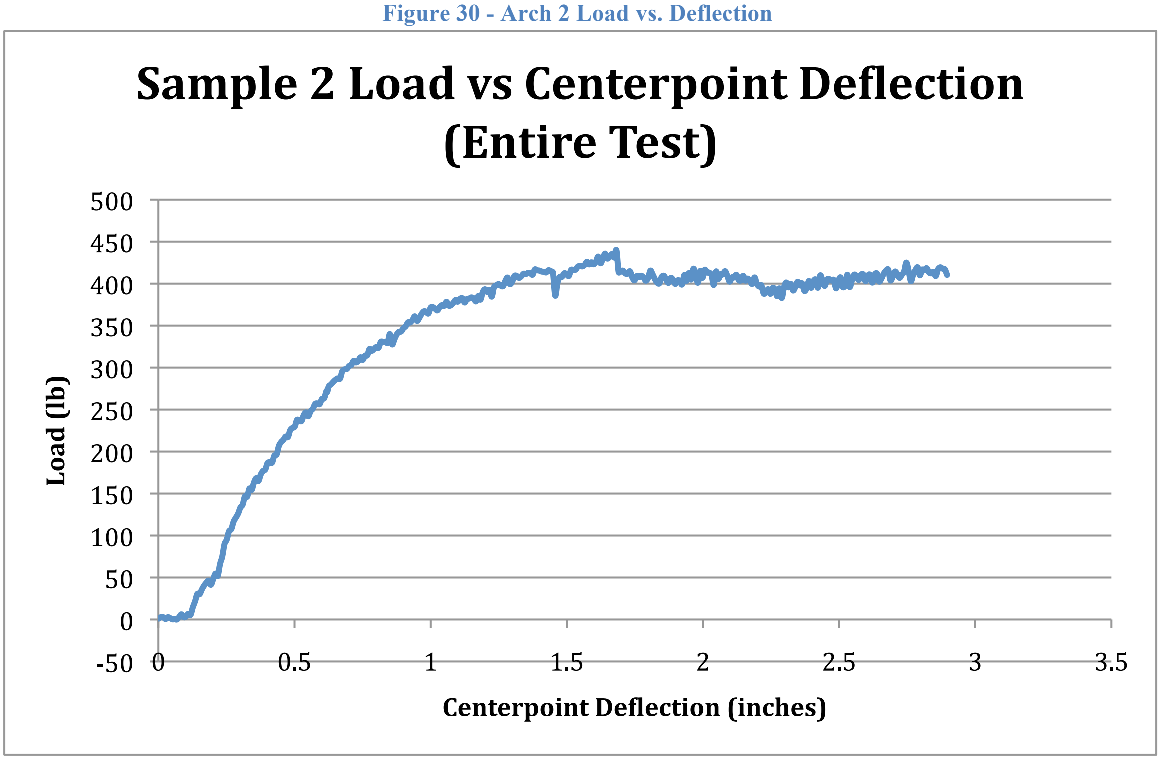


Figure 31 - Arch 2 Complete Load vs. Deflection

<u>Arch Sample 3</u>

Arch three was tested using the final restraint system as presented in the methodology section. The deflection results are presented in Figure 34 and Figure 35. The deformation results are presented in Figure 32. Images of the failure are presented in Figure 33.

 T=0 min	 T=1 min	 T=2 min
 T=3 min	 T=4 min	 T=5 min
 T=6 min	 T=7 min	 T=8 min


T=9 min


T=10 min


T=11 min

Figure 32 - Image Sequence of Arch Test 3

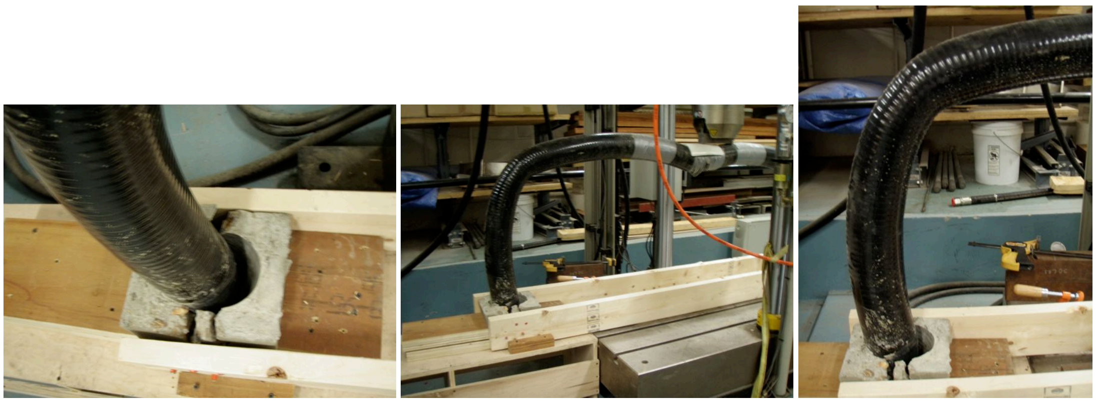


Figure 33 - Arch 3 Failure

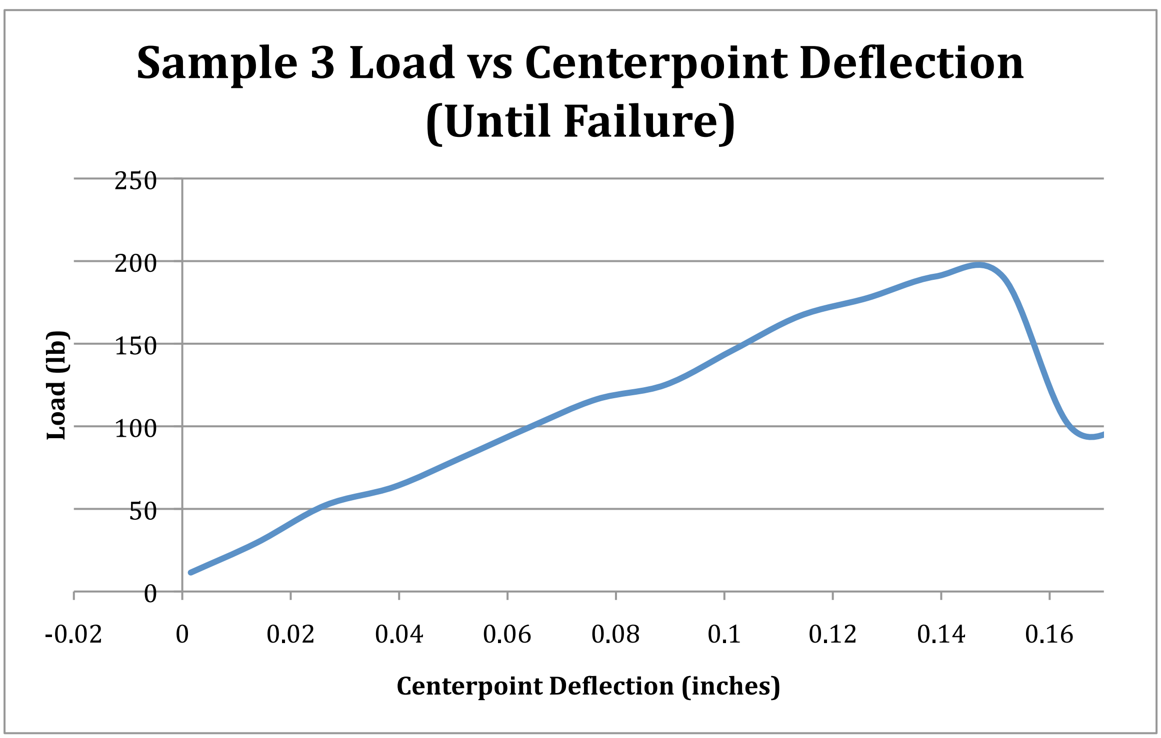


Figure 34 - Arch 3 Load vs. Deflection

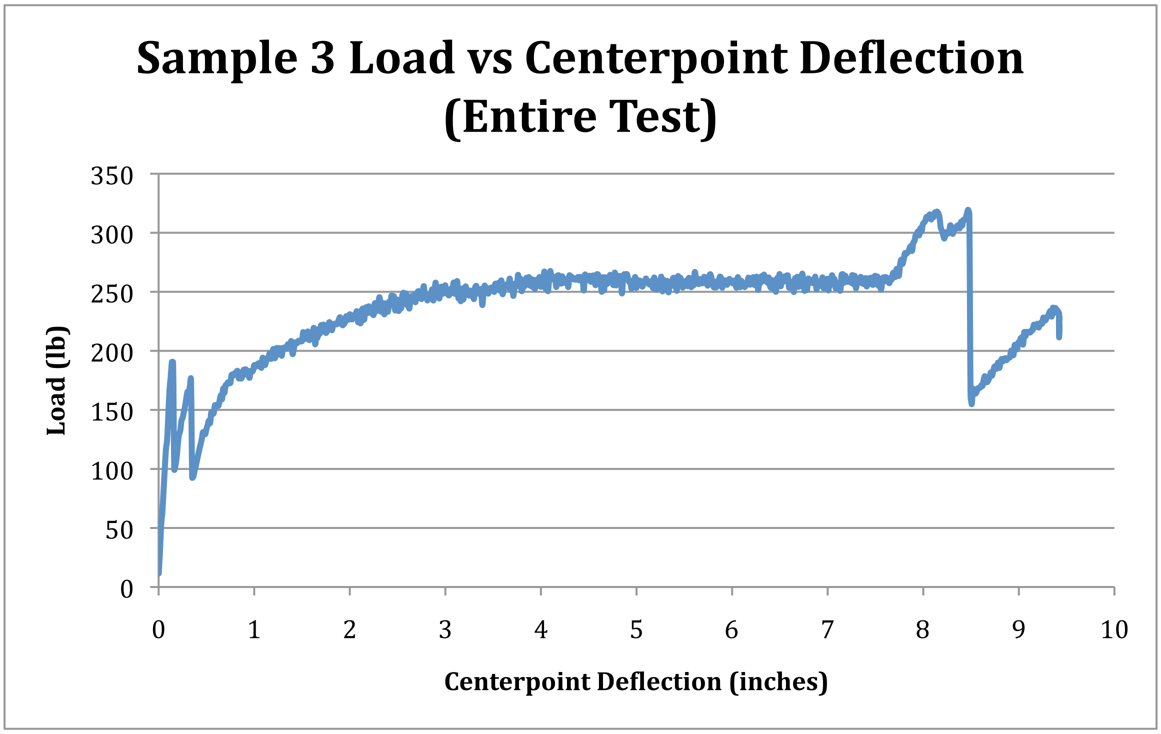
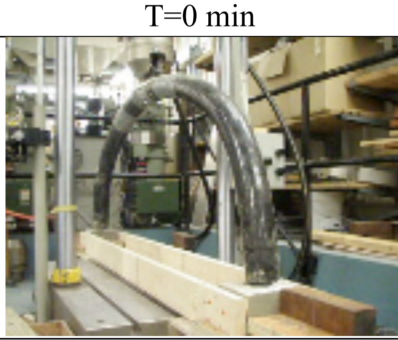


Figure 35 - Arch 3 Complete Load vs. Deflection

<u>Arch Sample 4</u>

Arch four was tested using the final restraint system as presented in the methodology section. The deflection results are presented in Figure 38 and Figure 39. The deformation results are presented in Figure 36. Images of the failure are presented in Figure 37.

 T=0 min	 T=1 min	 T=2 min
		

T=3 min	T=4 min	T=5 min
 T=6 min	 T=7 min	 T=8 min
 T=9 min	 T=10 min	 T=11 min
 T=12 min		

Figure 36 - Image Sequence of Arch Test 4

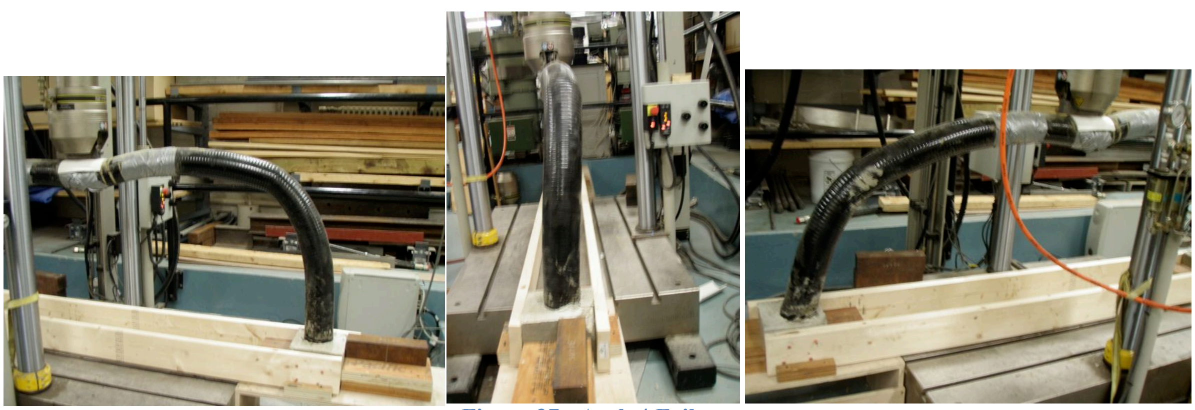


Figure 37 - Arch 4 Failure

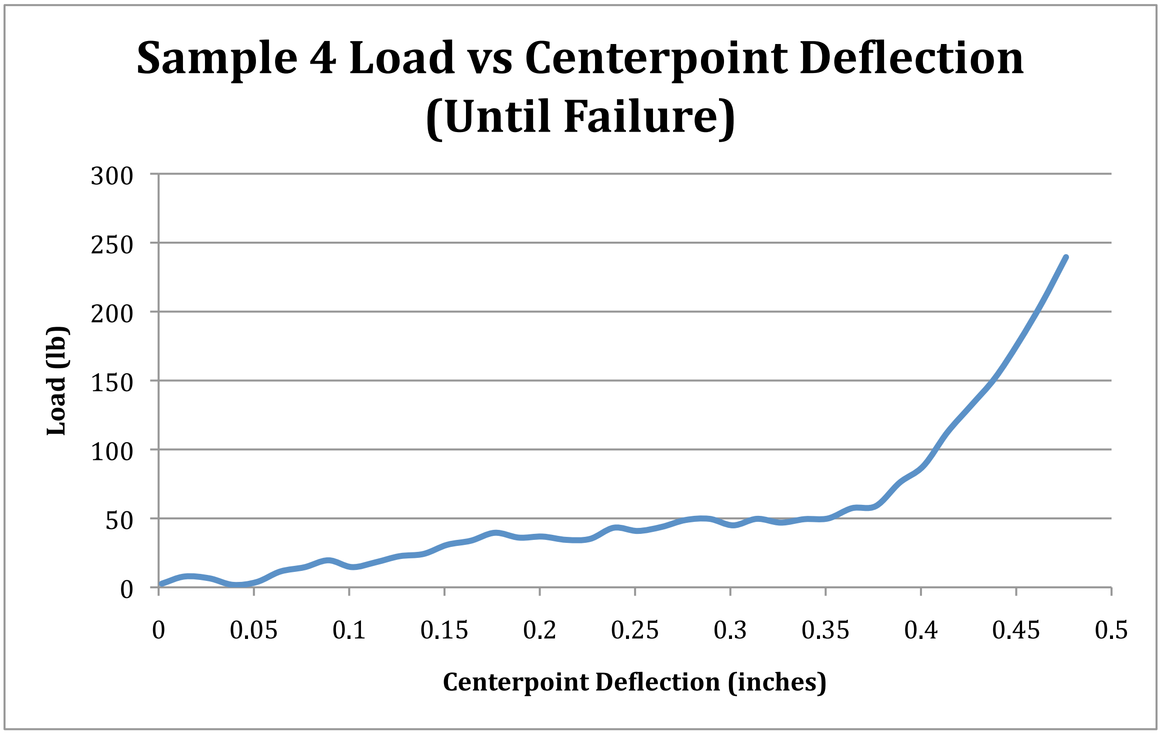


Figure 38 - Arch 4 Load vs. Deflection

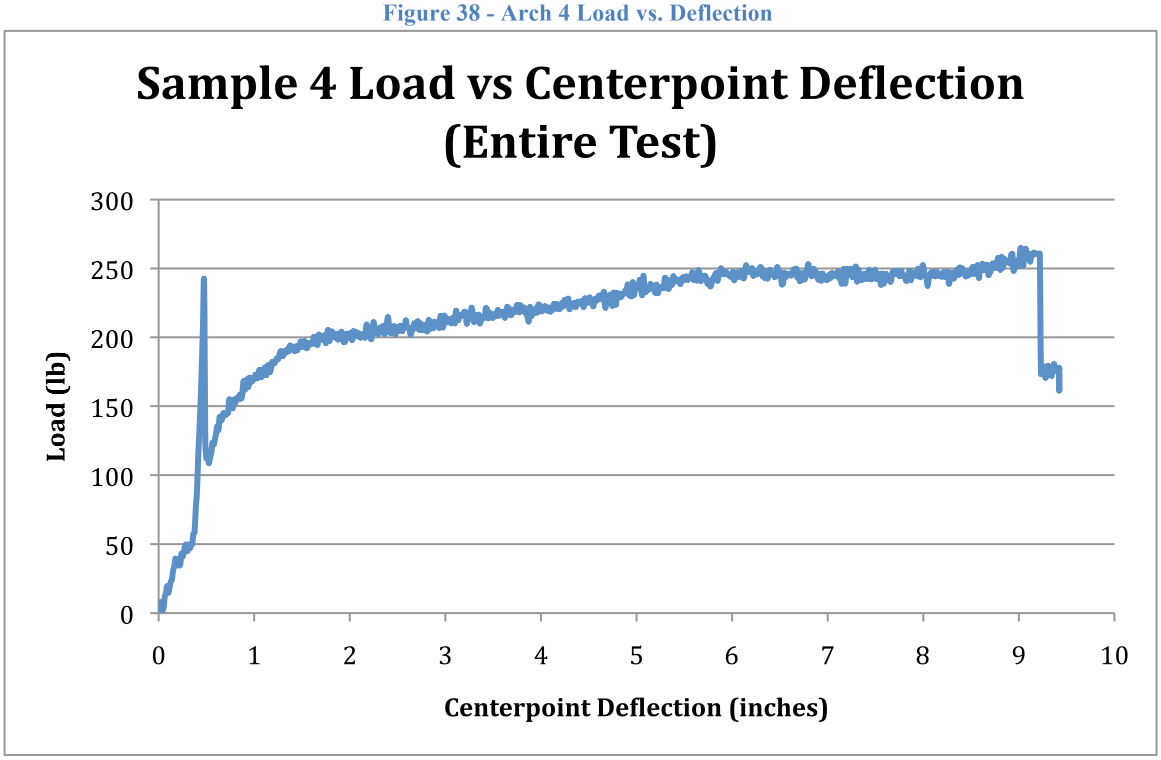


Figure 39 - Arch 4 Complete Load vs. Deflection

Arch Sample 5

Arch five was tested using the final restraint system as presented in the methodology section. The deflection results are presented in Figure 42 and Figure 43. The deformation results are presented in Figure 40. Images of the failure are presented in Figure 41.

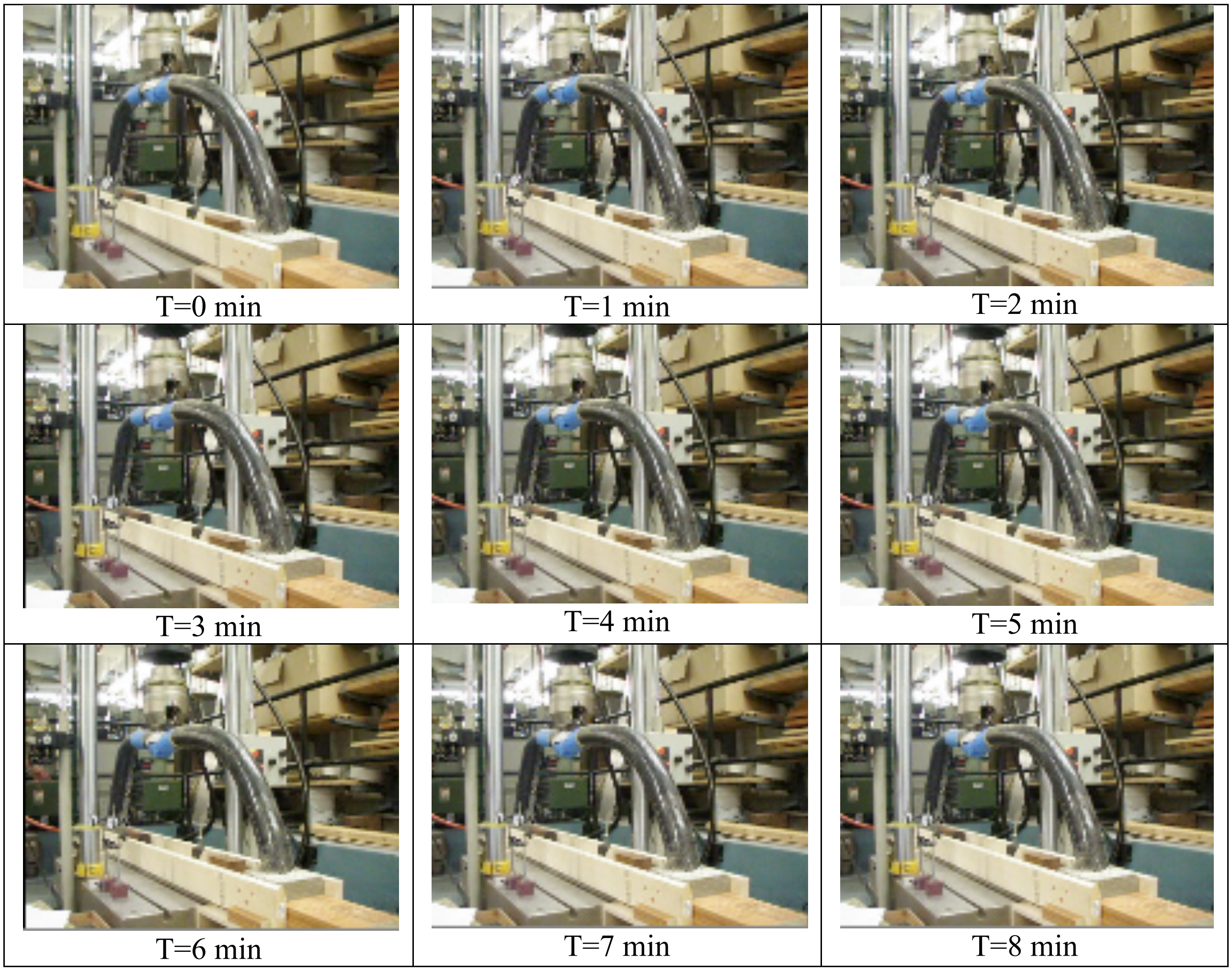


Figure 40 - Image Sequence of Arch Test 5

Figure 41 - Arch 5 Failure

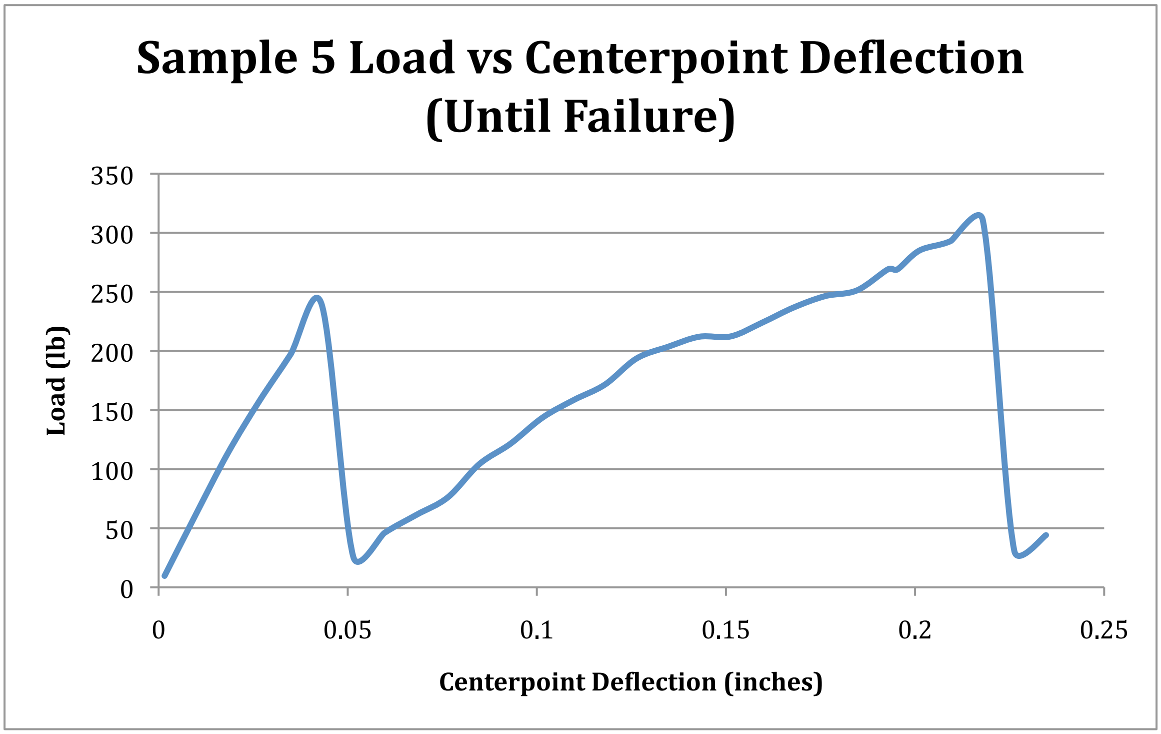


Figure 42 - Arch 5 Load vs. Deflection

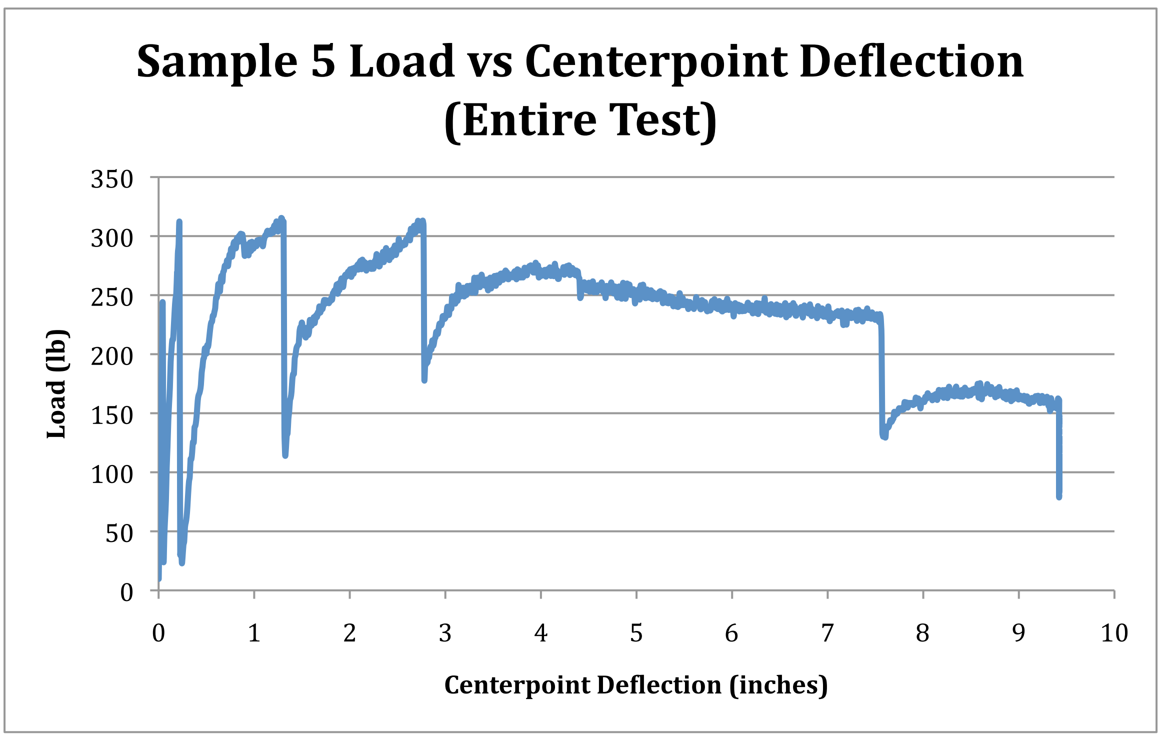


Figure 43 - Arch 5 Complete Load vs. Deflection

Mini Arch Tests

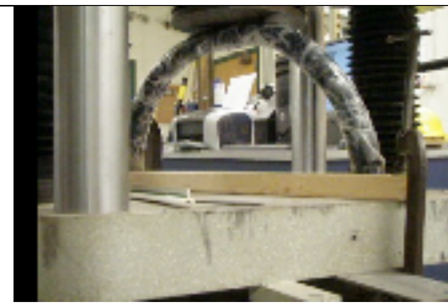
The purpose of the mini arch tests were to help determine why the large arches failed under such small loads. The main parameter tested during the mini arch tests was the center point deflection versus the load applied. The total deformation was captured in video and is presented in a series of frames. The machine printouts are presented in Appendix H.

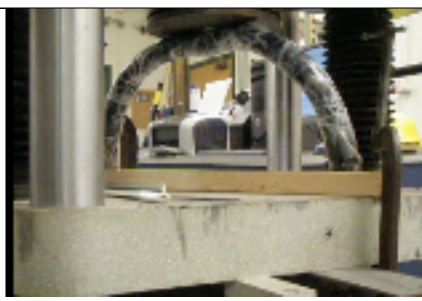
Mini Arch 1

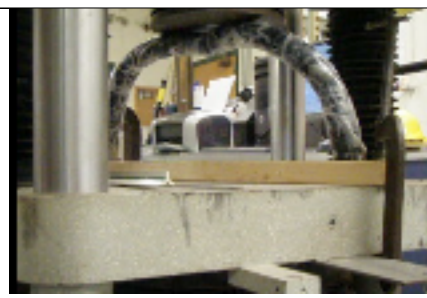
The deflection results for mini arch 1 are presented in Figure 46. The deformation results are presented in Figure 44. Images of the failure are presented in Figure 45.


T=0 min


T=1 min


T=2 min


T=3 min


T=4 min


T=5 min


T=6 min

Figure 44 - Image Sequence of Mini Arch 1 Test

Figure 45 - Mini Arch 1 Failure

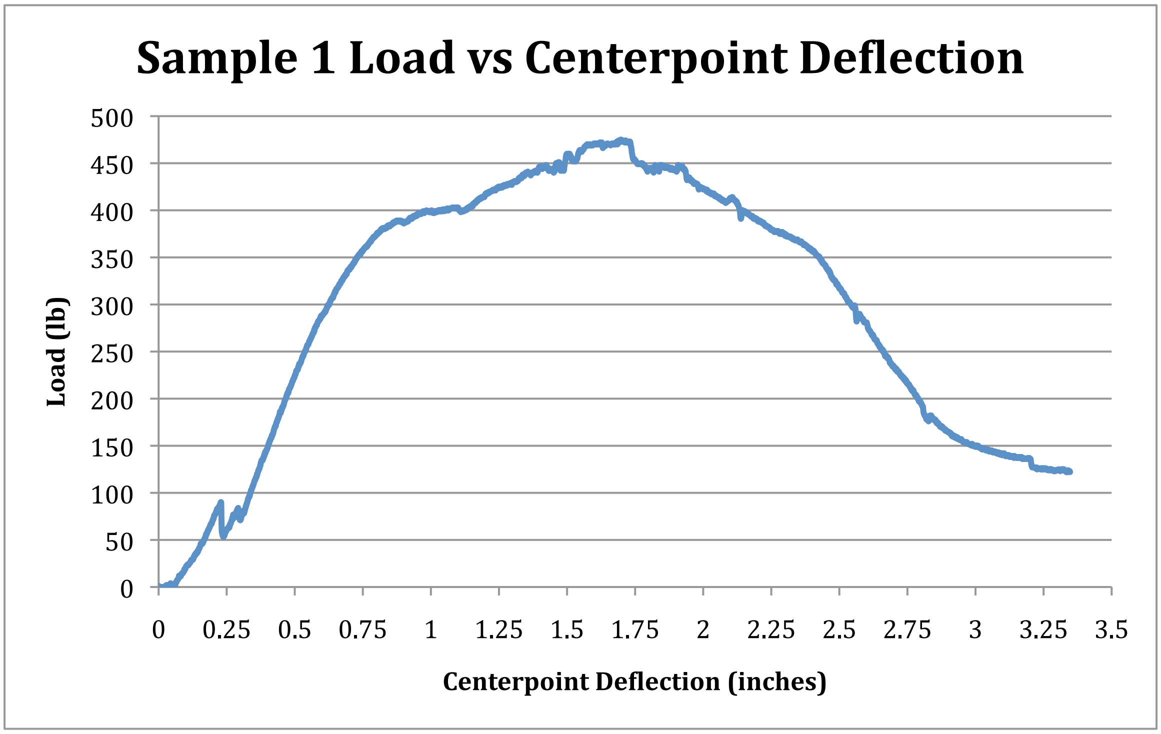


Figure 46 - Mini Arch 1 Load vs. Deflection

Mini Arch 2

The deflection results for mini arch 1 are presented in Figure 49. The deformation results are presented in Figure 47. An image of the failure is presented in Figure 48.

T=0 s	T=30s	T=60s

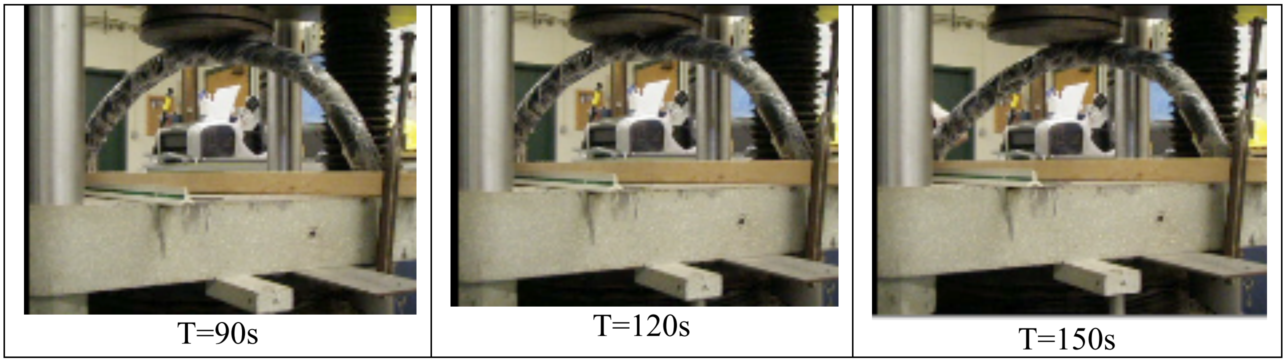


Figure 47 - Image Sequence of Mini Arch Test 2

Figure 48 - Mini Arch Failure

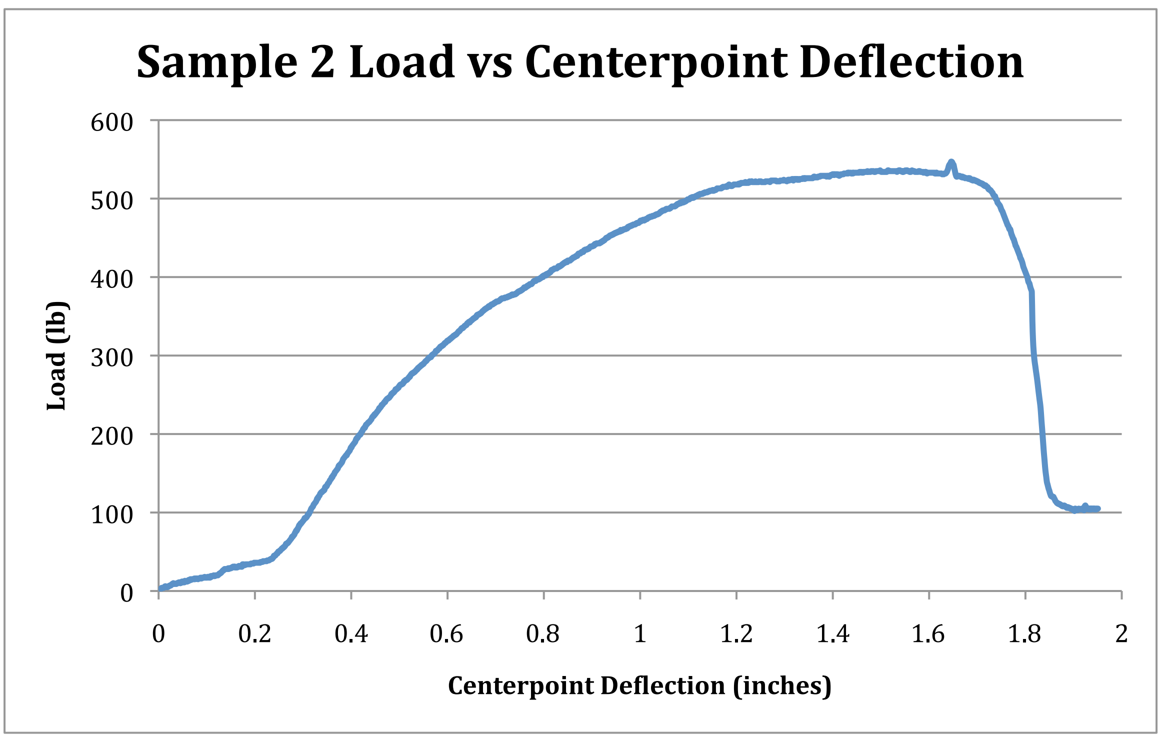


Figure 49 - Mini Arch 2 Load vs. Deflection

Finite Element Computer Analysis

The finite element analysis was conducted to have a comparison for the physical arches that were tested.

Using F'c of 1500 PSI and load of 250lb

The first simulation was done using parameters that line up with arch test three and four. The tabular results are presented in Table 4. The graphical results are presented in Figure 50,

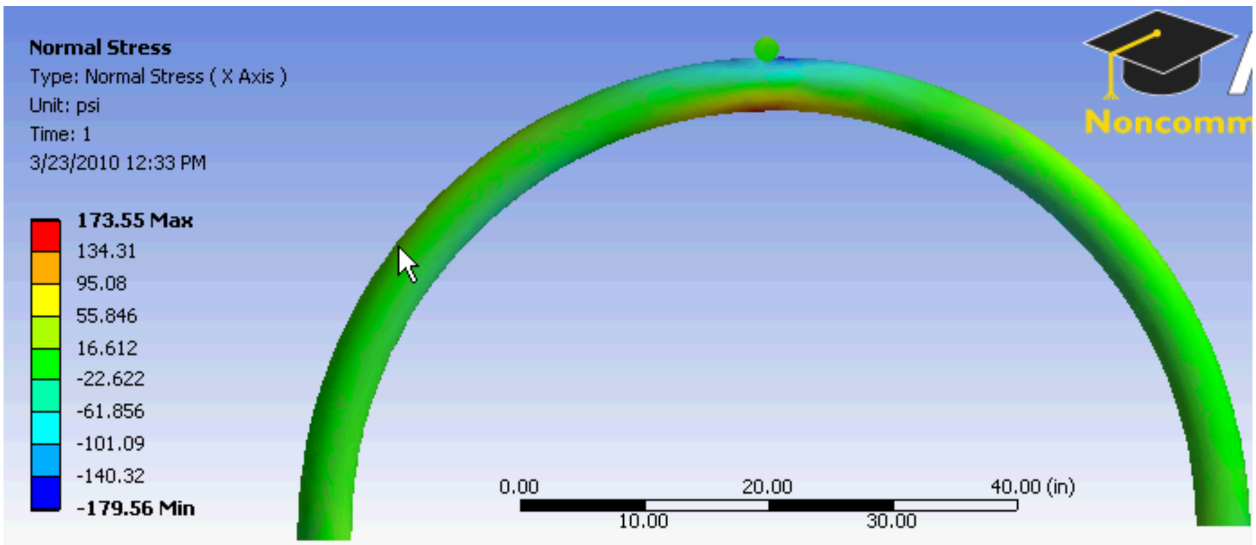


Figure 51, Figure 52, Figure 53, and Figure 54.

Table 4 - Parameter Set 1: Results

Type	Total Deformation	Normal Stress	Shear Stress	Normal Elastic Strain	Shear Elastic Strain
Orientation		X Axis	XY Plane	X Axis	XY Plane
Results					
Minimum	0. in	-179.56 psi	-45.192 psi	-9.2108e-005 in/in	-5.5665e-005 in/in
Maximum	4.6063e-003 in	173.55 psi	46.882 psi	9.0501e-005 in/in	5.7746e-005 in/in

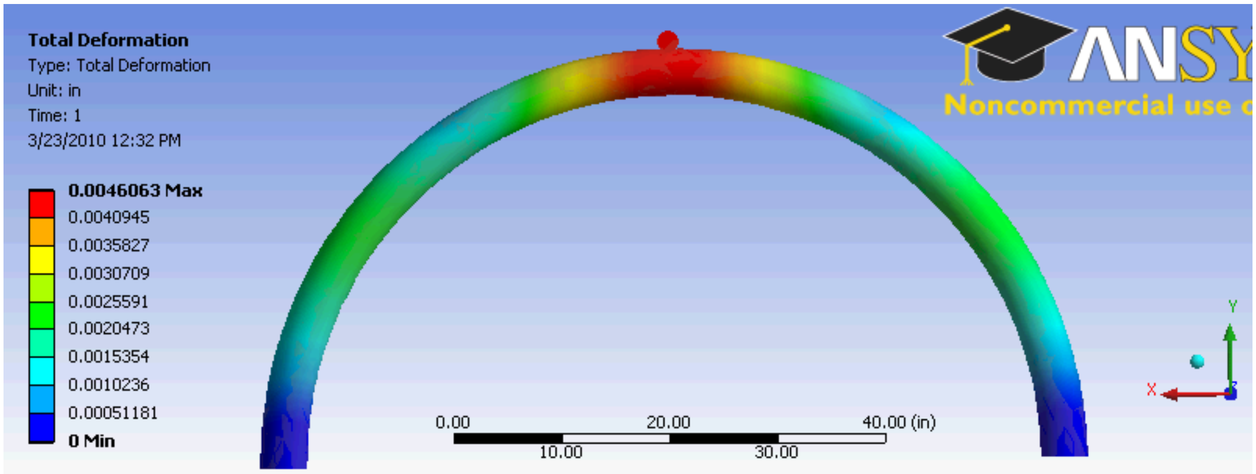


Figure 50 - Parameter Set 1: Total Deformation

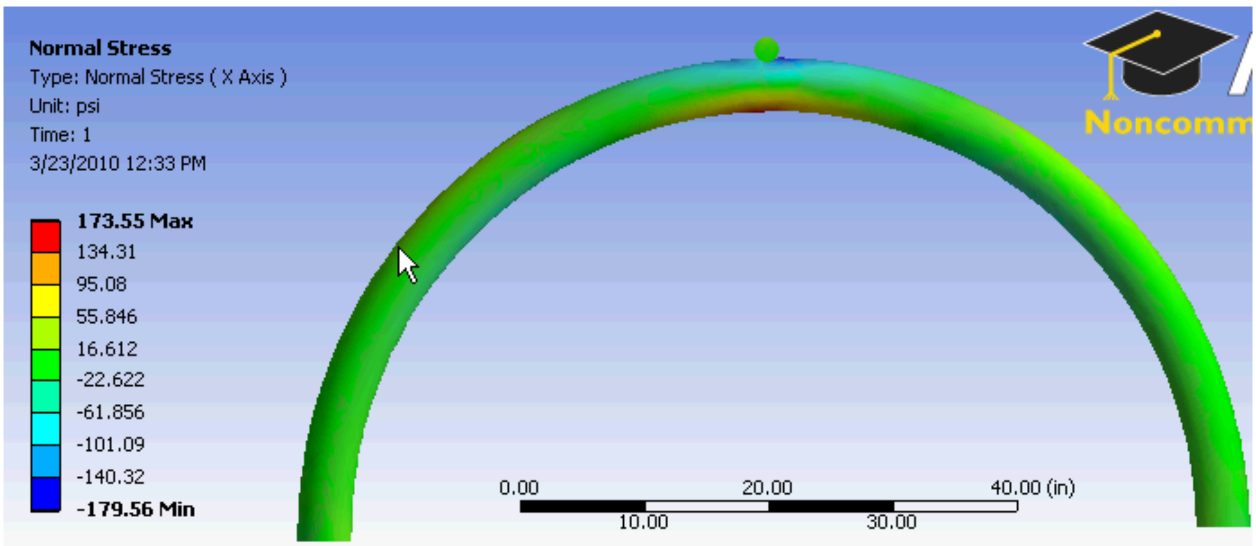


Figure 51 - Parameter Set 1: Normal Stress

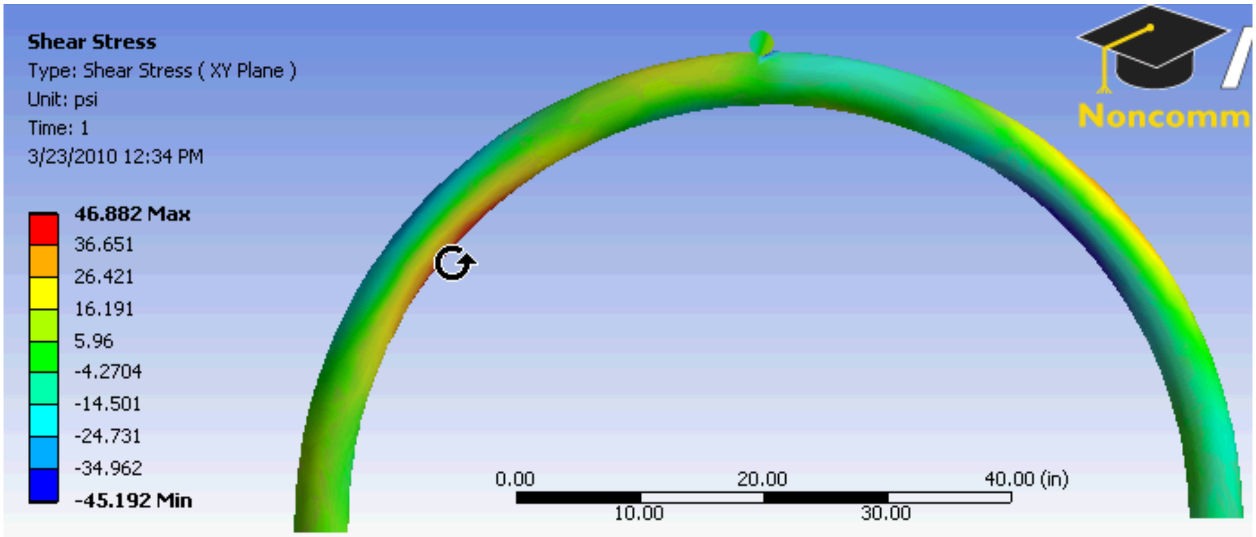


Figure 52 - Parameter Set 1: Shear Stress

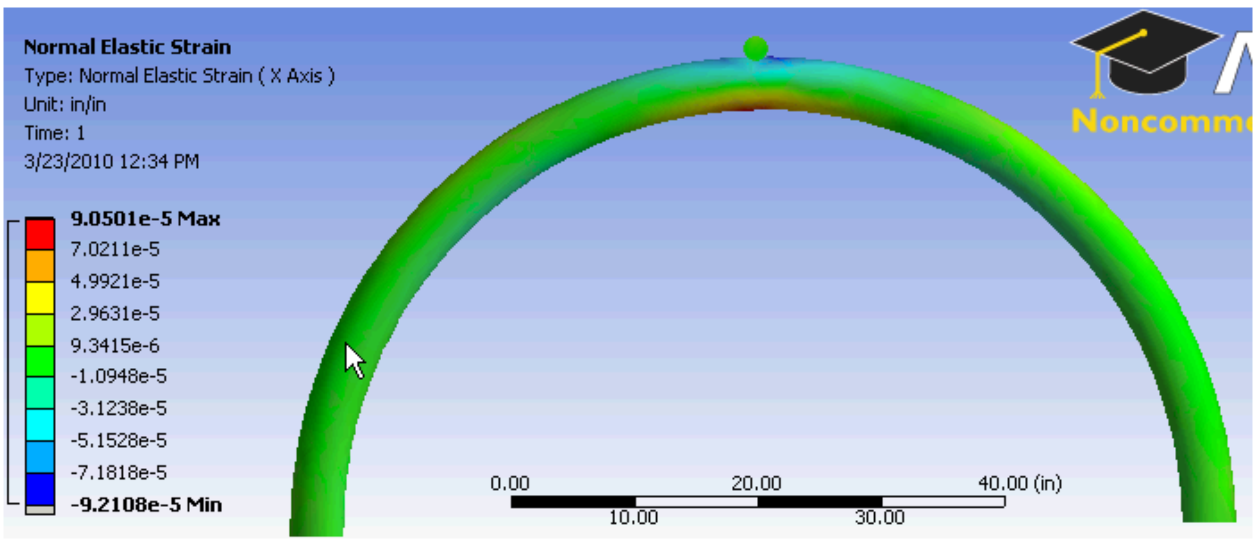


Figure 53 - Parameter Set 1: Normal Elastic Strain

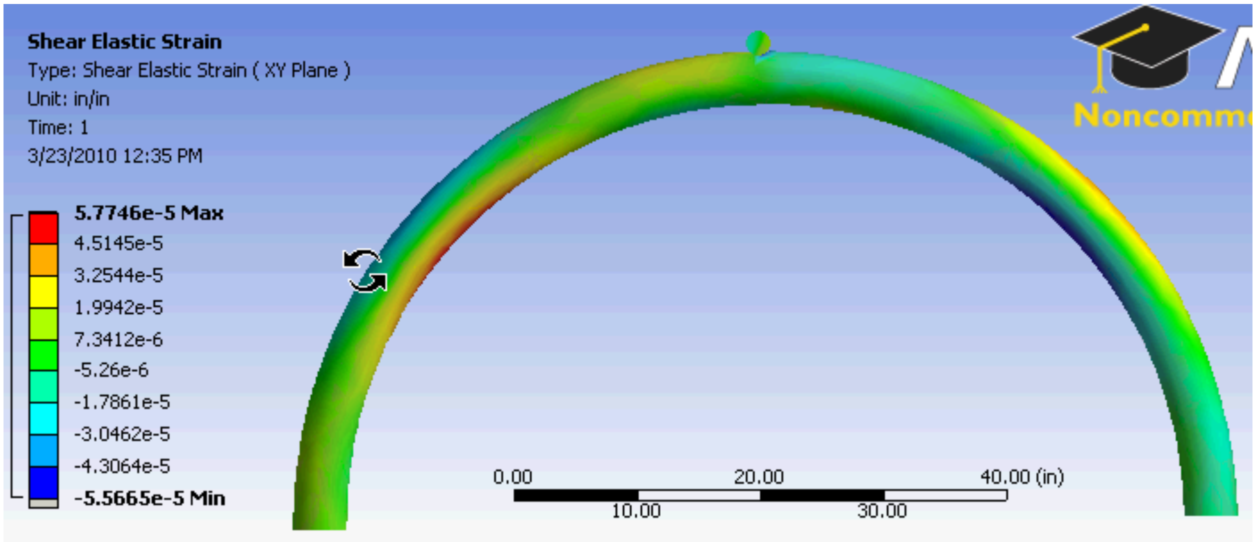


Figure 54 - Parameter Set 1: Shear Elastic Strain

Using F'c of 3000 PSI and load of 800lb

The first simulation was done using parameters that generally line up with arch test one and two. The tabular results are presented in Table 5. The graphical results are presented in Figure 55, Figure 56, Figure 57, Figure 58, and Figure 59.

Table 5 - Parameter Set 2: Results

Type	Total Deformation	Normal Stress	Shear Stress	Normal Elastic Strain	Shear Elastic Strain
Orientation		X Axis	XY Plane	X Axis	XY Plane
Results					
Minimum	0. in	-574.59 psi	-144.62 psi	-1.8043e-004 in/in	-1.0904e-004 in/in
Maximum	9.0231e-003 in	555.35 psi	150.02 psi	1.7728e-004 in/in	1.1312e-004 in/in

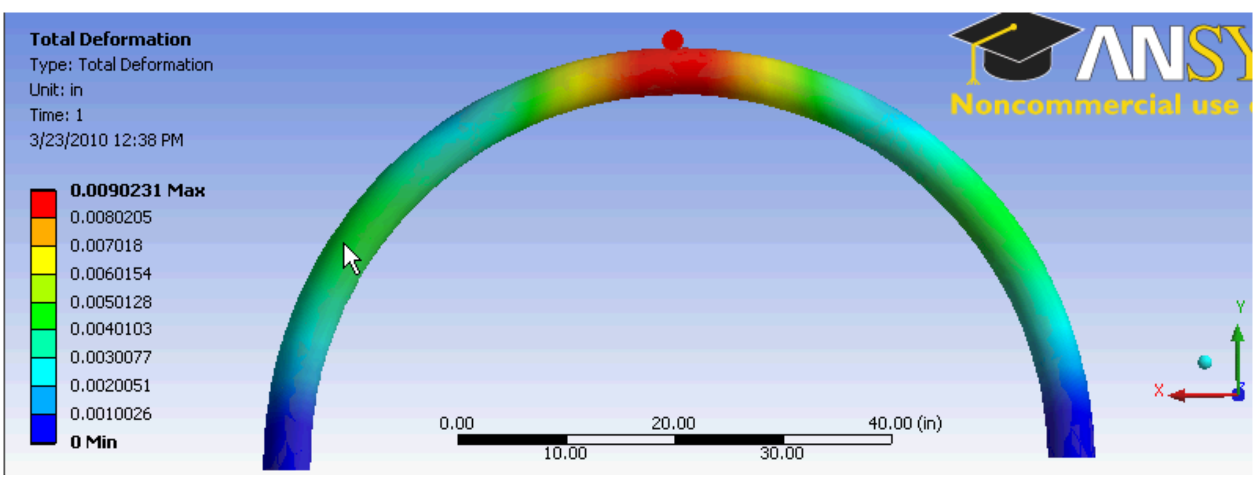


Figure 55 - Parameter Set 2: Total Deformation

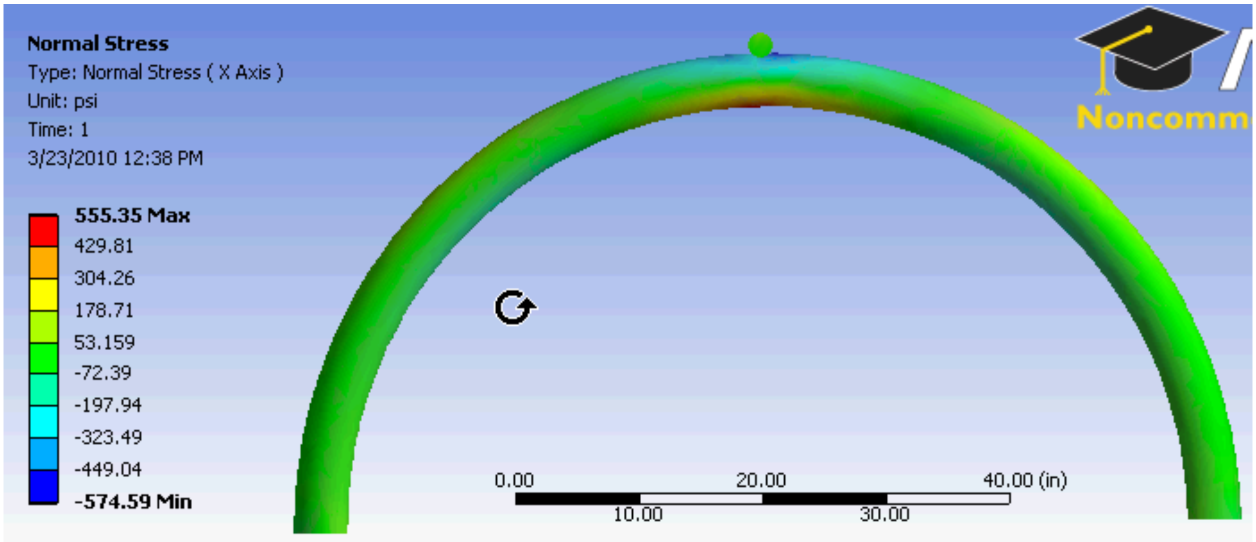


Figure 56 - Parameter Set 2: Normal Stress

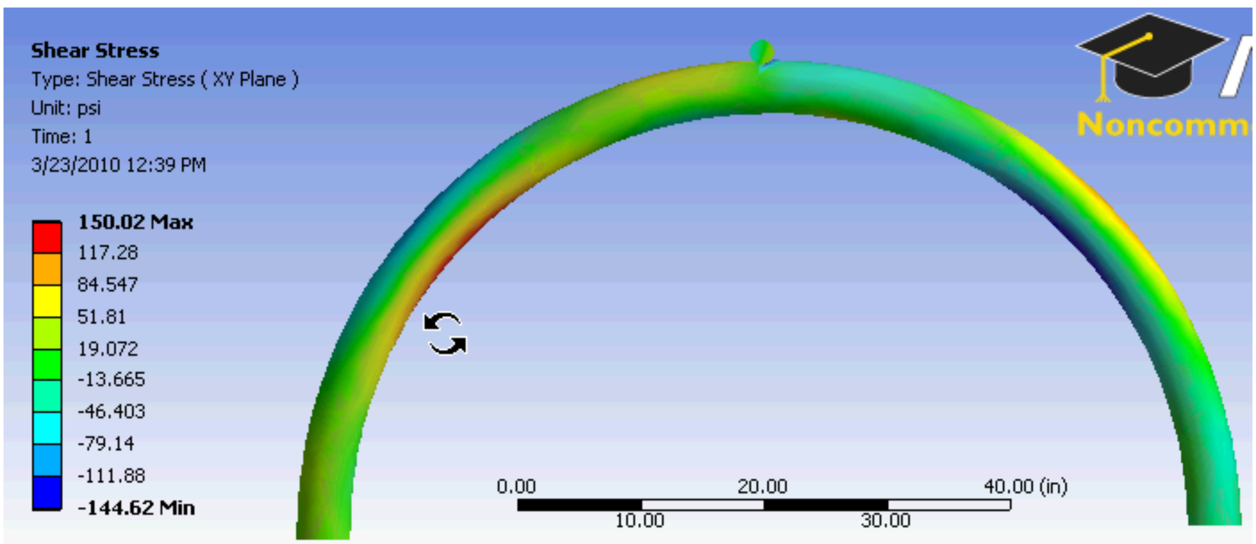


Figure 57 - Parameter Set 2: Shear Stress

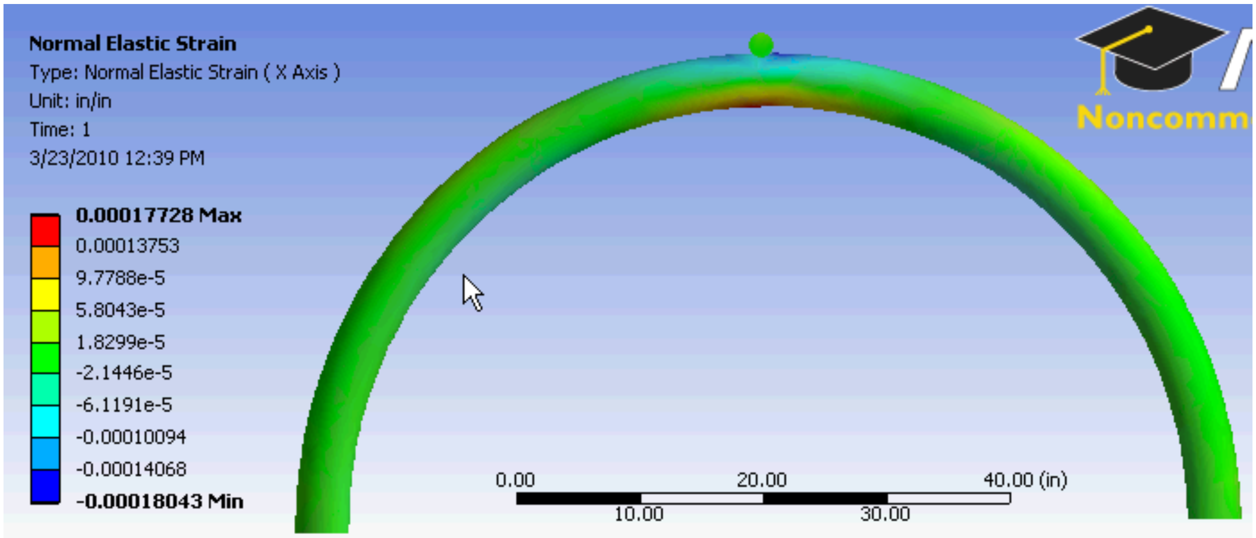


Figure 58 - Parameter Set 2: Normal Elastic Strain

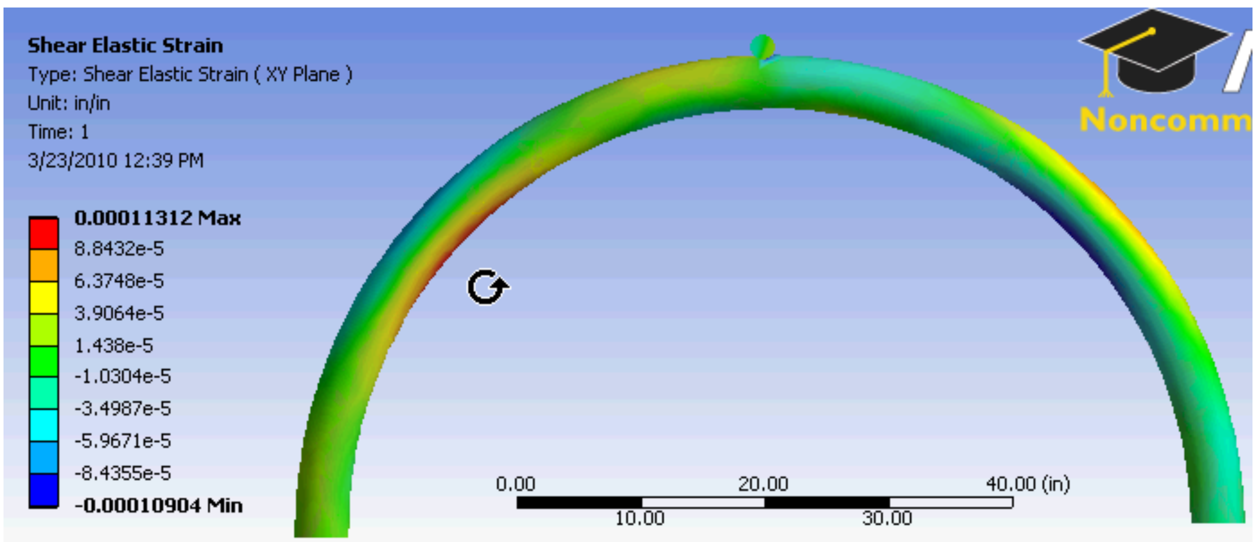


Figure 59 - Parameter Set 2: Shear Elastic Strain

5) Analysis and Recommendations

The results from arch test three, four and five were compared with the finite element analysis for an f'c of 1500 PSI. The finite element analysis was conducted after the arch test utilizing the concrete data from the cylinder test, and the load amount from the arch test. The finite element analysis agrees with the arch test by showing that the tensile forces in the arch exceeded the tensile capacity of the concrete. The finite element analysis showed that the peak tensile stress was 173 PSI (

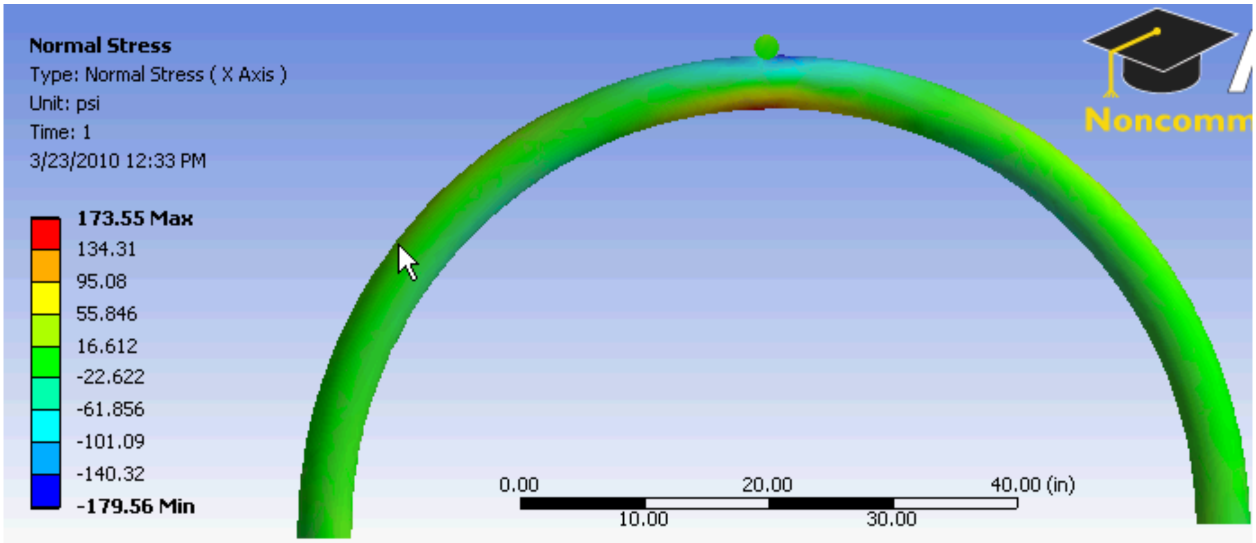


Figure 51) while the ACI estimated capacity of the concrete in tension was 251 PSI. The actual deflection at failure (Sample 3, Figure 34) was .15" while the finite analysis failure occurred at .005".

The comparison for the failure stresses fall somewhat near each other, while the deflections are several orders apart. There are several factors that could be causing the discrepancy. The main reason is the geometry of the scale arch. The scale arch did not have the perfect geometry of a semi-circle when viewed across any plane. This led to much higher tensile forces than anticipated, causing the concrete to fail. As the top of the arch deformed and caused tensile forces, the geometry in other areas of the arch also changed, leading to other failure areas.

Even though the results from arch one and two can be disregarded because they were broken before testing, they were compared to the finite element analysis for and f'c of 3000 PSI. The comparison, as well as the analysis is very similar to the comparison above.

Small amounts of rebar should be inserted into the top of arch to absorb the tensile forces, because this is the most likely place for tension to occur. If the top of the arch does not deform, the deformation over the rest of the arch should be limited. A more robust bracing system should be used when pouring the concrete to maintain the geometry better. The first two arches were poured without any bracing until after they began to set. They deformed across the major plane as well as laterally during the pouring process. The remaining large sample arches were poured utilizing bracing as depicted in Figure 6. While it generally kept the arch in the proper geometry, it was not precise enough to limit the amount of tension that occurred during loading.

The soil-concretes that were tested all had approximately 1500 PSI of compressive strength. There was no noticeable performance with the use of fiberglass fibers. The use of larger, rougher fibers may improve the tensile capacity of the concrete.

6) Conclusions

The goals of the project were to design, construct and load test scale arches to determine the feasibility of using soil-concrete in arches for bridge supports; to conduct a finite element analysis; and to make recommendations for design guidelines based on the results. The first goal was met with the successful design, construction and load testing of five 10’ arches and two smaller scale 3’ arches. The goal to determine the feasibility of using soil-cement for bridge supports was met through the use of three soil-cement mix designs as well as cylinder testing. The finite element analysis was conducted using ANSYS Workbench 12 and was successful in confirming the failure of the big arches. The design recommendations were presented in the previous section. The project met all of its goals within the allotted timeframe and a basis was set for the future development and study of the subject.

7) Bibliography

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Appendix

Appendix A: Arch Geometry Calculations

Arch Calculation Spreadsheet

Appendix B: Concrete Mix Design Calculations

The concrete mix calculations were all done using the Total-Volume Method outlined in chapter x of the PCI handbook.

Footings:

Cement Content
=Water/WC ratio = (340-35) pcy/.45 = 677 lb/cubic yard
755/27= 25 lb/cubic foot

Coarse Aggregate Content (Max 13/4" Size(1/5 of 4" diameter pipe))(assume 100 pcf)
100pcf * .63 = 63 lb/cubic foot
*27=1701

Water Volume = (305) /(62.4) = 4.9 cu. ft. per cu. yd.
Cement Volume = (677)/(3.15*62.4) = 3.4 cu. ft. per cu. yd.
CA Volume = (1701)/(2.65*62.4) = 10.3 cu. ft. per cu. yd.
Air Volume = 0.035*27 = .95 cu. ft
Total Volume of known ingredients = 19.5 cu. ft.
Coarse Volume = 27-19.5 = 7.5 ft^3
Weight of sand = 7.5*2.6*62.4=1216.8 lb/cubic yard

		Need 2.2 + 50% = 3.3 Cubic Feet	
Material	**PCY (lb)**	**PCF (lb)**	**3.3 Ft^3 (lb)**
Water	305	11	**37**
Cement	677	25	**83**
.75" Gravel	1701	63	**208**
Sand	1217	45	**149**

Arch 1:

Cement Content
=Water/WC ratio = (340-35) pcy/.45 = 677 lb/cubic yard
755/27= 25 lb/cubic foot

Coarse Aggregate Content (Max 13/4" Size(1/5 of 4" diameter pipe))(assume 100 pcf)
100pcf * .63 = 63 lb/cubic foot
*27=1701

Water Volume = (305) /(62.4) = 4.9 cu. ft. per cu. yd.
Cement Volume = (677)/(3.15*62.4) = 3.4 cu. ft. per cu. yd.
CA Volume = (1701)/(2.65*62.4) = 10.3 cu. ft. per cu. yd.
Air Volume = 0.035*27 = .95 cu. ft

Total Volume of known ingredients = 19.5 cu. ft.
Coarse Volume = 27-19.5 = 7.5 ft^3
Weight of sand = 7.5*2.6*62.4=1216.8 lb/cubic yard

Need .84 + 50% = 3.3 Cubic Feet

Material	**PCY (lb)**	**PCF (lb)**	**1.25 Ft^3 (lb)**	**Material**
Water	305	11	**14**	**Water**
Cement	677	25	**31**	**Cement**
Gravel	1701	63	**79**	**Gravel**
Sand	1217	45	**56**	**Sand**
Air		0	**0**	**Air**

Gravel is split between .75" and 3/8"

Arch 2:

Cement Content
=Water/WC ratio = (340-35) pcy/.45 = 677 lb/cubic yard
755/27= 25 lb/cubic foot

Coarse Aggregate Content (Max 13/4" Size(1/5 of 4" diameter pipe))(assume 100 pcf)
100pcf * .63 = 63 lb/cubic foot
*27=1701

Water Volume = (305) /(62.4) = 4.9 cu. ft. per cu. yd.
Cement Volume = (677)/(3.15*62.4) = 3.4 cu. ft. per cu. yd.
CA Volume = (1701)/(2.65*62.4) = 10.3 cu. ft. per cu. yd.
Air Volume = 0.035*27 = .95 cu. ft
Total Volume of known ingredients = 19.5 cu. ft.
Coarse Volume = 27-19.5 = 7.5 ft^3
Weight of sand = 7.5*2.6*62.4=1216.8 lb/cubic yard

	Lbs (1.25'^3)	**KG**	% by Wt
Water	14	**6.4**	7.73%
Cement	31	**14.1**	17.13%
.75" Gravel	40	**18.2**	22.10%
3/8" Gravel	40	**18.2**	22.10%
Sand	28	**12.7**	15.47%
Silica	28	**12.7**	15.47%
Fibers			

Arch 3 and 4:

*Arch 4 is the same mix as arch 3 except for the addition of fibers
Cement
Content
Water/WC ratio = (300-35) pcy/.55 = 482 lb/cubic yard

Coarse Aggregate Content (Max 3/4" Size(1/5 of 4" diameter pipe))(assume 100 pcf)
100pcf * .55 = 55 lb/cubic
foot

Water Volume.	4.25	Cu. ft. per cu. yd.
Cement Volume	2.45	cu. ft. per cu. yd.
CA Volume	8.98	cu. ft. per cu. yd.

Air Volume = 0.035*27 = .95 cu. ft

Total Volume of known ingredients		16.62937871
sand Volume	10.37	cu. ft. per cu. yd.
Weight of sand	1682.53	

Need 2.2 + 50% = 3.3 Cubic Feet

Material	**PCY (lb)**	**PCF (lb)**	**2.75'^3**	**Kg**	**Material**
Water	265	10	**27**	12.3	**Water**
Cement	482	18	**49**	22.3	**Cement**
.75" Gravel	1485	55	**151**	68.8	**.75" Gravel**
Sand	561	21	**57**	26.0	**Sand**
Soil	1122	42	**114**	51.9	**Soil**
Mix 4 adds fiber					

<u>Arch 5:</u>

Cement
Content
Water/WC ratio = (300-35) pcy/. 55 = 482 lb/cubic yard

Coarse Aggregate Content (Max 3/4" Size(1/5 of 4" diameter pipe))(assume 100 pcf)
100pcf * .1375 = 13.75 lb/cubic foot

Water Volume.	4.25	Cu. ft. per cu. yd.
Cement Volume	2.45	cu. ft. per cu. yd.
CA Volume	2.24	cu. ft. per cu. yd.

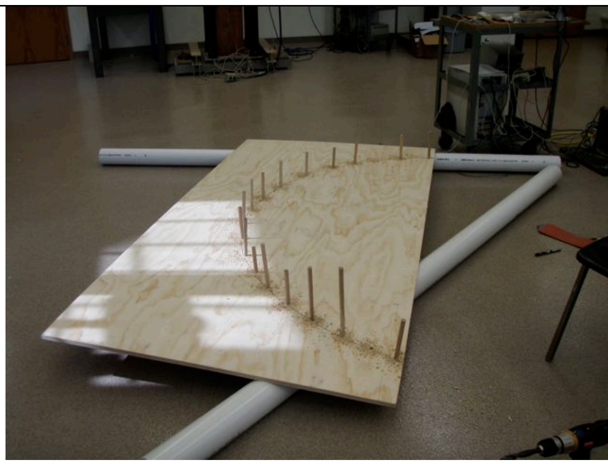
Air Volume = 0.035*27 = .95 cu. ft

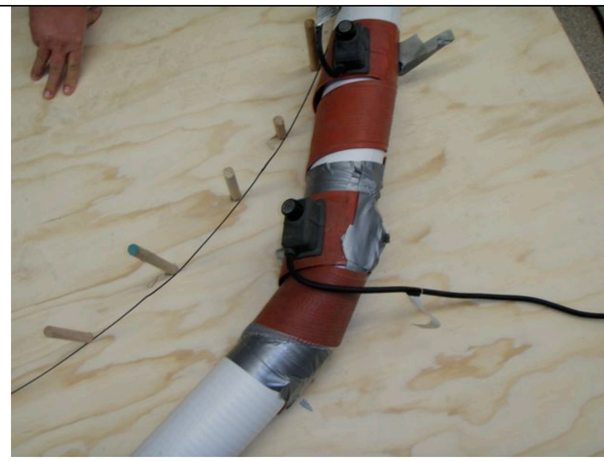
Total Volume of known ingredients		9.892562068
sand Volume	17.11	cu. ft. per cu. yd.
Weight of sand	2775.51	

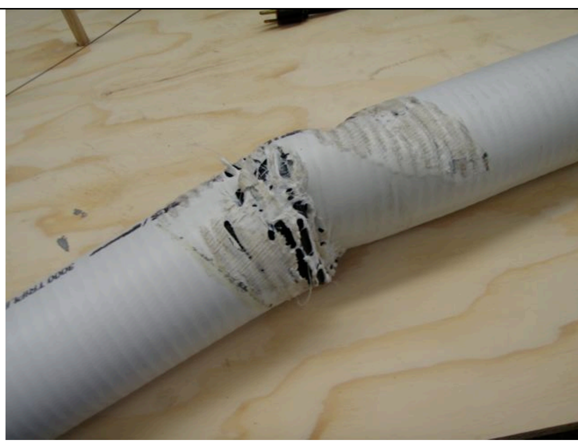
		1.25			
Material	**PCY (lb)**	**PCF (lb)**	**2.75'^3**	**Kg**	**Material**

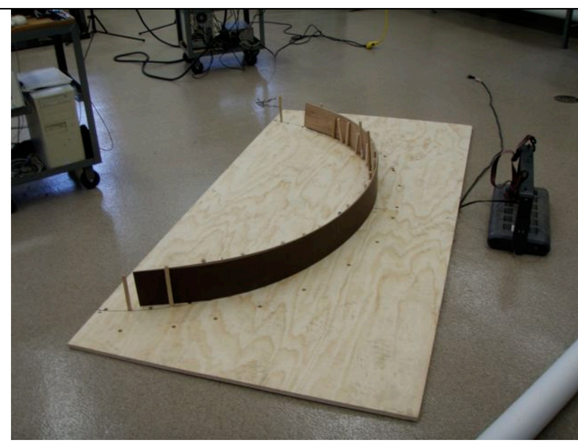
Water	265	10	**12**	5.6	**Water**
Cement	482	18	**22**	10.1	**Cement**
.75" Gravel	371	14	**17**	7.8	**.75" Gravel**
Sand	1387	51	**64**	29.2	**Sand**
Soil	1387	51	**64**	29.2	**Soil**

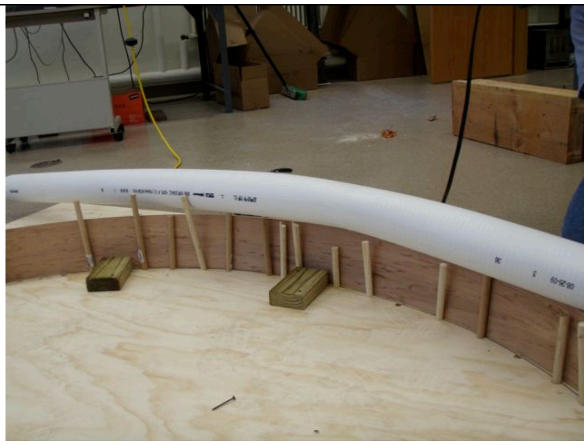
Appendix C: Non-Flexible PVC Bending Attempts











Due to the possibility of saving $600, the decision was made to attempt to bend non-flexible PVC pipe into the shape of an arch. The pipes were 10' sections of pipe at $10/ea from Home Depot. A jig was built on a 4'x8' piece of 3/8" Plywood to assist with the bending process. The jig consisted of wooden dowels that were screwed into the plywood. The jig was modified several times throughout the process.

<u>Bending Attempt 1:</u>

During the first bending attempt, the end of the PVC pipe was clamped to the jig and two heating pads were wrapped around the pipe. The PVC pipe was flexed too much before the heat could take affect, causing the pipe to buckle.

<u>Bending Attempt 2:</u>

During the second bending attempt the heating pads were left on the PVC for too long, causing the pipe to completely melt through, creating a large gap in the pipe.

<u>Bending Attempt 3:</u>

The jig was heavily modified after the second bending attempt. To prevent the pip from kinking along the dowels, a thin sheet of plywood was places in a semicircle on the jig, allowing for a more even distribution of pressure. The heating method was changed from using heating pads to a high-powered space heater that would be held over the pipe, as it was being bend. This attempt resulted in kink and the melting through of the pipe.

Bending Attempt 4:

A final attempt was made at bending the PVC pipe using the same method as attempt 3. This attempt also failed due to buckling after bending a third of the pipe.

Conclusions:

The attempts at bending the pipe were all failures and the procedure was deemed unfeasible. A significant amount of time was invested in each bending attempt, which would have been limiting even if one of the bending attempts were successful due to the need to produce multiple arches.

Appendix D: Concrete Pouring Log

See Appendix B for Mix Design

Footings:

Date Poured: 11/10/09

Slump Test: 3”

Lab Notes: Plastic bags places over forms to assist curing.



<u>Arch 1:</u>

Date Poured: 11/23/09

Slump Test: 1”

Lab Notes: Initial flap pouring system was unfeasible, so holes were drilled into the top of arches. Attempted pouring without arch bracing. The arch began to collapse so a simple bracing system was implemented. Only used manual Roding to eliminate air pockets.

Arch 1 was fractured in several locations during movement sometime around 12/15/09

<u>Arch 2:</u>

Date Poured: 11/30/09

Slump Test: 1”

Lab Notes: The mix absorbed too much water because of the silica fume so an additional 8.82 Kg of water was added to mix which originally consisted of 6.4 Kg of water. An F’c test tube was poured using excess concrete. The mechanical vibrator was used to eliminate air pockets.

Arch 2 was fractured in several locations during movement on 12/2/09 and sometime around 12/15/09

Arch 3 and 4:

Date Poured: 12/2/09

Slump Test: .5”, 1”

Lab Notes: We are getting good at putting the concrete into the arch. The same mix design was used for arch 3 and 4 except for fibers that were added to the mix after arch 3 was poured. The mechanical vibrator was used to eliminate air pockets.

Arch 5:

Date Poured: 12/4/09

Slump Test: 3”

Lab Notes: The mechanical vibrator was used to eliminate air pockets.

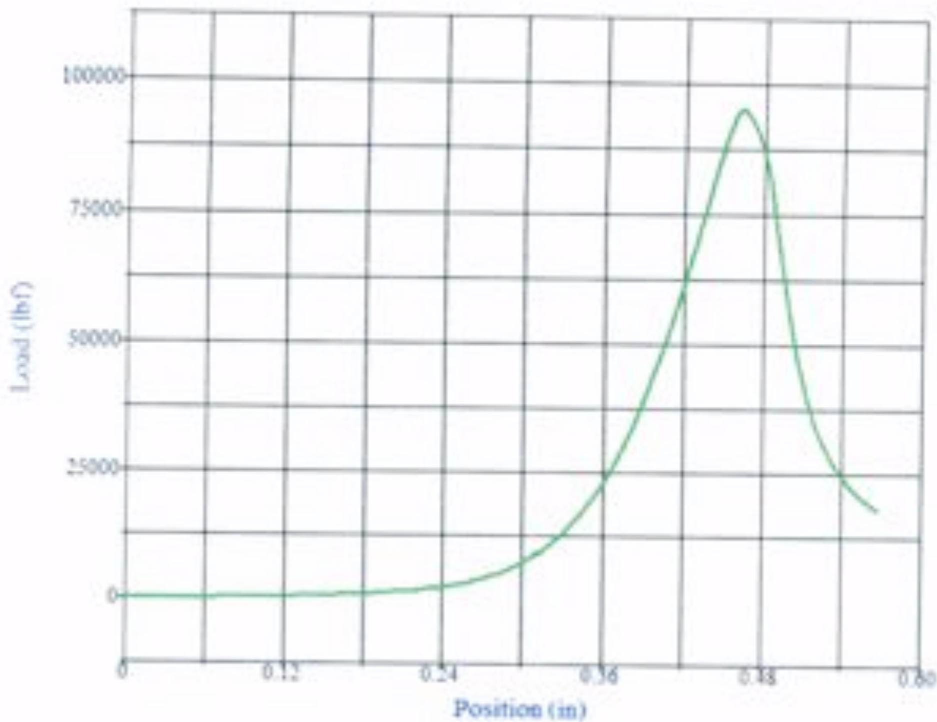
Appendix E: Cylinder Testing and Calculations

Standard Cylinders were made for mix 2,3 and 4:

Weights:

CEINSTRON1466

10:19:17 AM 2/10/2010

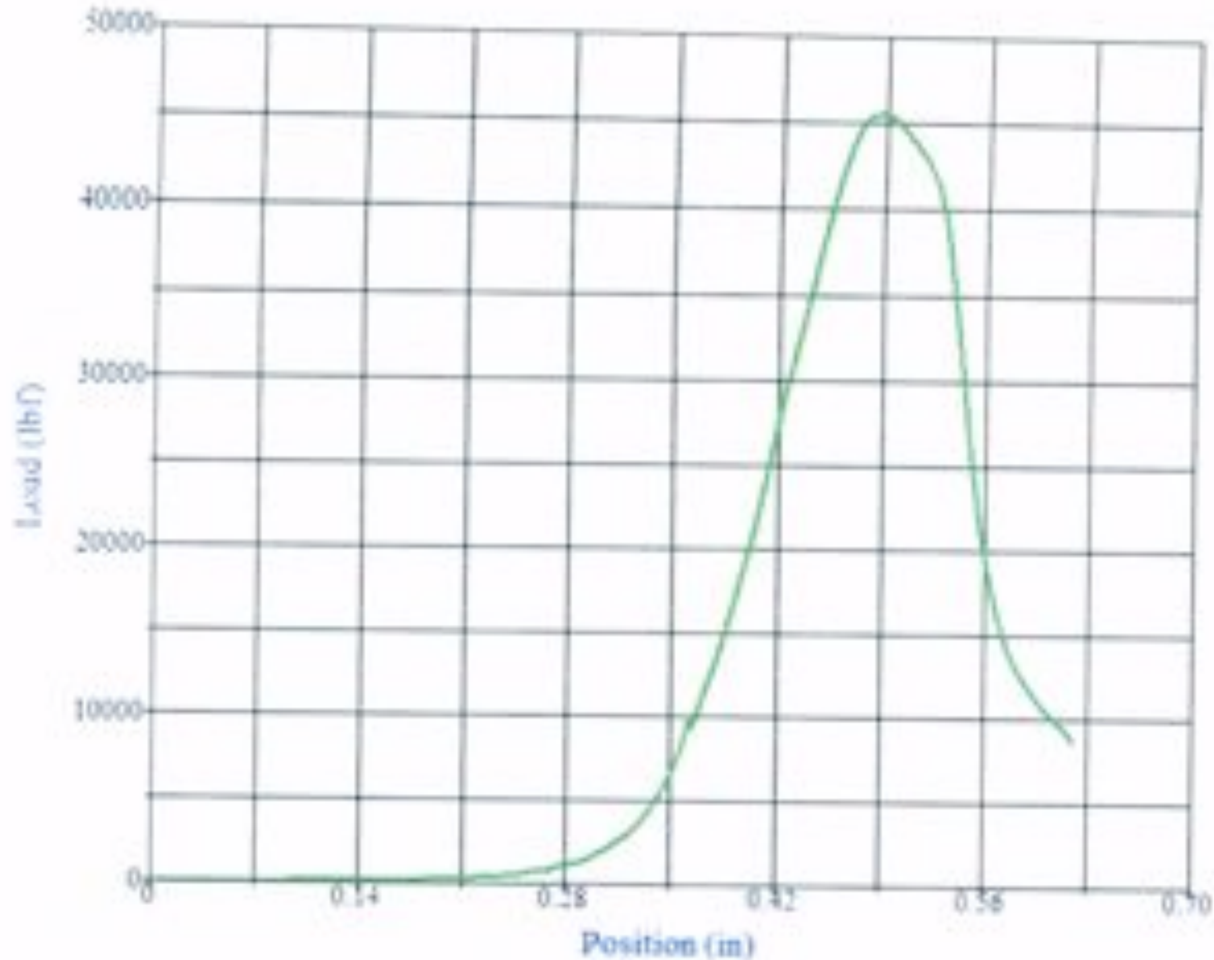


Test Summary

Counter:	466
Elapsed Time:	00:01:44
Procedure Name:	6X12 Cylinder
Start Date:	2/10/2010
Start Time:	10:17:01 AM
End Date:	2/10/2010
End Time:	10:18:45 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Concrete
Comments:	Samp-2

Test Results

Area:	28.2743 in²
Compressive Strength:	3358 psi
Peak Load:	94947 lbf
Diameter:	6.0000 in

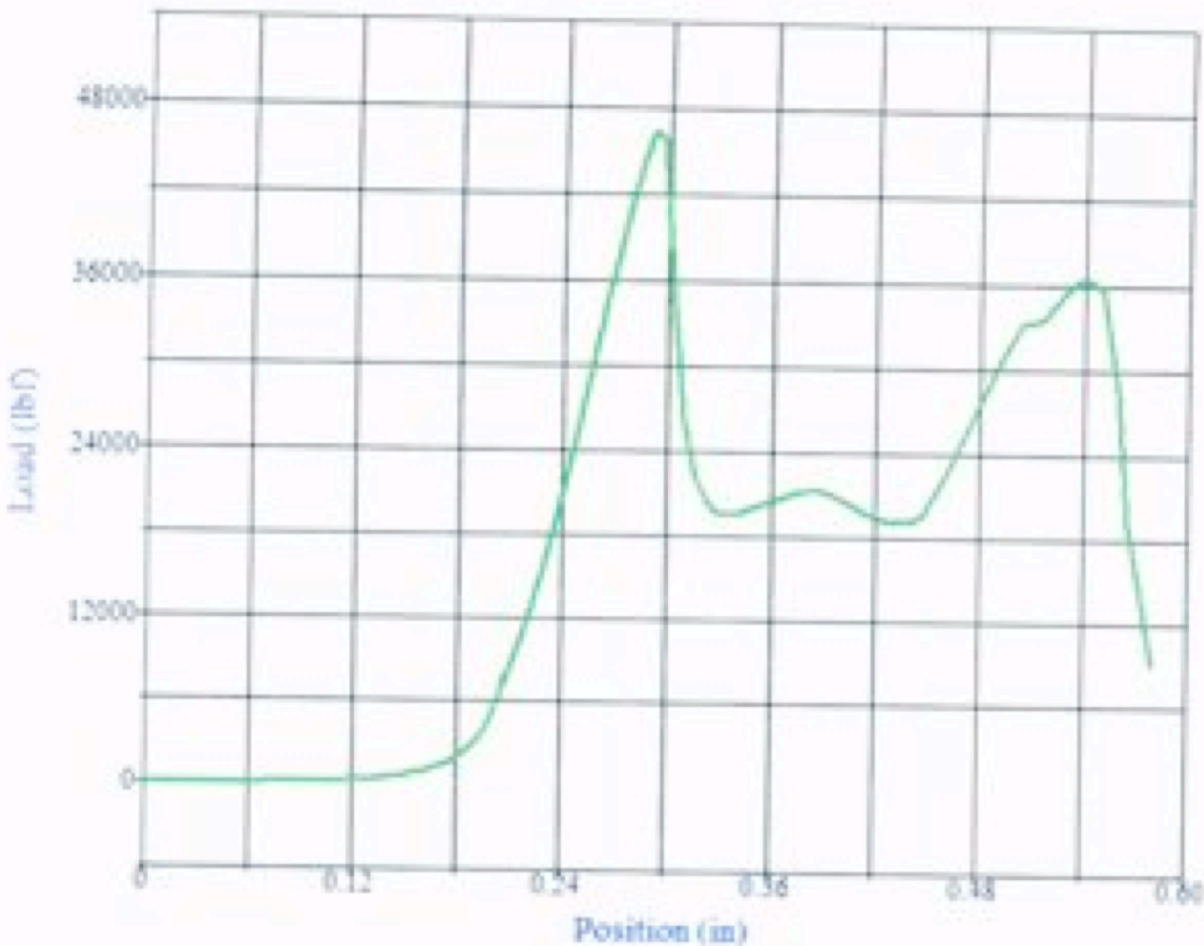


Test Summary

Counter:	468
Elapsed Time:	00:00:51
Procedure Name:	6X12 Cylinder
Start Date:	2/10/2010
Start Time:	10:28:13 AM
End Date:	2/10/2010
End Time:	10:29:04 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Concrete
Comments:	Samp-4

Test Results

Area:	28.2743 in²
Compressive Strength:	1607 psi
Peak Load:	45424 lbf
Diameter:	6.0000 in



Test Summary

Counter:	467
Elapsed Time:	00:00:54
Procedure Name:	6X12 Cylinder
Start Date:	2/10/2010
Start Time:	10:22:52 AM
End Date:	2/10/2010
End Time:	10:23:46 AM
Workstation:	CEINSTRON1
Tested By:	default
Material:	Concrete
Comments:	Samp 3

Test Results

Area:	28.2743 in²
Compressive Strength:	1638 psi
Peak Load:	46322 lbf
Diameter:	6.0000 in

Appendix F: Arch Testing and Calculations

Order Tested: Arch 2, 1, 5, 3, and 4

Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

Company:

Lab name: Samp 5 2/26/10

Operator ID:

Test date: 2/26/10

Name:

Number of specimens: 1

Temperature:

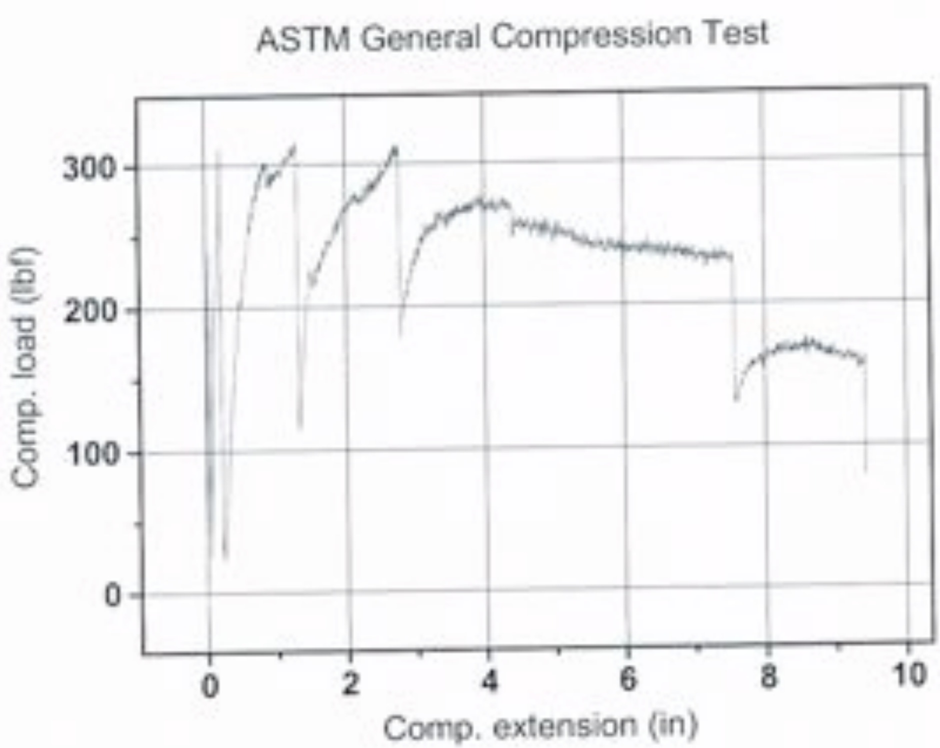
Humidity:

Speed 1: 0.50 in/min

Note 1: Sackett Harbor Bridge

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	315.28	1.281
Mean	315.28	1.281
S.D.	0.00	0.000
Minimum	315.28	1.281
Maximum	315.28	1.281
Range	0.00	0.000

Worc. Polytechnic Inst.

100 Institute Road

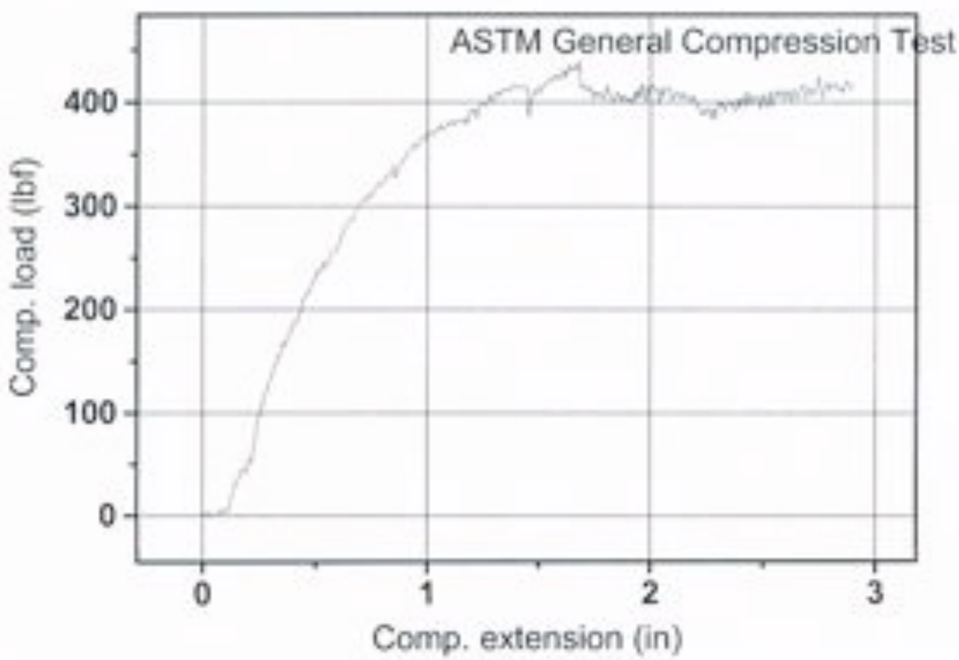
Worc. Mass. 01609

Company:		Name:		
Lab name:	WPI	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	2/12/10	Humidity:		
		Speed 1:	0.50	in/min

Note 1: 2-11-10 Samp2

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	439.74	1.680
Mean	439.74	1.680
S.D.	0.00	0.000
Minimum	439.74	1.680
Maximum	439.74	1.680
Range	0.00	0.000

Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

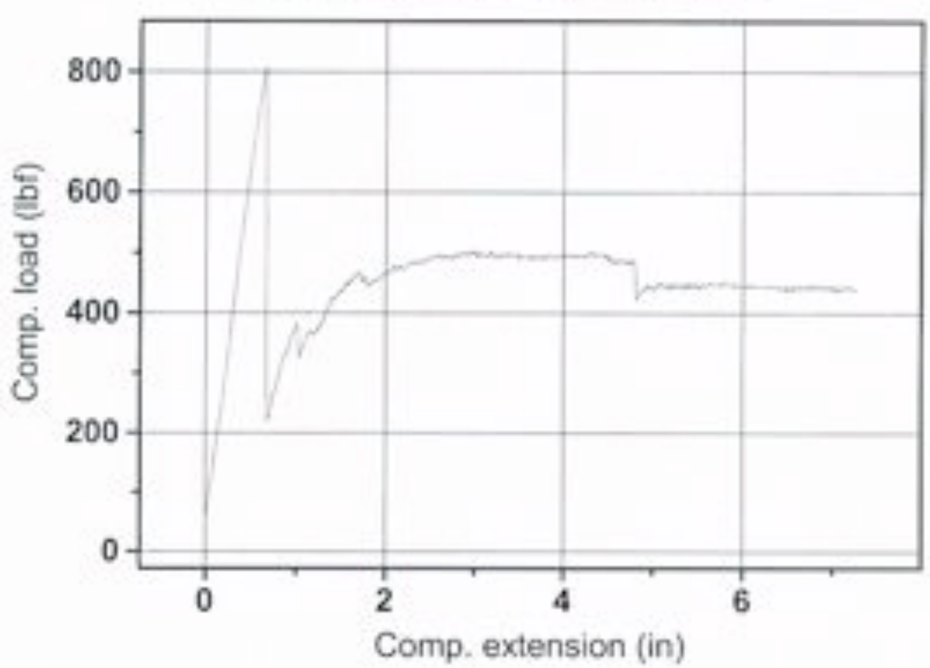
Company:		Name:		
Lab name:	Samp1 2/19/2010	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	2/19/10	Humidity:		
		Speed 1:	1.00	in/min

Note 1: Sackett Harbor Bridge

Note 2:

Note 3:

ASTM General Compression Test



	Maximum Load (lbf)	Comp. Ext. (in)
1	-	-
2	380.31	0.316
3	696.11	0.450
4	808.02	0.666
Mean	628.14	0.478
S.D.	221.81	0.177
Minimum	380.31	0.316
Maximum	808.02	0.666
Range	427.71	0.350

Worc. Polytechnic Inst.

100 Institute Road

Worc. Mass. 01609

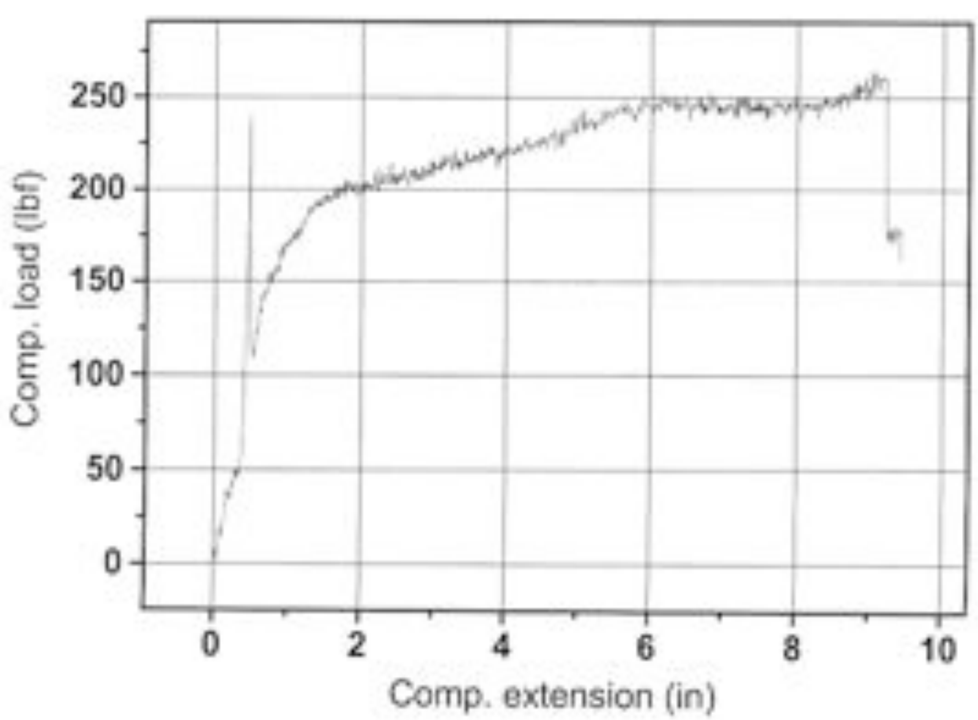
Company:		Name:		
Lab name:	Samp 4 3-1-10	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	2/26/10	Humidity:		
		Speed 1:	0.75	in/min

Note 1:

Note 2:

Note 3:

ASTM General Compression Test



	Maximum Load (lbf)	Comp. Ext. (in)
1	264.90	9.017
Mean	264.90	9.017
S.D.	0.00	0.000
Minimum	264.90	9.017
Maximum	264.90	9.017
Range	0.00	0.000

Worc. Polytechnic Inst.

100 Institute Road

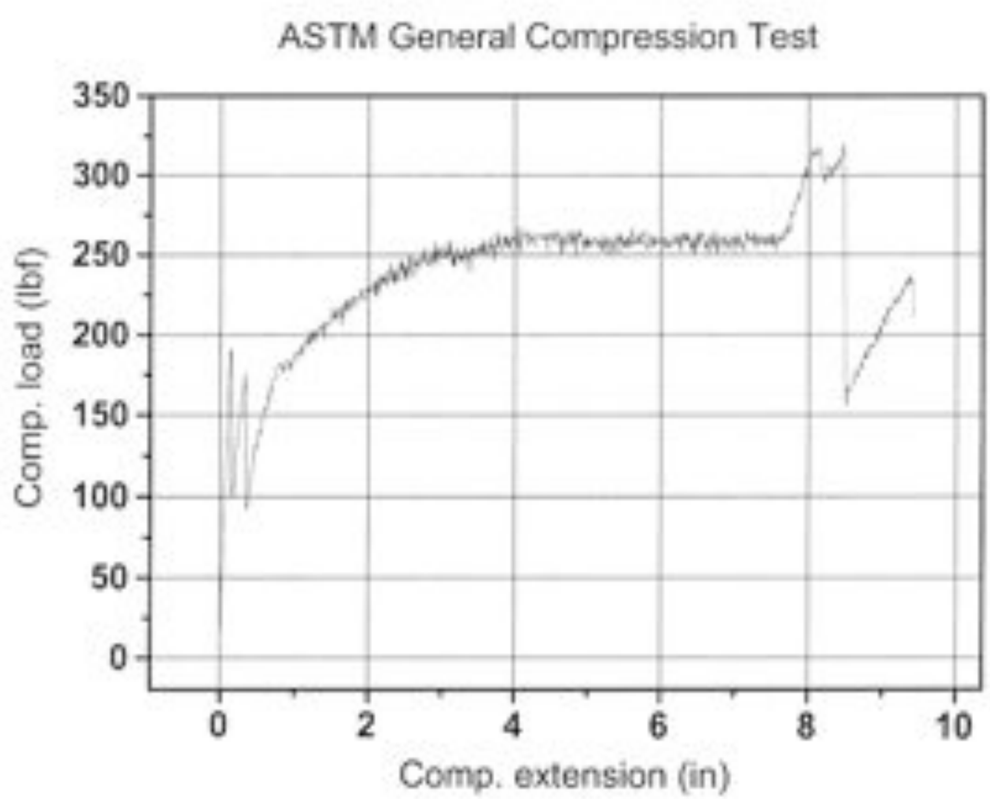
Worc. Mass. 01609

Company:		Name:		
Lab name:	Samp 3 3-2-10	Number of specimens:	1	
Operator ID:		Temperature:		
Test date:	3/1/10	Humidity:		
		Speed 1:	0.75	in/min

Note 1:

Note 2:

Note 3:



	Maximum Load (lbf)	Comp. Ext. (in)
1	319.46	8.468
Mean	319.46	8.468
S.D.	0.00	0.000
Minimum	319.46	8.468
Maximum	319.46	8.468
Range	0.00	0.000

Appendix G: Ansys Analysis

Parameters 1

First Saved	Saturday, March 20, 2010
Last Saved	Tuesday, March 23, 2010
Product Version	11.0 SP1 Release

TABLE 1

Unit System	U.S. Customary (in, lbm, lbf, °F, s, V, A)
Angle	Degrees
Rotational Velocity	rad/s

TABLE 2
Model > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	R:\MQP\Arch Sucess.agdb
Type	DesignModeler
Length Unit	Inches
Element Control	Program Controlled
Display Style	Part Color
Bounding Box	
Length X	76.72 in
Length Y	40. in
Length Z	4.36 in
Properties	
Volume	1709. in^3
Mass	142.12 lbm
Statistics	

Bodies	1
Active Bodies	1
Nodes	2923
Elements	1350
Preferences	
Import Solid Bodies	Yes
Import Surface Bodies	Yes
Import Line Bodies	Yes
Parameter Processing	Yes
Personal Parameter Key	DS
CAD Attribute Transfer	No
Named Selection Processing	No
Material Properties Transfer	No
CAD Associativity	Yes
Import Coordinate Systems	No
Reader Save Part File	No
Import Using Instances	Yes
Do Smart Update	No
Attach File Via Temp File	No
Analysis Type	3-D
Mixed Import Resolution	None
Enclosure and Symmetry Processing	Yes

TABLE 3
Model > Geometry > Parts

Object Name	*Solid*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Material	Concrete 3
Stiffness Behavior	Flexible
Nonlinear Material Effects	Yes
Bounding Box	
Length X	76.72 in
Length Y	40. in
Length Z	4.36 in
Properties	
Volume	1709. in³
Mass	142.12 lbm
Centroid X	1.0285e-006 in
Centroid Y	23.148 in
Centroid Z	5.6087e-007 in
Moment of Inertia Ip1	17768 lbm·in²
Moment of Inertia Ip2	91366 lbm·in²
Moment of Inertia Ip3	1.088e+005 lbm·in²
Statistics	

Nodes	2923
Elements	1350

TABLE 4
Model > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Advanced	
Relevance Center	Coarse
Element Size	Default
Shape Checking	Standard Mechanical
Solid Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Initial Size Seed	Active Assembly
Smoothing	Low
Transition	Fast
Statistics	
Nodes	2923
Elements	1350

TABLE 5
Model > Analysis

Object Name	*Static Structural*
State	Fully Defined
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Options	
Reference Temp	71.6 °F

TABLE 6
Model > Static Structural > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Nonlinear Controls	
Force Convergence	Program Controlled

Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Output Controls	
Calculate Stress	Yes
Calculate Strain	Yes
Calculate Results At	All Time Points
Analysis Data Management	
Solver Files Directory	R:\MQP\Final Param1 Simulation Files\Static Structural\
Future Analysis	None
Save ANSYS db	No
Delete Unneeded Files	Yes
Nonlinear Solution	No

TABLE 7
Model > Static Structural > Loads

Object Name	*Fixed Support*	*Fixed Support 2*	*Force 2*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Face		
Definition			
Type	Fixed Support		Force
Suppressed	No		
Define By			Components
X Component			0. lbf (ramped)
Y Component			-250. lbf (ramped)
Z Component			0. lbf (ramped)

FIGURE 1
Model > Static Structural > Force 2

TABLE 8
Model > Static Structural > Solution

Object Name	*Solution*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.

TABLE 9
Model > Static Structural > Solution > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0

Update Interval	2.5 s
Display Points	All

TABLE 10
Model > Static Structural > Solution > Results

Object Name	*Total Deformation*	*Normal Stress*	*Shear Stress*	*Normal Elastic Strain*	*Shear Elastic Strain*
State	Solved				
Scope					
Geometry	All Bodies				
Definition					
Type	Total Deformation	Normal Stress	Shear Stress	Normal Elastic Strain	Shear Elastic Strain
Display Time	End Time				
Orientation		X Axis	XY Plane	X Axis	XY Plane
Results					
Minimum	0. in	-179.56 psi	-45.192 psi	-9.2108e-005 in/in	-5.5665e-005 in/in
Maximum	4.6063e-003 in	173.55 psi	46.882 psi	9.0501e-005 in/in	5.7746e-005 in/in
Information					
Time	1. s				
Load Step	1				
Substep	1				
Iteration Number	1				

TABLE 11
Concrete 3 > Constants

Structural	
Young's Modulus	1.916e+006 psi
Poisson's Ratio	0.18
Density	8.316e-002 lbm/in³
Thermal Expansion	7.7778e-006 1/°F
Tensile Yield Strength	0. psi
Compressive Yield Strength	0. psi
Tensile Ultimate Strength	240. psi
Compressive Ultimate Strength	1500. psi
Thermal	
Thermal Conductivity	9.6298e-006 BTU/s·in·°F
Specific Heat	0.18615 BTU/lbm·°F

Parameters 2

First Saved	Saturday, March 20, 2010
Last Saved	Tuesday, March 23, 2010
Product Version	11.0 SP1 Release

TABLE 1

Unit System	U.S. Customary (in, lbm, lbf, °F, s, V, A)
Angle	Degrees
Rotational Velocity	rad/s

TABLE 2
Model > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	R:\MQP\Arch Sucess.agdb
Type	DesignModeler
Length Unit	Inches
Element Control	Program Controlled
Display Style	Part Color
Bounding Box	
Length X	76.72 in
Length Y	40. in
Length Z	4.36 in
Properties	
Volume	1709. in^3
Mass	142.12 lbm
Statistics	
Bodies	1
Active Bodies	1
Nodes	2923
Elements	1350
Preferences	
Import Solid Bodies	Yes
Import Surface Bodies	Yes
Import Line Bodies	Yes
Parameter Processing	Yes
Personal Parameter Key	DS
CAD Attribute Transfer	No
Named Selection Processing	No
Material Properties Transfer	No
CAD Associativity	Yes
Import Coordinate Systems	No
Reader Save Part File	No
Import Using Instances	Yes
Do Smart Update	No
Attach File Via Temp File	No
Analysis Type	3-D
Mixed Import Resolution	None
Enclosure and Symmetry Processing	Yes

TABLE 3
Model > Geometry > Parts

Object Name	*Solid*
State	Meshed

Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Material	Concrete 3
Stiffness Behavior	Flexible
Nonlinear Material Effects	Yes
Bounding Box	
Length X	76.72 in
Length Y	40. in
Length Z	4.36 in
Properties	
Volume	1709. in³
Mass	142.12 lbm
Centroid X	1.0285e-006 in
Centroid Y	23.148 in
Centroid Z	5.6087e-007 in
Moment of Inertia Ip1	17768 lbm·in²
Moment of Inertia Ip2	91366 lbm·in²
Moment of Inertia Ip3	1.088e+005 lbm·in²
Statistics	
Nodes	2923
Elements	1350

TABLE 4
Model > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Advanced	
Relevance Center	Coarse
Element Size	Default
Shape Checking	Standard Mechanical
Solid Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Initial Size Seed	Active Assembly
Smoothing	Low
Transition	Fast
Statistics	
Nodes	2923
Elements	1350

TABLE 5
Model > Analysis

Object Name	*Static Structural*
State	Fully Defined
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Options	
Reference Temp	71.6 °F

TABLE 6
Model > Static Structural > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Nonlinear Controls	
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Output Controls	
Calculate Stress	Yes
Calculate Strain	Yes
Calculate Results At	All Time Points
Analysis Data Management	
Solver Files Directory	R:\MQP\Final Param2 Simulation Files\Static Structural\
Future Analysis	None
Save ANSYS db	No
Delete Unneeded Files	Yes
Nonlinear Solution	No

TABLE 7
Model > Static Structural > Loads

Object Name	*Fixed Support*	*Fixed Support 2*	*Force 2*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Face		
Definition			
Type	Fixed Support		Force
Suppressed	No		

Define By		Components
X Component		0. lbf (ramped)
Y Component		-800. lbf (ramped)
Z Component		0. lbf (ramped)

FIGURE 1
Model > Static Structural > Force 2

TABLE 8
Model > Static Structural > Solution

Object Name	*Solution*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.

TABLE 9
Model > Static Structural > Solution > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All

TABLE 10
Model > Static Structural > Solution > Results

Object Name	*Total Deformation*	*Normal Stress*	*Shear Stress*	*Normal Elastic Strain*	*Shear Elastic Strain*
State	Solved				
Scope					
Geometry	All Bodies				
Definition					
Type	Total Deformation	Normal Stress	Shear Stress	Normal Elastic Strain	Shear Elastic Strain
Display Time	End Time				
Orientation		X Axis	XY Plane	X Axis	XY Plane
Results					
Minimum	0. in	-574.59 psi	-144.62 psi	-1.8043e-004 in/in	-1.0904e-004 in/in
Maximum	9.0231e-003 in	555.35 psi	150.02 psi	1.7728e-004 in/in	1.1312e-004 in/in
Information					
Time	1. s				
Load Step	1				
Substep	1				
Iteration Number	1				

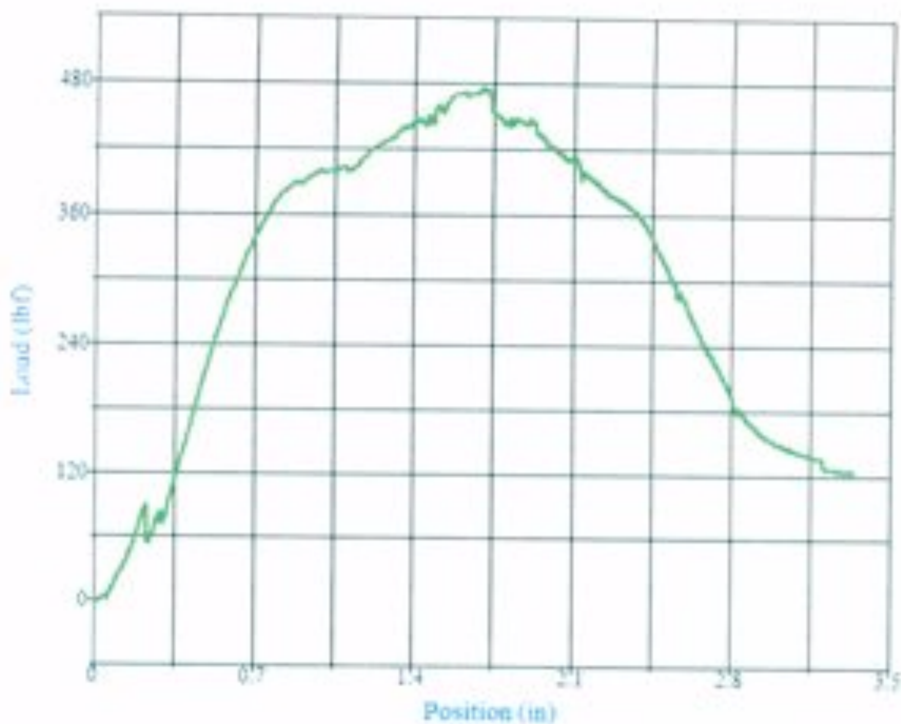
TABLE 11
Concrete 3 > Constants

Structural	
Young's Modulus	3.13e+006 psi
Poisson's Ratio	0.18
Density	8.316e-002 lbm/in³
Thermal Expansion	7.7778e-006 1/°F
Tensile Yield Strength	0. psi
Compressive Yield Strength	0. psi
Tensile Ultimate Strength	340. psi
Compressive Ultimate Strength	3000. psi
Thermal	
Thermal Conductivity	9.6298e-006 BTU/s·in·°F
Specific Heat	0.18615 BTU/lbm·°F

Appendix H: Mini Arch Testing and Calculations

(Note: It was a point load compression test, not spit-tensile as listed)

CEINSTRON10 10:11:02 AM 3/19/2010



Test Summary

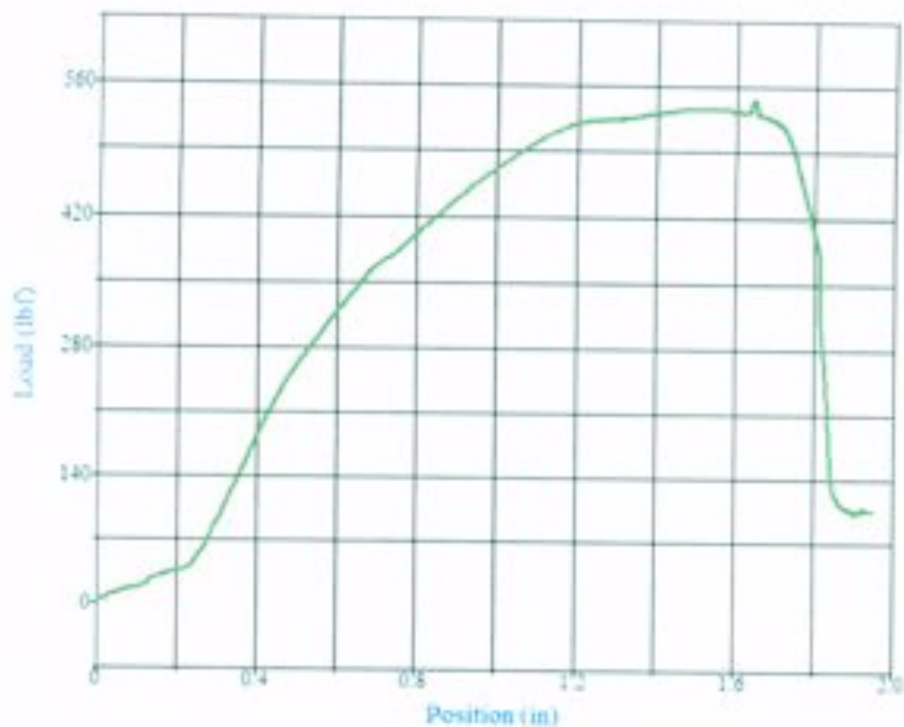
Counter:	0
Elapsed Time:	00:06:44
Material:	Concrete
Lab:	
Sample:	Mini Tube-1
Specimen Identification:	3/17/10
Procedure Name:	dpel Concrete Split Tensile
Start Date:	3/19/2010
Start Time:	10:04:00 AM
End Date:	3/19/2010
End Time:	10:10:44 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	2.0000 in
Area:	3.1416 in²
Peak Load:	475 lbf

CEINSTRON10

10:24:43 AM 3/19/2010



Test Summary

Counter:	0
Elapsed Time:	00:02:37
Material:	concrete
Lab:	
Sample:	mini tube-2
Specimen Identification:	3/17/10
Procedure Name:	dpel Concrete Split Tensile
Start Date:	3/19/2010
Start Time:	10:21:29 AM
End Date:	3/19/2010
End Time:	10:24:06 AM
Workstation:	CEINSTRON1
Tested By:	default

Test Results

Diameter:	2.0000 in
Area:	3.1416 in²
Peak Load:	547 lbf