# Phase I:
# Evaluation of the Compressive Strength Behavior of Octaform™ Concrete Forming System

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# Outline

- Problem Statement
- Phase I
  - Casting
  - Test Set-up and DAQ
- Test Results
- Conclusions and Future Work

# Problem Statement

Is Octaform more than a forming system (as far as structural strength is concerned)?

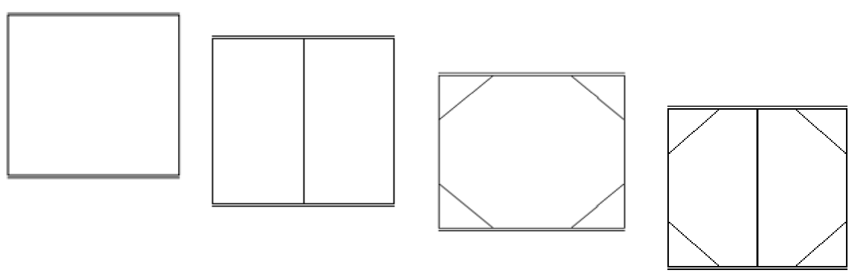
Does Octaform do anything to the compressive strength (f'c) of concrete?

Research at Seattle University indicated increase in compressive strength when Octaform is used. Does this apply to full-scale columns?

# Phase I was designed to understand the behavior of un-reinforced columns!

| Column Height Inches | Configuration |
|---|---|
| 20 | Config. 1 |
| | Config. 2 |
| | Config. 3 |
| | Config. 4 |
| | Control |
| 36 | Config. 1 |
| | Config. 2 |
| | Config. 3 |
| | Config. 4 |
| | Control |
| 72 | Config. 1 |
| | Config. 2 |
| | Config. 3 |
| | Config. 4 |
| | Control |

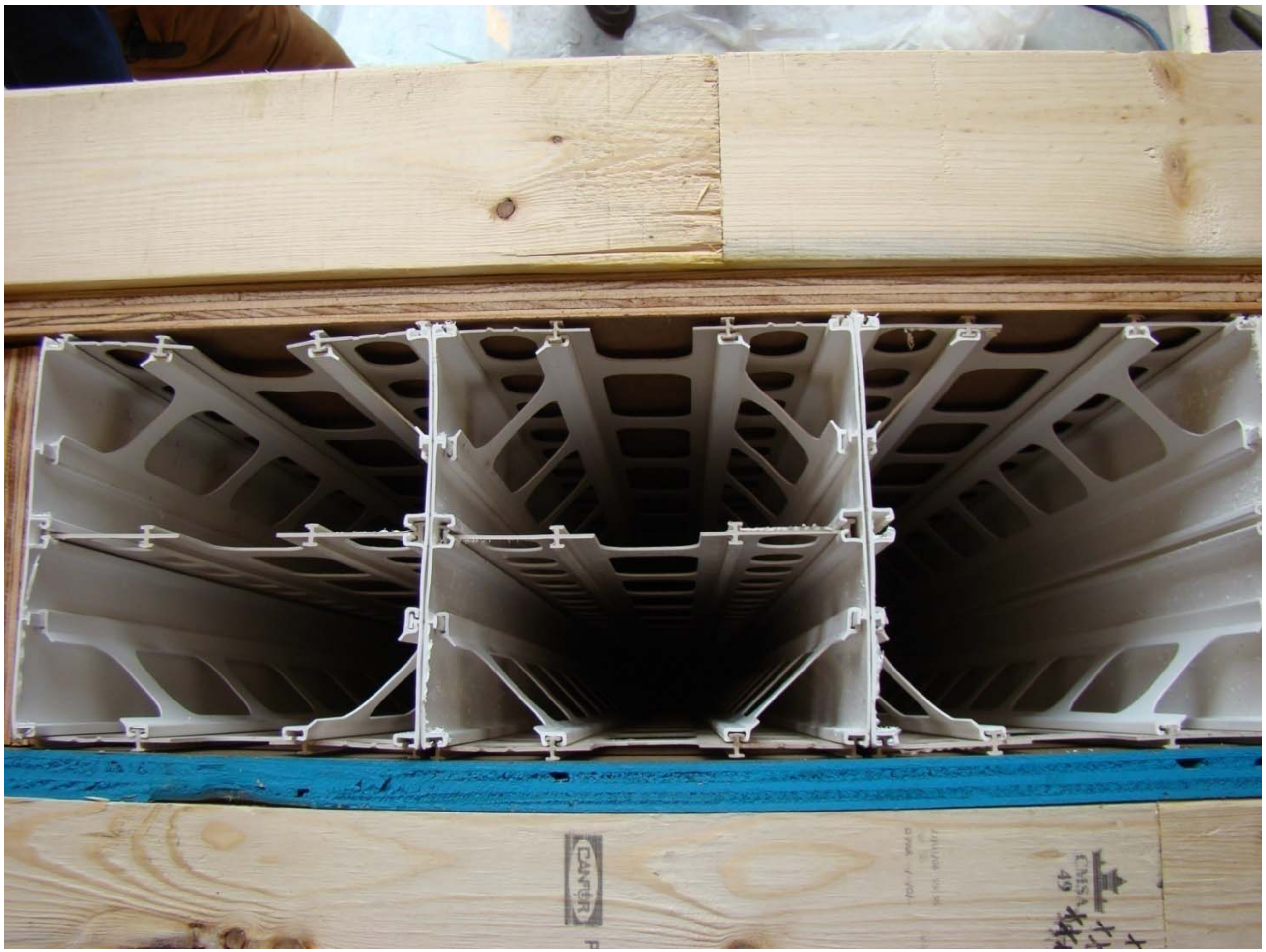
- Three heights: 1.67' to 6'
- Cross section: 6" x 6"
- Four configurations compared to control



OCTAFORM™
CONCRETE FORMING SYSTEMS

BCIT™

# Assembly (Octaform Systems Inc)



# Mix Design / Concrete Pour (RMC)

# Mix Design / Casting (RMC)

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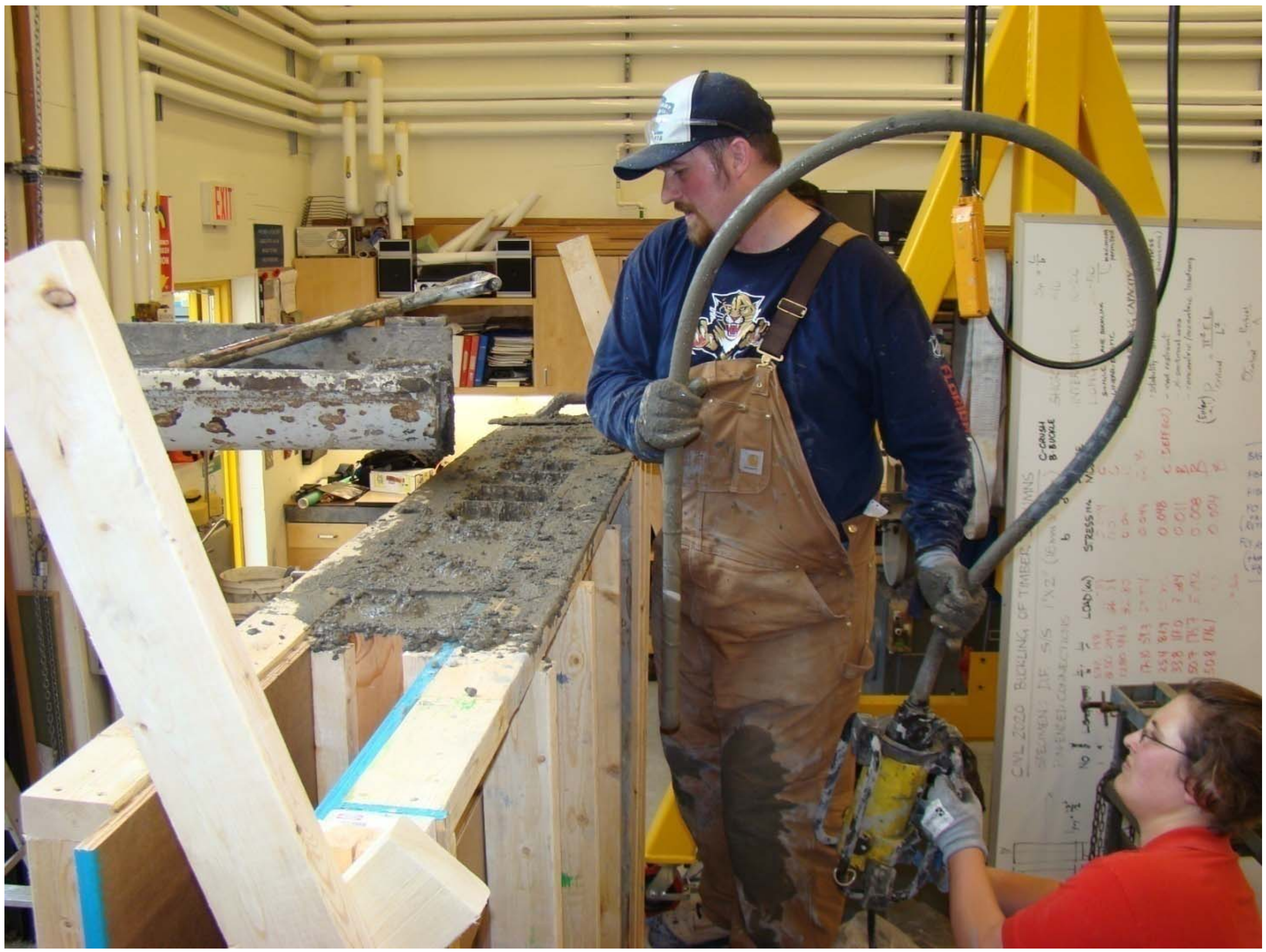
# Concrete Pour / Vibration



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# Fresh Properties- Slump

# Fresh Properties- Air Content

# Casting cylinders for compression test

# Test Set-up

# Test Set-up

- One dial gauge
- Two LVDTs for deflection
- One load cell
- DAQ and computer

# Results

# Results (Fresh Properties)

Slump:

Target = 80+-20mm

Recorded = ~ 180 mm

Air content:

Target = 1-4%

Recorded = 2.8%

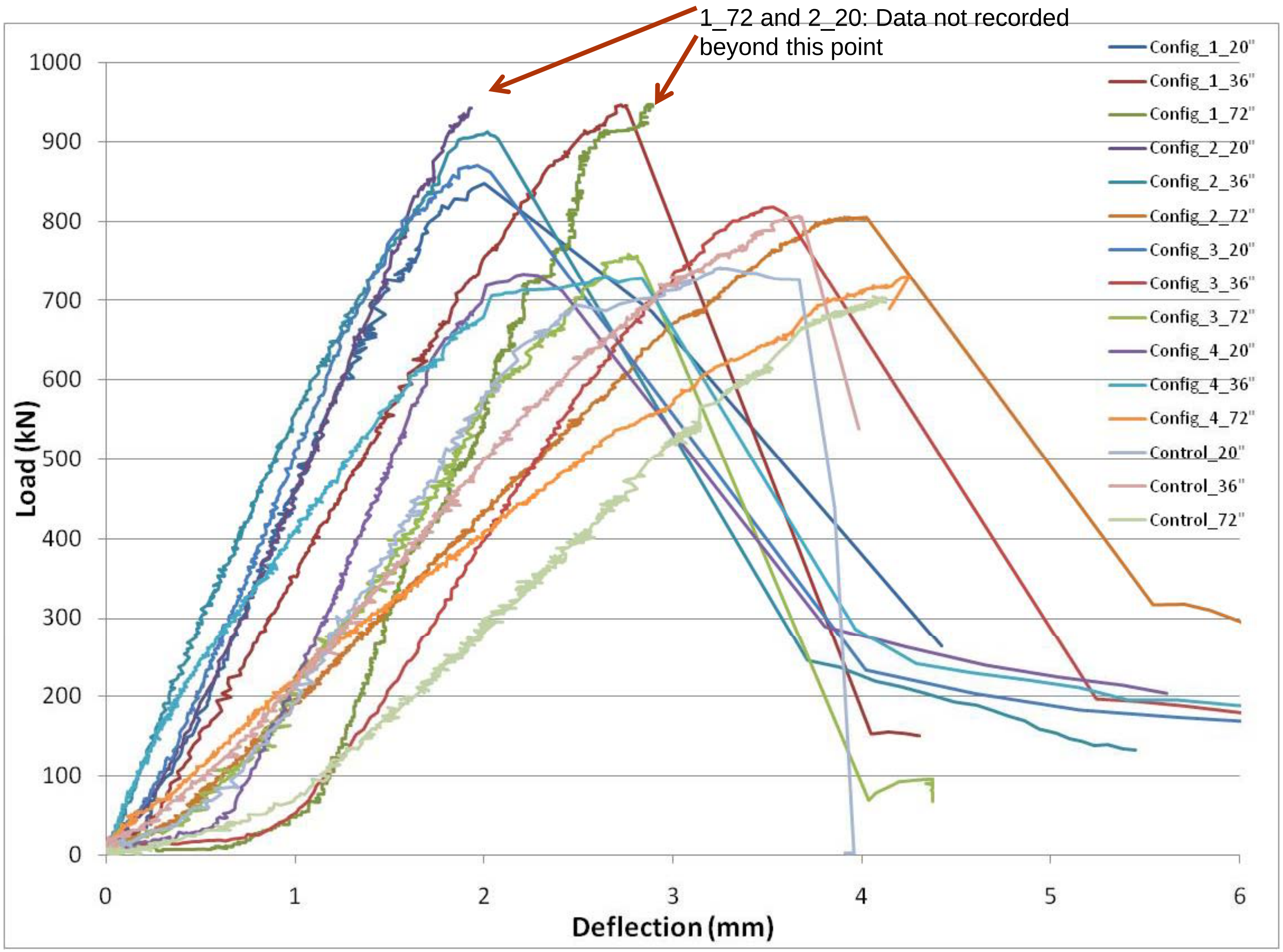
# Results- Compressive strength

- Target f’c = 20 MPa
- Average of six specimens = 38 MPa
- Resulted in some columns reaching the load capacity of the machine

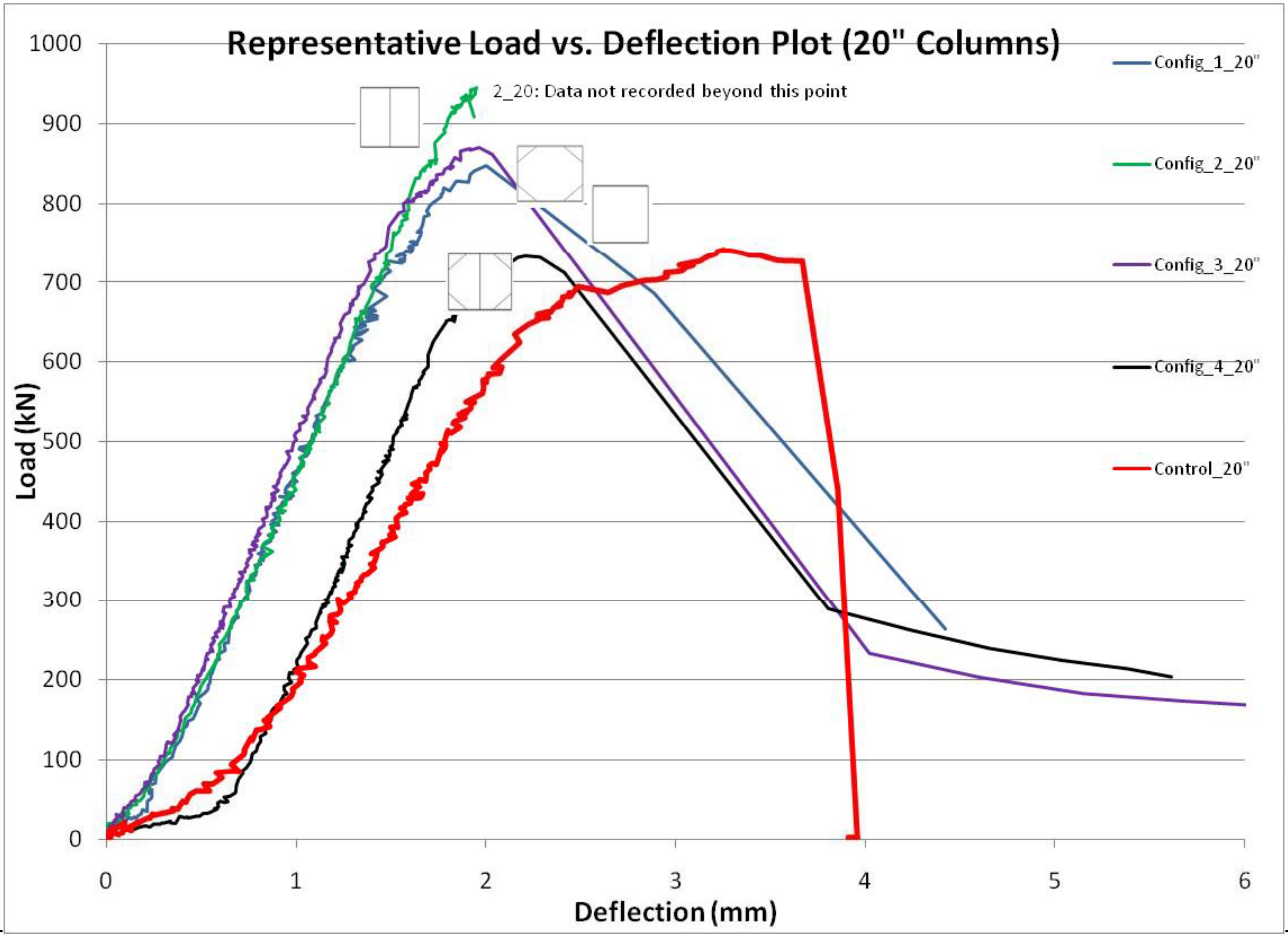
# Issues / Concerns Addressed

- Especially with long columns
  - Not 100% straight
    - Didn't seem to affect the results too much, since columns failed by crushing and not buckling
  - Not horizontal and levelled
    - Grinding was done on the top of the columns, the loading head swivelled
  - Voids in a few long columns
    - These values have not been included in averaging

# Representative Load vs. deflection curves

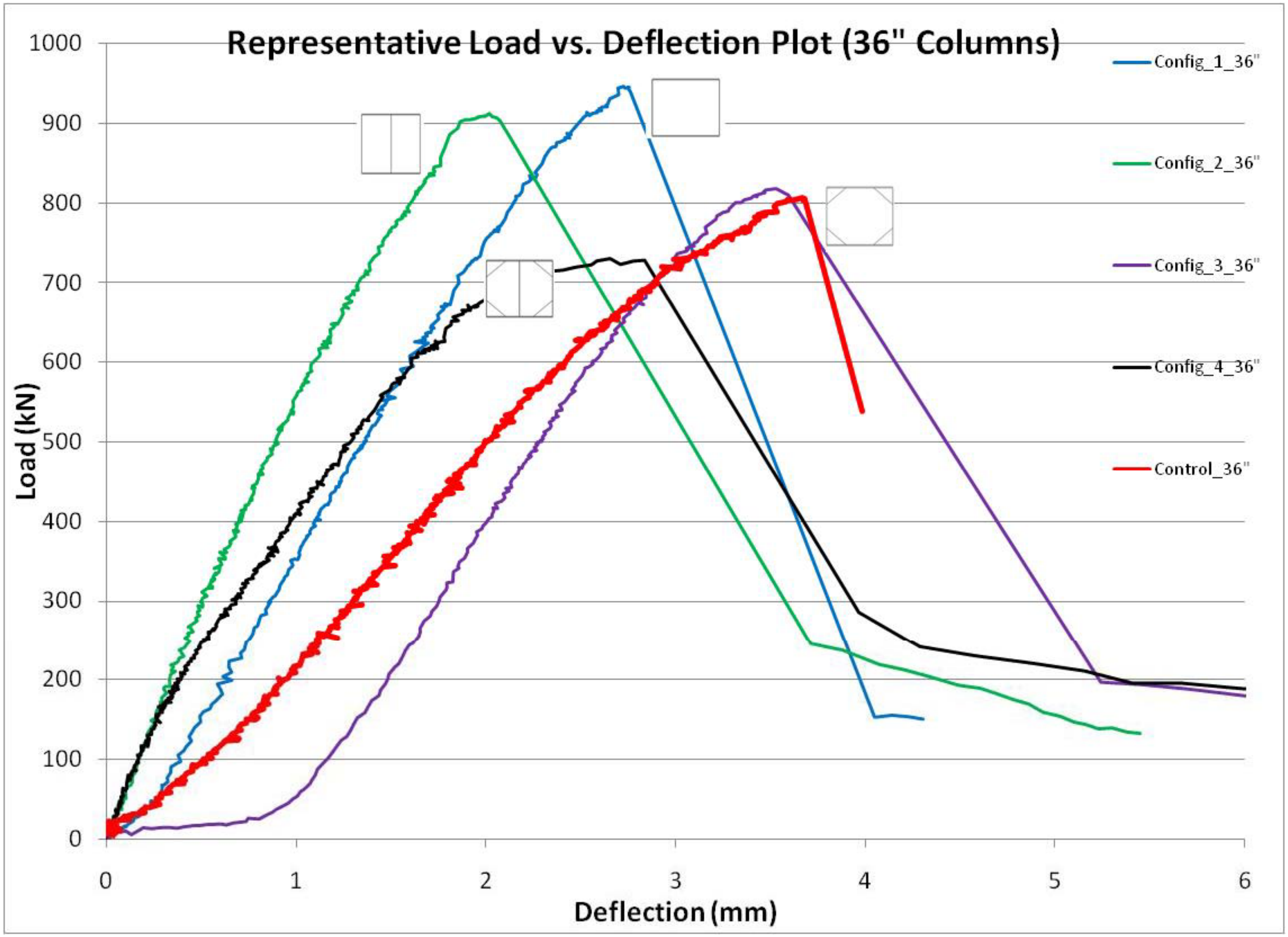


# 20” Columns

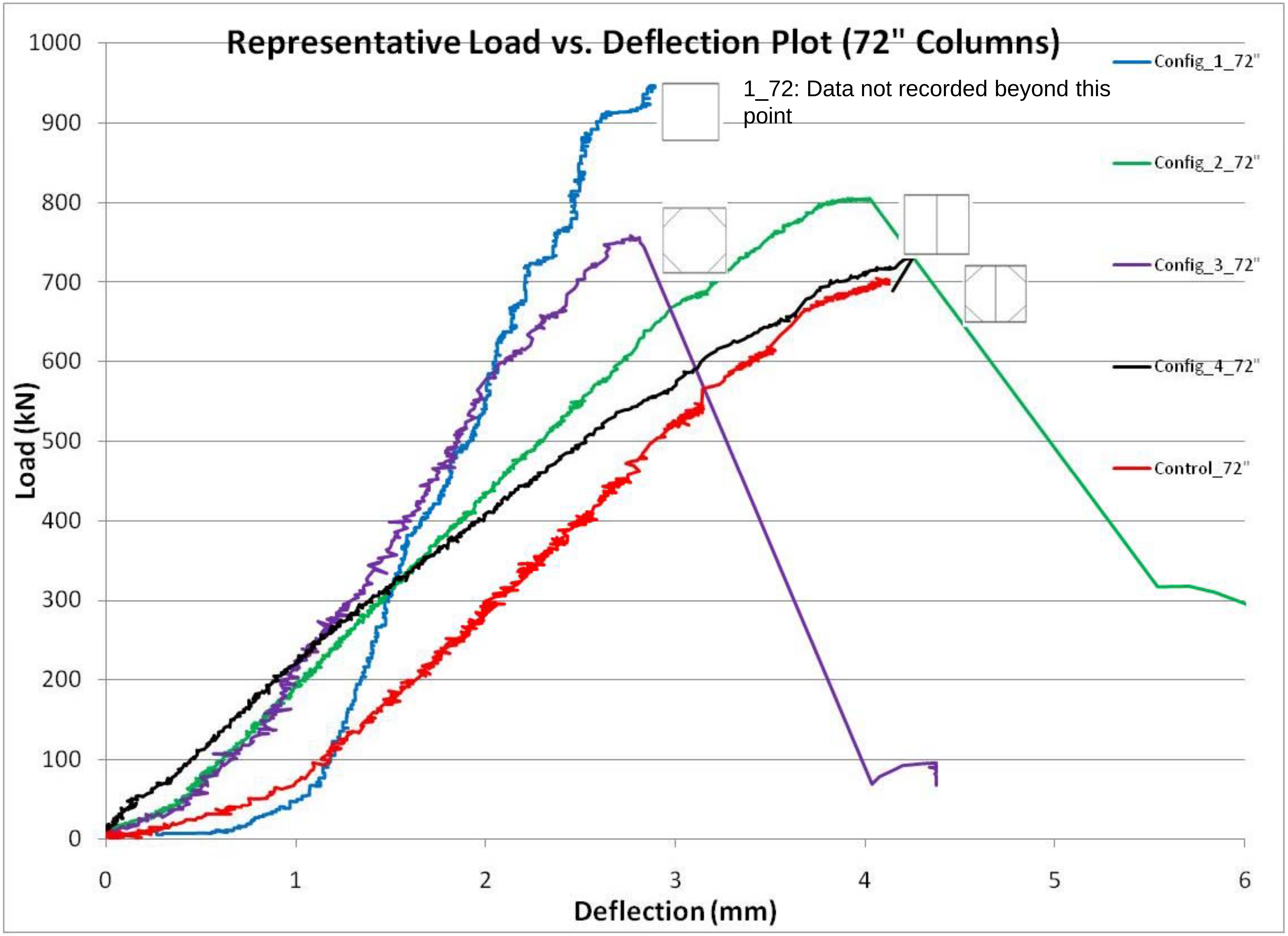


Representative Load vs. Deflection Plot (20" Columns)
2_20: Data not recorded beyond this point
Config_1_20"
Config_2_20"
Config_3_20"
Config_4_20"
Control_20"
Load (kN)
1000
900
800
700
600
500
400
300
200
100
0
Deflection (mm)
0
1
2
3
4
5
6

# 36” Columns


Representative Load vs. Deflection Plot (36" Columns)
Load (kN)
Deflection (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
1
2
3
4
5
6
Config_1_36"
Config_2_36"
Config_3_36"
Config_4_36"
Control_36"

# 72” Columns



Representative Load vs. Deflection Plot (72" Columns)
1_72: Data not recorded beyond this point
Load (kN)
Deflection (mm)
0
100
200
300
400
500
600
700
800
900
1000
0
1
2
3
4
5
6
Config_1_72"
Config_2_72"
Config_3_72"
Config_4_72"
Control_72"

# Detailed Analysis (20" and 36")

| Column Height | Configuration | Designation | Peak Load | Avg Peak Load | Increase in Load |
|---|---|---|---|---|---|
| Inches | | | kN | kN | % |
| 20 | Config. 1 | 1-20 | 935 | 892 | 22 |
| | | 2-20 | 848 | | |
| | Config. 2 | 3-20 | 968 | 957 | 31 |
| | | 4-20 | 945 | | |
| | Config. 3 | 5-20 | 870 | 890 | 22 |
| | | 6-20 | 910 | | |
| | Config. 4 | 7-20 | 716 | 725 | -1 |
| | | 8-20 | 733 | | |
| | Control | 9-20 | 888 | 730 | - |
| | | 10-20 | 742 | | |
| | | 11-20 | 718 | | |
| 36 | Config. 1 | 1-36 | 912 | 930 | 10 |
| | | 2-36 | 947 | | |
| | Config. 2 | 3-36 | 726 | 913 | 8 |
| | | 4-36 | 913 | | |
| | Config. 3 | 5-36 | 942 | 880 | 4 |
| | | 6-36 | 817 | | |
| | Config. 4 | 7-36 | 730 | 748 | -11 |
| | | 8-36 | 766 | | |
| | Control | 9-36 | 892 | 844 | - |
| | | 10-36 | 807 | | |
| | | 11-36 | 833 | | |

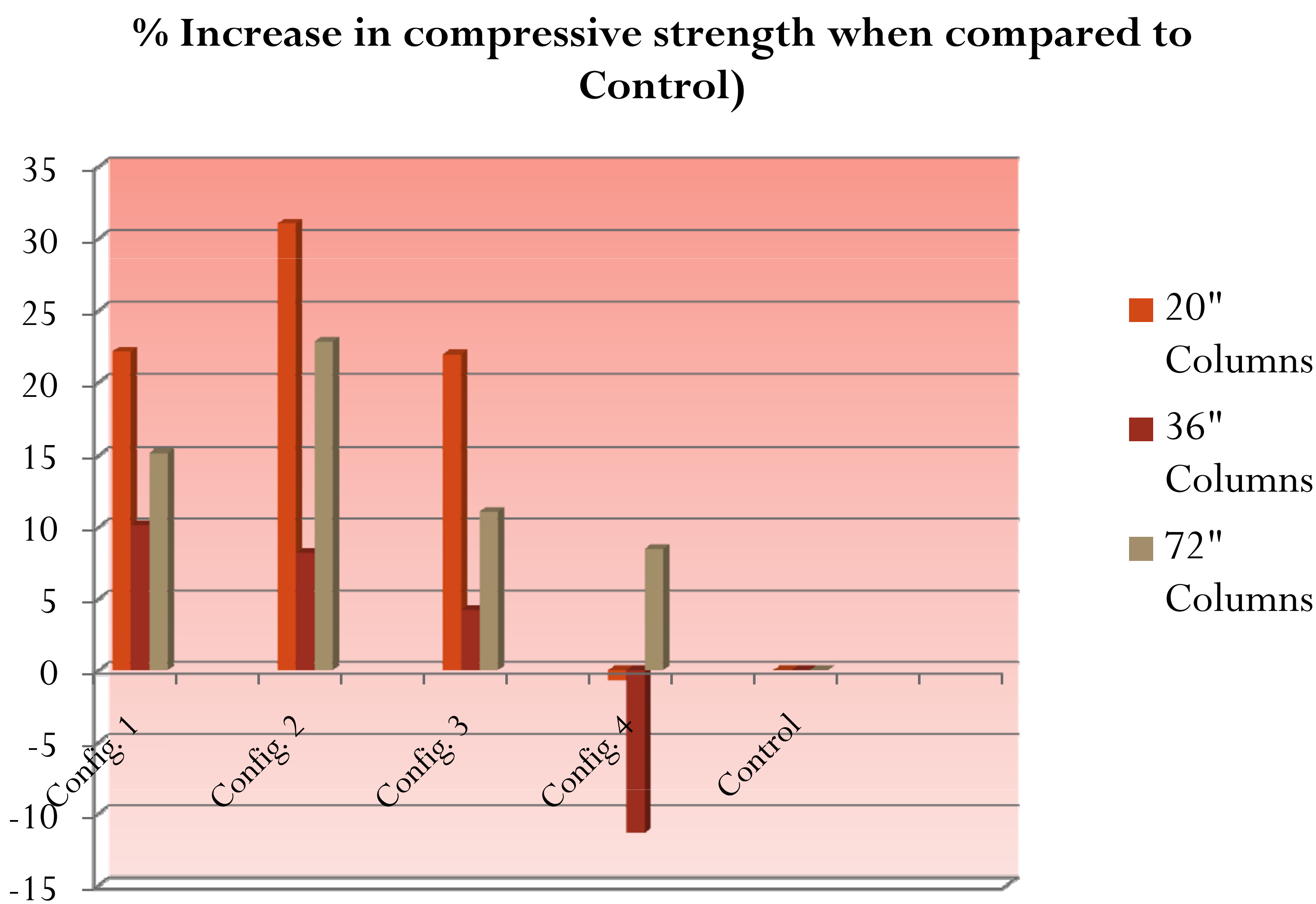
*Numbers highlighted in gray are not included in calculating the average*

# Detailed Analysis (72")

| Column Height | Configuration | Designation | Peak Load | Avg Peak Load | Increase in Load |
|---|---|---|---|---|---|
| Inches | | | kN | kN | % |
| 72 | Config. 1 | 1-72 | 608 | 775 | 15 |
| | | 2-72 | 775 | | |
| | Config. 2 | 3-72 | 848 | 827 | 23 |
| | | 4-72 | 805 | | |
| | Config. 3 | 5-72 | 736 | 748 | 11 |
| | | 6-72 | 759 | | |
| | Config. 4 | 7-72 | 494 | 730 | 8 |
| | | 8-72 | 730 | | |
| | Control | 9-72 | 462 | 673 | - |
| | | 10-72 | 705 | | |
| | | 11-72 | 641 | | |

Numbers highlighted in gray are not included in calculating the average

# % Increase Compared to Control



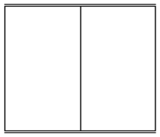
# Damage in Specimens / Containment: Secondary Benefit!

Control: Post compression


Octaform: Post compression

# Damage in Specimens / Containment: Secondary Benefit!

# Conclusions

- Full scale unreinforced column (6 feet) tests have been completed. Structural as opposed to material level.
- PVC encasement significantly affects the compressive strength of columns
  - Range of: -11% (36”, config. 4) to 31%
  - Average increase of 12%
  - Not including the config. 4, an average increase of 25%, 8%, and 16% for 20”, 36” and 72” columns
- Most effective configurations 1  and 2 

# Conclusions

- Secondary Benefits
  - Control specimens fail in a very brittle mode, Octaform columns experience a drop in peak load but continue to carry load after peak
    - This indicates enhanced energy absorption capacity
  - Minimal spalling of concrete in Octaform columns

# Future Work / What's next?

- Findings from Phase I can feed into subsequent phases
  - Deliverables from phase I: photos, DVDs, Raw data and analyzed results (copy of this presentation)
- Phase II: test of columns with reinforcement (longitudinal and lateral). Long columns are expected to buckle in one direction (6" x 4")
- Phase III: test of columns with biaxial loading
- Phase IV: Modelling and ??
- Other: Due to the confinement of concrete observed in phase I, some dynamic tests such as seismic, blast, and impact may be considered
- Issues and concerns (horizontal surface, straightness of columns, voids, high f'c, etc.) noted in Phase I should be addressed in Phase II

# Acknowledgments

- Dave Rischardson (President, Octaform Systems Inc.) for sponsoring this research project
- Staff at Octaform: Tania, Jaret….
- BCIT AI: Ken Zeleschuk
- BCIT students: Carsen, Matthew, Martin

Questions?

09-24

# EVALUATION OF THE COMPRESSIVE STRENGTH BEHAVIOUR OF THE OCTAFORM CONCRETE FORMING SYSTEM (PHASE II)

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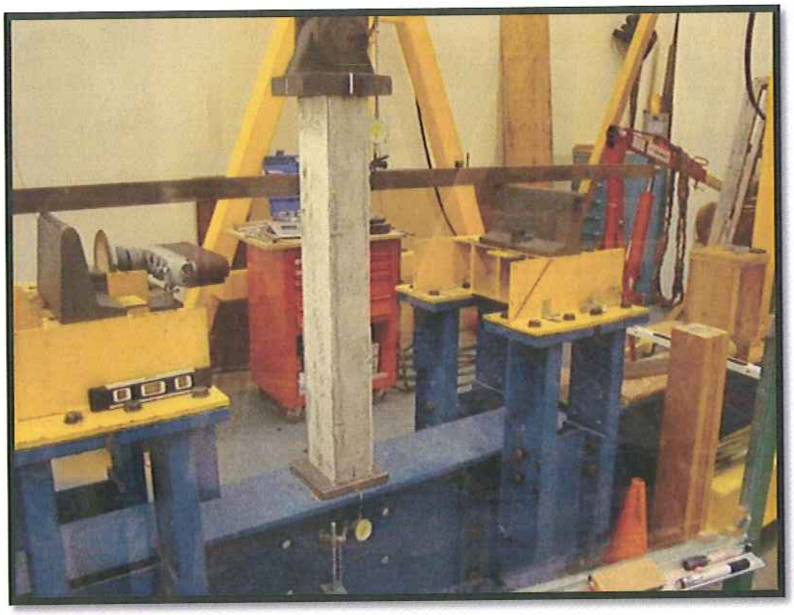

APRIL 6, 2009

BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY

BURNABY, B.C.

## SUMMARY AND PROBLEM STATEMENT

The Octaform Concrete Forming System (OCFS) project is part of an analysis that was performed on a series of concrete columns fabricated with polyvinyl chloride (PVC) stay-in-place formwork. The main objective of this project (phase II) was to predict the behaviour of OCFS especially for rectangular columns. The behaviour of rectangular columns was not previously tested by the company and was not completely understood. The test results obtained in the laboratory were verified by creating a model that could predict the stress-strain and load carrying capacity of a short column.

There were six columns divided in three configurations, and two types of concrete mix designs (batch 1, batch 2). Configuration 1 and configuration 2 used OCFS panels and connectors. Batch 1 had a compressive strength twice as strong as batch 2. Each column had approximate cross section of 6" x 4 ", and a length of 36".

The manufacturing process of the columns started in early January due to the long curing process of the concrete. Concrete cylinders were also cast to provide data on the strength of the concrete.

Results obtained for batch 1, indicated an increase in axial compressive capacity for the control column. Results for batch 2 indicated similar behaviour to the results encountered in phase I, where the OCFS columns had higher load carrying capacity. The load vs. deflection graphs were converted into stress vs. strain graphs and presented similar results.

The predicted results from the theoretical Euler's model, overestimated the mechanical properties of both concrete and OCFS. However, the predicted results from the axial load capacity model gave a more realistic value that approached to the results obtained from the lab.

For future work, it is recommended to keep the number of samples to a minimum of three per configuration, and to use a single type of testing machine. Graphs and tables have been created to help analyze the results and compare them with the theoretical values.

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## ACKNOWLEDGMENT

I would like to thank the following people who help me to complete this project

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- Rishi Gupta, who offer me the project and who answer all my questions and guide me from start to finish in all the aspects of this project.
- Deanna Levis, who help me organise my ideas, and write this report.
- Ken Zeleschuk, for his support, assistance and recommendations in the structural lab.

TABLE OF CONTENTS

# TABLE OF GRAPHICS

## List of Tables



## List of Figures

## 1.0 INTRODUCTION

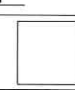
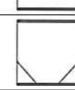
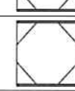
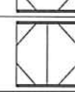
The sponsor for this project is Ms. Tania Burgess from Octaform Concrete Forming Systems Inc. based out of Vancouver. OCFS is a company that since 1997 has created an advanced PVC technology to produce a stay in place formwork. The PVC panels combined with concrete and any other reinforcement materials offer a variety of benefits in comparison to plain concrete. Cost-effectiveness, versatility, energy efficiency and adaptable design are some of the advantages of this stay in place technology.

Concrete is a main construction material used to build different types of structures; however, its mechanical properties are not completely understood when used alone or combined with stay-in-place PVC formwork. Therefore, the main objective of this project was to create a model that explained the influence of PVC panels and connectors on the structural performance of short concrete columns.

The analysis will help the sponsor to get a better idea of the behaviour of this composite system. This project is also the continuation of a series of tests that OCFS and the Civil Engineering Department at British Columbia Institute of Technology have been performing since 2008.

Phase I was the first series of experiments, columns of three different heights and five different configurations were tested. Table 1, shows the different configurations and sizes used in phase I.

Table 1: Column configuration and height specification (Phase I)

| Size | Height | Configuration Type | |
|---|---|---|---|
| | | Control |  |
| | | Configuration I |  |
| 6" x 6" | 20", 36", 72" | Configuration II |  |
| | | Configuration III |  |
| | | Configuration IV |  |

Overall, the results obtained in phase I, showed configuration I and II as the strongest columns in supporting the uniaxial load. These results also showed that the control configuration and configuration III and IV were the ones with the lowest compressive resistance under the same loading conditions.

Phase II, was then designed with the goal of finding an agreement between experimental result and analytical predictions. The proportions of PVC panels and connectors played an important role in the behaviour of the concrete column strength.

Due to limited time available in the CIVL 4090 course, the number of samples was restricted to six. This situation has affected the end result of the analysis and is recommended to keep the number of samples to a minimum of three per configuration. The reason for this is that concrete is a material that does not behave uniformly. Different samples might give different result; therefore, it will give more representative results if more samples are tested. Table 2 shows the configurations used in the second part of this project.

Table 2: Column configuration and height specification (Phase II)

| Size | Height | Configuration Type |
|---|---|---|
| 6" x 4" | 36" | Control |
| | | Configuration I |
| | | Configuration II |

The size 6" x 4" was chosen because OCFS does not have any information in the structural behaviour of a column of this cross sectional area.

The objectives of this experimental investigation were

- development and analysis of load vs. deflection graphs
- comparison of the compressive behaviour of different configurations of PVC encased columns
- conversion of load vs. deflection data into stress vs. strain graphs for further analysis
- creation of a model to predict the load carrying capacity of a control column and a reinforced column with OCFS

## 2.0 MANUFACTURING PROCESS OF COLUMNS

### 2.1 Framing

Framing was the first activity done in this project. The material used was ⅜ "plywood that was previously used in Phase I. Computer aided design (CAD) drawings were done to size the new pieces of plywood. Figure 1 shows the final wood frame assembly.


Figure 1: Final Wood Frame assembly

The wood frame basically consists of a base of approximate 36" x 36" x ¾" in thickness. There were six pieces of plywood of about 15" x 36"x ⅜ "in thickness. The middle panels were of about 5½ "wide by 36 "long. Overall, the dimensions of the three different configurations were different by ½" because the PVC inserts presented different dimensions.

Measurements were taken separately for each configuration. The reason for this is that the panels and connectors inside the wood frame needed to fit without bending them. A small tolerance of about ⅛" was allowed to provide just enough room to slide the PVC panels in and out. This was done in order to maintain a uniform cross section along the length of the column, preventing the formation of undesirable shapes and air voids.

Appendix A shows in more detail constructions sketches that helped to design the wood frame. The frame was assembled using screws with pre-drilled holes so the plywood would not shear. There were some modifications as to where the lateral supports were located on the frame. Figure 2 shows the final product prior to the concrete pouring process.

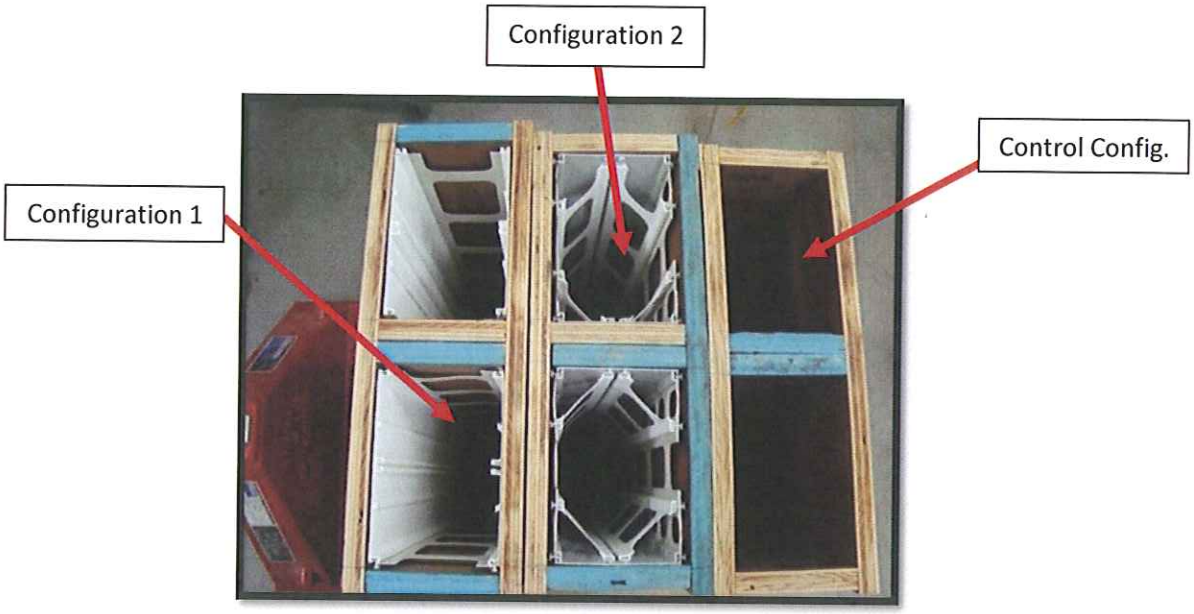



Figure 2: Top view of Wood Frame

The inside walls of the frame were oiled so the PVC panels were easy to removed at the time of the stripping.

## 2.2 Design, Preparation and Placement of Concrete Mix

### 2.2.1 Mix Design

The next step was to design the concrete mix that was used to cast the columns. The initial concept was to design two different mixes with different strengths so the influence of the concrete strength could be compared.

Phase I had a single mix design with a compressive strength of about 37 MPa. Such strength produced in some cases columns that could not be brought to failure under axial compression, and so exceeded the machine testing capacity. For this reason the mixes designed for phase II presented a lower compressive strength capacity.

Table 3 shows the example of mix design. This mix design was modified for the 20 MPa strength requirements that batch 1 presented and the same mix was further modified to obtain a lower strength of 10 MPa for batch 2.

Table 3: Mix Design Example

| **Maximum water/binder ratio : 0.55** | | **Min strength: 20 MPa** | |
|---|---|---|---|
| **Max. size aggregate: 10mm** | | **Design Slump: 70 ± 30 mm** | |
| Ingredients | $Kg/m^3$ | | kg |
| Cement | 200 | | 21 |
| Water | 110 | | 11.55 |
| Coarse Aggregate | 796 | | 83.58 |
| Fine Aggregate | 1194 | | 125.37 |

Once the materials were measured, they were placed in plastic bags as shown in Appendix B. Plastic moulds were also prepared for concrete cylinders.

### 2.2.2 Mix Preparation

We proceeded with the mixture of the ingredients following standard (A23.2-2C), (A23.2-5C). In order to get a homogenous mix we used an electrical drum mixer of about 60 litres in capacity.

We first added the coarse aggregate and some of the mixing water, dispersing them apart. Then, we started the mixer and added the fine aggregate, cement and some more water with the mixer running. We let the mixer run for 3 minutes and then turned off. We then let the mix rest for 3 more minutes, covering the open end of the mixer with a plastic sheet to minimize evaporation. Lastly, we turned on the mixer and let it run for 2 more minutes.

Once, the batching sequence was done, we deposited the mix into a wheelbarrow and continued mixing to eliminate segregation. Temperature of batch 2 was 13°C with a slump test of 30 mm.

Figure 3 shows water being added while the mixer was rotating.

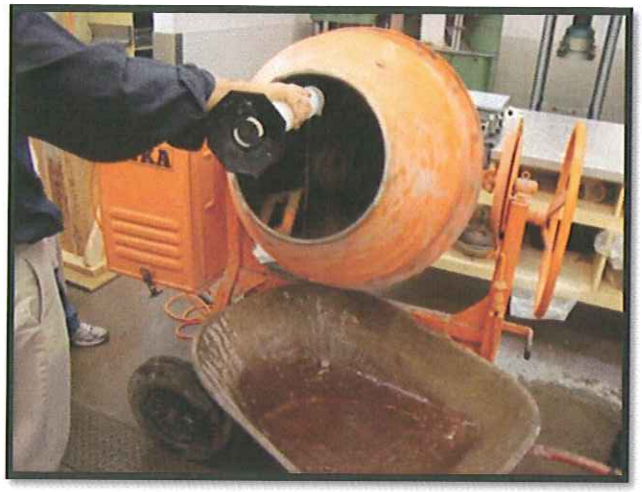


Figure 3: Batching Sequence

Some extra water was added to both batches to improve the workability of the concrete. Appendix C shows a series of pictures taken while the mixes were being prepared.

### 2.2.3 Placement Concrete Mix

After the mixes were prepared, pouring of the mixes was continued into the wood frame. This step was quickly done before the mixes started to harden. To achieve an even distribution of the concrete we used an electric needle vibrator. This action helped the concrete flow through the PVC panels. We also set aside some concrete to cast cylinders for later tests as specified by CSA standard (A23.2-3C). Like any other experiment the cylinders were tested to estimate the strength of the concrete and to ensure that the testing machine could bring the columns to failure. In total 6 cylinders were cast, three from each batch.

After 4 days, a cement paste was added to the top of each column due to the hydration of the concrete that caused shrinkage in the original length of the column.

### 2.2.4 Curing and Stripping Process

The curing process of the columns took place in the Structural Lab at BCIT. Normal conditions were present during the entire curing process. A plastic sheet was place on top of the columns that acted as a moisture retarder, and helped to enhance the hydration process. Once the columns had gained enough strength, the wood frame was removed. This was done 15 days after they were cast.

Figure 4 shows how the columns looked after the wood frame was removed.

Figure 4: Stripping Wood Frame

Appendix D shows other pictures taken of the stripped columns, where some cracking happened in the paste applied to the top part of columns. This deficiency was fixed later on by removing the brittle cement paste and instead capping them using sulphur, so the top cross section of the column remained flat and uniform. It was important to maintain a constant cross section area, so the actuator applied the force perpendicular to the ground. The columns kept curing for 28 days until they reached the required strength.

## 3.0 COLUMNS AND CYLINDERS STRENGTH TEST RESULTS

### 3.1 Cylinder Strength Test Results

Cylinders were capped and tested in accordance with the CSA standard (A23.2-9C). The ends of each cylinder were clean with dry air, and a sulphur compound was applied to the smooth bottom surface of the cylinder first, the same procedure was performed on the rough top surface.

CSA standard specifies cylinder strength tests to be done at 28 or more days, but due to time constrains in this project, cylinders were tested at 23 days in the concrete lab at BCIT. The cylinders were exposed to a compressive force that brought them to failure. Most of the cylinders failed in shear, particularly those from batch 2. Both batches looked very brittle, and granular particles could be seen on the surface area.

Table 4 and Table 5 shows the results obtained for each batch of cylinders.

Table 4: Test Result Cylinders Batch 1

| | CYLINDERS BATCH 1 | TEST RESULTS | |
|---|---|---|---|
| No. | MASS (kg/m³) | (MPa) | (psi) |
| 1 | 2383 | 17.7 | 31280 |
| 2 | 2384 | 18.5 | 32633 |
| 3 | 2358 | 17.2 | 30342 |
| **Avg** | **2375** | **17.8** | **31418** |

Table 5: Test Result Cylinders Batch 2

| | CYLINDERS BATCH 2 | TEST RESULTS | |
|---|---|---|---|
| No. | MASS (Kg/m³) | (MPa) | (psi) |
| 1 | 2239 | 11.0 | 19475 |
| 2 | 2332 | 8.3 | 14583 |
| 3 | 2294 | 8.4 | 14810 |
| **Avg** | **2288** | **9.2** | **16289** |

Cylinders from batch 1 were almost twice as strong as cylinders from batch 2. This is due to the difference in quantities of materials and the amount of water added to the mix.

### 3.2 Column Strength Test Results

Column tests were conducted in the structural lab at BCIT. A High-Strength Testing Frame equipped with a servo-controlled actuator (444 KN in capacity) was used for the tests. The software used was NI Lab VIEW from National Instruments Data Acquisition System, which was configured to measure the load and displacement that the actuator applied to the columns.

Each column was mounted in this frame aligned with the longitudinal axis of the actuator as shown in Figure 5 and Figure 6.


Figure 5: High-Strength Testing Frame

The actuator load was controlled from the computer at a rate of loading of approximately 0.17 KN/sec. The data was collected through the servo control valve and transferred to the computer. The computer program created a file with the data obtained from the tests and was transferred to excel where further analysis was performed.

Prior to each test, measurements were taken for all columns. Table 6 shows the average dimensions taken to each column.

Table 6: Table of Column Dimensions

| TYPE | | DIMENSIONS | | | |
|---|---|---|---|---|---|
| BATCH | CONFIGURATION | WIDTH (mm) | LENGTH (mm) | HEIGHT (mm) | AREA ($mm^2$) |
| 1 | CONTROL | 103 | 156 | 918 | 16053 |
| | CONFIGURATION 1 | 103 | 162 | 914 | 16709 |
| | CONFIGURATION 2 | 113 | 156 | 918 | 17535 |
| 2 | CONTROL | 102 | 152 | 914 | 15484 |
| | CONFIGURATION 1 | 108 | 165 | 918 | 17823 |
| | CONFIGURATION 2 | 111 | 156 | 918 | 17288 |

Two gauges were set up as a back up to measure the deflection. One of the gauges was located on the top attached to the head rod of the actuator and the second was located underneath the wide flange beam that the base of the column rested on. Figure 6 shows the location of the two gauges.

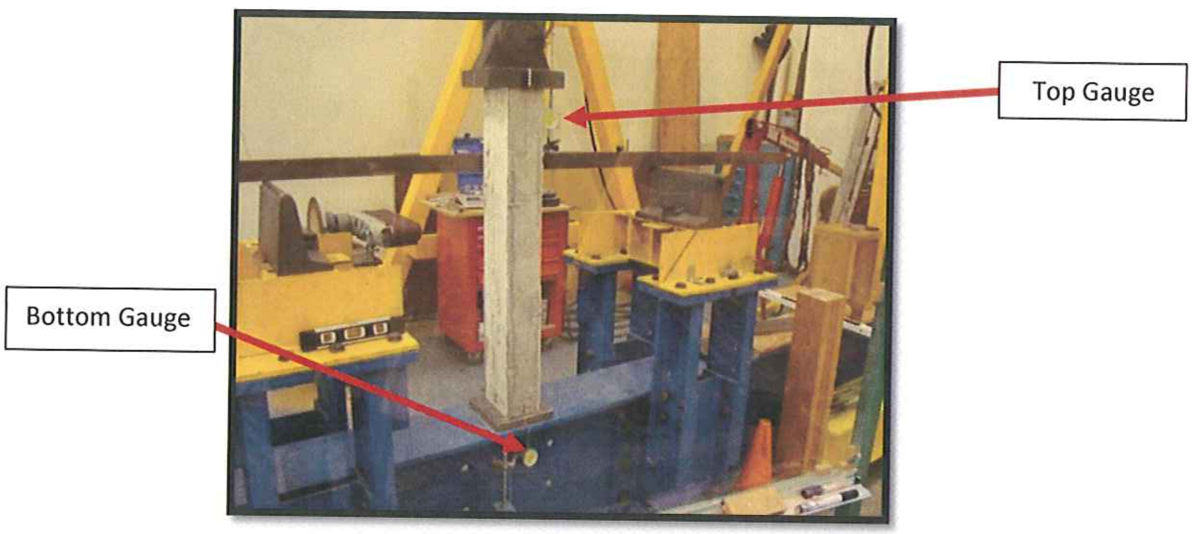



Figure 6: Column Set-Up

Column testing began in mid February and ended on the first week of March. Appendix E shows columns of different configurations after they failed.

For better understanding, a classification to distinguish the different types of configurations as well as the two types of batches was created. The two blue colour curves in Figure 7 identify the Configuration 1. The dark blue belongs to the column made from the strongest batch while the light blue line belongs to the column made from the weakest batch. The green line refers to Configuration 2 and red line refers to the Control configuration. Appendix F shows individual graphs of load vs. deflection for each configuration for more clarity.

Figure 7 shows the results of load vs. deflection obtained from the test conducted to each column.

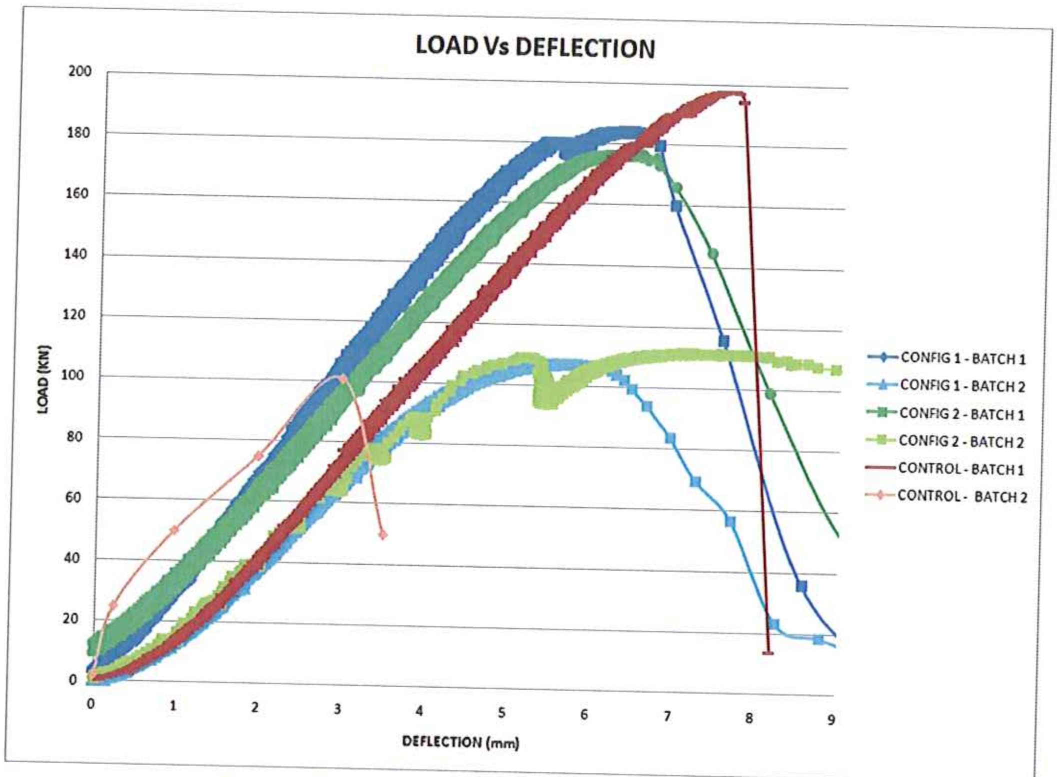



Figure 7: General Load Vs Deflection Curves

Every column had a different cross sectional area and length due to constructions practices. To account for this in the analysis, a decision was made to convert the load vs. deflection data to stress vs. strain. The stress and strain values were calculated using the following equations:

Equation 1: Normal Strain Equation $\mathcal{E} = \frac{\Delta L}{L}$ (Hibbeler, 2008)

Where,

$\mathcal{E} = \textbf{strain}$

$\Delta L = \text{change in length}$

$L = \text{original length}$

Equation 2: Normal Stress equation $\sigma = \frac{F}{A}$ (Hibbeler, 2008)

Where,

$\sigma = \text{stress (MPa)}$

$F = \text{applied force (KN)}$

$A = \text{cross section area (m}^2\text{)}$

Table 7 summarizes the final results obtained for each column using equations Equation 1, Equation 2 and the data collected from test.

Table 7: Peak Load, Stress, Strain, and Deflection results

| TYPE | | PEAK LOAD (KN) | PEAK DEFLECTION (mm) | PEAK STRAIN (ε) | STRESS - σ actual (MPa) | STRESS - σ 6x4 (MPa) | % DIFF. |
|---|---|---|---|---|---|---|---|
| BATCH | CONFIGURATION | | | | | | |
| 1 | CONTROL | 198 | 8.8 | 0.0100 | 12.3 | 12.8 | 4.0 |
| | CONFIGURATION 1 | 184[1] | 8.6[1] | 0.0110 | 11.1 | 11.9 | 6.8 |
| | CONFIGURATION 2 | 176[1] | 9.2[1] | 0.0058 | 9.5 | 11.4 | 20.2 |
| 2 | CONTROL | 101[2] | 3.5[2] | 0.0038 | 6.5 | 6.5 | 0.4 |
| | CONFIGURATION 1 | 107 | 7.7 | 0.0076 | 5.8 | 6.4 | 11.4 |
| | CONFIGURATION 2 | 112 | 12.0 | 0.0220 | 6.4 | 7.2 | 11.7 |

[1]This column was reloaded, which probably affected the peak load and stress values.
[2]Value shown on table was last value recorded before failure.

The maximum peak load was developed by Control batch 1. Configuration 1 and configuration 2 from batch 1 needed to be reloaded. After the load was applied, the first time, the column tried to buckle and moved away from the actuator neutral axis. The last data recorded for control configuration from batch 2 was at 101 KN.

The maximum stress was also developed by Control batch 1 as shown in Figure 8. Maximum deflection and strain was presented in Configuration 2 - batch 2. Appendix G shows individual graphs of stress vs. strain for each of configuration.

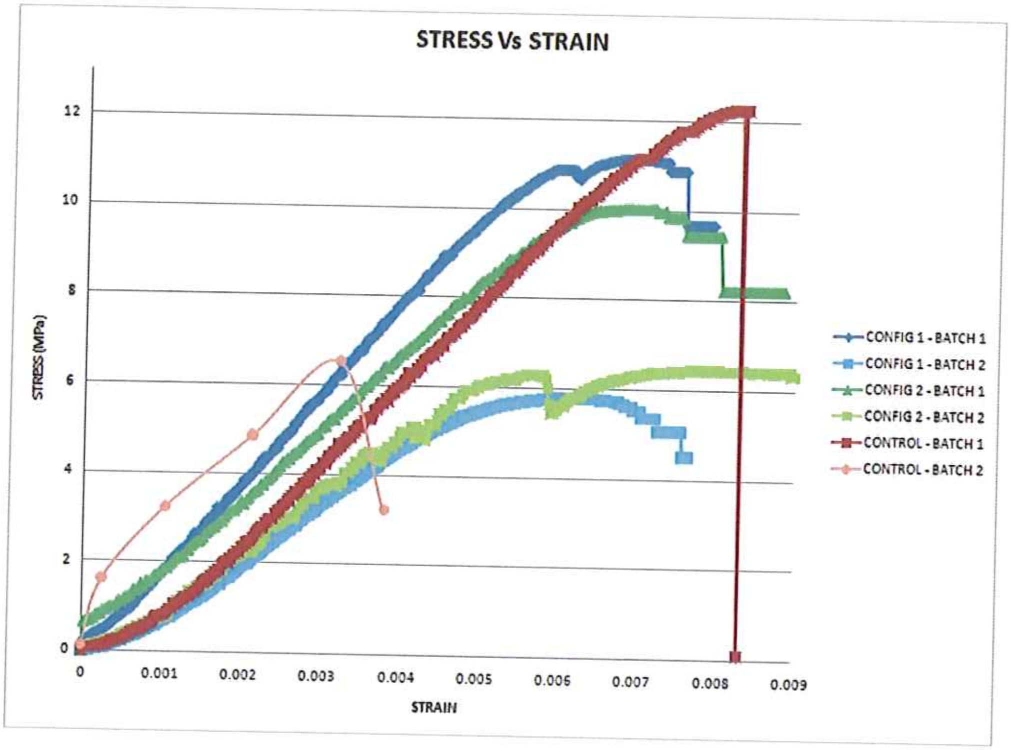



Figure 8: General Stress Vs Strain Graph

It is clear from **Table 7** that the effect of using measured cross sectional areas as opposed to assuming constant cross sectional area is very significant. A change of up to 20% was observed. This result

## 4.0 DISCUSSION OF RESULTS

End results of this experiment were similar to those obtained in phase I. Batch 1 had an average strength of 18 MPa and batch 2 an average strength of 9 MPa, as shown in Table 4 and Table 5. These values were lower than the concrete strength used in phase I, which was of about 35 MPa.

In phase I a Tinius Olsen compressive machine was used. The load was applied uniformly to the column using a spherical ball-bearing steel plate. The bottom section lifts up, while the top section of the frame remained fixed. The set up mode of the columns in this machine did not allow the columns to buckle. In phase II the machine used allowed to rotate, causing in some movement in the columns.

### 4.1 Batch 1

The control configuration presented a higher load capacity in batch 1 than the other two OCFS configurations shown in Table 7. However, the two OCFS columns had to be reloaded because during the first trial-test the column moved away from the actuator axis. This action caused a significant change in the properties of the columns. Figure 7 shows how the control configuration failed suddenly, which means that after the peak load was reached, the column could not take any more load, this explains the almost vertical line at the end of the curve. Figure 9 shows a control configuration column after failure, the top part of the column was divided in two.

Figure 9: Control column after failure

Even though, OCFS columns had a lower loading capacity, the results obtained in this project agreed with those obtained in phase I. If we count the fact that both OCFS columns needed reloading as well as that the column configuration 1 was left with a considerable amount of pressure in the structural lab for a few days until the experiment was re-started. This might have affected the mechanical properties of the column.

Figure 10 shows how an OCFS column did not fail like the control and the whole columns remained in one piece; this is due to the PVC encasement panels. This configuration could still resist some load even after had reached the peak load.

Figure 10: OCFS column after failure

At about 180 KN it had a crest of failure and it failed completely at 184 KN

### 4.2 Batch 2

Batch 2 had lower strength capacity, but the results obtained for this batch were again similar to those encountered in phase I. Figure 7 shows the load vs. deflection graph and Figure 8 shows the stress vs. strain graph. Values are very close to each other, but in this case the stronger column was OCFS configuration 2 with a peak value of 112 KN. The deflection presented in this configuration was of about 12mm as shown in Table 7. This table also shows how this configuration after reached the peak load continued resisting the force from the actuator. This was due to the encasement of the PVC.

### 4.3 Theoretical Peak Load Values

Table 8 shows the theoretical values obtained with the application of Euler's Formula for Column Buckling (shown below). The table shows what the critical load capacity of a column is found by using two different axis of symmetry.

Equation 3: Euler's Formula for Column Buckling $$Pcr = \frac{\pi^2 * E * I}{(K * L)^2}$$

Where,

Pcr = critical load (KN)

E = material's modulus of elasticity (MPa)

I = moment of inertia $(mm^4)$

L = column length (m)

K = factor support condition

Table 8: Theoretical Critical Load based on Euler's Formula

| TYPE | | Pcr (KN) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | K1 = 1 | | K2 = 2 | | K3 = 0.5 | | K4 = 0.7 | |
| BATCH | CONFIGURATION | Ix | Iy | Ix | Iy | Ix | Iy | Ix | Iy |
| 1 | CONTROL | 6716 | 2985 | 1679 | 746 | 26864 | 11940 | 13706 | 6092 |
| | CONFIGURATION 1 | 5688 | 2448 | 1422 | 612 | 22750 | 9790 | 11607 | 4995 |
| | CONFIGURATION 2 | 4995 | 2206 | 1249 | 551 | 19982 | 8824 | 10195 | 4502 |
| 2 | CONTROL | 4828 | 2146 | 1207 | 536 | 19314 | 8584 | 9854 | 4379 |
| | CONFIGURATION 1 | 4104 | 1766 | 1026 | 442 | 16418 | 7065 | 8376 | 3605 |
| | CONFIGURATION 2 | 3613 | 1595 | 903 | 399 | 14450 | 6381 | 7373 | 3256 |

The K values identify the different types of support conditions a column can have.

- K1 pin ends
- K2 fix and free ends
- K3 both fix ends
- K4 pin and fix ends

The values shown in Table 8 overestimated the mechanical properties of the column. As mention earlier, concrete does not behave homogeneously which is why the Euler's equation gave unexpected result.

All this values differ from the ones obtained in the testing lab. Therefore, a more realistic approached was taken by using the Axial Load Capacity equation

Equation 4: Axial Load Capacity Equation $\mathbf{P = (Ac * f'c) + (Ap * fp)}$

Where,

$\mathrm{P = load\ (KN)}$

$\mathrm{Ac = area\ of\ concrete\ (mm^2)}$

$f'\mathrm{c = concrete\ compressive\ strength\ (MPa)}$

$\mathrm{Ap = area\ of\ PVC\ (mm^2)}$

$f\mathrm{p = PVC\ compressive\ strength\ (MPa)}$

Table 9: Theoretical load based on Axial Load Capacity formula

| TYPE | | P (KN) |
|---|---|---|
| **BATCH** | **CONFIGURATION** | |
| 1 | CONTROL | 294 |
| | CONFIGURATION 1 | 286 |
| | CONFIGURATION 2 | 275 |
| 2 | CONTROL | 209 |
| | CONFIGURATION 1 | 204 |
| | CONFIGURATION 2 | 197 |

Values shown in Table 9 were closer to the practical values obtained from the test, however, these values still overestimate the material properties of the column.

The comparison of Euler's formula, the Axial formula and test result for configuration 1 are shown in Figure 11

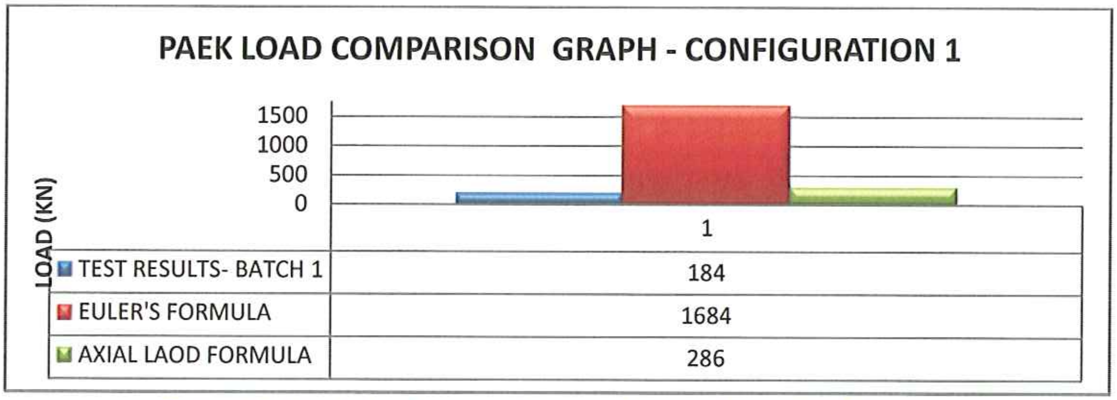



Figure 11: Peak load comparison results- configuration 1

This analytical model presented a peak value of 1684 KN for the Euler's formula, which compared with actual result obtained from the lab of 184 KN, clearly do not matched. Similar results were obtained for the other type of configurations.

## 5.0 CONCLUSIONS AND RECOMENDATIONS

- the predicted results from the theoretical Euler's equation overestimated the structural properties of the concrete and OCFS columns
- axial load capacity equation gave values that approximated to the ones obtained in the lab
- concrete is a construction material with a non-homogeneous behaviour, which makes any model prediction a simple estimate.
- Confinement is a property that OCFS columns have and helps them to remained in one piece as well as increase their compressive strength.
- PVC panels produce small increases in axial compression capacity; therefore, is necessary to calculate the stress vs. strain values
- It is recommended for future tests, to keep the number of samples to a minimum of three per configuration, so relevant and more accurate results can be obtain.

## REFERENCES

A23.2-2C, C. S. (2004). Making Concrete Mixes in the Laboratory. In *Method of Test for Concrete.* Toronto: Canadian Standards Association.

A23.2-3C, C. Making and Curing Concrete Compression and Flexural Test Specimens. In *Method of Test for Concrete.* Toronto: Canadian Standard Association.

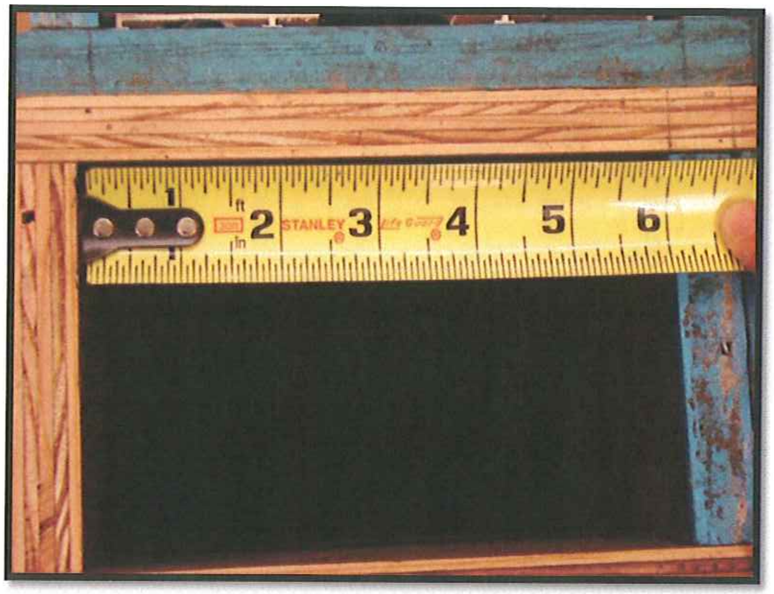
A23.2-5C, C. S. (2004). Slump of Concrete. In *Methods of Test of Concrete.* Toronto: Canadian Standard Association.

A23.2-9C, C. Compressive Strength of Cylindrical Concrete Specimens. In *Methods of Test for Concrete.* Toronto: Canadian Satandard Association.

Hibbeler, R. (2008). *MECHANICS OF MATERIALS.* New Jersey: Pearson Education Inc.

# APPENDICES

## APPENDIX A: WOOD FRAME AND CAD DRAWINGS




Wood Frame measurements

Elevation view of Wood Frame

# APPENDIX B: MATERIAL QUANTITIES

Material preparation

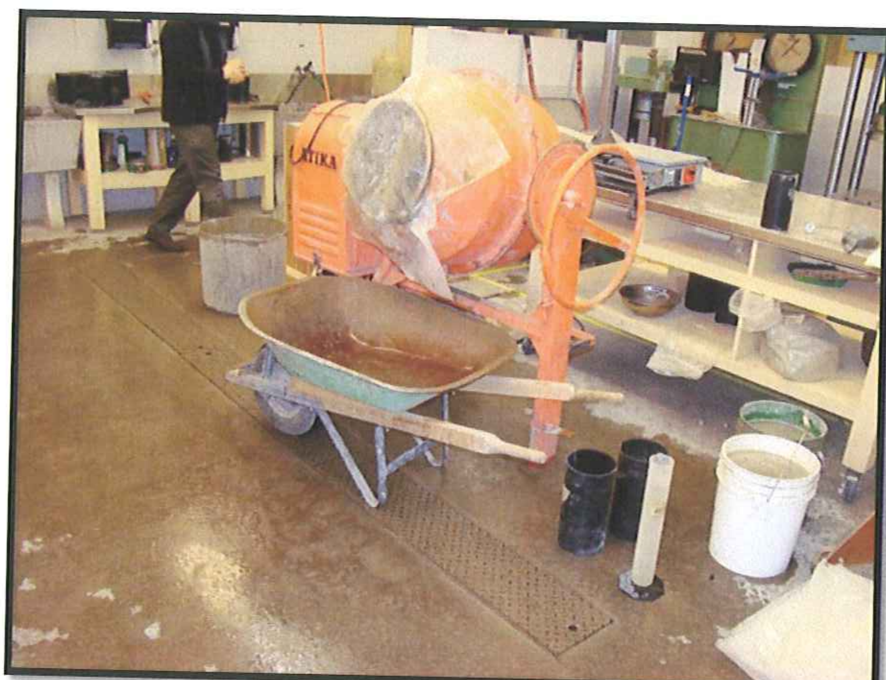
Cylinders preparation for concrete cast

# APPENDIX C: CONCRETE MIX PREPARATION


Electrical drum mixer

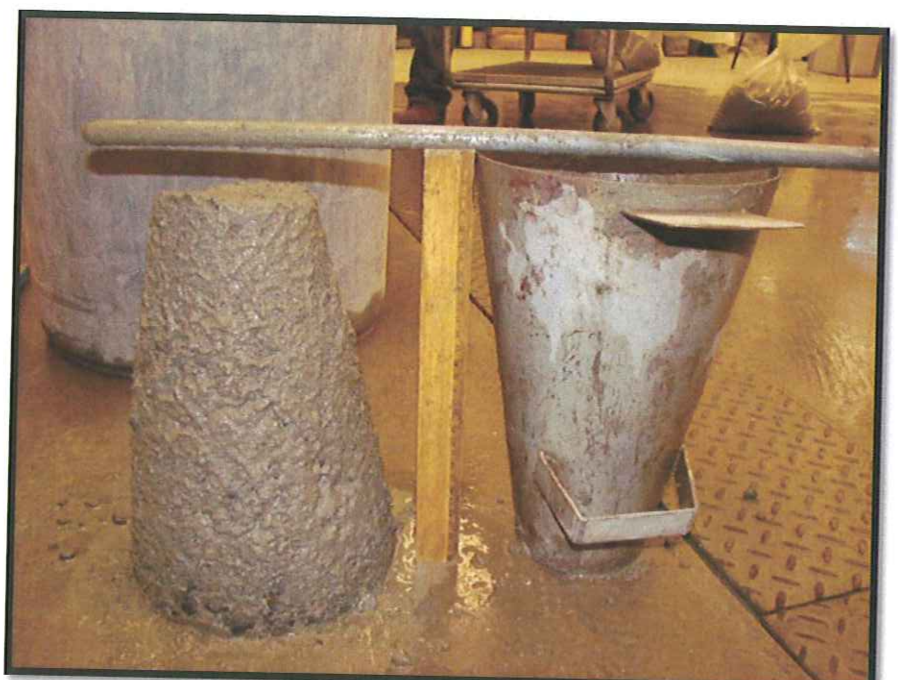

Tools used for mix preparation


Concrete mix preparation



Procedure following CSA standard (covering the open end of the mixer)


Procedure following CSA standard (mixer run for 3 min)



Slump Test following CSA standard

Concrete cylinder cast

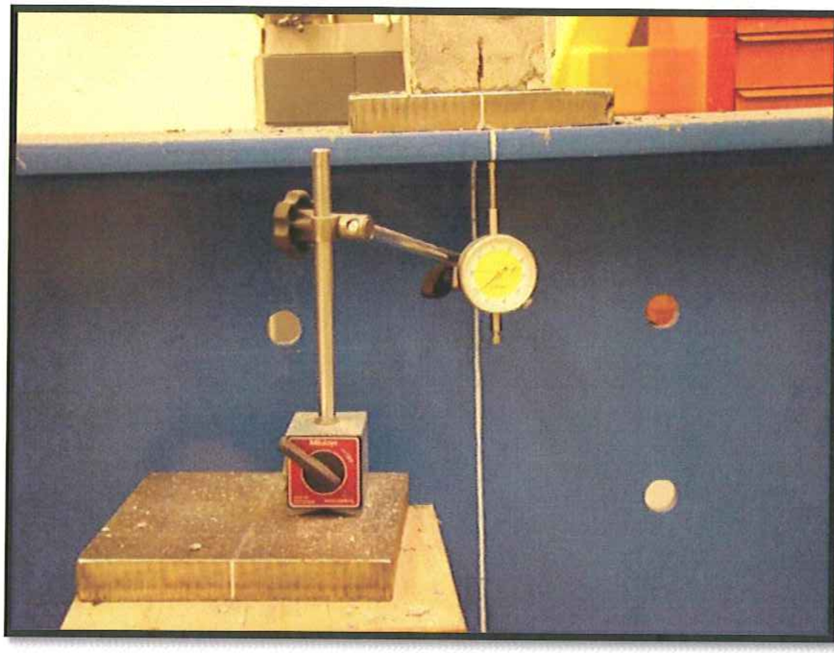
## APPENDIX D: STRIPPING WOOD FRAME


Woof Frame stripping

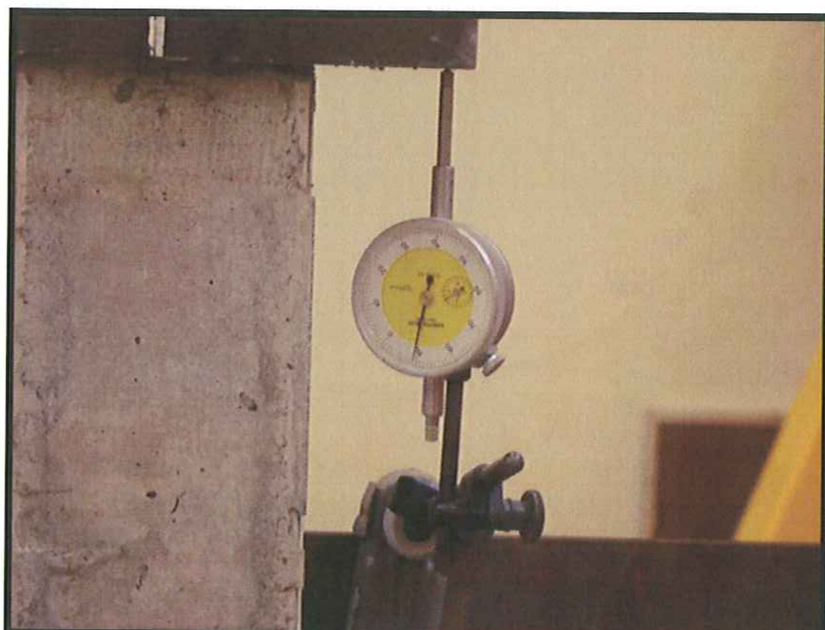
Cracks formed on top concrete paste

Side view of columns during stripping

# APPENDIX E: COLUMNS FAILURE MODES



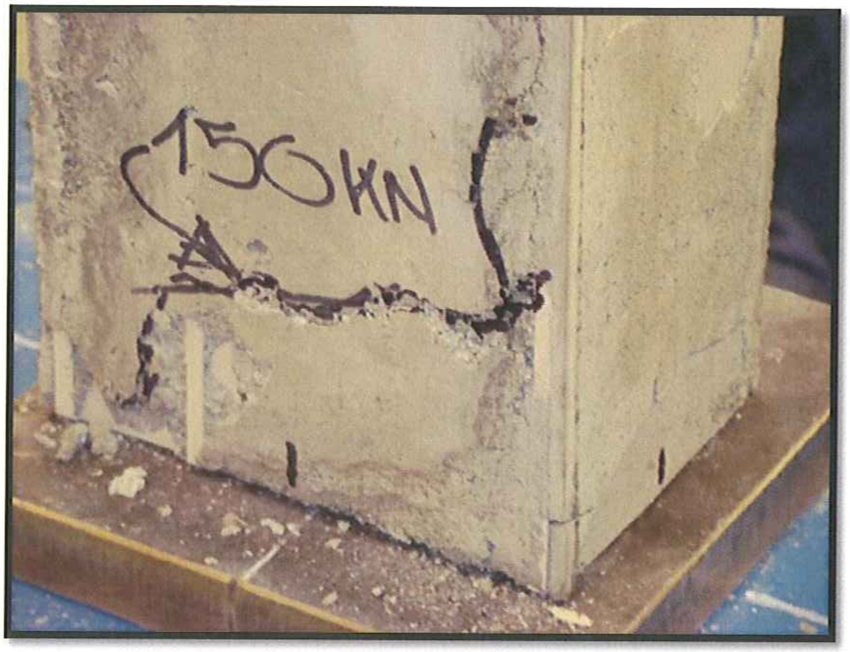
Gauge set-up underneath wide flange



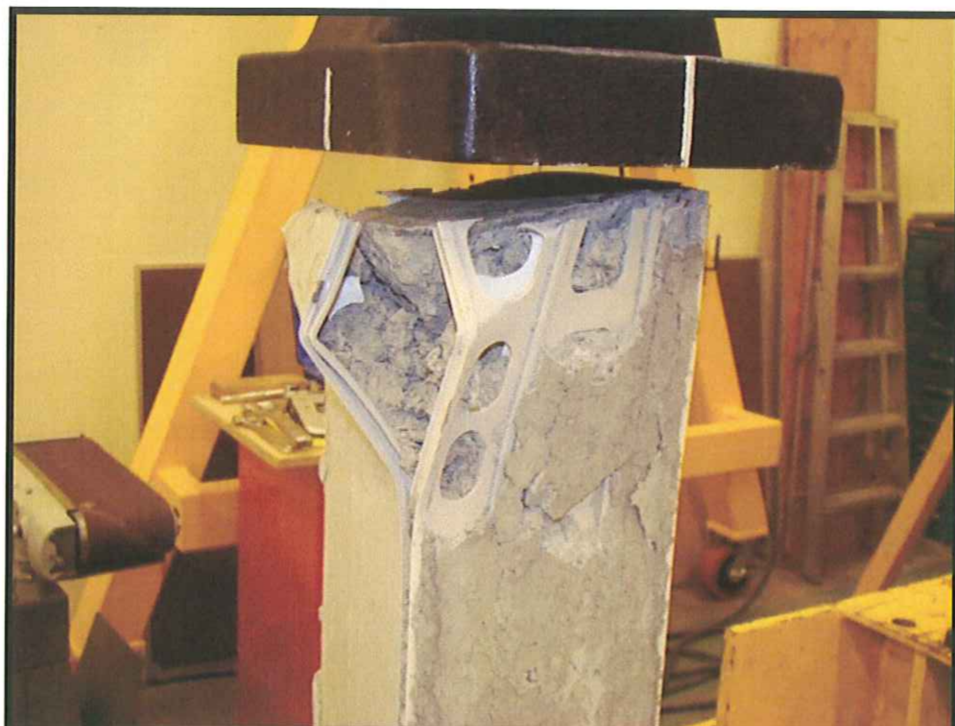
Gauge set-up at actuator head rod

Configuration 1 after failure

Configuration 2 after failure

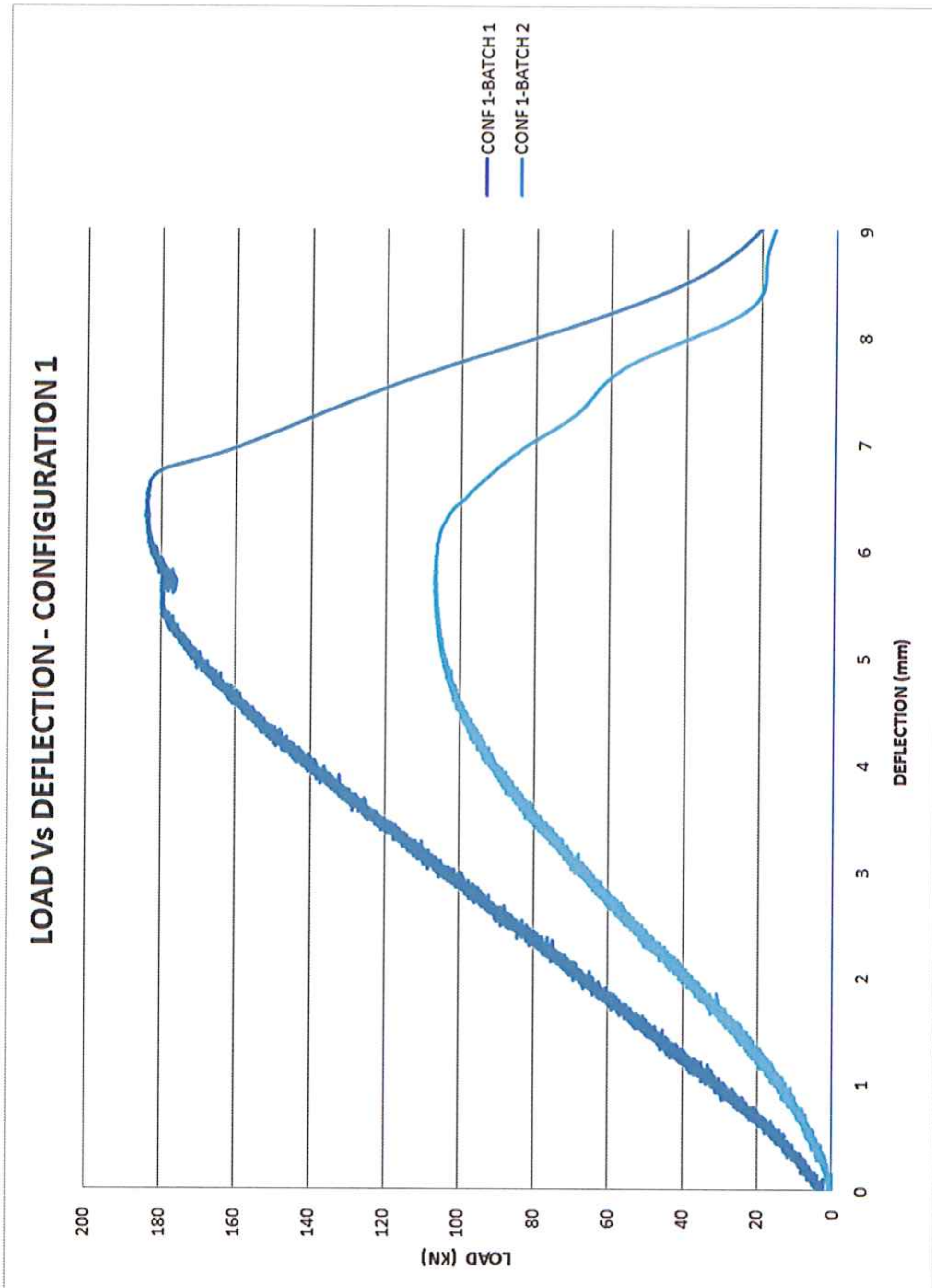


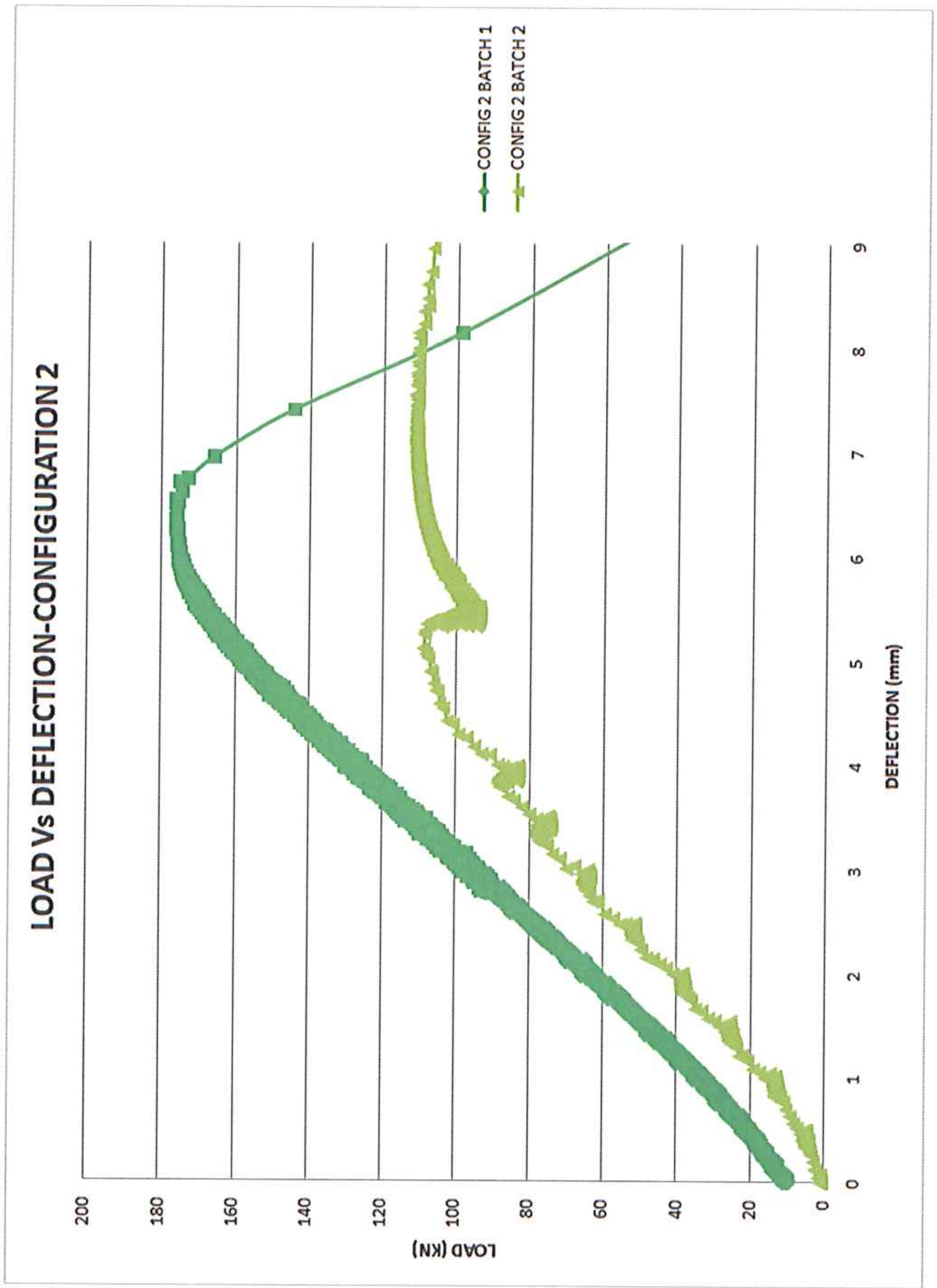

Configuration 2, needed reloading after reached 150 KN

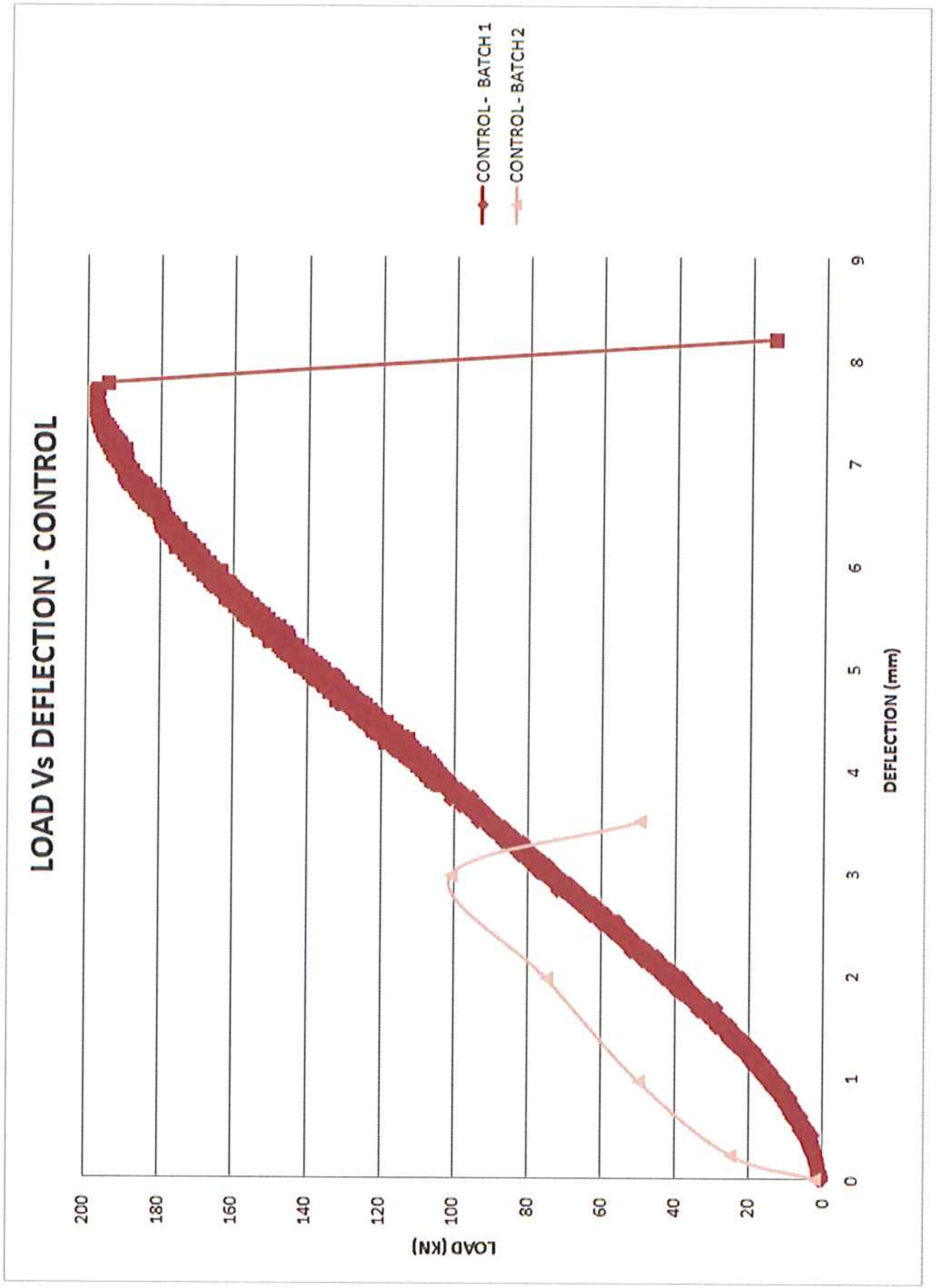


Configuration 2, after failure

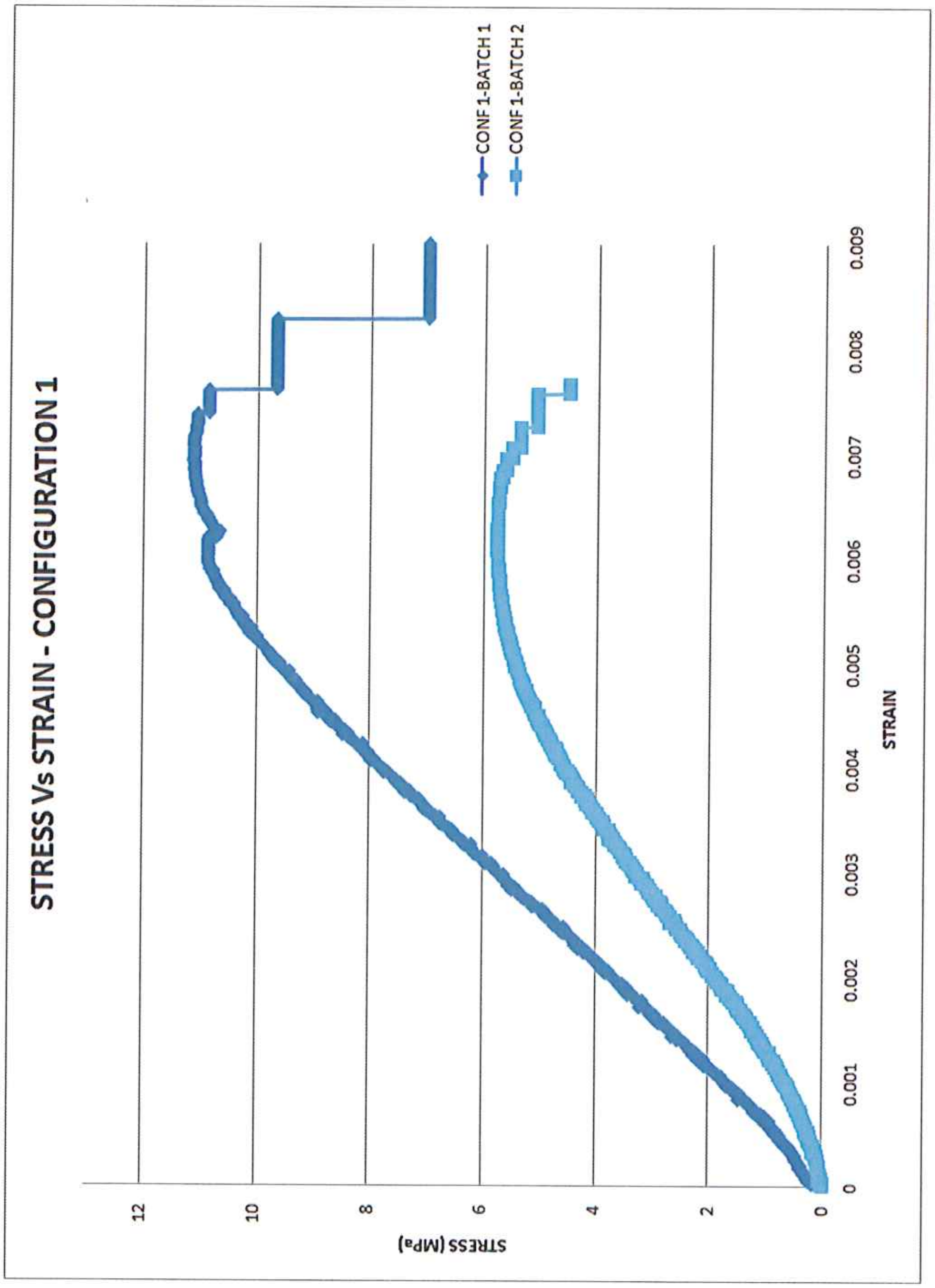
## APPENDIX F: LOAD Vs DEFLECTION GRAPHS

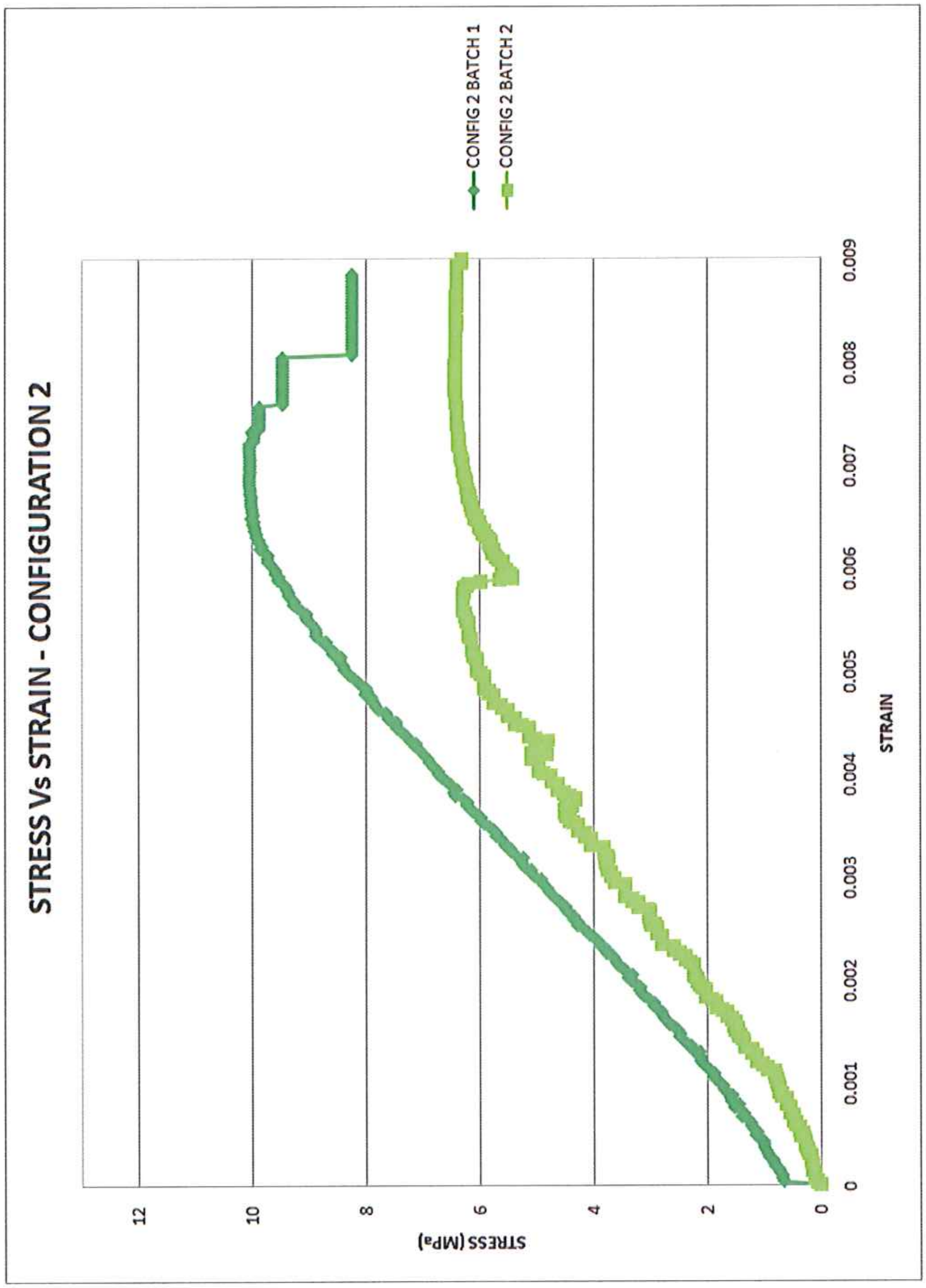

LOAD Vs DEFLECTION - CONFIGURATION 1
LOAD (KN)
0
20
40
60
80
100
120
140
160
180
200
DEFLECTION (mm)
0
1
2
3
4
5
6
7
8
9
CONF 1-BATCH 1
CONF 1-BATCH 2

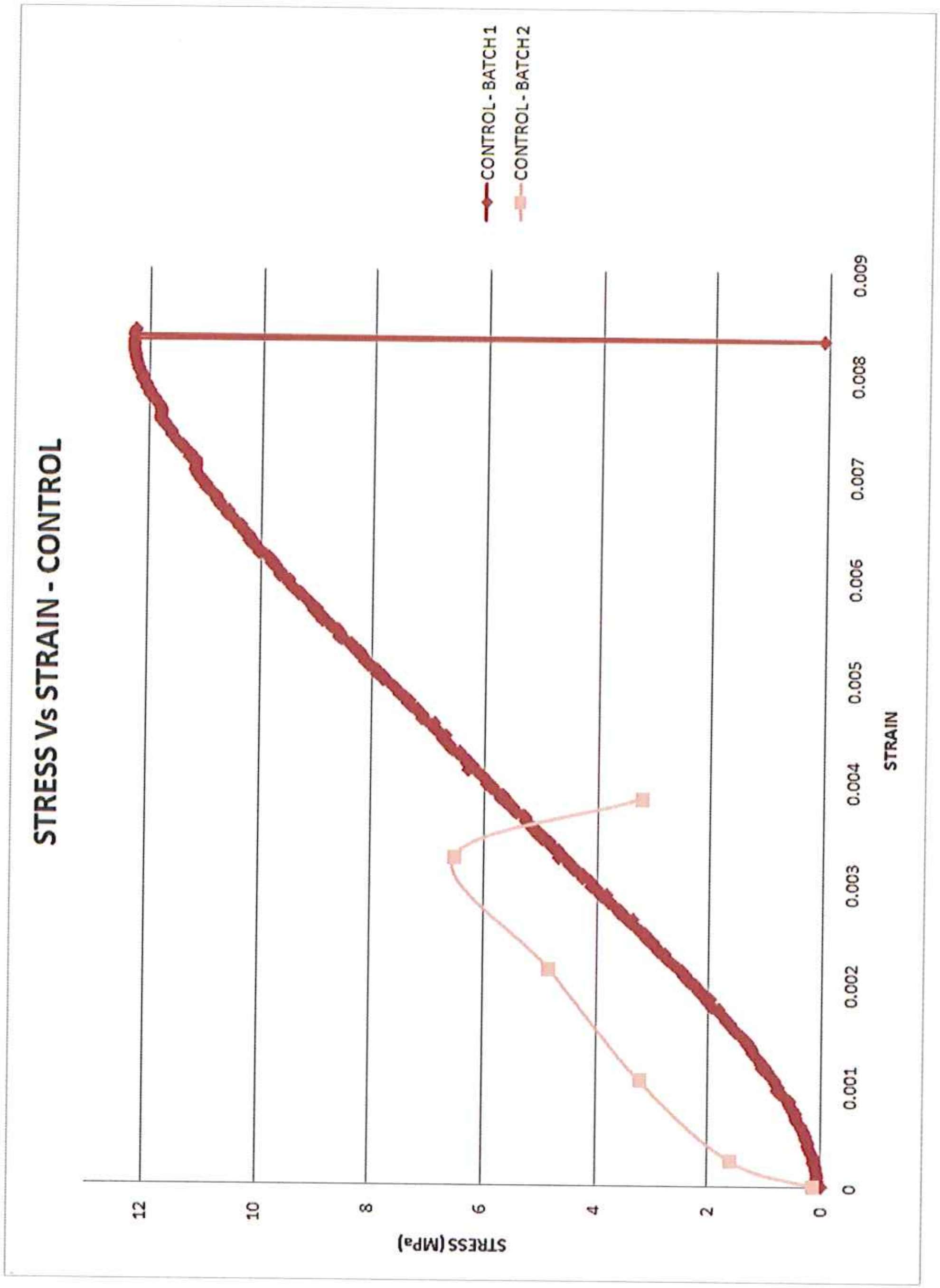

LOAD Vs DEFLECTION-CONFIGURATION 2
LOAD (KN)
0
20
40
60
80
100
120
140
160
180
200
0
1
2
3
4
5
6
7
8
9
DEFLECTION (mm)
CONFIG 2 BATCH 1
CONFIG 2 BATCH 2

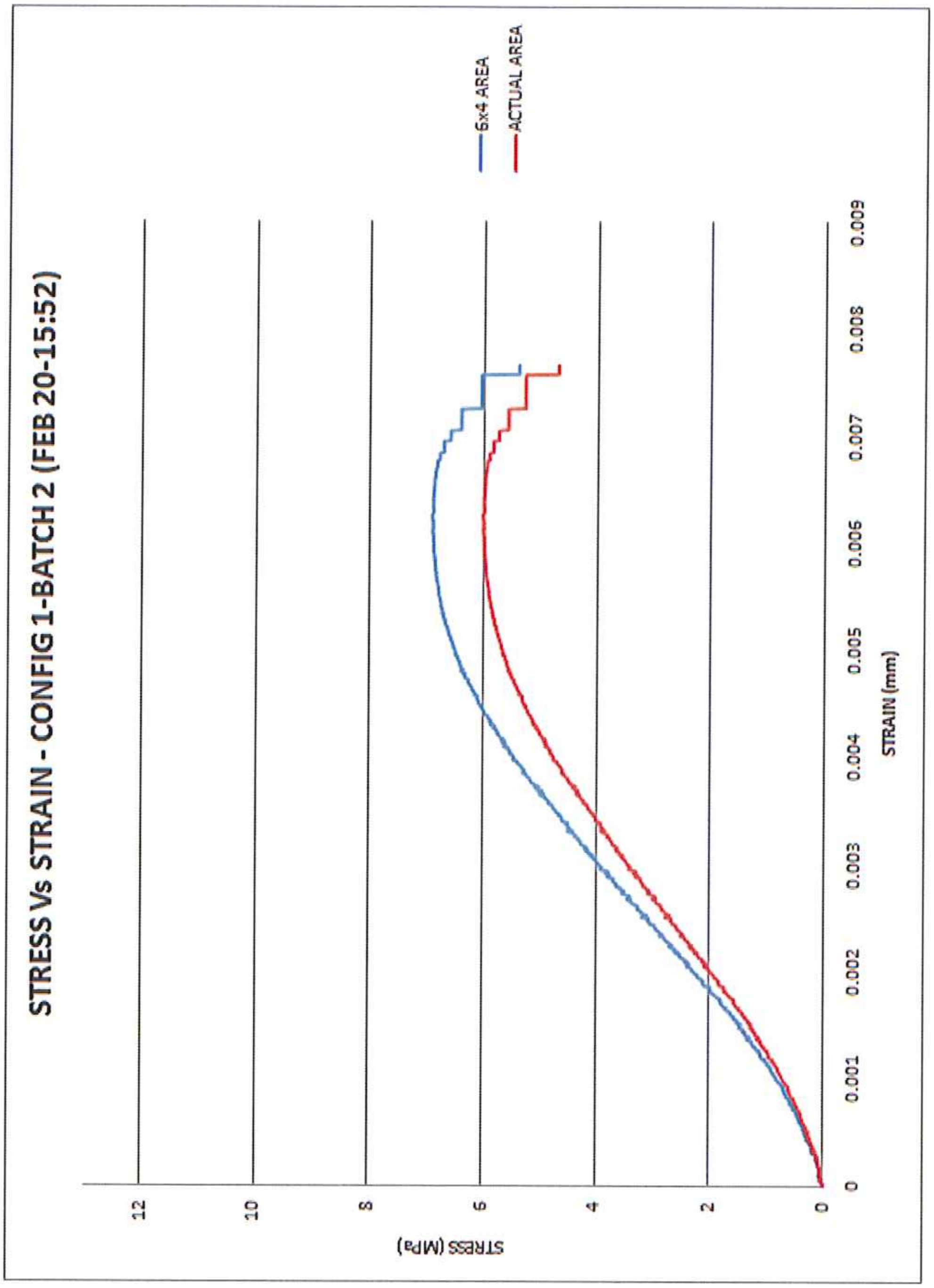

LOAD Vs DEFLECTION - CONTROL
LOAD (KN)
0
20
40
60
80
100
120
140
160
180
200
DEFLECTION (mm)
0
1
2
3
4
5
6
7
8
9
CONTROL - BATCH 1
CONTROL - BATCH 2

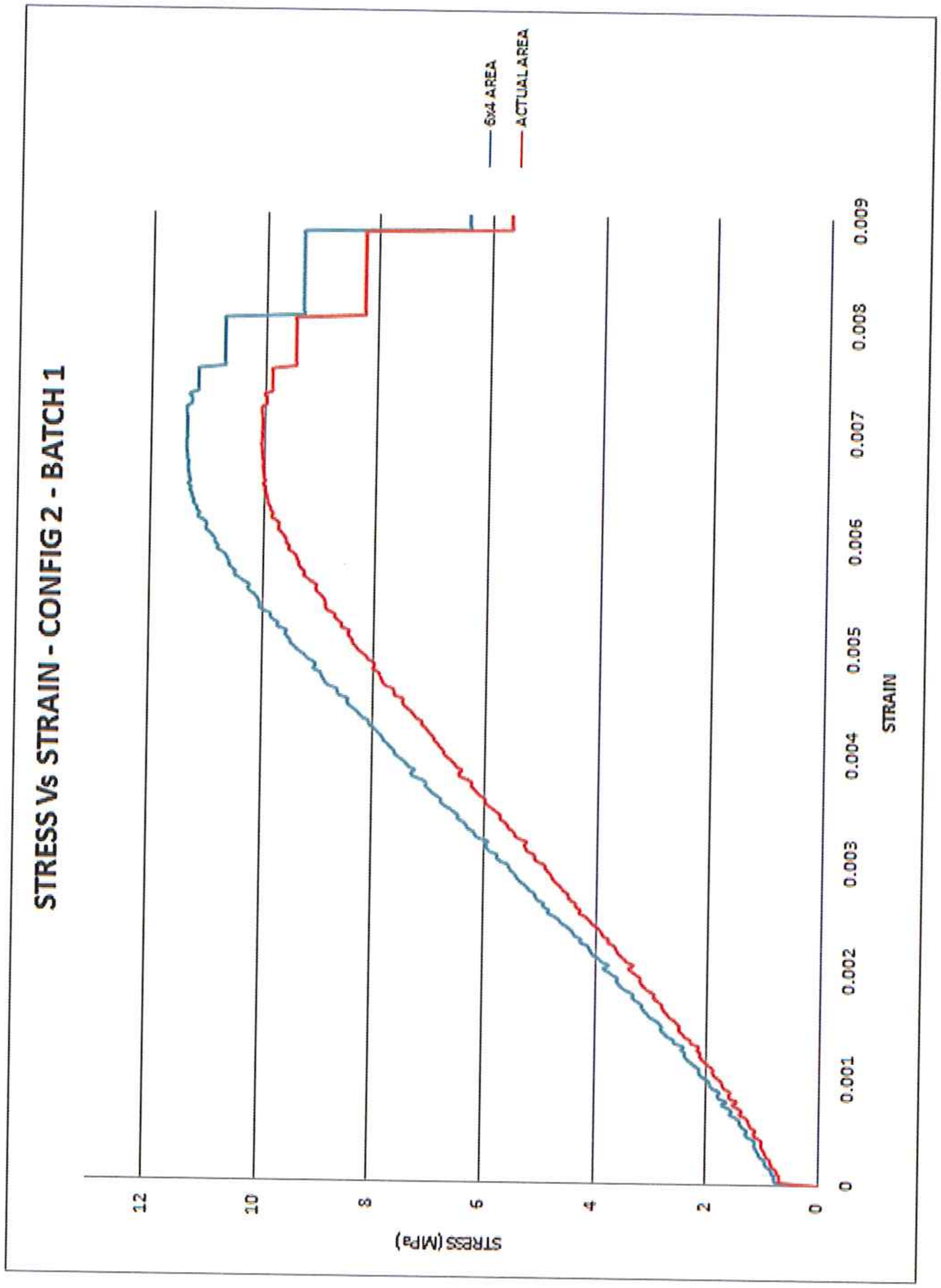
# APPENDIX G: STRESS Vs STRAIN GRAPHS

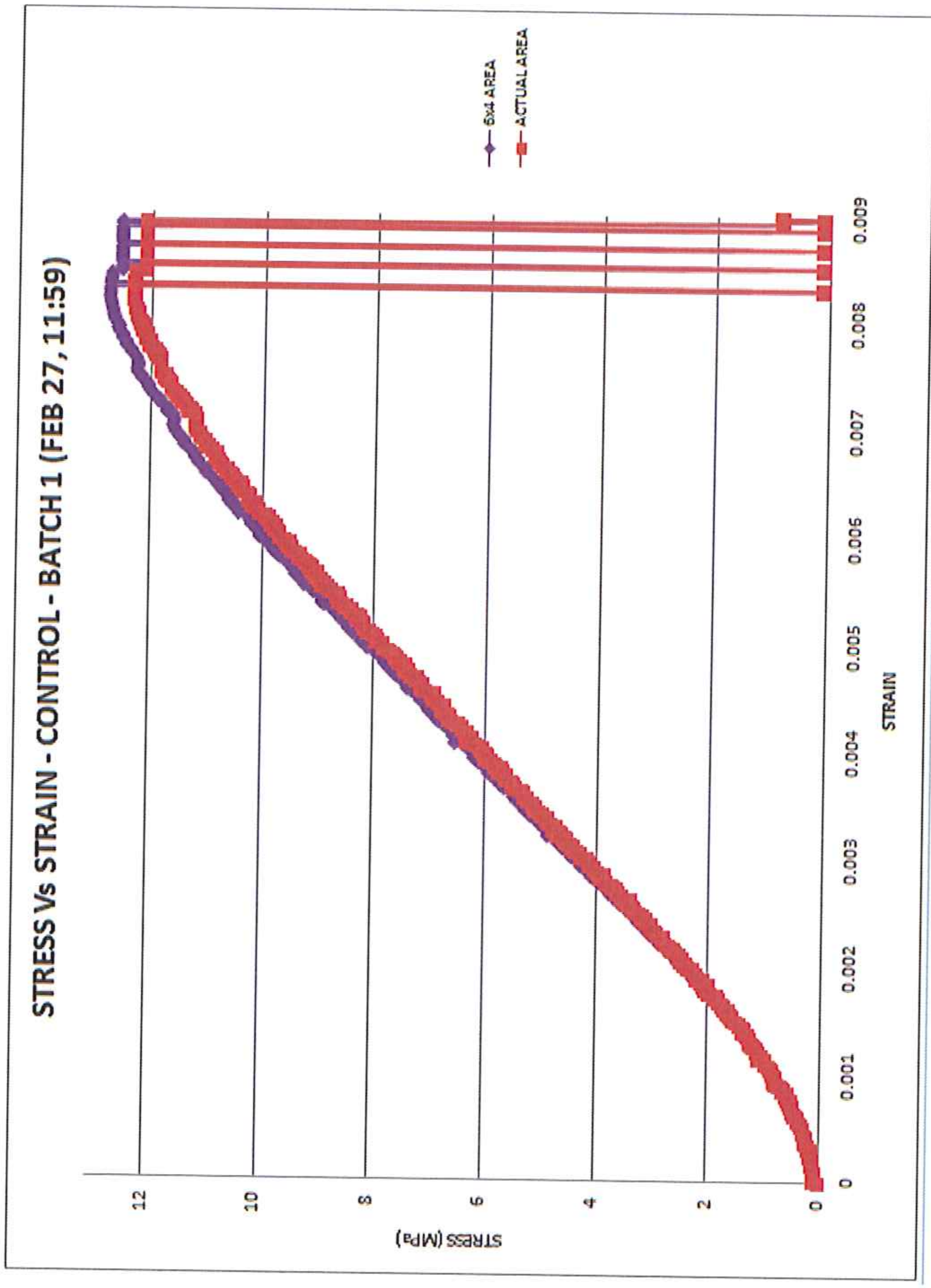

STRESS Vs STRAIN - CONFIGURATION 1
CONF 1-BATCH 1
CONF 1-BATCH 2
STRESS (MPa)
0
2
4
6
8
10
12
STRAIN
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009

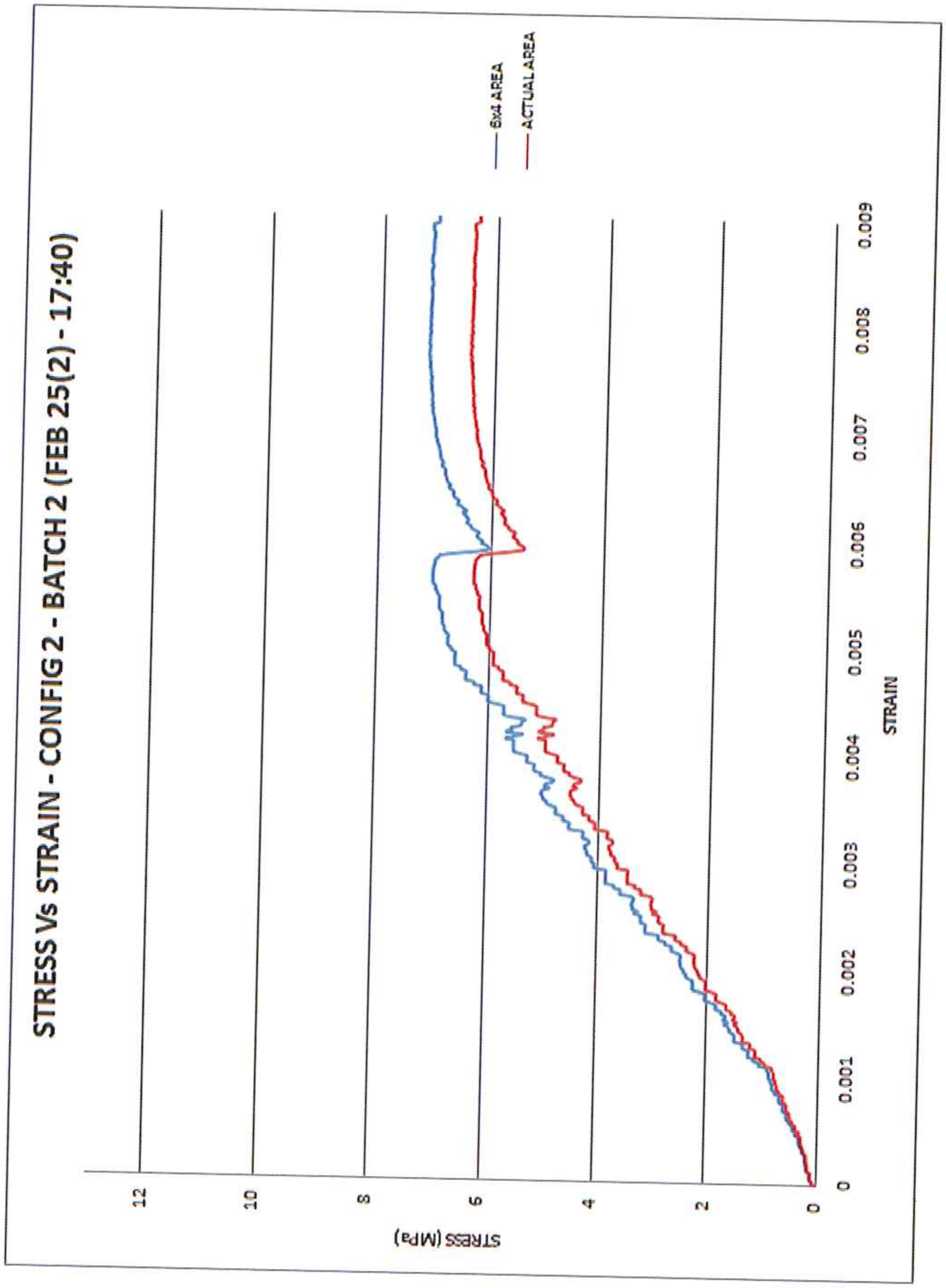

STRESS Vs STRAIN - CONFIGURATION 2
STRESS (MPa)
STRAIN
CONFIG 2 BATCH 1
CONFIG 2 BATCH 2
0
2
4
6
8
10
12
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009


STRESS Vs STRAIN - CONTROL
STRESS (MPa)
0
2
4
6
8
10
12
STRAIN
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
CONTROL - BATCH 1
CONTROL - BATCH 2


STRESS Vs STRAIN - CONFIG 1-BATCH 2 (FEB 20-15:52)
STRESS (MPa)
0
2
4
6
8
10
12
STRAIN (mm)
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
6x4 AREA
ACTUAL AREA


STRESS Vs STRAIN - CONFIG 2 - BATCH 1
STRESS (MPa)
12
10
8
6
4
2
0
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
STRAIN
6x4 AREA
ACTUAL AREA


STRESS Vs STRAIN - CONTROL - BATCH 1 (FEB 27, 11:59)
6x4 AREA
ACTUAL AREA
STRESS (MPa)
STRAIN
0
2
4
6
8
10
12
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009


STRESS Vs STRAIN - CONFIG 2 - BATCH 2 (FEB 25(2) - 17:40)
6x4 AREA
ACTUAL AREA
STRESS (MPa)
0
2
4
6
8
10
12
STRAIN
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009