# Implementation of Moment Frame Connections

# Scaled to Residential Construction

## Rivet Connected I-joist Moment Frames

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# Table of Contents

List of Tables ..... 2

List of Figures ..... 3

Abstract ..... 4

Introduction ..... 5

Synthesis of Research ..... 6

RCI (Rivet Connected I-joist) Detail ..... 9

Testing Procedure ..... 11

Results ..... 16

Testing Results ..... 16

Analysis of failure ..... 22

Strength Analysis ..... 24

Future design ..... 27

Future Design Calculations ..... 28

Conclusions ..... 30

Works Cited ..... 32

Appendix ..... i

Appendix List of Figures ..... iv

Addendum ..... v

Methodology of Testing the RCI Frames ..... v

Methodology to Accurately Calculate Yield Mode for Engineered Wood Products following Johnson and Woeste Process ..... v

# List of Tables

Table 1: Amplitude for Cyclic Test for the Fastener Pattern 1 Following ASTM E2126 ..... 14
Table 2: Hysteretic Tabulated Data ..... 21
Table 3: Tabulates the values of both the WMEL portal frame and the VA Model at 0.24”, 0.48” and Ultimate lateral displacement ..... 26
Table 4: Future Design Yield Mode Results with a 3/8” thick web ..... 29
Table 5: Future Design Yield Mode Results with; a 7/16" thick web ..... 29

# List of Figures

Figure 1: Bottom Flange Rendering Showing Routed out Section ..... 10
Figure 2: Gusset Plate Detail IIncluding the Three Fastener Patterns ..... 10
Figure 3: CherryMate Rivet ..... 11
Figure 4: Typical Hollow Fastener Load vs. Extension Graph Outlined in ASTM 1575-03. Using a 5% offset the Yield Point was Determined. ..... 12
Figure 5: Test Apparatus Following ASTM 1575-03 ..... 12
Figure 6: Testing Moment Apparatus ..... 16
Figure 7: Brittle Failure of Predrilled Cherry Mate Fastener ..... 17
Figure 8: Ductile Failure of a Post Drilled Cherry Mate Fastener Showing Crushing of the Hollow Tube ..... 18
Figure 9: Testing Apparatus ..... 19
Figure 10: Specimen C3.1 strait Net Section Rupture ..... 22
Figure 11: Specimen C3.2 Net Section Rupture Engaging more of the Gusset Plate ..... 22
Figure 12: Specimen C1.1 Sliced Through the web Showing Little to no Crushing of the Fasteners ..... 23
Figure 13: Specimen C1.1 Showing Crushing of the Gusset Plate ..... 23
Figure 14: Specimen C1.1 Sliced Along the Length of the Fastener ..... 23
Figure 15: Fastener Showing Plastic Deformations from Double Shear Lloading ..... 24
Figure 16: Comparing the Number of 6_1 Walls that can be Implemented to Portal Frame Layouts that are more Flexible. ..... 27
Figure 17: Purposed Next for I-joist OSB Gusset Plate ..... 28

## Abstract

Moment connections between I-joist members, using a custom gusset plate fabricated out of Oriented Strand Board (OSB), were investigated. These moment connections may be valuable in frames with the intent to implement them in residential construction. Much research has been done with moment frame connections, but the research to date has been for large cross-section members[5-7]. The focus of this research and testing was to scale previous research down to a simple moment frame that is safe, efficient and cost effective. The connection developed through this research is referred to as RCI (Rivet Connected I-joist).

The I-joists are manufactured with a performance pro OSB web and Douglas fir Laminated Veneer Lumber (LVL) flanges. To allow for high ductility (safety) and possible field construction, CherryMate Pop rivets were used to connect the gusset plates to the I-joists. These mechanical fasteners are oriented in a circular pattern. The advantage of a circular layout in moment connections is that all of the fasteners experience equal loading. This prevents premature failure due to the loss of a single fastener. The moment connections exceeded design capacity while still allowing .03rad of rotation before failure. The failure mode of the frames was a net section rupture of the OSB gusset plate. This was not the way the frames were designed to fail. The two primary reasons the gusset plate control failed was; the weaker than anticipated OSB product (SG<0.5) used in the gusset plate, and a stronger than anticipated glue bonding the flanges of an I-joist to the web. The strengths and weaknesses of this design, established through testing, have led to new design elements to improve the performance of the connections.

# Introduction

The portal frames tested were designed for the Washington State University Organic Farm residential structures. These single story structures will house students year round. The Pullman area has moderately high snow loads of 30psf and design wind loads of -11.6psf and 13.9 for the roof and walls respectively. Analysis using VA (Visual Analysis) showed the factored ASD load combination of D+S, has the greatest moment of 1050lb ft for a frame spaced 4' on center and spanning 16'.

Meeting the requirements for deflection and ductility are the primary concerns encountered when using timber moment. Conventional residential construction consists of many shear panels and thousands of fasteners spaced out over the entire structure. When conventional shear walls undergo seismic loading, the nails yield and dissipate an immense amount of energy. In comparison, moment connections by nature resist this same load, but all of the force is directed to two moment connections per frame. Therefore, it is difficult to accomplish ductility while still falling within the limits for story drift.

The RCI (Rivet Connected I-joist) moment frame was designed to meet and exceed the deflection and ductility requirements. The connection developed through this project is comprised of multiple fasteners, ranging from 23 to 32 per connection. The RCI approach provides ductility during cyclic loading much like shear walls. The OSB gusset plate is designed to fit like a puzzle piece between the two flanges of the I-joists, leaving only enough room to approach the deflection limit before the gusset plate bears on the flange. The rivets take up the load initially and provide resistance up to design load and deflection. Once the loads exceed the design limits, the gusset plate bears on the flanges of the I-joist, providing a

temporary increase in stiffness before the flanges break away. This pushes the entire load back into the fasteners which are designed to follow a Yield Mode IV failure of the rivets, with little to no damage to the web of the I-joist and gusset plates. This process allows for the time and warning needed before structural collapse, to permit safe egress for occupants during a seismic event.

## Synthesis of Research

Research conducted by Kasal (2004) tested two glulam moment frames with bolted connections and densified material at the connection between the beam and the column. The densified material increased the crushing strength of the wood fibers and forced the connection to transfer force to the ductile steel of the bolts. Kasal also wrapped the connection in fiberglass, attempting to increase the ductility of the connection.[5] The deflections were excessive and without the added fiberglass, the results would be inadequate. Although wrapping the connections with fiberglass solves the ductility problem, it is not an elegant solution. The RCI moment frame was hypothesized to solve these same issues but on a smaller scale with even greater ductile response.

The goal of this project was to design a moment frame connection system that would be cost effective and constructed from readily available products. In addition, the aspects of sustainability, constructability and deconstructability were considered in the design.

Using I-joists for the beams and columns of the moment frames accomplished several goals. I-joist products make efficient use of materials and are widely used in residential construction. I-joist products are sustainable, consistent and they can resist large moments

with less material compared to solid sawn lumber, LVL, LSL (Laminated Strand Lumber) or PSL (Parallel Strand Lumber). Since I-joists are an engineered wood product, it can be manufactured with small diameter trees, putting less strain on our forests. I-joists bearing APA-EWS trademarks follow rigorous quality assurance manufacturing processes that ensure each and every member meets the strength and stiffness critical for that member. Because of this manufacturing process, APA-EWS I-joists have fewer imperfections that cause warping in other wood products. Without this product's stringent quality control, which reduces construction tolerances, the intricacies of this project would have been rendered impossible.[1]

With the structural members decided on, the connections were pivotal to the success of the moment frames. Batchelar (2004) examined multiple ways to use mechanical fasteners to create a moment connection between two wood members. The pros and cons of each fastener type were discussed at length. The focus was specifically to connect two glulam members into a moment connection that was ductile, not brittle.[2] Moment frames have historically had low ductility and this research was focused on combating the problem. The five types of fasteners discussed were nails, bolts, glued cross-lapped joints, epoxy grouted steel rods and drift pins as means to acquire a satisfactory joint. From the Kasal research, bolts were not the solution, as it put too much stress in very concentrated areas. Epoxy grouted steel rods and drift pins are only appropriate for use in heavy timber projects, and provided no option for post deconstruction reuse. That left only nails and cross lapped joints as feasible for this project's scale. Nails provide a tight connection between wood and fastener, and are easy to install. They allow for an increase of ductility if there are enough of them but they are not deconstructable without damage to the member, so would only be used as a last resort. Glued cross-lapped

joints were a very appealing connection. They could be scaled to a LVL layup type connection where the actual veneers are cross-laminated together to form the moment connection. However, this connection has little to no ductility. The failure would occur in the wood fiber or in the glue layer, both of which would be catastrophic failures.[2]

Bachanan (1989) explored a connection with circular fastener patterns to establish a moment connection between two glulams.[3] From this article, an innovative connection detail was conceived using circular fastener pattern of pop rivets that would have the ductility of nails but the deconstructability of bolts. Pop rivets are quick to install and easy to drill out and remove. Although rivets are primarily used to connect metal plates, they can be just as effective with wood members. The primary hurdle was finding a company that could manufacture pop rivets to the necessary dimensions. Mass produced pop rivets currently have a maximum length of 1.25". The length required for the RCI moment frame tested, was 2.375". An innovative product called a two part CherryMate Pop rivet uses a common pop rivet in combination with a hollow tube. This allows for a large enough gage length in the fastener to accommodate the 2.375" required.

## RCI (Rivet Connected I-joist) Detail

The bottom flange of the top I-joist was routed out a half inch to accept a routed out gusset plate as shown in Figure 1 and Figure **2**. The gusset plates were constructed using one inch thick OSB. A 0.5" groove was created using a router to accept the flange as shown in Figure 2. This allowed the I-joist beam to maintain its strength for transferring bearing loads from the roof to the foundation. The number of rivets used for each connection were determined using the yield mode equations in the NDS (National Design Specification for Wood Construction 2005). Three different circular fastener patterns were used. Fastener Pattern 1 consists of one circle of 23 fasteners with a diameter of 4.5". Fastener Pattern 2 had 2 circles with diameters of 4.5" and 3.5" and 18 fasteners in each circle. Fastener Pattern 3 had three circles of fasteners with diameters of 4.5", 3.5", and 2.5" and 10 fasteners per circle. The shape of the gusset plate was designed to provide a flush connection on the outer face of the frame. The T-shape gusset plate will provide room for an elliptical fastener pattern if future designs needed more capacity without switch to a larger I-joist. The gusset plate was cut to allow a 1/16in to 1/8 gap to provide space for the gusset plates to move within the flanges before bearing.

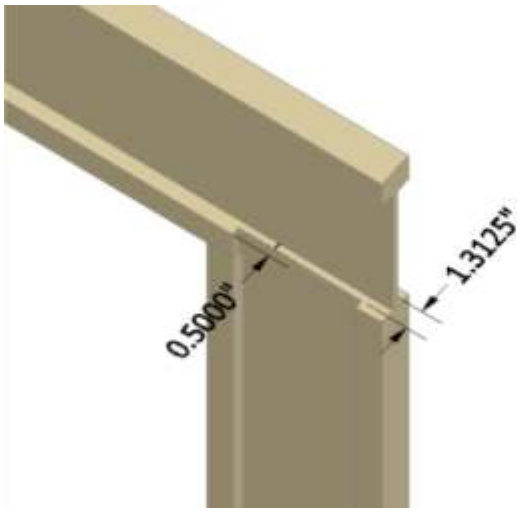


Figure 1: Bottom flange rendering showing routed out section

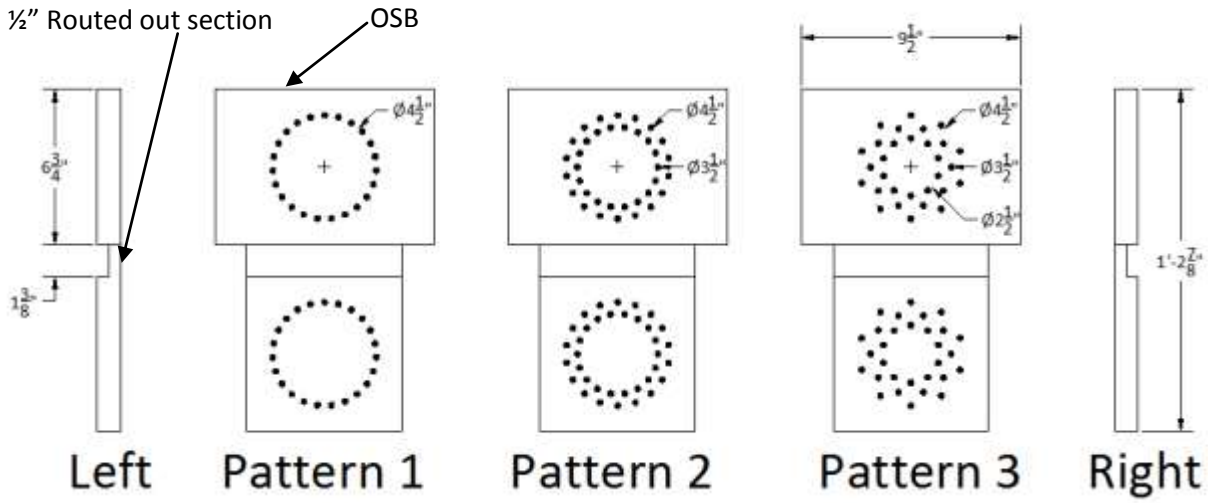


Figure 2: Gusset Plate Detail Including the Three Fastener Patterns

The fasteners used were aluminum CherryMate rivet ¼"dia with a gauge length of 2-1/8" to 2-3/8" as shown in Figure 3.

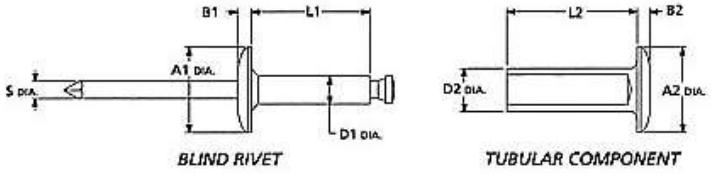


Figure 3: Manufactures Diagram of CherryMate Rivet

## Testing Procedure

Fifteen CherryMate rivets were constructed to a length of 2-3/8". They were tested following ASTM F 1575-03. This test loads a dowel at three bending points as shown in Figure 4. The test was performed with the CherryMate rivet, L=2-3/8". The standard states that $S_{bp}$ should equal 11.5 times the diameter of the fastener (depicted in Table 1 of the standard) this would be $S_{bp}$=2.9" with a ¼" diameter fastener. Since the CherryMate rivet being tested was 2-3/8" long, less than the recommended 2.9", the standard states that $S_{bp}$ should be as wide as possible. $S_{bp}$ was set to 2" as to not interfere with the heads of the CherryMate rivet while being crushed. The rate of displacement controlled loading was constant at $r_L$=0.25in/min. From the load displacement curve, using 5% of the diameter offset, $P_{Yield}$ was found as shown in Figure 5. The yield moment and nominal bending yield strength were then calculated.

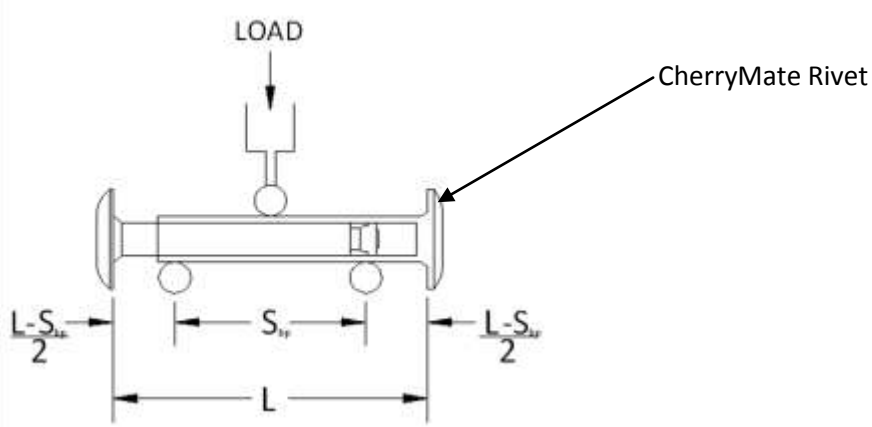


Figure 4: Test Apparatus Following ASTM 1575-03 to Acquire the $F_{yb}$ for the CherryMate Pop Rivets

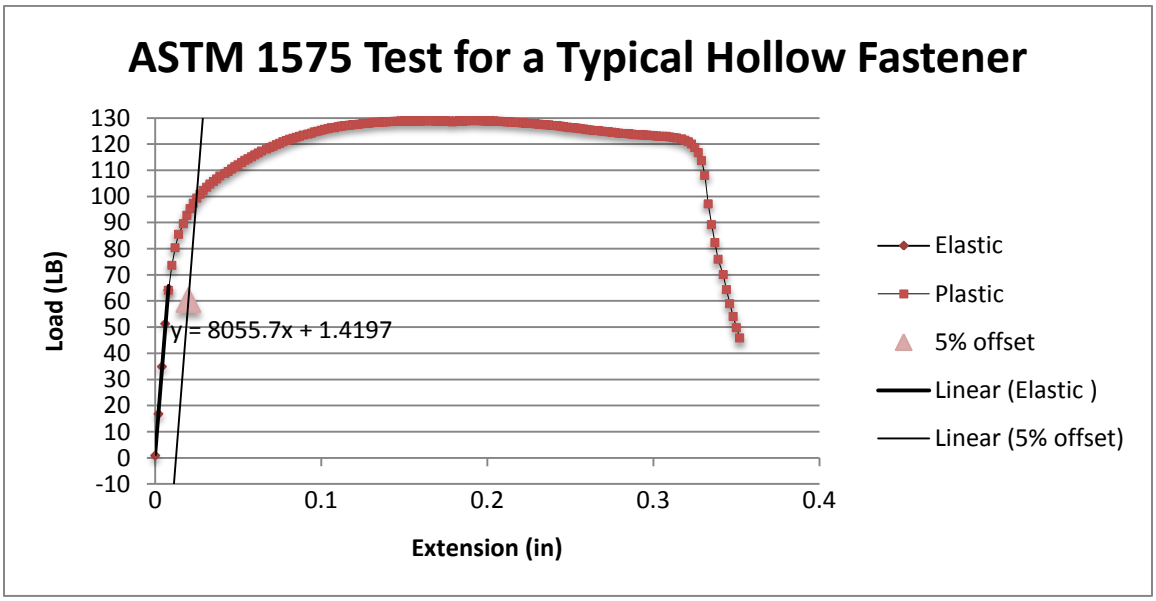


Figure 5: Typical Hollow Fastener Load vs. Extension Graph Outlined in ASTM 1575-03. Using a 5% offset, the Yield Point was Determined.

The $F_{yb}$ is derived for a solid cross section fastener for ASTM 1575-03. The strength of the CherryMate rivet will be low, since it's a hollow fastener. By using ASTM 1575-03, the $F_{yb}$ calculated, can be directly plugged into the solid fastener yield mode equations. Using the yield mode equations, the moment connections were designed and constructed using 1 to 3 rows of fasteners spaced .5 in apart.

Each of these configurations was tested in bending 3 times. The first moment connection test of each fastener configuration was a monotonic test to find the maximum displacement. The CUREE Basic Load Protocol defines failure as the point at which the load drops to 0.8 post peak load in the monotonic test. The displacement at .8Peak represents 100% of the connection's displacement capacity. The remaining two frames were cyclically tested, following the CUREE Basic Load Protocol. With this displacement, the cyclic protocol was defined by Table 3 in ASTM E2126-09 and displacements for the fastener Pattern 1 are shown in Table 1.

Table 1: Amplitude for Cyclic Test for the Fastener Pattern 1 Following ASTM E2126

| CUREE Protocol of M1 | | | |
|---|---|---|---|
| Process | Cycle | Displacement Peaks | % of Delta |
| 1 | 6 | 0.050738961 | 5.0% |
| 2 | 1 | 0.076108442 | 7.5% |
| 3 | 6 | 0.053275909 | |
| 4 | 1 | 0.101477923 | 10.0% |
| 5 | 6 | 0.071034546 | |
| 6 | 1 | 0.202955845 | 20.0% |
| 7 | 3 | 0.142069092 | |
| 8 | 1 | 0.304433768 | 30.0% |
| 9 | 3 | 0.213103638 | |
| 10 | 1 | 0.405911691 | 40.0% |
| 11 | 2 | 0.284138183 | |
| 12 | 1 | 0.710345459 | 70.0% |
| 13 | 2 | 0.497241821 | |
| 14 | 1 | 1.014779226 | 100.0% |
| 15 | 2 | 0.710345459 | |
| 16 | 1 | 1.319212994 | 130.0% |
| 17 | 2 | 0.923449096 | |
| 18 | 1 | 1.623646762 | 160.0% |
| 19 | 2 | 1.136552734 | |
| 20 | 1 | 1.92808053 | 190.0% |
| 21 | 2 | 1.349656371 | |
| 22 | 1 | 2.232514298 | 220.0% |
| 23 | 2 | 1.562760009 | |
| 24 | 1 | 2.536948066 | 250.0% |
| 25 | 2 | 1.775863646 | |
| 26 | 1 | 2.841381834 | 280.0% |
| 27 | 2 | 1.988967284 | |
| 28 | 1 | 3.145815602 | 310.0% |
| 29 | 2 | 2.202070921 | |
| 30 | 1 | 3.45024937 | 340.0% |
| 31 | 2 | 2.415174559 | |
| 32 | 1 | 3.754683138 | 370.0% |
| 33 | 2 | 2.628278197 | |

Each cycle follows the pattern outlined in the left column of Table 1. The first pattern is 6 cycles at a low displacement. The second pattern has a peak displacement and then 6 cycles of 70% of that peak. Pattern 3 is the same as Pattern 2, except only 3 - 70% cycles were run after the peak, and pattern 4 has only 2 - 70% cycles following the peak.

A pictorial representation of the testing apparatus is shown in Figure 6. Throughout the testing, displacement and load data were recorded for each specimen. A displacement pot was set up underneath the sample to monitor any movement of the bottom plate. To reach the design moment, the tension/compression load from the actuator was 375lb. A hysteretic graph of load vs. displacement was created with this data. Then the backbone curve was plotted and the stiffness, peak displacement, max displacement and peak load were tabulated. During the testing, the failure mechanisms were noted and included in the analysis.

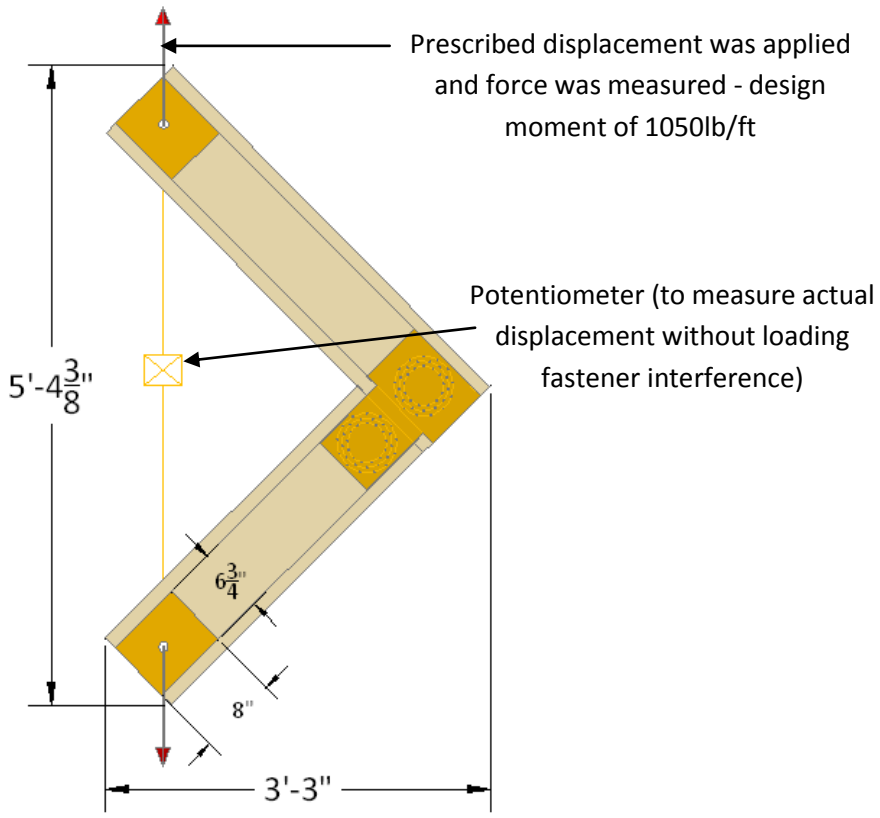


Figure 6: Pictorial Representations of the Testing Moment Apparatus

# Results

## Testing Results

The CherryMate Rivets delivered were not hollow as previously depicted by the manufacturer in Figure **3**. They were completely solid except for a small section designed to accept the Pop Rivets. These solid rivets were tested with the ASTM 1575 standard and the dowel bearing yield strength ($F_{yb}$) was calculated to be 31000psi. The fasteners were not designed for bending and the joint between the solid section and the hollow section failed every time, causing a brittle failure as shown in Figure 7. The yield mode that governed the connection using the solid rivets, was Mode I failure at 200lb/rivet crushing the wood before a

Mode IV at 310lb/rivet. The fasteners needed to be hollow, so they were drilled out with a milling machine to achieve accurate results. After testing the hollow fasteners using the same standard, most of the fasteners showed a large plateau region and significant crushing of the hollow tubing as shown in Figure 8. The $F_{yb}$ was calculated to be 18500psi which was close to a Mode IV failure (Mode I=200lb/rivet, Mode IV=240lb/rivet). This calculation is highly reliant on the specific gravity (SG) of the side and main member. OSB has a SG=0.5 but the web of an I-joist is a denser OSB material which was conservatively assumed to be 0.6. If the SG for the web is actually closer to 0.65 the connection will most definitely follow a Mode 4 failure (see Amendment Section of the Appendix for a more accurate process to select a SG value for yield mode analysis). The decision was made to continue fabrication with these fasteners.

Figure 7: Brittle Failure of Predrilled Cherry Mate Fastener

Figure 8: Ductile Failure of a Post Drilled Cherry Mate Fastener Showing Crushing of the Hollow Tube

The test apparatus for testing the frames is shown in Figure 9. It is constructed with 11 kip actuator suspended in a load frame. There are clevis connectors at the top and bottom to provide pinned connections to the specimen, fabricated by Bills Welding in Pullman WA. The frames as well as the load cell are braced laterally as shown.

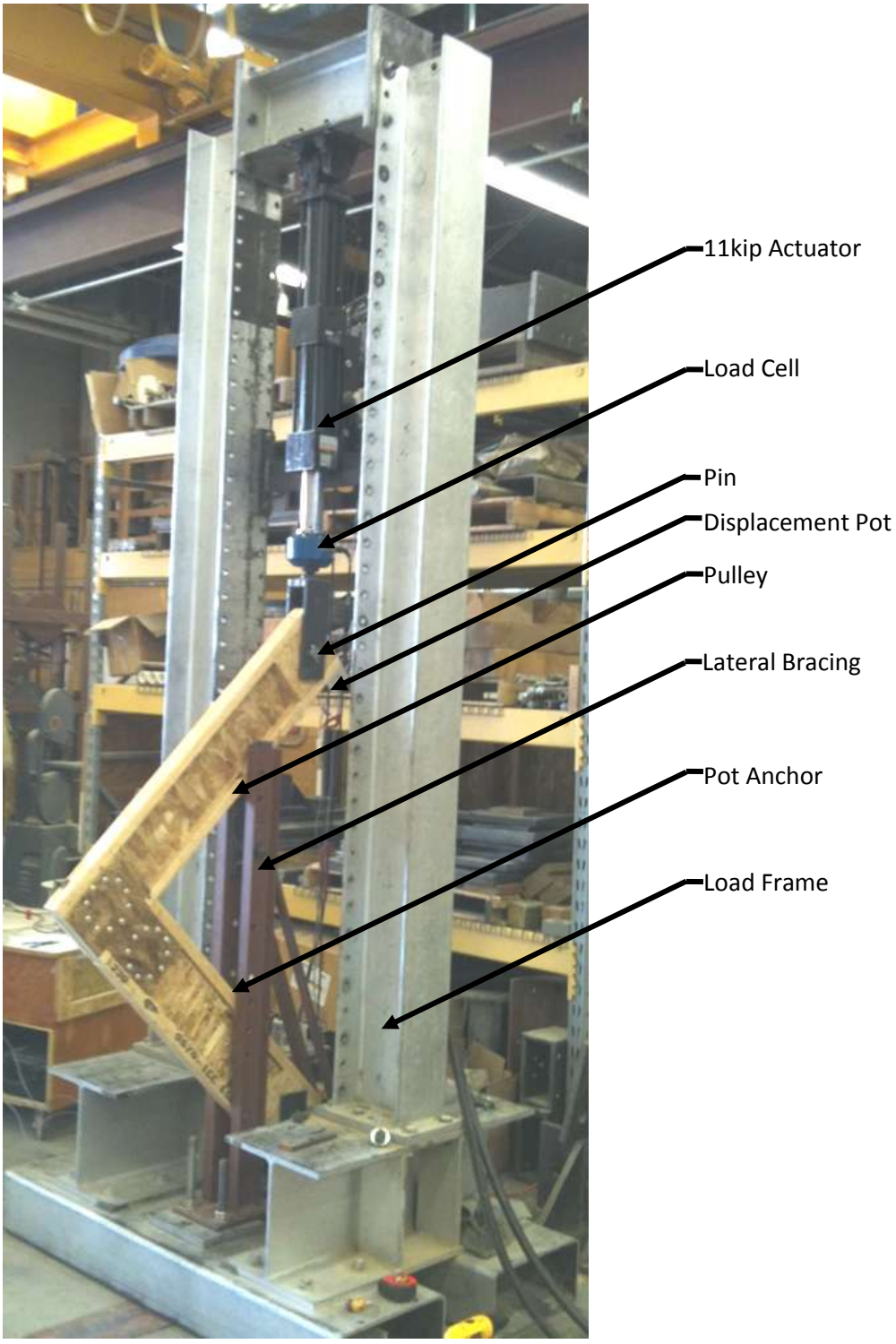


Figure 9: Testing Apparatus Used to Test Both the Monotonic and Cyclic Tests

The load was measured and recorded between the pin connections of the frame. Displacement was measured and recorded between the midpoint of the beam and column. Base movement was also measured and recorded but was negligible. The monotonic tests were run at 0.5in/min. The specimens failed at a rate slow enough to avoid any inertial effects. Initially, the rivets resisted the load until the gusset plate began to bear on the lower and upper flange. At this point, it was the gusset plate that was being tested, not the CherryMate rivets. In every case, the gusset plate failed before the top or bottom flange broke free. There was no reference strength for the glue holding the web to the flange in iLevels documentation. It did state that I-joist flanges should not be loaded in a way that will rip off the flanges. It was assumed that the glue would not bear heavy loads, let alone 11000lb, which some of the specimens experienced before the gusset plate failed.

From this data, the CUREE protocol was developed for each fastener pattern as shown in the appendix. The remaining two frames per fastener patterns were tested with the calculated CURRE protocols. All of the samples failed with a net section rupture of the gusset plate. While observing the failure of the first 5 cyclic tests, a hypothesis was made, that once the edge of the T-shaped gusset plate made contact with the flange, a fulcrum point was developed. This point induced extra loading on the gusset plate, pushing it to failure faster. A typical net section rupture of a gusset plate is shown in Figure 10. The last specimen was modified to eliminate these fulcrum points as shown in Figure 11. However, what this modified connection did not eliminate, was the bearing of the routed out section on the routed out flange. The modified design was the first step in developing a ductile failure but with the routed out section, the frame still failed at the gusset plate. Some relevant values acquired

from analysis of the hysteretic data are shown in Table 2. The bilinear stiffness was calculated from the slopes of the backbone curve envelope. Rotation was calculated using the geometry of the connection and the displacement pot. The maximum load was defined at the point at 80% post peak moment. Yield moment and displacement were not calculated because the frames failure was too brittle.

Table 2: Hysteretic Tabulated Data

| | Stiffness lb in/rad | | Stiffness lb in/degree | | Transfer moment (lb in) | Peak Moment (lb in) | Peak Rotation (Rad) | Max Rotation (Rad) |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | | | | |
| C1.1 | 1602000 | 1068000 | 28000 | 19000 | 9200 | 23900 | 0.0263 | 0.0283 |
| C1.2 | 523000 | 649000 | 9000 | 11000 | 8700 | 20800 | 0.0311 | 0.0415 |
| C2.1 | 845000 | 914000 | 15000 | 16000 | 17000 | 25500 | 0.0276 | 0.0271 |
| C2.2 | 847000 | 959000 | 15000 | 17000 | 9900 | 29200 | 0.0307 | 0.0300 |
| C3.1 | 810000 | 824000 | 14000 | 14000 | 12100 | 27500 | 0.0339 | 0.0396 |
| C3.2MOD | 504000 | 724000 | 9000 | 13000 | 13700 | 23800 | 0.0319 | 0.0356 |
| 0 | | | | | | | | |
| SD | 176000 | 129000 | 3000 | 2000 | 3300 | 3000 | 0.0028 | 0.0061 |
| AVG | 706000 | 814000 | 12000 | 14000 | 13300 | 25400 | 0.0310 | 0.0348 |
| CV | 25.0% | 15.8% | 25.0% | 15.8% | 24.8% | 11.7% | 9.1% | 17.6% |
| | | | | Outlier :Did not include in SD AVG CV | | | | |

Figure 10: Specimen C3.1 Failed with a Strait Net Section Rupture

Figure 11: Specimen C3.2 Net Section Rupture Engaging More of the Gusset Plate

## Analysis of failure

Examination of the connections post testing, revealed little to no crushing of the hollow dowels. A slice of Specimen C1.1 through the middle of the web as shown in Figure 12, depicts two things. First, it shows the dowels experienced little to no crushing, and second, that the

web of the I-joist was also not crushed. Removing the I-joist, Figure 13 shows that while there was no crushing of the web, there was slight crushing of the gusset plate around the fasteners. The fastener yielded slightly before failure as shown in Figure 14 and Figure **15**, which are slices of the same Specimen C1.1. If the flanges broke away, the rivets had a lot more capacity available to provide energy dissipation and displacement prior to failure.

Figure 12: Specimen C1.1 Sliced Through the Web Showing no Crushing of the Web and or Fasteners

Figure 13: Specimen C1.1 Showing Crushing of the Gusset Plate

Figure 14: Specimen C1.1 Sliced Along the Length of the Fastener

Figure 15: Fastener Showing Plastic Deformations from Double Shear Loading

The OSB material used to manufacture the gusset plates was an iLevel stair tread product which was found to be a less dense than normal OSB with a SG=0.48 (see Appendix Table 1: Specific Gravity Check). This may explain the slight crushing around the fasteners. The moment capacity of the gusset plate was calculated to be 8150lb, factoring in the geometry of the testing apparatus the capacity of the gusset plate would be reached at 675lb applied by the actuator. The maximum the gusset plate was able to withstand was 1100lb, with most failing around 875lb. This would be a factor of safety ranging from 1.3 to 1.6 which is very low for this type of material. A common factor of safety would range from 2.5 to 3.

## Strength Analysis

From a strength and stiffness perspective, the frames did sufficiently well. The design capacity of 1050lb in was met and exceeded by at least a factor of 19. This is primarily due to the gusset plates bearing on the flanges and not the rivets. The story drift that would occur if these were implemented in an 8' tall portal frame at design load, would only be 0.08" (neglecting the deflection of the I-joist members) when the limit is $.02h_{sx}$=1.92" for Occupancy

Category I or II in ASCE7 Table 12.12-1. Stiffness for each frame was calculated from slopes of the backbone curve. Specimens were fit to a bilinear stiffness that could then be modeled in Visual Analysis (VA). The member stiffness was calculated from iLevel's documentation and the moment of inertia and section modulus were calculated and input into the VA for an accurate model. The RCI moment connections were modeled as semi rigid, following a bilinear stiffness distribution to match the test data. After the model was complete, the frame was pushed to its ultimate moment and the joint rotation was checked against the test data. The model showed a 10.4% over prediction for peak moment and a 14.9% under prediction for maximum rotation when compared to test data. The model is stiffer and stronger than the test data by the percentages stated previously. Therefore, future designers must at a minimum reduce their peak moment by 10.4% and increase their maximum rotation by 14.9% to ensure a conservative design.

This model allows comparison of connection data that was acquired previously to the full frame test specimens. As a comparison, Pryor (2005) studied the performance of wood shear walls with large openings. The specimens tested in the report were 8ft tall - 12 ft long walls with large openings in the middle. The construction of the walls included two thin wall sections with 7/8in thick OSB sheathing on one side and ½in gypsum on the other. A header constructed by sandwiching 1/2in OSB in between two 2X12s, nailed together with 16d nails spaced 6in o.c. along the top and bottom edge, attached the two wall segments. The wall sheathing overlapped the header, using two rows of 8d common nails spaced 3 in o.c. along the edges, and 3in apart in the field. This totaled 28 nails through the sheathing into the header on each side. Simpson LSTA24 straps were used on the gypsum side of the wall. The report

tabulated the load applied by the actuator at .24in and .48 in and at ultimate. The VA model was also pushed into the same displacements and the values were tabulated as shown in Table 3. Portal Frame 6_1 on average had 2.4 times the strength of the VA model. The frames that were tested for the WMEL report were designed as shear wall replacements, to be used when a designer wants to put a large opening in a shear wall. Therefore, its strength must be comparable to a fully sheathed shear wall. I-joist fames do not have to be constrained in this manner. As shown in Figure 16, multiple frames can be implemented for each one shear wall. In conclusion, from a stiffness and strength perspective, the I-joist frames designed in this report are directly comparable to the portal frame specimen 6_1.

Table 3: Values of WMEL portal frame and the VA Model at 0.24", 0.48" and Ultimate lateral displacement

| Comparison to WMEL Portal Frame 6_1 | | | |
|---|---|---|---|
| Specimen | Load (lb) | | |
| | Displacement =0.24" | Displacement=0.48" | Displacement=Ult |
| 6_1 | 333 | 600 | 1665 |
| VA Model | 165.7 | 331.5 | 504.2 |

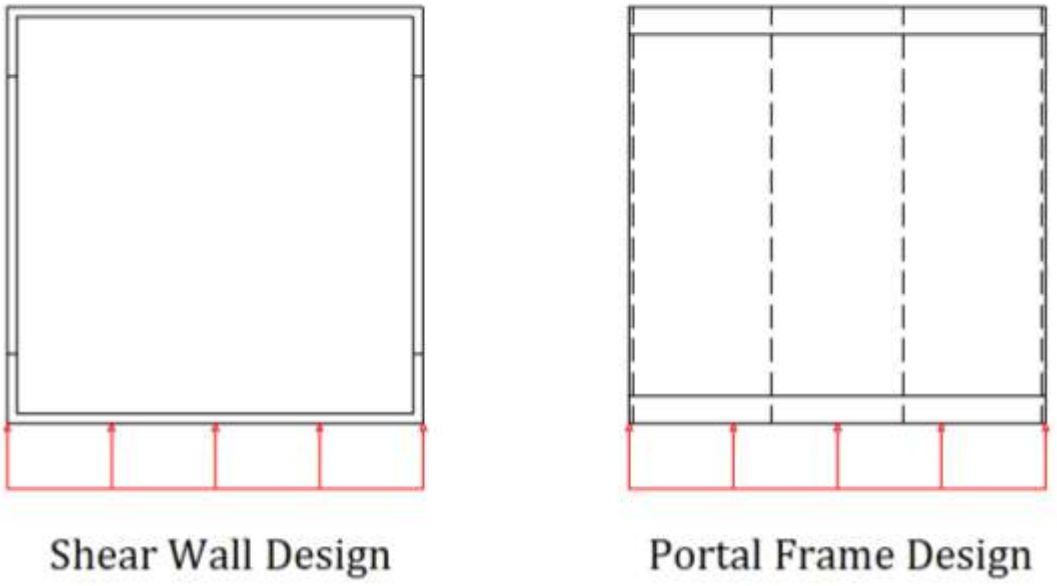


Figure 16: Comparing the number of 6_1 walls that can be Implemented to Portal Frame Layouts that are more Flexible.

## Future design

The hollow dowel fasteners that were used in this experiment have the potential to increase the ductility of current timber frame construction. Future research is needed to continue the advancements proposed in this report. The first test needed, will be one to determine the accurate capacity for the glue that holds the flanges to the web of a common I-joist. The strength of this glue is a lot stronger than iLevel implies in their documentation. With this capacity determined, the system can be modeled more definitively. Another design concern is the premature bearing of the gusset plate on the flanges of the I-joist. Trimming the corners of the gusset plate decreased the stiffness of the connection while engaging more of the gusset plate. This could be taken a step further by having a completely rounded gusset plate as shown in Figure 17.

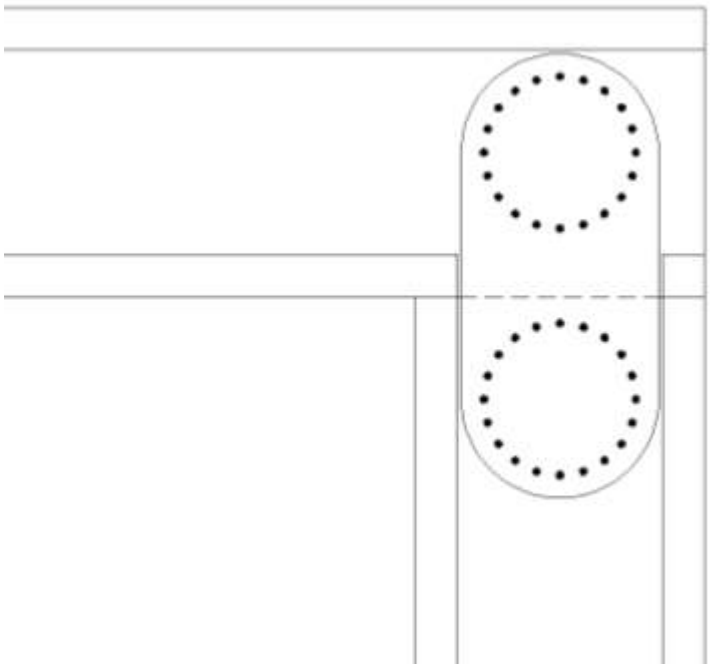

Figure 17: Purposed next design for an I-joist OSB gusset plate. This gusset plate is not routed out at all in the center to increase the net section rupture capacity. It is also rounded at the top and bottom to further reduce any bearing between the gusset plate and the flanges.

To prevent binding of the gusset plate, the flange of the I-joist should be completely routed out to the thickness of the web or completely removed in the connection location. With the gusset plate not being routed out, the gusset plate strength would be doubled due to a doubled total thickness from 1" of material to 2" of material. Eliminating this routed out section will also reduce fabrication time.

## Future Design Calculations

The calculations of any future design using engineered wood products should follow Johnson and Woeste's process outlined in the Addendum section of the Appendix. For a sample calculation the bearing capacity of the web of the I-joist acquired through ASTM D 5456 will be

assumed to be 6700psi for a 1/4” dowel. Looking this value up in NDS 2005 Table 11.3.2 will result in an Equivalent Specific Gravity (ESG) of 0.585. With this ESG and the recommended ESG for the normal OSB gusset plate of 0.5, the yield mode calculation results are shown in Table 4 for a TJI 230 9.5” deep I-joist.

Table 4: Future Design Yield Mode Results with a 3/8” thick web

| | | |
|---|---|---|
| Double Shear Yield Mode I in the main member | 209 | lb |
| Double Shear Yield Mode I in the Side member | 773 | lb |
| Double Shear Yield Mode III in the Side member | 310 | lb |
| Double Shear Yield Mode IV | 242 | lb |

By assuming the bearing capacity to equal 6700psi the connection fails as a Mode I bearing capacity failure of the web. In this case, the web thickness would have to be increased to 7/16” to insure a Yield Mode IV failure. The results for a TJI 560 11-7/8” deep I-joist are shown in Table 5.

Table 5: Future Design Yield Mode Results with; a 7/16" thick web

| | | |
|---|---|---|
| Double Shear Yield Mode I in the main member | 244 | lb |
| Double Shear Yield Mode I in the Side member | 773 | lb |
| Double Shear Yield Mode III in the Side member | 310 | lb |
| Double Shear Yield Mode IV | 242 | lb |

With the Yield Mode IV capacity of 242lb the total number of rivets per connection can be determined for each fastener pattern. By stepping to a larger I-joist, the diameter of the connection can be increased to 7.75”, which results in less rivets necessary for the 1050lbin required moment. The total number of rivets per connection for fastener pattern one, two and three will equal 14, 16 and 18 rivets respectively. By using Johnson and Woeste’s process, the bearing capacity is accurately input into the yield mode equations which will insure a more accurate model of systems performance.

## Conclusions

Brittle failure of the moment connection and meeting serviceability deflection requirements are the greatest issues with any timber portal frame. Often when one of these issues is solved the other issue experiences increased difficulty (i.e., if the frame gets more stiff to meet deflection requirements, the moment connections become brittle and vice versa.) There is a small window between a brittle failure and meeting story drift limits with timber frames, and more research is needed on how different types of connections act under cyclic loading to advance the current understanding on how to construct a successful portal frame.

The rivet connected I-joist moment frames tested in this report performed much better than expected when it came to stiffness and strength. The design portion that needs improvement is creating a connection system that will allow the hollow dowels to have greater influence with regard to the connection’s failure mode. Aluminum is an extremely ductile material, and during the testing of the hollow fasteners, showed close to perfect ductility with a long plateau region before failure. Introducing geometric layouts to fully engage these ductile

hollow fasteners will provide the best balance of strength and stiffness without sacrificing ductility.

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# Appendix

This appendix outlines the calculations performed in the design and analysis of the RCI frames. Firstly, the results from the ASTM 1575 testing of the hollow fasteners to calculate $F_{yb}$ are given. Secondly, the design calculations are shown. This includes the beam and column design, yield mode calculations, bearing capacity calculations and the net section calculation. Thirdly, the monotonic test data and development of The CUREE protocols are shown. Fourthly, the cyclic analysis including inputs to refine the data, hysteresis analysis, and results are shown. Fifthly, a specific gravity check of the OSB gusset plate material is shown. Lastly, the future design calculations for yield mode, bearing capacity and connection design are presented.

# Appendix List of Tables

Appendix Table 1: Supplies for Project ..... vi
Appendix Table 2: Calculations to find fastener yield bending strength from ASTM 1575 ..... vii
Appendix Table 3: Design Calculations for the I-joist Beam ..... ix
Appendix Table 4: Design Calculations for the I-joist Beam Cont. ..... x
Appendix Table 5: Design Calculations for the I-joist Column ..... xi
Appendix Table 6: Design Calculations for the I-joist Column Cont. ..... xii
Appendix Table 7: Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis ..... xiii
Appendix Table 8: Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis Cont. ..... xiv
Appendix Table 9: Yield Mode Calculations for Hollow Fasteners ..... xv
Appendix Table 10: Gusset Plate Net Section Rupture ..... xvi
Appendix Table 11: CUREE Protocol for Fastener Pattern 1 ..... xvii
Appendix Table 12: CUREE Protocol for Fastener Pattern 2 ..... xix
Appendix Table 13: CUREE Protocol for Fastener Pattern 3 ..... xxi
Appendix Table 14: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C1-1 ..... xxiii
Appendix Table 15: Backbone Data for C1-1 ..... xxv
Appendix Table 16: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C1-2 ..... xxvi
Appendix Table 17: Backbone Data for C1-2 ..... xxviii
Appendix Table 18: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C2-1 ..... xxix
Appendix Table 19: Backbone Data for C2-1 ..... xxxi
Appendix Table 20: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C2-1 ..... xxxii
Appendix Table 21: Backbone Data for C2-2 ..... xxxiv
Appendix Table 22: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C3-1 ..... xxxv
Appendix Table 23: Backbone Data for C3-1 ..... xxxvii
Appendix Table 24: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C3-2MOD ..... xxxviii
Appendix Table 25: Backbone Data for C3-2MOD ..... xl
Appendix Table 26: Cyclic Test Results and Comparison to VA Model ..... xli
Appendix Table 27: VA Calculations to find Rotation and Comparison to WMEL Report ..... xliii
Appendix Table 28: Specific Gravity Check ..... l

Appendix Table 29: Future Design Yield Mode Calculations for Hollow Fasteners .....li
Appendix Table 30: Future Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis .....lii
Appendix Table 31: Future Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis Cont. .....liii

# Appendix List of Figures

Appendix Figure 1: Load vs. Extension for all hollow specimens following ASTM 1575 ..... viii
Appendix Figure 2: Monotonic Analysis for Specimen M1 with Delta located at 80% post peak. This Delta is used to set up the CUREE Protocol ..... xviii
Appendix Figure 3: Monotonic Analysis for Specimen M2 with Delta located at 80% post peak. This Delta is used to set up the CUREE Protocol ..... xx
Appendix Figure 4: Monotonic Analysis for Specimen M3 with Delta located at 80% post peak. This Delta is used to set up the CUREE Protocol ..... xxii
Appendix Figure 5: Hysteretic Analysis of C1-1 ..... xxiv
Appendix Figure 6: Hysteretic Analysis of C1-2 ..... xxvii
Appendix Figure 7: Hysteretic Analysis of C2-1 ..... xxx
Appendix Figure 8: Hysteretic Analysis of C2-2 ..... xxxiii
Appendix Figure 9: Hysteretic Analysis of C3-1 ..... xxxvi
Appendix Figure 10: Hysteretic Analysis of C3-2MOD ..... xxxix
Appendix Figure 11: Stiffness Relationships between Specimens ..... xlii
Appendix Figure 12: VA Print out #1 ..... xliv
Appendix Figure 13: VA Print out #2 ..... xlv
Appendix Figure 14: VA Print out #3 ..... xlvi
Appendix Figure 15: VA Print out #4 ..... xlvii
Appendix Figure 16: VA Print out #5 ..... xlviii
Appendix Figure 17: VA Print out #6 ..... xlix

# Addendum

## Methodology of Testing the RCI Frames

The approach to acquire the specific gravity and the bearing capacity of the web and the I-joist was to measure specific gravity then calculate fastener bearing capacity from Table 11.3.2 in the NDS 2005. Thus method is used for solid sawn lumber and a different methodology should be use for engineered lumber because it does not flow the same relationships. Due to the failure of the gusset plate before a definitive yield mode formed the comparison between experimental and calculated yield mode was inconclusive. As seen in the report the performance of the RCI frames was not judged by weather the correct yield mode was achieved but from a strength and stiffness perspective. Future designs that provide increased ductility and allow for the failure to occur in the fasteners however should follow Johnson and Woeste process below to accurately model the failure modes of the fasteners used in the construction of the frames.

## Methodology to Accurately Calculate Yield Mode for Engineered Wood Products following Johnson and Woeste Process

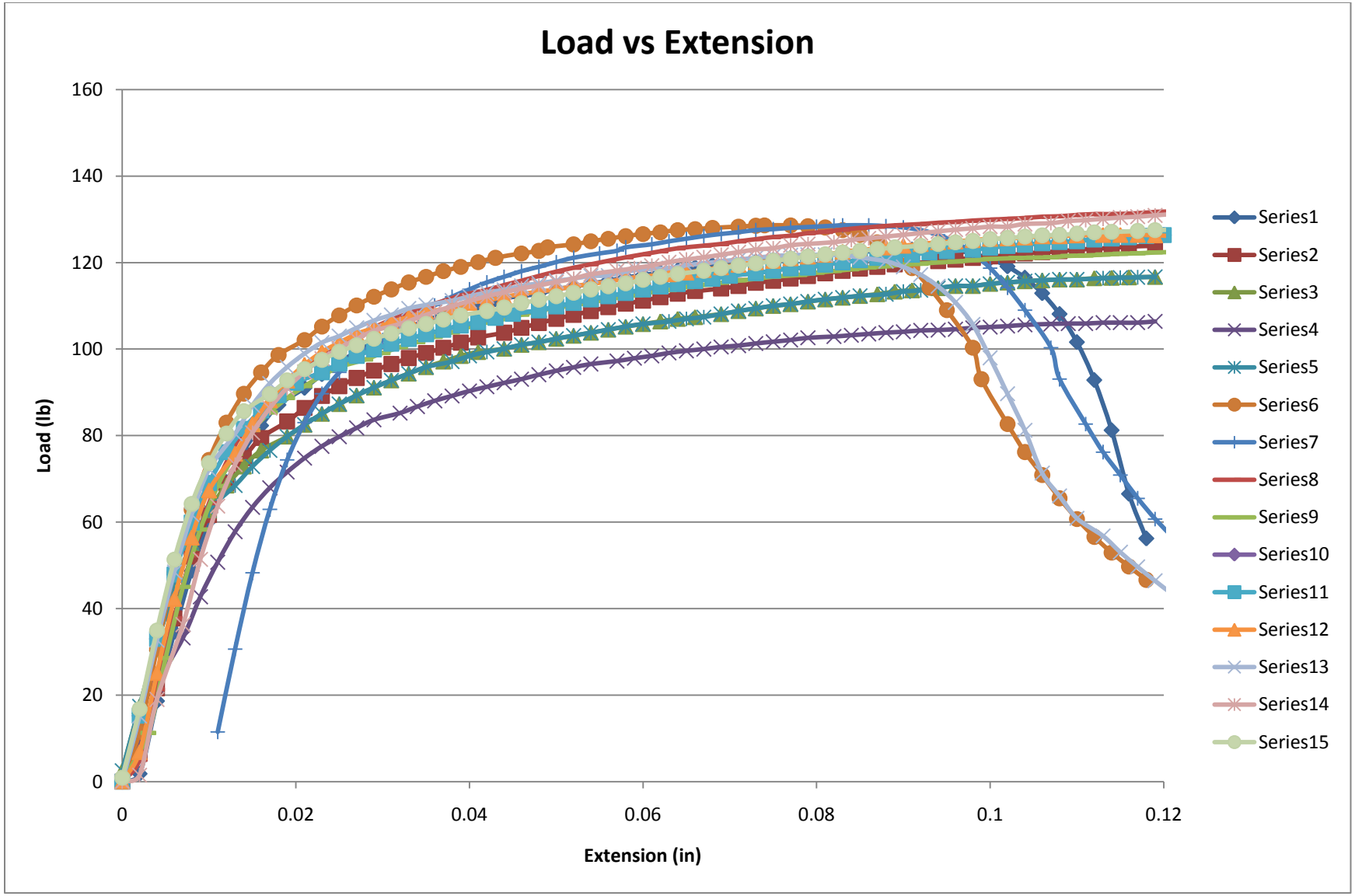
This is quite intuitive instead of measuring the SG and then using a relationship to acquire dowel bearing strength one just measures dowel bearing strength directly. Engineers are accustom to calculating yield modes with SG as the strength parameters so this report back solves for a equivalent SG (ESG) using the equations or linearly interpolating from table 11.3.2 in the NDS 2005. Now the dowel bearing strength and an ESG that can be used to calculate yield modes just as if one was using solid sawn lumber.[4]

**Appendix Table 2: Supplies for Project**

| **Item** | **#** | **Manufactures** | **Distributors** | **cost** |
|---|---|---|---|---|
| TJI 230 9.5" deep 14' long | 12 | iLevel | Colfax lumber | $319.2 |
| Cherrymate rivet<br>¼”dia 2-1/8x2-3/8<br>aluminum | 1000 | | Fastenal in<br>Moscow | $340 |
| OSB step<br>1”x12”x12’ | 10 | Structo wood ilevel | Pullman Building<br>Supply | $17.50 per board |
| | | | Grand total | $834.2<br>plus shipping & tax |

**Appendix Table 3: Calculations to find fastener yield bending strength from ASTM 1575**

| Drilled Hollow Fasteners | | | | | | |
|---|---|---|---|---|---|---|
| | D in | P lb | Sbp in | My lb in | S in^3 | Fyb (psi) |
| #1 | 0.25 | 100 | 2 | 50 | 0.002604 | 19200 |
| #2 | 0.25 | 92 | 2 | 46 | 0.002604 | 17664 |
| #3 | 0.25 | 88 | 2 | 44 | 0.002604 | 16896 |
| #4 | 0.25 | 85 | 2 | 42.5 | 0.002604 | 16320 |
| #5 | 0.25 | 100 | 2 | 50 | 0.002604 | 19200 |
| #6 | 0.25 | 109 | 2 | 54.5 | 0.002604 | 20928 |
| #7 | 0.25 | 98 | 2 | 49 | 0.002604 | 18816 |
| #8 | 0.25 | 103 | 2 | 51.5 | 0.002604 | 19776 |
| #9 | 0.25 | 96 | 2 | 48 | 0.002604 | 18432 |
| #10 | 0.25 | 96 | 2 | 48 | 0.002604 | 18432 |
| #11 | 0.25 | 96 | 2 | 48 | 0.002604 | 18432 |
| #12 | 0.25 | 104 | 2 | 52 | 0.002604 | 19968 |
| #13 | 0.25 | 105 | 2 | 52.5 | 0.002604 | 20160 |
| #14 | 0.25 | 105 | 2 | 52.5 | 0.002604 | 20160 |
| #15 | 0.25 | 100 | 2 | 50 | 0.002604 | 19200 |
| Max | 0.25 | 109 | 2 | 54.5 | 0.002604 | 20928 |
| Min | 0.25 | 85 | 2 | 42.5 | 0.002604 | 16320 |
| AVG | 0.25 | 98.46667 | 2 | 49.23333 | 0.002604 | 18905.6 |
| SD | 0 | 6.57774 | 0 | 3.28887 | 0 | 1262.926 |




**Appendix Figure 1: Load vs. Extension for all hollow specimens following ASTM 1575**

**Appendix Table 4: Design Calculations for the I-joist Beam**

| Portal frame analysis with timber | | | |
|---|---|---|---|
| Beam TJI 230 9.5 in Depth | | | |
| Bending factors | | | |
| Flange Depth | 1.375 | | |
| Flange Width | 2.3125 | | |
| Thickness web | 0.375 | | |
| Depth | 9.5 | | |
| EI | 206000000 | | |
| I | 115.5673014 | | |
| A (Flanges) | 6.359375 | | |
| E | 1782511.121 | | |
| Fb | 2,900 | psi | |
| Emin' | 580,000 | psi | |
| d | 3.950 | in (equivalent d) | |
| b | 1.875 | in (equivalent b) | |
| S | 4.876098708 | in^3 | |
| lu | 24 | in | Compression |
| lu | 24 | in | Bending |
| Cd | 1.6 | | |
| Cm | 1 | | |
| Ct | 1 | | |
| Type | 5 | LSL=1;LVL=2;PSL=3;Solid sawn=4 ijoist=5 | |
| CF | 1 | For iJoist | |
| Cfu | 1 | | |
| Ci | 1 | | |
| Cr | 1.15 | | |
| Fb* | 5336 | | |
| Cl | 0.97 | | |
| Fb' | 5155.746275 | | |
| | | | |
| Shear Factors | | | |
| Fv | 290 | | |
| Cd | 1.6 | | |
| Cm | 1 | | |
| Ct | 1 | | |
| Ci | 1 | | |
| Fv' | 464 | | |
| | | | |
| Compression Factors | | | |
| Fc | 2900 | | |
| Cd | 1.6 | | |
| Cm | 1 | | |

**Appendix Table 5: Design Calculations for the I-joist Beam Cont.**

| | | | |
|---|---|---|---|
| Ct | 1 | | |
| Cf | 1 | | |
| Ci | 1 | | |
| Fc* | 4640 | | |
| Cp | 0.53 | | |
| | FcE | 3043.4443 | |
| | | Emin' | 580000 |
| | | le | 49.44 |
| | | d | 3.950128588 |
| | x | 0.6559147 | |
| | c | 0.8 | |
| | Cp | 0.5337269 | |
| Fc' | 2476.492873 | | |
| Combine compression plus bending | | | |
| FcE1 | 3043.444272 | | |
| fc | 0 | psi | |
| | | 0 | lb |
| | | 0 | |
| fb | 2724.309083 | psi | |
| | | 1107 | lbft |
| | | 13284 | lbin |
| Fc' | 2476.492873 | | |
| Check | OK | | |
| Fb' | 5155.746275 | | |
| Check | OK | | |
| efficiency | 0.528402473 | | |
| Check | OK | | |
| L | 16 | ft | |
| Load | 35.5 | Lb/ft^2 | |
| Spacing | 4 | Ft | |
| EI | 206000000 | Lbin^2 | For iJoist |
| w | 142 | Lb/ft | |
| Delta allow | 1.066666667 | in | |
| Delta | 0.16569602 | | |
| Check | Deflection OK | | |

**Appendix Table 6: Design Calculations for the I-joist Column**

| Column TJI 230 9.5 in Depth | | | | | |
|---|---|---|---|---|---|
| Bending factors | | | | | |
| Flange Depth | 1.375 | | | | |
| Flange Width | 2.3125 | | | | |
| Thickness web | 0.375 | | | | |
| Depth | 9.5 | | | | |
| EI | 206000000 | | | | |
| I | 115.5673014 | | | | |
| A (Flanges) | 6.359375 | | | | |
| | | | | | |
| Fb | 2,600 | psi | | | |
| Emin' | 965,710 | psi | | | |
| d | 3.950 | in (equivalent d) | | | |
| b | 1.875 | in (equivalent b) | | | |
| S | 4.876098708 | in^3 | | | |
| lu | 144 | in | Compression | | |
| lu | 144 | in | Bending | | |
| Cd | 1.6 | | | | |
| Cm | 1 | | | | |
| Ct | 1 | | | | |
| Type | 5 | LSL=1;LVL=2;PSL=3;Solid sawn=4 ijoist=5 | | | |
| CF | 1 | For iJoist | | | |
| Cfu | 1 | | | | |
| Ci | 1 | | | | |
| Cr | 1 | | | | |
| Fb* | 4160 | | | | |
| Cl | 0.73 | | | | |
| | RB | 18.256571 | | | |
| | | le | 296.64 | | |
| | | | lu | 144 | |
| | | d | 3.950128588 | | |
| | | b | 1.875 | | |
| | | | | | |
| | FbE | 3476.879 | | | |
| | | Emin' | 965710 | | |
| | x | 0.8357882 | | | |
| | Cl | 0.7343127 | | | |
| | | | | | |
| Fb' | 3054.740814 | | | | |
| | | | | | |
| Shear Factors | | | | | |
| Fv | 290 | | | | |
| Cd | 1.6 | | | | |
| Cm | 1 | | | | |

**Appendix Table 7: Design Calculations for the I-joist Column Cont.**

| | | | | |
|---|---|---|---|---|
| Ct | 1 | | | |
| Ci | 1 | | | |
| Fv' | 464 | | | |
| | | | | |
| Compression Factors | | | | |
| Fc | 2510 | | | |
| Cd | 1.6 | | | |
| Cm | 1 | | | |
| Ct | 1 | | | |
| Cf | 1 | | | |
| Ci | 1 | | | |
| Fc* | 4016 | | | |
| Cp | 0.20 | | | |
| | FcE | 814.15357 | | |
| | | Emin' | | 965710 |
| | | le | | 296.64 |
| | | d | | 9.5 |
| | x | 0.2027275 | | |
| | c | 0.9 | | |
| | Cp | 0.1978476 | | |
| Fc' | 794.5561623 | | | |
| Combine compression plus bending | | | | |
| | | | | |
| FcE1 | 814.1535704 | | | |
| fc | 150.958231 | psi | | |
| | | 960 | lb | |
| | | 150.95823 | | |
| fb | 1870.347699 | psi | | |
| | | 760 | lbft | |
| | | 9120 | lbin | |
| Fc' | 794.5561623 | | | |
| Check | OK | | | |
| | | | | |
| | | | | |
| Fb' | 3054.740814 | | | |
| Check | OK | | | at top |
| | | | | |
| efficiency | 0.787741573 | | | |
| Check | OK | | | |

**Appendix Table 8: Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis**

| Web Bearing Strength 1 row | | | |
|---|---|---|---|
| G | 0.5 | | |
| D | 0.25 | in | see P73 NDS |
| t | 0.375 | | |
| R connection | 2.75 | | |
| | | lb | |
| Max Moment | 12500 | in | |
| Fe | 4650 | psi | |
| Abearing | 0.09375 | | |
| Dowel Capacity | 435.9375 | lb | |
| Dowel Moment | 1198.828 | | |
| # Dowels | 11 | | |
| min spacing | 0.7513 | OK | |
| Fastener Capacity | | | |
| Dowel Capacity | 202.6532 | lb | |
| Dowel Moment | 557.2964 | | |
| # Dowels | 23 | | |

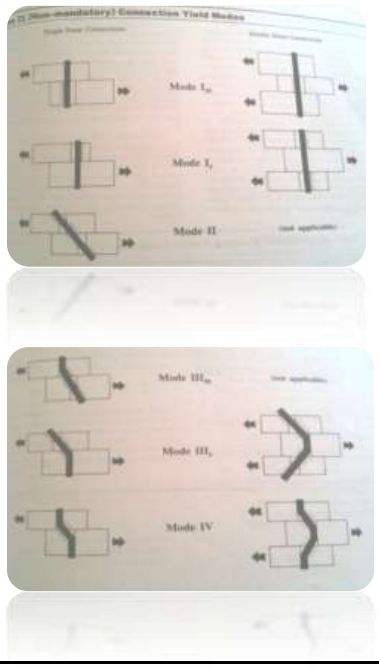
| Web Bearing Strength 2 row | | | |
|---|---|---|---|
| G | 0.5 | | |
| D | 0.25 | in | see P73 NDS |
| t | 0.375 | | |
| R1 connection | 2.75 | | |
| R2 Connection | 2.25 | | |
| | | lb | |
| Max Moment | 12500 | in | |
| Fe | 4650 | psi | |
| Abearing | 0.09375 | | |
| Dowel Capacity | 435.9375 | | |
| Dowel Moment2 | 980.8594 | | |
| Dowel Moment1 | 1198.828 | | |
| # Dowels Per Row | 6 | | |
| # Dowels total | 12 | | |
| min spacing 1 | 1.3291 | OK | |
| min spacing 2 | 1.0875 | OK | |
| Fastener Capacity | | | |
| Dowel Capacity | 202.6532 | | |
| Dowel Moment1 | 557.2964 | | |
| Dowel Moment 2 | 455.9698 | | |
| # Dowels Per Row | 13 | | |
| # Dowels total | 26 | | |

**Appendix Table 9: Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis Cont.**

| Web Bearing Strength 3 row | | | |
|---|---|---|---|
| | | | |
| G | 0.5 | | |
| D | 0.25 | in | see P73 NDS |
| t | 0.375 | | |
| R1 Connection | 2.75 | | |
| R2 Connection | 2.25 | | |
| R3 Connection | 1.75 | | |
| | | lb | |
| Max Moment | 12500 | in | |
| Fe | 4650 | psi | |
| Abearing | 0.09375 | | |
| Dowel Capacity | 435.9375 | | |
| Dowel Moment1 | 1198.828 | | |
| Dowel Moment2 | 980.8594 | | |
| Dowel Moment3 | 762.8906 | | |
| # Dowels Per Row | 5 | | |
| # Dowels total | 15 | | |
| | | | |
| min spacing 1 | 1.7279 | OK | |
| min spacing 2 | 1.4137 | OK | |
| min spacing 3 | 1.0996 | OK | |
| | | | |
| Fastener Capacity | | | |
| Dowel Capacity | 202.6532 | | |
| Dowel Moment1 | 557.2964 | | |
| Dowel Moment 2 | 455.9698 | | |
| Dowel Moment 3 | 354.6431 | | |
| # Dowels Per Row | 10 | | |
| # Dowels total | 30 | | |

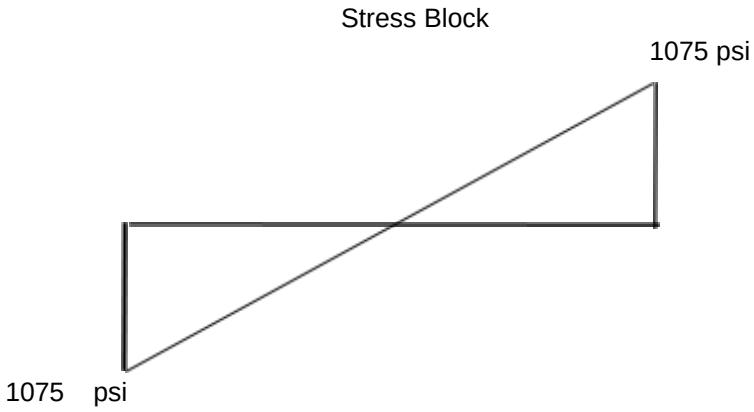
## Appendix Table 10: Yield Mode Calculations for Hollow Fasteners

| Capacity of CherryMate Rivets for iJoist with 1in Gusset Plates | | | |
|---|---|---|---|
| D | 0.24999 | 1/4 | in (see 11.3.6 Reduction term Table 11.3.1B) |
| theta | 90 | degrees | (maximum angle to grain 0-90 Table 11.3.1B) |
| Kth | 1.25 | | |
| lm | 0.38 | | main member dowel bearing length in |
| ls | 1 | | side member dowel bearing length in |
| Gm | 0.6 | | specific gravity of main member table 11.3.2A P74 |
| Gs | 0.5 | | specific gravity of side member table 11.3.2A P74 NDS |
| Fyb | 18500 | | p160 psi For nails |
| MMO | 0 | | Is the main member stress orientation; =0 for perpendicular; =1 for parallel; =Degree orientation if neither |
| SMO | 0 | | Is the side member stress orientation; =0 for perpendicular; =1 for parallel; =Degree orientation if neither |
| Rd1 | 2.9999 | | |
| Rd2 | 2.9999 | | |
| Rd34 | 2.9999 | | |
| Fem | 6484.946 | | Main Member Dowel Bearing Strength NDS Table 11.3.2 |
| Fes | 4636.742 | | |
| Re | 1.3986 | | |
| Rt | 0.375 | | |
| k1 | 0.356082 | | |
| k2 | 1.829589 | | |
| k3 | 0.970107 | | |
| ZImDS | 202.6532 | lb | |
| ZIsDS | 772.7851 | lb | |
| ZIIIsDS | 308.5117 | lb | |
| ZIVDS | 240.593 | lb | |
| ZImSS | 202.6532 | lb | |
| ZIsSS | 386.3926 | lb | |
| ZIISS | 137.5874 | lb | |
| ZIIImSS | 97.64355 | lb | |
| ZIIIsSS | 154.2558 | lb | |
| ZIVSS | 120.2965 | lb | |
| Min DS | 202.6532 | | |
| Min SS | 97.64355 | | |



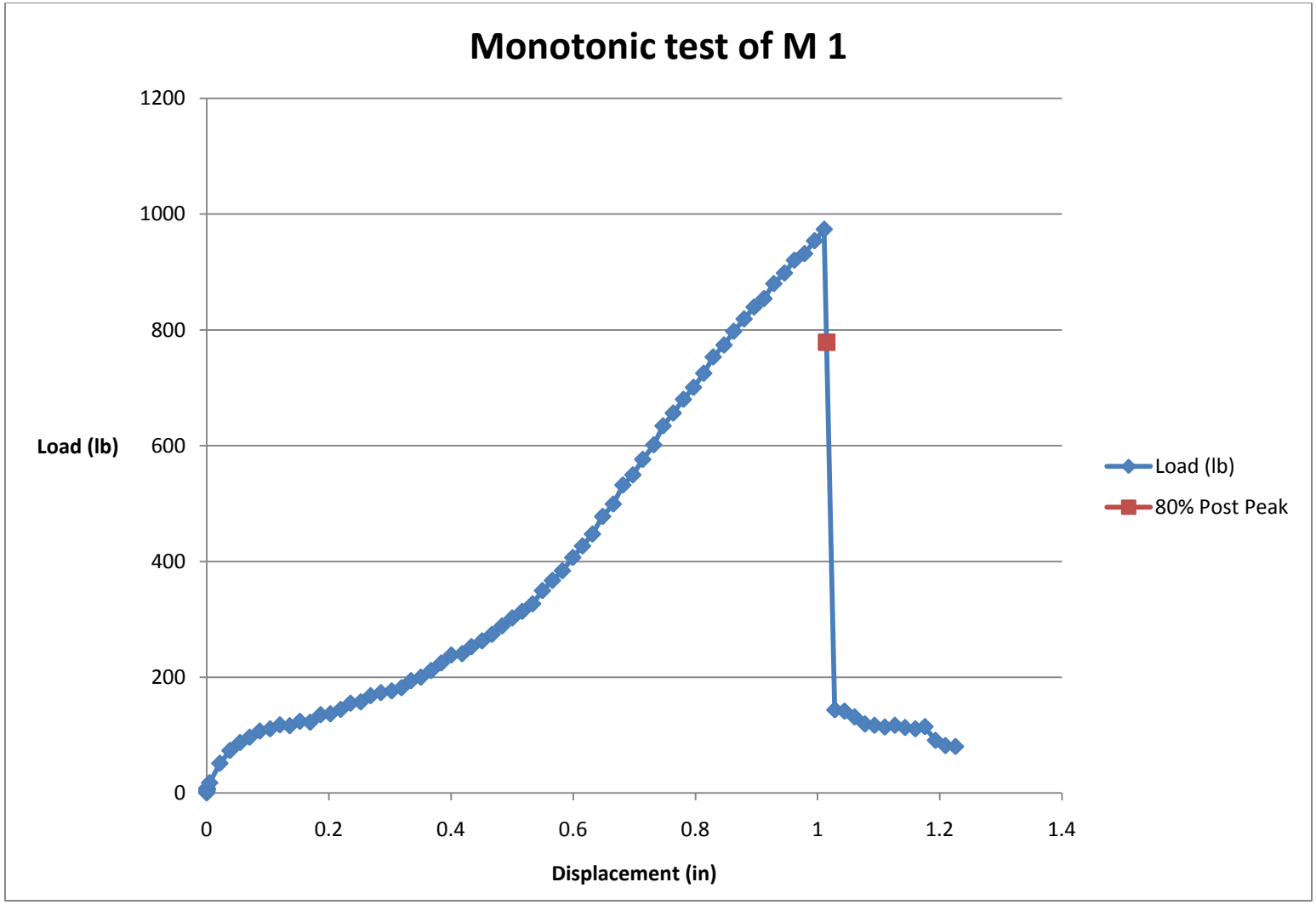
**Appendix Table 11: Gusset Plate Net Section Rupture**

| Gusset Plate Net Section Rupture | | | |
|---|---|---|---|
| Total thickness | 1 | in | |
| Width | 6.75 | in | |
| Ft | 1075 | psi | From iLevel's Documentation |
| Area of Stress Block | 3628.125 | lb | |
| Distance to resultant | 2.25 | | |
| Moment capacity | 8163.281 | | |
| Gusset plate Moment=19.5*Actuator Force | | | |
| Load Duration | 1.6 | | |
| Actuator Force = | 670 | | |



**Appendix Table 12: CUREE Protocol for Fastener Pattern 1**

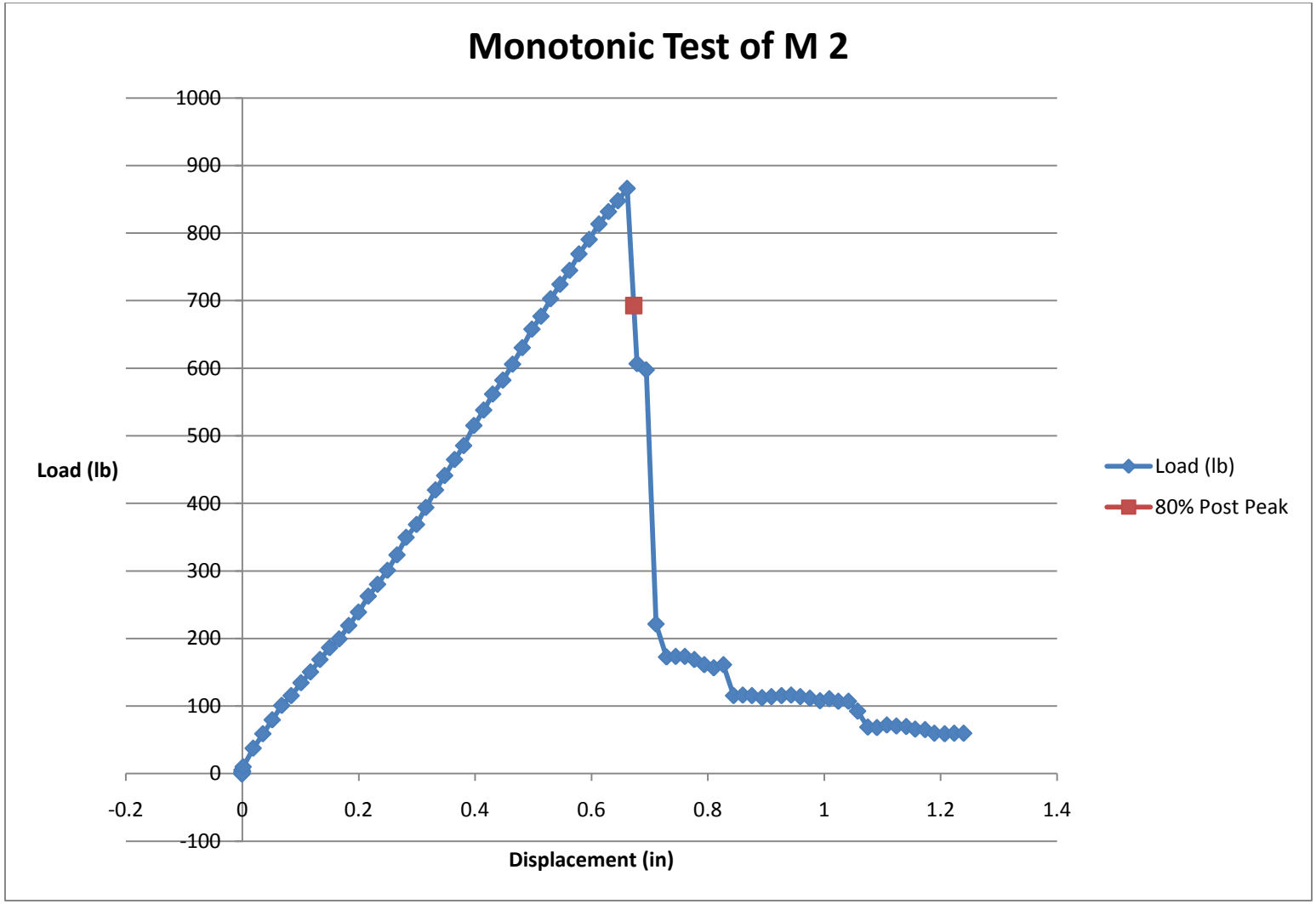
| CUREE Protocol of M1 | | | |
|---|---|---|---|
| | | Peak Displacement= 1.014779 | |
| Process | Cycle | Displacement Peaks | |
| 1 | 6 | 0.050738961 | 5.0% |
| 2 | 1 | 0.076108442 | 7.5% |
| 3 | 6 | 0.053275909 | |
| 4 | 1 | 0.101477923 | 10.0% |
| 5 | 6 | 0.071034546 | |
| 6 | 1 | 0.202955845 | 20.0% |
| 7 | 3 | 0.142069092 | |
| 8 | 1 | 0.304433768 | 30.0% |
| 9 | 3 | 0.213103638 | |
| 10 | 1 | 0.405911691 | 40.0% |
| 11 | 2 | 0.284138183 | |
| 12 | 1 | 0.710345459 | 70.0% |
| 13 | 2 | 0.497241821 | |
| 14 | 1 | 1.014779226 | 100.0% |
| 15 | 2 | 0.710345459 | |
| 16 | 1 | 1.319212994 | 130.0% |
| 17 | 2 | 0.923449096 | |
| 18 | 1 | 1.623646762 | 160.0% |
| 19 | 2 | 1.136552734 | |
| 20 | 1 | 1.92808053 | 190.0% |
| 21 | 2 | 1.349656371 | |
| 22 | 1 | 2.232514298 | 220.0% |
| 23 | 2 | 1.562760009 | |
| 24 | 1 | 2.536948066 | 250.0% |
| 25 | 2 | 1.775863646 | |
| 26 | 1 | 2.841381834 | 280.0% |
| 27 | 2 | 1.988967284 | |
| 28 | 1 | 3.145815602 | 310.0% |
| 29 | 2 | 2.202070921 | |
| 30 | 1 | 3.45024937 | 340.0% |
| 31 | 2 | 2.415174559 | |
| 32 | 1 | 3.754683138 | 370.0% |
| 33 | 2 | 2.628278197 | |




**Appendix Figure 2: Monotonic Analysis for Specimen M1 with Delta located at 80% post peak. This Delta is used to set up the CUREE Protocol**

**Appendix Table 13: CUREE Protocol for Fastener Pattern 2**

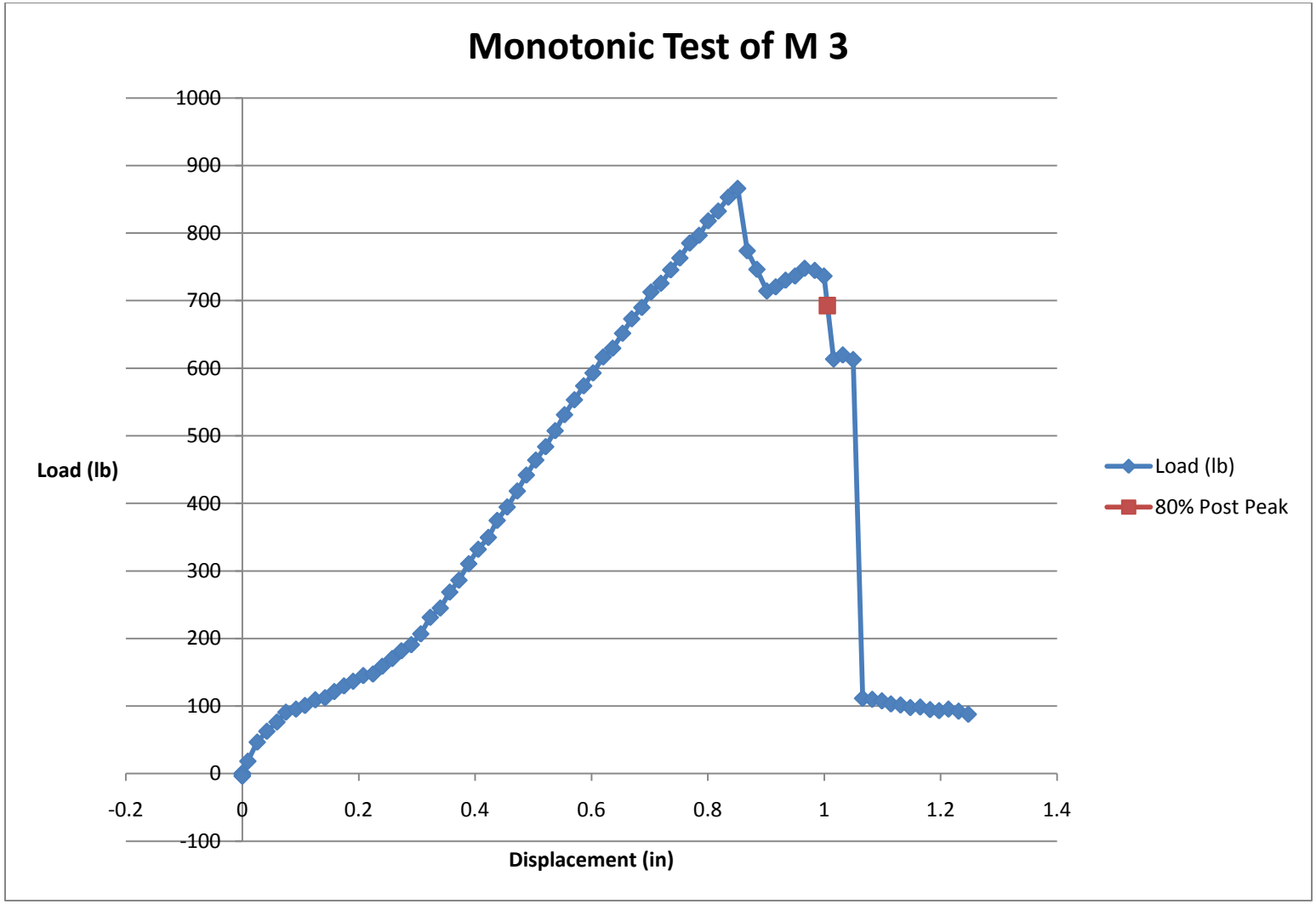
| CUREE Protocol of M2 | | | |
|---|---|---|---|
| Process | Cycle | Displacement Peaks | 0.672686 |
| 1 | 6 | 0.033634277 | 0.05 |
| 2 | 1 | 0.050451416 | 0.075 |
| 3 | 6 | 0.035315991 | |
| 4 | 1 | 0.067268554 | 0.1 |
| 5 | 6 | 0.047087988 | |
| 6 | 1 | 0.134537108 | 0.2 |
| 7 | 3 | 0.094175976 | |
| 8 | 1 | 0.201805662 | 0.3 |
| 9 | 3 | 0.141263964 | |
| 10 | 1 | 0.269074216 | 0.4 |
| 11 | 2 | 0.188351952 | |
| 12 | 1 | 0.470879879 | 0.7 |
| 13 | 2 | 0.329615915 | |
| 14 | 1 | 0.672685541 | 1 |
| 15 | 2 | 0.470879879 | |
| 16 | 1 | 0.874491204 | 1.3 |
| 17 | 2 | 0.612143842 | |
| 18 | 1 | 1.076296866 | 1.6 |
| 19 | 2 | 0.753407806 | |
| 20 | 1 | 1.278102528 | 1.9 |
| 21 | 2 | 0.89467177 | |
| 22 | 1 | 1.479908191 | 2.2 |
| 23 | 2 | 1.035935733 | |
| 24 | 1 | 1.681713853 | 2.5 |
| 25 | 2 | 1.177199697 | |
| 26 | 1 | 1.883519515 | 2.8 |
| 27 | 2 | 1.318463661 | |
| 28 | 1 | 2.085325178 | 3.1 |
| 29 | 2 | 1.459727624 | |
| 30 | 1 | 2.28713084 | 3.4 |
| 31 | 2 | 1.600991588 | |
| 32 | 1 | 2.488936502 | 3.7 |
| 33 | 2 | 1.742255552 | |
| 34 | 1 | 2.690742165 | 4 |
| 35 | 2 | 1.883519515 | |
| 36 | 1 | 2.892547827 | 4.3 |
| 37 | 2 | 2.024783479 | |
| 38 | 1 | 3.094353489 | 4.6 |
| 39 | 2 | 2.166047443 | |
| 40 | 1 | 3.296159152 | 4.9 |
| 41 | 2 | 2.307311406 | |
| 42 | 1 | 3.497964814 | 5.2 |
| 43 | 2 | 2.44857537 | |
| 44 | 1 | 3.699770476 | 5.5 |
| 45 | 2 | 2.589839334 | |
| 46 | 1 | 3.901576139 | 5.8 |
| 47 | 2 | 2.731103297 | |




**Appendix Figure 3: Monotonic Analysis for Specimen M2 with Delta located at 80% post peak. This Delta is used to set up the CUREE Protocol**

**Appendix Table 14: CUREE Protocol for Fastener Pattern 3**

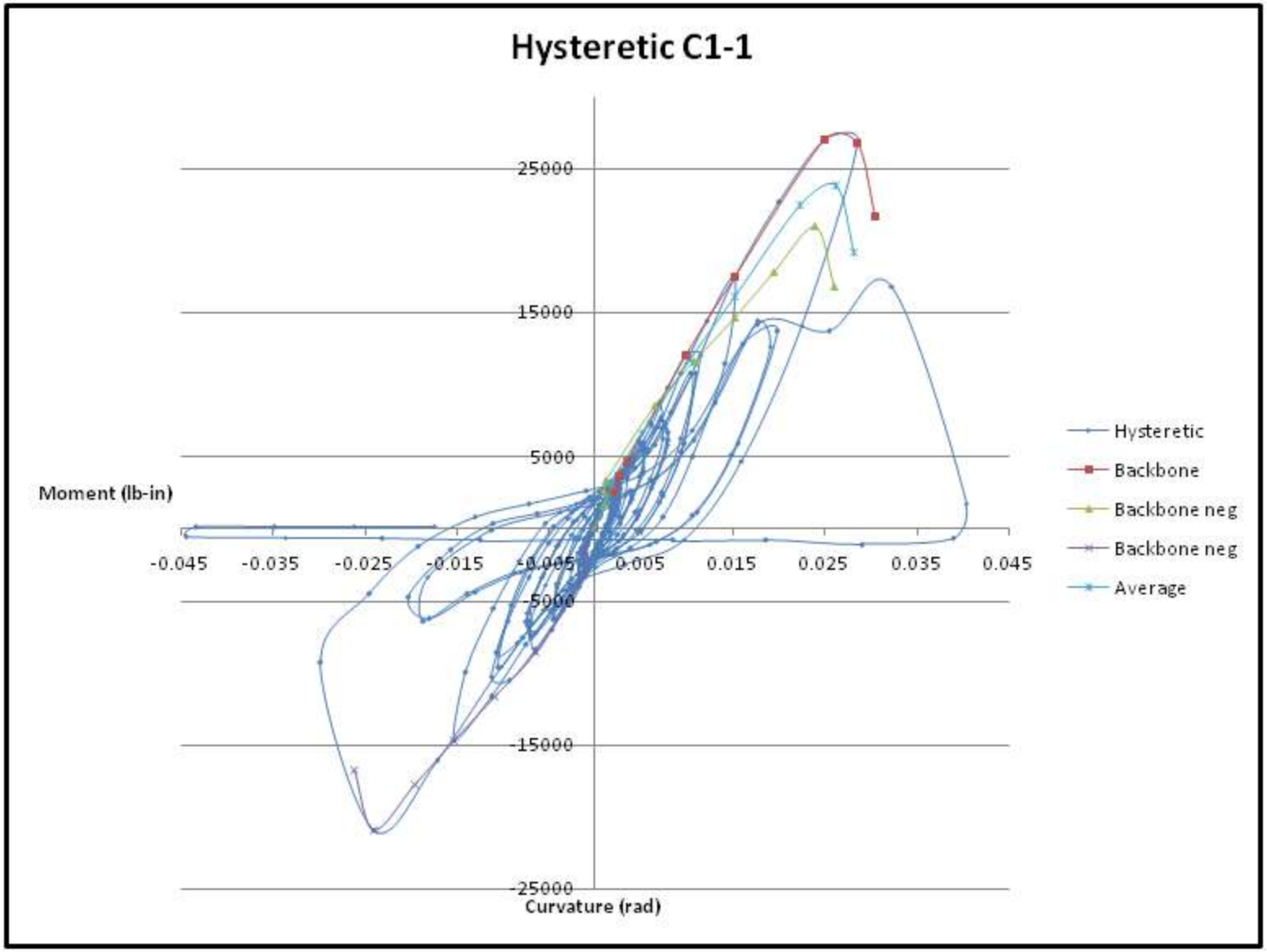
| CUREE Protocol of M3 | | | |
|---|---|---|---|
| Process | Cycle | Displacement Peaks | 1.005289 |
| 1 | 6 | 0.050264466 | 0.05 |
| 2 | 1 | 0.075396699 | 0.075 |
| 3 | 6 | 0.052777689 | |
| 4 | 1 | 0.100528932 | 0.1 |
| 5 | 6 | 0.070370253 | |
| 6 | 1 | 0.201057865 | 0.2 |
| 7 | 3 | 0.140740505 | |
| 8 | 1 | 0.301586797 | 0.3 |
| 9 | 3 | 0.211110758 | |
| 10 | 1 | 0.402115729 | 0.4 |
| 11 | 2 | 0.28148101 | |
| 12 | 1 | 0.703702526 | 0.7 |
| 13 | 2 | 0.492591768 | |
| 14 | 1 | 1.005289323 | 1 |
| 15 | 2 | 0.703702526 | |
| 16 | 1 | 1.30687612 | 1.3 |
| 17 | 2 | 0.914813284 | |
| 18 | 1 | 1.608462917 | 1.6 |
| 19 | 2 | 1.125924042 | |
| 20 | 1 | 1.910049714 | 1.9 |
| 21 | 2 | 1.3370348 | |
| 22 | 1 | 2.211636511 | 2.2 |
| 23 | 2 | 1.548145557 | |
| 24 | 1 | 2.513223308 | 2.5 |
| 25 | 2 | 1.759256315 | |
| 26 | 1 | 2.814810104 | 2.8 |
| 27 | 2 | 1.970367073 | |
| 28 | 1 | 3.116396901 | 3.1 |
| 29 | 2 | 2.181477831 | |
| 30 | 1 | 3.417983698 | 3.4 |
| 31 | 2 | 2.392588589 | |
| 32 | 1 | 3.719570495 | 3.7 |
| 33 | 2 | 2.603699347 | |




**Appendix Figure 4: Monotonic Analysis for Specimen M3 with Delta located at 80% post peak. This Delta is used to set up the CUREE Protocol**

**Appendix Table 15: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C1-1**

| Code Inputs for | C1-1 |
|---|---|
| Refinement | 15 |
| Start Cut | 75 |
| End cut | 0 |
| | |
| Results | |
| Area Under backbone Curve= | 500.9359 |
| Stiffness1 | 1602318 |
| Stiffness2 | 1068182 |
| | |
| PeakLoad | 23884.91 |
| PeakDisp | 0.026279 |
| MaxDisp | 0.028274 |
| Moment | 9216.122 |
| | |
| | |
| | |




**Appendix Figure 5: Hysteretic Analysis of C1-1**

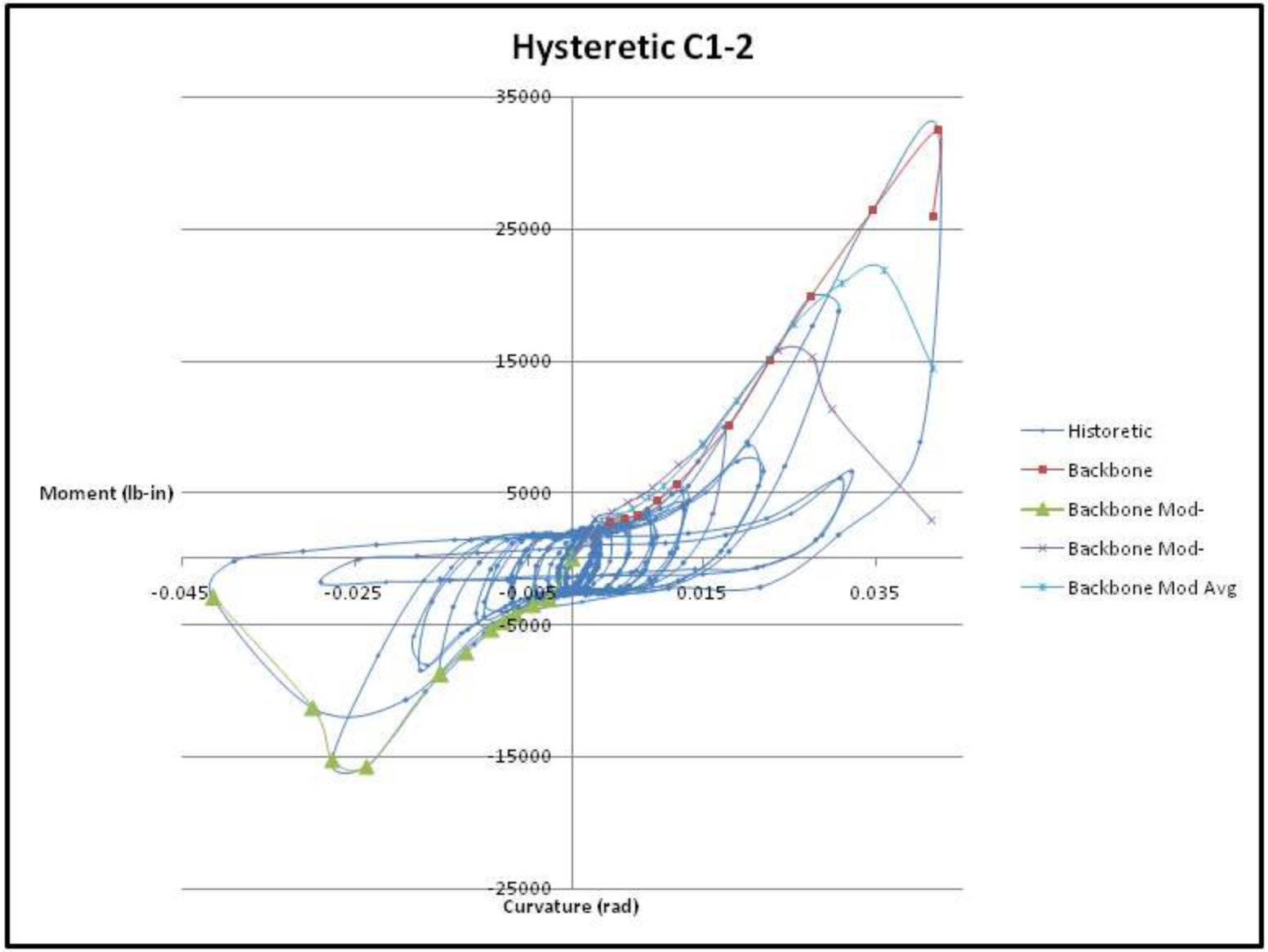
**Appendix Table 16: Backbone Data for C1-1**

| Backbone Mod+ | | Backbone Mod- | | Backbone Mod- | | Backbone Mod avg | | Stiffness |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.00188 | 2488.229 | 0.001063 | 1637.553 | -0.00106 | -1637.55 | 0.001471 | 2062.891 | 1402204 |
| 0.002636 | 3636.634 | 0.001124 | 2456.33 | -0.00112 | -2456.33 | 0.00188 | 3046.482 | 1620620 |
| 0.002043 | 2785.963 | 0.001185 | 3275.106 | -0.00119 | -3275.11 | 0.001614 | 3030.534 | 1877414 |
| 0.003596 | 4636.164 | 0.006477 | 8549.129 | -0.00648 | -8549.13 | 0.005037 | 6592.647 | 1308921 |
| 0.009971 | 12057.75 | 0.01085 | 11621.44 | -0.01085 | -11621.4 | 0.010411 | 11839.6 | 1137250 |
| 0.015162 | 17500.68 | 0.015223 | 14693.75 | -0.01522 | -14693.8 | 0.015192 | 16097.21 | 1059561 |
| 0.024931 | 27043.14 | 0.019586 | 17817.84 | -0.01959 | -17817.8 | 0.022258 | 22430.49 | 1007736 |
| 0.02861 | 26827.89 | 0.023949 | 20941.93 | -0.02395 | -20941.9 | 0.026279 | 23884.91 | 908883.6 |
| 0.030501 | 21634.51 | 0.026047 | 16753.54 | -0.02605 | -16753.5 | 0.028274 | 19194.03 | 678858.7 |

| | |
|---|---|
| Stiffness1 | 1602318 |
| Stiffness2 | 1068182 |
| | |
| PeakLoad | 23884.91 |
| PeakDisp | 0.026279 |
| MaxDisp | 0.028274 |
| Moment | 9216.122 |

**Appendix Table 17: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C1-2**

| Code Inputs for | C1-2 |
|---|---|
| Refinement | 15 |
| Start Cut | 75 |
| End cut | 0 |
| | |
| Results | |
| Area Under backbone Curve= | 593.9998 |
| Stiffness1 | 523331.6 |
| Stiffness2 | 649269.3 |
| | |
| PeakLoad | 20820.17 |
| PeakDisp | 0.031124 |
| MaxDisp | 0.041514 |
| Moment | 8675.601 |
| | |
| | |
| | |




**Appendix Figure 6: Hysteretic Analysis of C1-2**

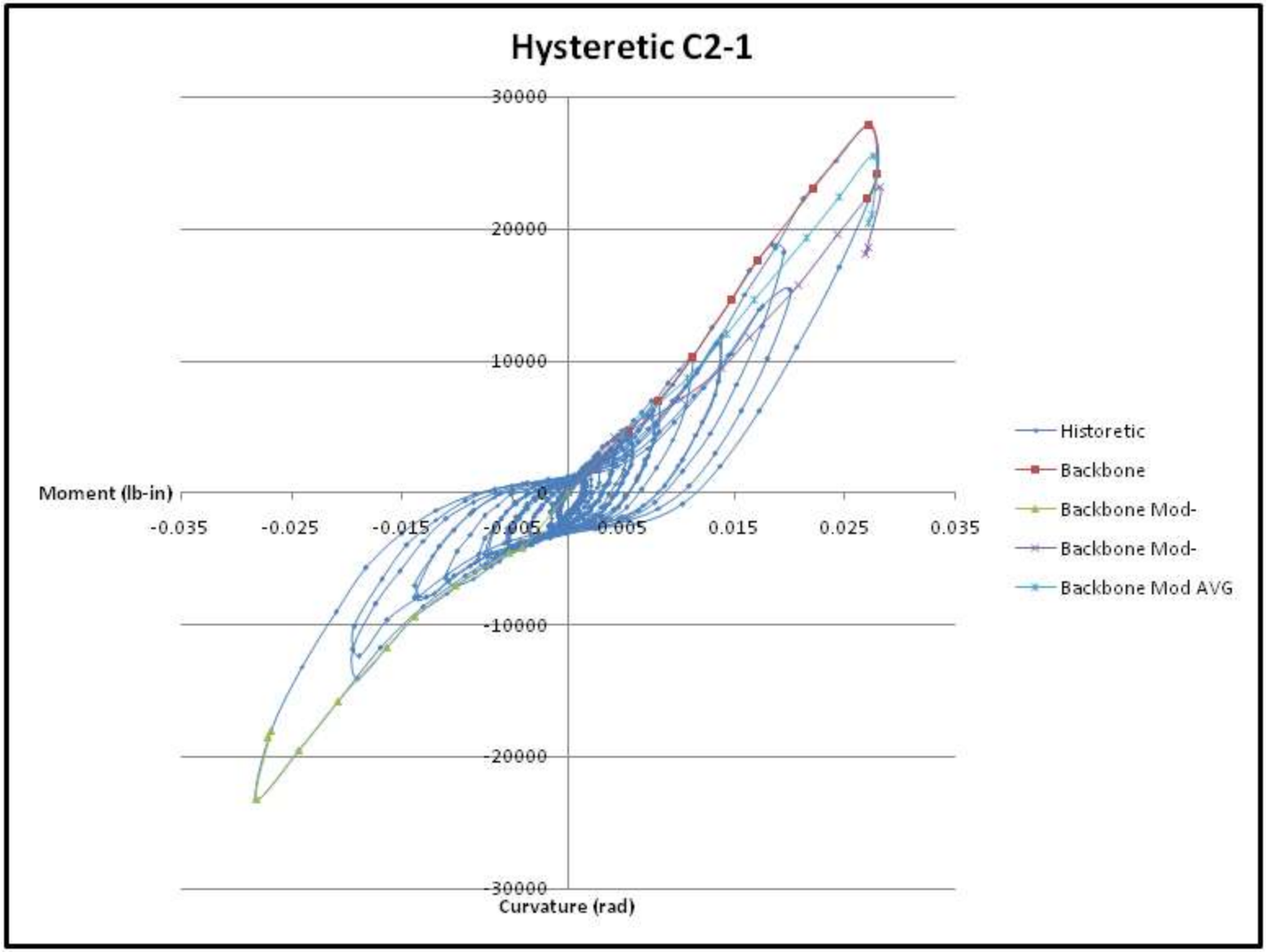
**Appendix Table 18: Backbone Data for C1-2**

| Fitted Backbone Data for C1-2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Backbone Mod | | Backbone Mod- | | Backbone Mod- | | Backbone Mod Avg | | Stiffness |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 0.004291 | 2785.943 | -0.0027 | -3062.43 | 0.002697 | 3062.428 | 0.003494 | 2924.185 | 836914.2 |
| 0.006109 | 2977.316 | -0.00456 | -3487.74 | 0.004556 | 3487.742 | 0.005333 | 3232.529 | 606140.6 |
| 0.007519 | 3275.016 | -0.0065 | -4274.56 | 0.006498 | 4274.564 | 0.007008 | 3774.79 | 538601.7 |
| 0.009849 | 4380.777 | -0.00791 | -4816.96 | 0.007908 | 4816.96 | 0.008878 | 4598.868 | 517997.4 |
| 0.011974 | 5571.538 | -0.00932 | -5359.36 | 0.009317 | 5359.356 | 0.010646 | 5465.447 | 513395.7 |
| 0.018084 | 10121.41 | -0.01223 | -7070.8 | 0.012229 | 7070.797 | 0.015157 | 8596.102 | 567149.2 |
| 0.022866 | 14989.27 | -0.01514 | -8782.24 | 0.015141 | 8782.238 | 0.019004 | 11885.75 | 625442.4 |
| 0.027547 | 19877.04 | -0.02372 | -15733.1 | 0.023725 | 15733.1 | 0.025636 | 17805.07 | 694540.5 |
| 0.034538 | 26355.27 | -0.02771 | -15285.1 | 0.02771 | 15285.06 | 0.031124 | 20820.17 | 668935.5 |
| 0.042145 | 32445.78 | -0.02984 | -11330.2 | 0.029836 | 11330.23 | 0.035991 | 21888 | 608158.7 |
| 0.041599 | 25956.62 | -0.04143 | -2932.32 | 0.041429 | 2932.319 | 0.041514 | 14444.47 | 347943.5 |

| | |
|---|---|
| Stiffness1 | 523331.6 |
| Stiffness2 | 649269.3 |
| | |
| PeakLoad | 20820.17 |
| PeakDisp | 0.031124 |
| MaxDisp | 0.041514 |
| Moment | 8675.601 |

**Appendix Table 19: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C2-1**

| Code Inputs for | C2-1 |
|---|---|
| Refinement | 9 |
| Start Cut | 75 |
| End Cut | 0 |
| | |
| Results | |
| Area Under backbone Curve= | 362.931 |
| Stiffness1 | 845420.1 |
| Stiffness2 | 914388.8 |
| | |
| Peak Load | 25521.26 |
| Peak Disp | 0.027608 |
| Max Disp | 0.027067 |
| Moment | 17010.24 |
| | |
| | |
| | |




**Appendix Figure 7: Hysteretic Analysis of C2-1**

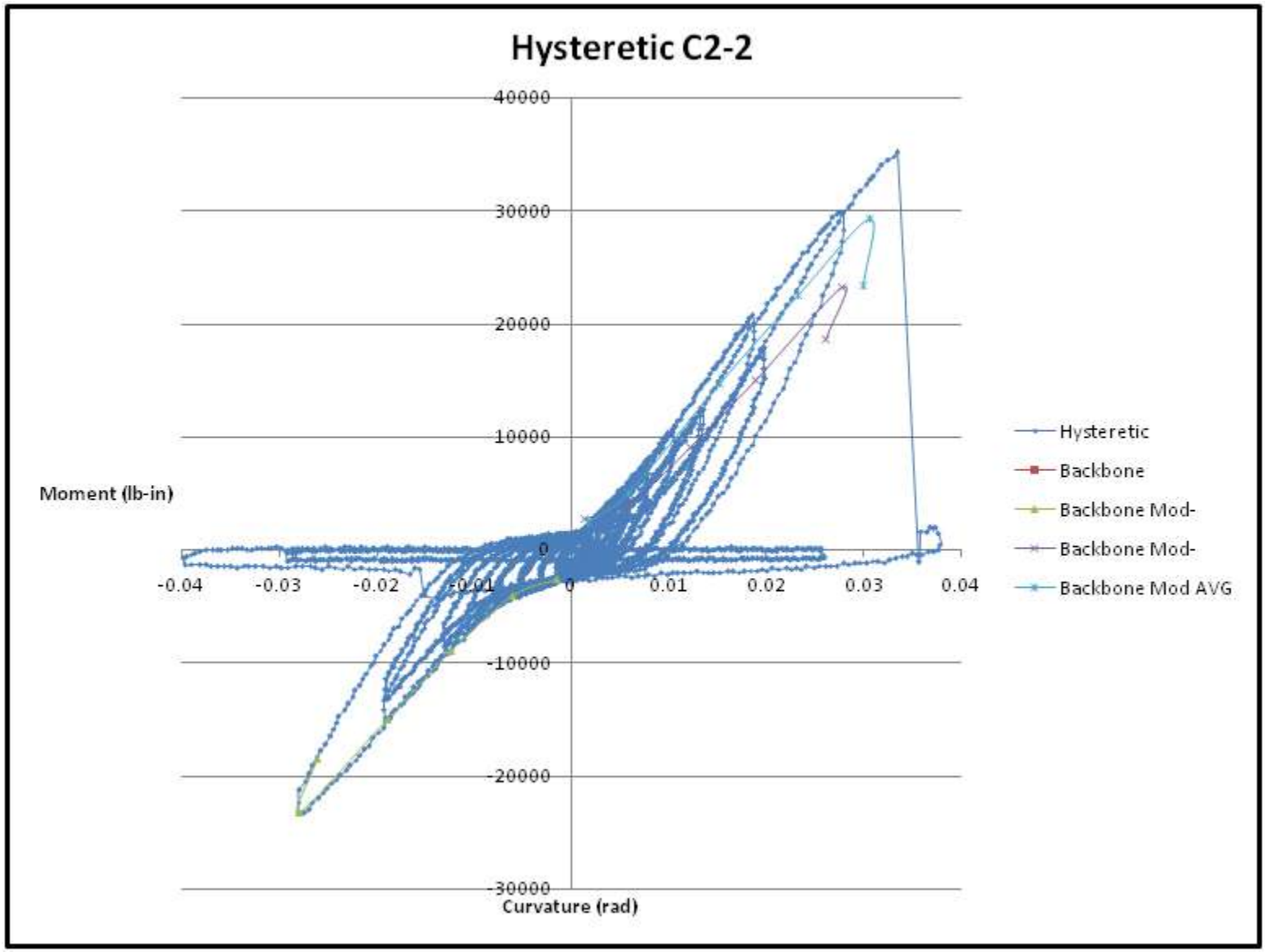
**Appendix Table 20: Backbone Data for C2-1**

| Fitted Backbone Data for C2-1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Backbone Mod | | Backbone Mod- | | Backbone Mod- | | Backbone Mod AVG | | stiffness |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 0.005456 | 4742.47 | -0.00415 | -4168.28 | 0.004148 | 4168.2838 | 0.004802 | 4455.38 | 927870.0251 |
| 0.008173 | 6975.322 | -0.00527 | -4572.33 | 0.005272 | 4572.328 | 0.006722 | 5773.83 | 858888.3436 |
| 0.011238 | 10228.75 | -0.01018 | -7081.52 | 0.010176 | 7081.5235 | 0.010707 | 8655.14 | 808364.675 |
| 0.014753 | 14587.53 | -0.01383 | -9441.62 | 0.013833 | 9441.6167 | 0.014293 | 12014.6 | 840578.3339 |
| 0.017144 | 17563.91 | -0.01639 | -11737.8 | 0.016388 | 11737.773 | 0.016766 | 14650.8 | 873848.8671 |
| 0.022171 | 22962.65 | -0.02082 | -15776.6 | 0.020823 | 15776.647 | 0.021497 | 19369.6 | 901042.6593 |
| 0.024614 | 25406.07 | -0.02434 | -19517.7 | 0.024338 | 19517.666 | 0.024476 | 22461.9 | 917715.5975 |
| 0.027056 | 27849.49 | -0.02816 | -23193 | 0.02816 | 23193.03 | 0.027608 | 25521.3 | 924408.1342 |
| 0.027833 | 24128.62 | -0.02689 | -18049.1 | 0.026893 | 18049.101 | 0.027363 | 21088.9 | 770710.4349 |
| 0.026949 | 22279.59 | -0.02719 | -18554.4 | 0.027186 | 18554.424 | 0.027067 | 20417 | 754301.5806 |

| | |
|---|---|
| Stiffness1 | 845420.0549 |
| Stiffness2 | 914388.797 |
| | |
| Peak Load | 25521.26037 |
| Peak Disp | 0.027608217 |
| Max Disp | 0.027067434 |
| Moment | 17010.2439 |

**Appendix Table 21: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C2-1**

| Code Inputs for | C2-2 |
|---|---|
| Refinement | 1 |
| Start Cut | 75 |
| End cut | 0 |
| | |
| Results | |
| Area Under backbone Curve= | 619.1721 |
| Stiffness1 | 847463 |
| Stiffness2 | 959041.4 |
| | |
| Peak Load | 29195.79 |
| Peak Disp | 0.030664 |
| Max Disp | 0.030026 |
| Moment | 9866.789 |
| | |
| | |
| | |




**Appendix Figure 8: Hysteretic Analysis of C2-2**

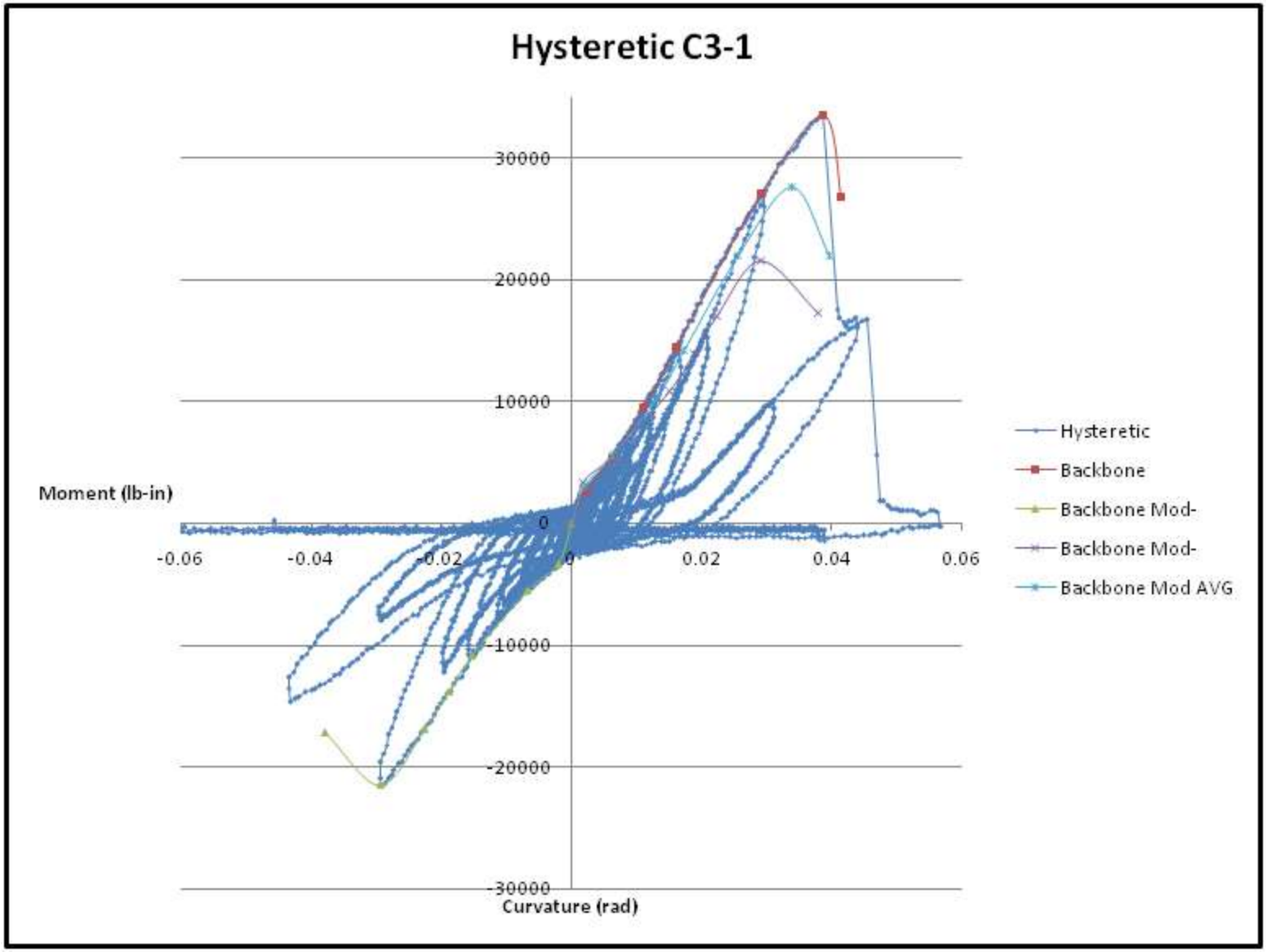
**Appendix Table 22: Backbone Data for C2-2**

| Fitted Backbone Data for C2-2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Backbone Mod | | Backbone Mod- | | Backbone Mod- | | Backbone Mod AVG | | Stiffness |
| 0.001982 | 2254.29 | -0.00139 | -2658.36 | 0.001389 | 2658.365 | 0.001686 | 2456.327 | 1457150 |
| 0.005762 | 5827.044 | -0.00601 | -4146.98 | 0.006007 | 4146.978 | 0.005885 | 4987.011 | 847463 |
| 0.018288 | 20455.37 | -0.01232 | -9037.76 | 0.012321 | 9037.762 | 0.015305 | 14746.57 | 963524.9 |
| 0.02771 | 29804.8 | -0.0189 | -15011.8 | 0.018901 | 15011.78 | 0.023306 | 22408.29 | 961485.8 |
| 0.033434 | 35177.11 | -0.02789 | -23214.5 | 0.027894 | 23214.46 | 0.030664 | 29195.79 | 952113.4 |
| 0.033957 | 28141.69 | -0.0261 | -18571.6 | 0.026095 | 18571.57 | 0.030026 | 23356.63 | 777885.4 |

| | |
|---|---|
| Stiffness1 | 847463 |
| Stiffness2 | 959041.4 |
| | |
| PeakLoad | 29195.79 |
| PeakDisp | 0.030664 |
| MaxDisp | 0.030026 |
| Moment | 9866.789 |

**Appendix Table 23: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C3-1**

| Code Inputs for | C3-1 |
|---|---|
| Refinement | 1 |
| Start Cut | 75 |
| End cut | 0 |
| | |
| Results | |
| Area Under backbone Curve= | 752.7446 |
| Stiffness1 | 809828.2 |
| Stiffness2 | 823874.5 |
| | |
| Peak Load | 27512.95 |
| Peak Disp | 0.033915 |
| Max Disp | 0.039604 |
| Moment | 12141.81 |
| | |
| | |
| | |




**Appendix Figure 9: Hysteretic Analysis of C3-1**

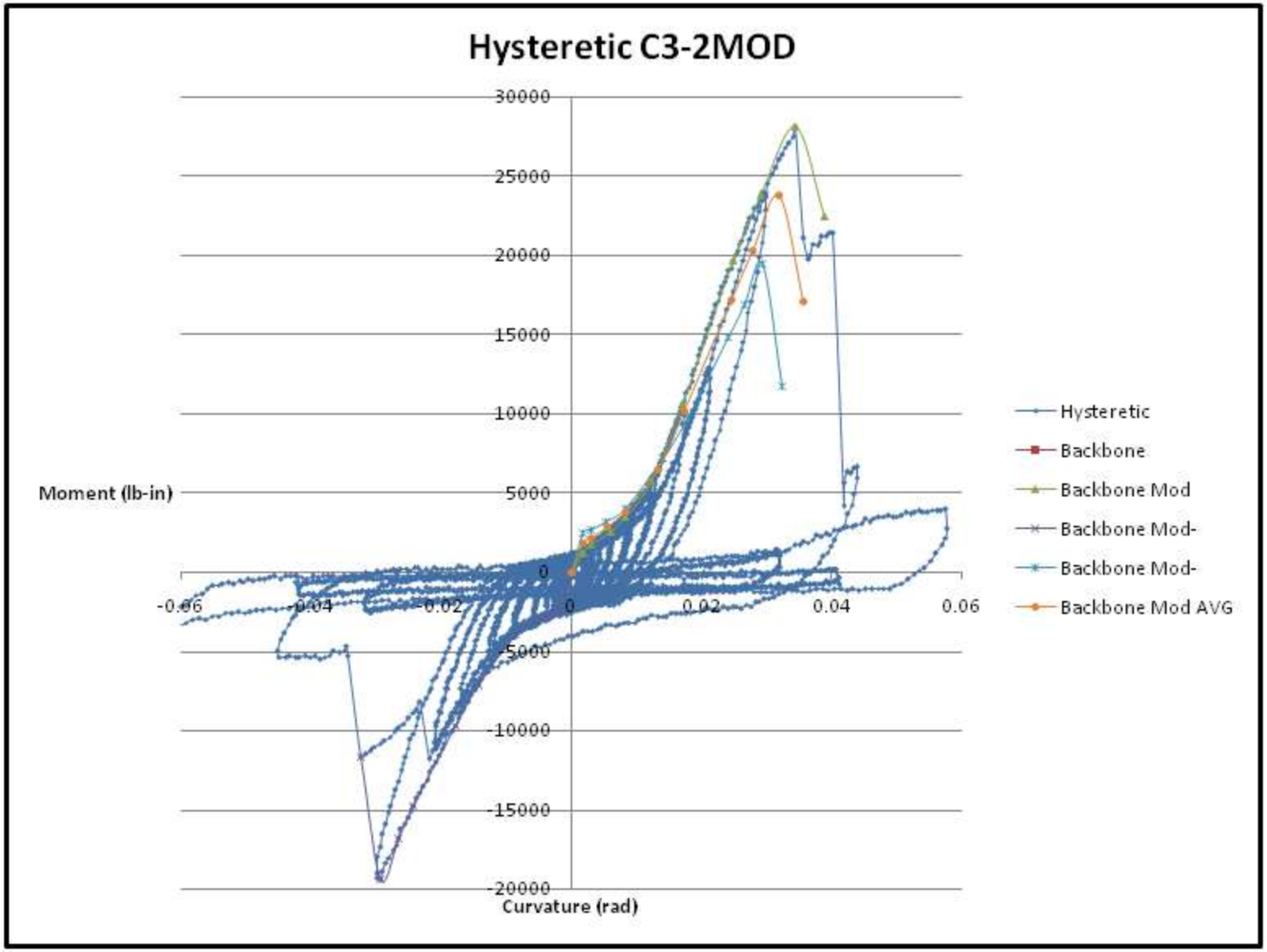
**Appendix Table 24: Backbone Data for C3-1**

| Fitted Backbone Data for C3-1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Backbone Mod | | Backbone Mod- | | Backbone Mod- | | Backbone Mod AVG | | stiffness |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 0.002411 | 2700.893 | -0.00194 | -3338.9 | 0.001941 | 3338.903 | 0.002176 | 3019.898 | 1387763 |
| 0.006334 | 5380.427 | -0.00658 | -5529.28 | 0.006579 | 5529.284 | 0.006457 | 5454.856 | 844822.1 |
| 0.010993 | 9420.684 | -0.01516 | -10844.9 | 0.015162 | 10844.89 | 0.013077 | 10132.79 | 774834.2 |
| 0.016183 | 14417.1 | -0.01879 | -13884.6 | 0.018789 | 13884.56 | 0.017486 | 14150.83 | 809251.3 |
| 0.029162 | 26976.27 | -0.02242 | -16924.2 | 0.022417 | 16924.23 | 0.025789 | 21950.25 | 851141.7 |
| 0.038648 | 33491.66 | -0.02918 | -21534.2 | 0.029182 | 21534.23 | 0.033915 | 27512.95 | 811230.4 |
| 0.041364 | 26793.33 | -0.03784 | -17227.4 | 0.037844 | 17227.39 | 0.039604 | 22010.36 | 555760.4 |

| | |
|---|---|
| stiffness1 | 809828.2 |
| stiffness2 | 823874.5 |
| | |
| Peak Load | 27512.95 |
| Peak Disp | 0.033915 |
| Max Disp | 0.039604 |
| Moment | 12141.81 |

**Appendix Table 25: Matlab Inputs to Refine Data and Results from Hysteresis for Specimen C3-2MOD**

| Code Inputs for | C3-2MOD |
|---|---|
| Refinement | 1 |
| Start Cut | 75 |
| End cut | 0 |
| | |
| Results | |
| Area Under backbone Curve= | 532.484 |
| Stiffness1 | 503896.2 |
| Stiffness2 | 724480.2 |
| | |
| Peak Load | 23763.89 |
| Peak Disp | 0.031911 |
| Max Disp | 0.035623 |
| Moment | 13671.25 |
| | |
| | |
| | |




**Appendix Figure 10: Hysteretic Analysis of C3-2MOD**

**Appendix Table 26: Backbone Data for C3-2MOD**

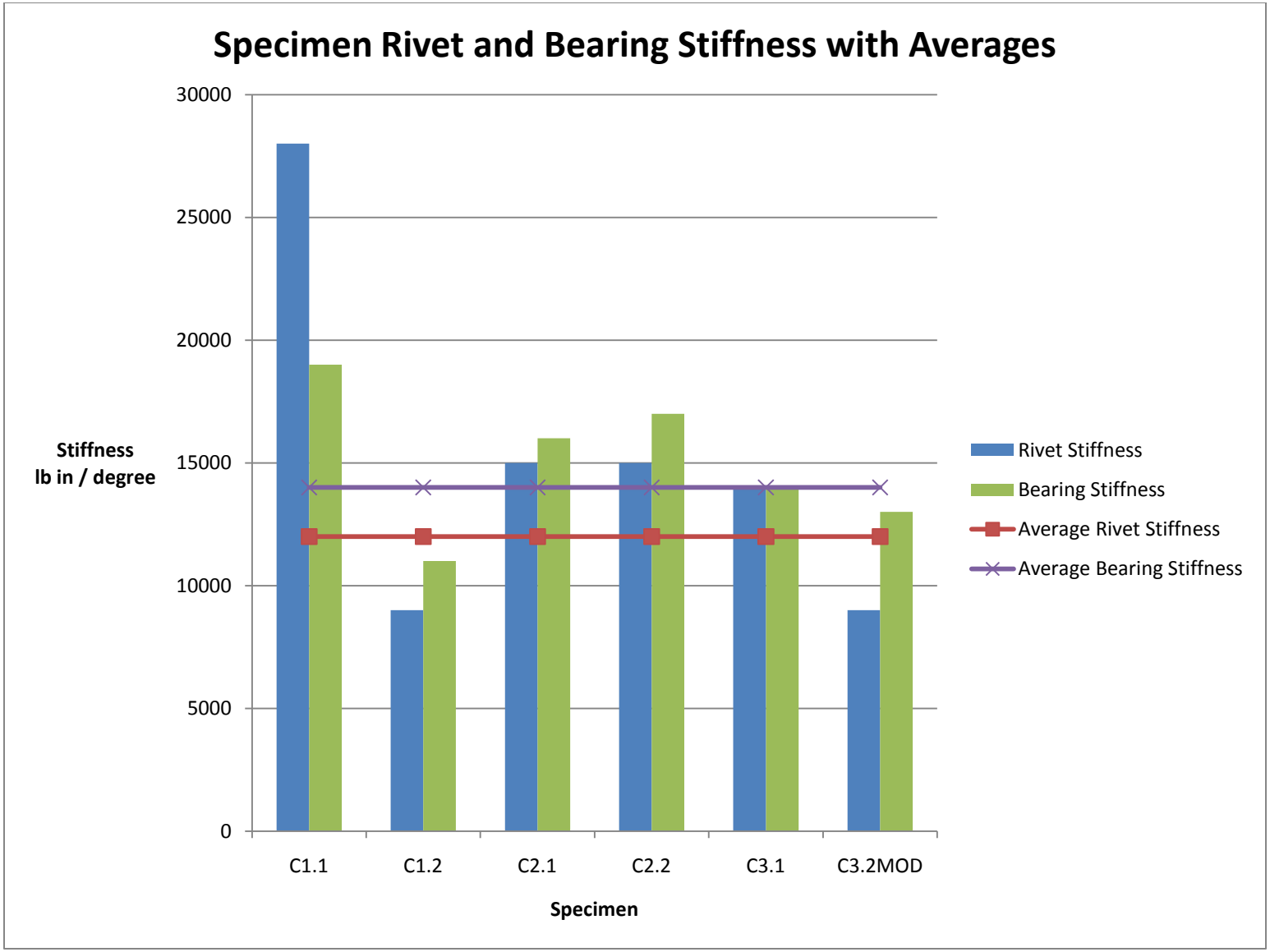
| Fitted Backbone Data for C3-2MOD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Backbone Mod | | Backbone Mod- | | Backbone Mod- | | Backbone Mod AVG | | Stiffness |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 0.001819 | 1233.48 | -0.00176 | -2424.43 | 0.001757 | 2424.427 | 0.001788 | 1828.954 | 1022989 |
| 0.003004 | 1680.08 | -0.00317 | -2637.09 | 0.003167 | 2637.087 | 0.003085 | 2158.584 | 699627.7 |
| 0.005986 | 2530.726 | -0.00537 | -3168.73 | 0.005374 | 3168.728 | 0.00568 | 2849.727 | 501711.6 |
| 0.008255 | 3508.925 | -0.00834 | -3934.25 | 0.008337 | 3934.247 | 0.008296 | 3721.586 | 448610.9 |
| 0.012342 | 5762.901 | -0.01422 | -7144.97 | 0.014222 | 7144.968 | 0.013282 | 6453.935 | 485927.2 |
| 0.017124 | 10546.85 | -0.01782 | -9696.18 | 0.017818 | 9696.184 | 0.017471 | 10121.52 | 579335.2 |
| 0.024992 | 19687.03 | -0.02417 | -14754.9 | 0.024174 | 14754.94 | 0.024583 | 17220.99 | 700521.5 |
| 0.029121 | 23723.84 | -0.02661 | -16858.7 | 0.026607 | 16858.71 | 0.027864 | 20291.28 | 728232.9 |
| 0.034497 | 28098.16 | -0.02933 | -19429.6 | 0.029325 | 19429.62 | 0.031911 | 23763.89 | 744686.1 |
| 0.038874 | 22478.53 | -0.03237 | -11669.4 | 0.032371 | 11669.43 | 0.035623 | 17073.98 | 479300 |

| | |
|---|---|
| Stiffness1 | 503896.2 |
| Stiffness2 | 724480.2 |
| | |
| Peak Load | 23763.89 |
| Peak Disp | 0.031911 |
| Max Disp | 0.035623 |
| Moment | 13671.25 |

**Appendix Table 27: Cyclic Test Results and Comparison to VA Model**

| Results From Cyclic Test data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Stiffness lb in/rad | | Stiffness lb in/degree | | Transfer moment | Peak Moment | Peak Rotation | Max Rotation |
| | 1 | 2 | 1 | 2 | | | | |
| C1.1 | 1602000 | 1068000 | 28000 | 19000 | 9200 | 23900 | 0.0263 | 0.0283 |
| C1.2 | 523000 | 649000 | 9000 | 11000 | 8700 | 20800 | 0.0311 | 0.0415 |
| C2.1 | 845000 | 914000 | 15000 | 16000 | 17000 | 25500 | 0.0276 | 0.0271 |
| C2.2 | 847000 | 959000 | 15000 | 17000 | 9900 | 29200 | 0.0307 | 0.0300 |
| C3.1 | 810000 | 824000 | 14000 | 14000 | 12100 | 27500 | 0.0339 | 0.0396 |
| C3.2MOD | 504000 | 724000 | 9000 | 13000 | 13700 | 23800 | 0.0319 | 0.0356 |
| | | | | | | | | |
| SD | 176000 | 129000 | 3000 | 2000 | 3300 | 3000 | 0.0028 | 0.0061 |
| AVG | 706000 | 814000 | 12000 | 14000 | 13300 | 25400 | 0.0310 | 0.0348 |
| CV | 25.0% | 15.8% | 25.0% | 15.8% | 24.8% | 11.7% | 9.1% | 17.6% |
| | | | | Outlier :Did not include in SD AVG CV | | | | |

| Error Analysis | | | | | |
|---|---|---|---|---|---|
| Selected for VA model | 9000 | 12000 | 10000 | 28400 | 0.0287 |
| Output from VA | | | | 35000 | 0.025726153 |
| % error | | | | 10.4% | 14.9% |




**Appendix Figure 11: Stiffness Relationships between Specimens**

**Appendix Table 28: VA Calculations to find Rotation and Comparison to WMEL Report**

VA_Data

Using VA to solve for the curvature expansion of the moment connection

Data for Joint in Beam

| Node Result | Case Name | DX(in) | DY (in) | RZ |
|---|---|---|---|---|
| N001 | D | 0 | 0 | -3.738 |
| N002 | D | 6 | 0.002 | -3.267 |
| N003 | D | 5.9955 | -0.0025 | -3.262 |
| N004 | D | 0 | 0 | -3.736 |

Data for Joint in Column

| Node Result | Case Name | DX(in) | DY (in) | RZ |
|---|---|---|---|---|
| N001 | D | 0 | 0 | -4.471 |
| N002 | D | 6 | 0.0123 | -1.802 |
| N003 | D | 5.9748 | -0.0128 | -1.779 |
| N004 | D | 0 | 0 | -4.459 |

Joint Deflection

| Node | Degree | Rad |
|---|---|---|
| 1 | 0.733 | 0.012793263 |
| 2 | -1.465 | -0.025569074 |
| 3 | -1.483 | -0.025883233 |
| 4 | 0.723 | 0.01261873 |
| average | | **-0.025726153** |

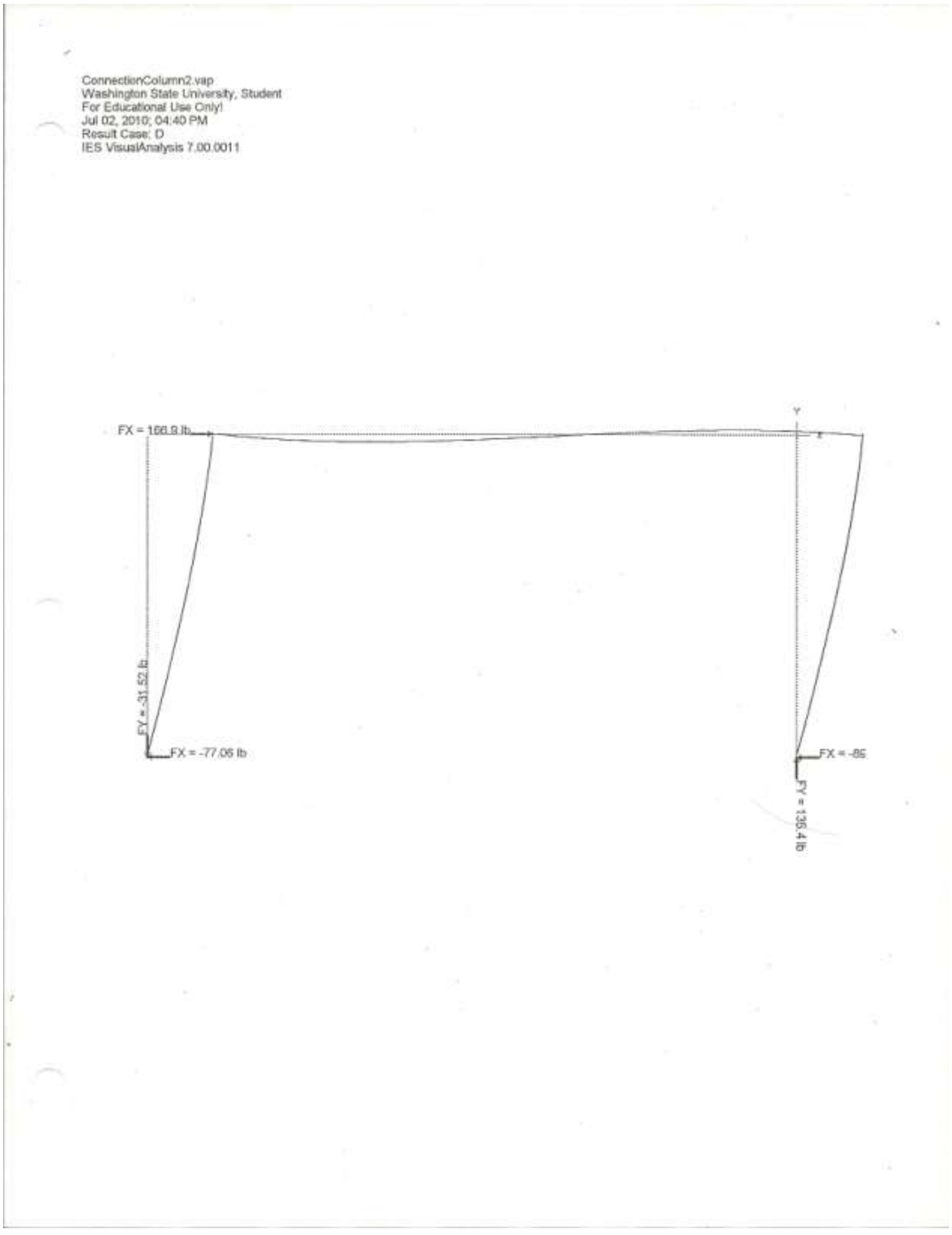
Member Forces for the Columns

| Beam | Fx | Vv | Mc |
|---|---|---|---|
| COL001 | 316.631 | 367.129 | 0 |
| COL001 | 342.597 | 367.129 | 35244.345 |
| COL002 | -420.496 | 369.999 | 0 |
| COL002 | -394.53 | 369.999 | 35519.886 |
| average | 368.5635 | 368.564 | 35382.1155 |

The load P that took to push the frame to 1 in set above was 700 lb

Comparison to WMEL Portal frame 6_1

| specimen | Displacement | Load (lb) Displacement=.48 | Displacement=Ult |
|---|---|---|---|
| 6_1 | 333 | 600 | 1665 |
| VA Model | 166.9 | 333.9 | 695.6 |
| Multiple | 1.995206711 | 1.796945193 | 2.393617021 |
| | Average | 2.061922975 | |




**Appendix Figure 12: VA Print out #1**

## ConnectionColumn2.vap

Company: Washington State University  Engineer: Student  Billing: For Educational Use Only!
VisualAnalysis 7.00 Report

## ɔdal Displacements

| Node | Result Case Name | DX in | DY in | RZ deg |
|---|---|---|---|---|
| N001 | D | **0.0000** | 0.0000 | -0.176 |
| N002 | D | **0.2400** | **0.0003** | -0.077 |
| N003 | D | 0.2389 | **-0.0007** | **-0.066** |
| N004 | D | 0.0000 | -0.0000 | **-0.181** |

## Member Extreme Results

| Member | Fx (lc) lb | Vy (lc) lb | Mz (lc) lb-in |
|---|---|---|---|
| BmX001 | -89.855 ( 1) | **-109.424 ( 1)** | **-8626.035 ( 1)** |
| BmX001 | -89.855 ( 1) | -57.491 ( 1) | 7397.778 ( 1) |
| COL001 | 31.525 ( 1) | 77.06 ( 1) | 0.000 ( 1) |
| COL001 | **2628.160 ( 1)** | 77.06 ( 1) | 7397.778 ( 1) |
| COL002 | **-135.390 ( 1)** | **89.855 ( 1)** | 0.000 ( 1) |
| COL002 | 2461.245 ( 1) | 89.855 ( 1) | **8626.035 ( 1)** |

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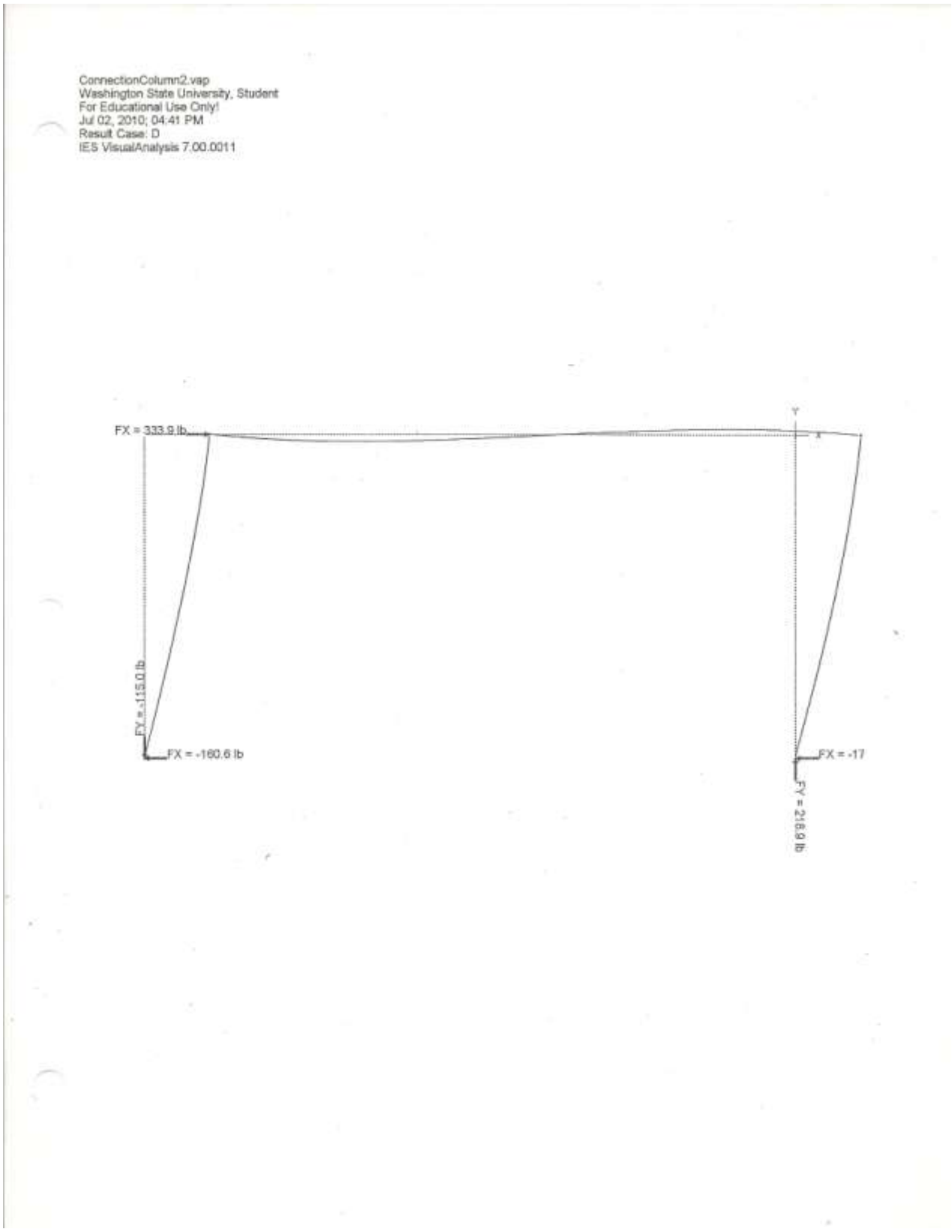
**Appendix Figure 13: VA Print out #2**




**Appendix Figure 14: VA Print out #3**

## ConnectionColumn2.vap

Company: Washington State University  Engineer: Student  Billing: For Educational Use Only!
VisualAnalysis 7.00 Report

### ɔdal Displacements

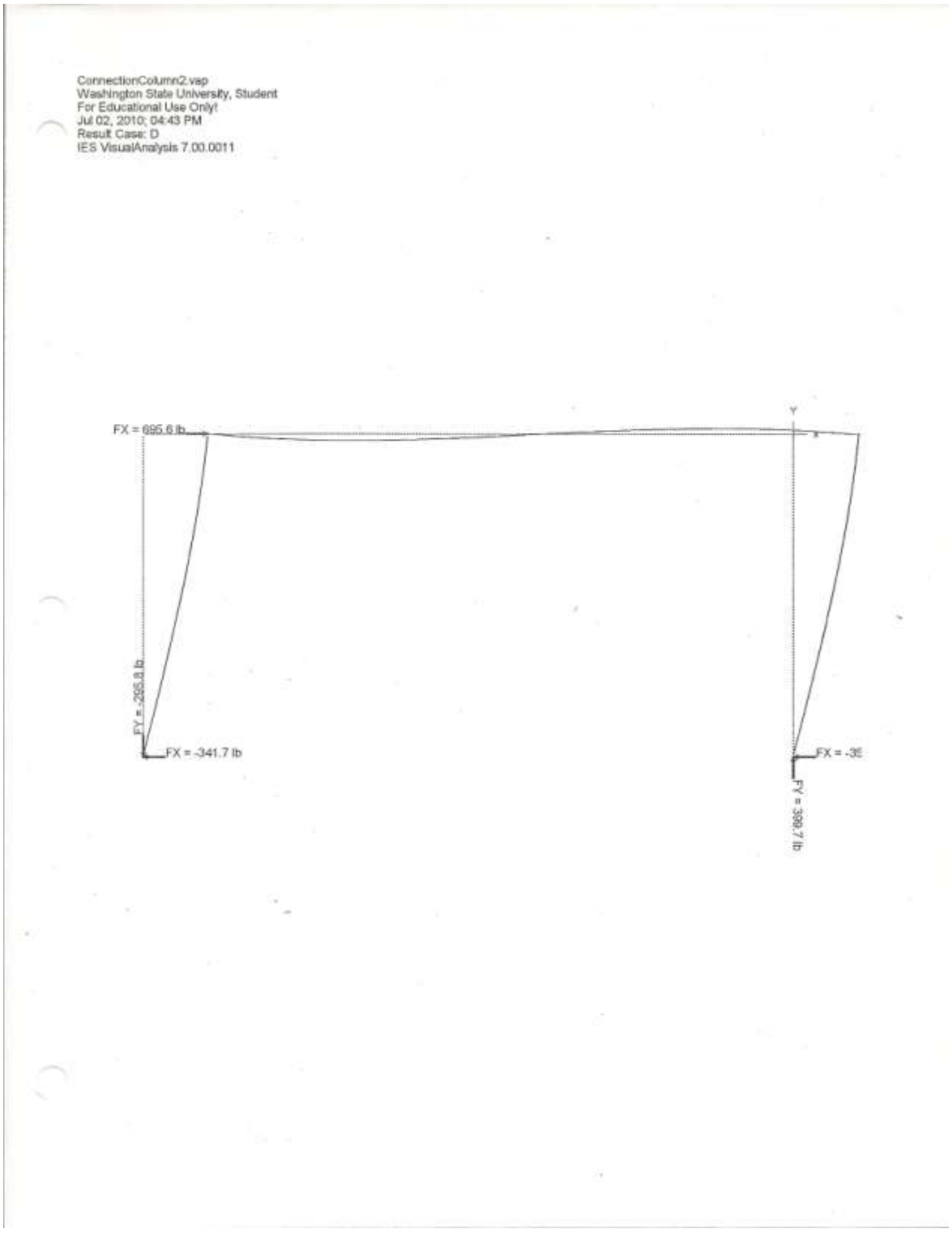
| Node | Result Case Name | DX in | DY in | RZ deg |
|---|---|---|---|---|
| N001 | D | **0.0000** | 0.0000 | -0.355 |
| N002 | D | **0.4800** | **0.0008** | -0.149 |
| N003 | D | 0.4779 | **-0.0012** | **-0.137** |
| N004 | D | 0.0000 | -0.0000 | **-0.359** |

### Member Extreme Results

| Member | Fx (lc) lb | Vy (lc) lb | Mz (lc) lb-in |
|---|---|---|---|
| BmX001 | -173.238 ( 1) | **-192.895 ( 1)** | **-16630.832 ( 1)** |
| BmX001 | -173.238 ( 1) | -140.962 ( 1) | 15419.399 ( 1) |
| COL001 | 114.996 ( 1) | 160.619 ( 1) | 0.000 ( 1) |
| COL001 | **2711.631 ( 1)** | 160.619 ( 1) | 15419.399 ( 1) |
| COL002 | **-218.861 ( 1)** | **173.238 ( 1)** | -0.00 ( 1) |
| COL002 | 2377.774 ( 1) | 173.238 ( 1) | **16630.832 ( 1)** |



**Appendix Figure 15: VA Print out #4**




**Appendix Figure 16: VA Print out #5**

## ConnectionColumn2.vap

Company: Washington State University  Engineer: Student  Billing: For Educational Use Only!
VisualAnalysis 7.00 Report

### Nodal Displacements

| Node | Result Case Name | DX in | DY in | RZ deg |
|---|---|---|---|---|
| N001 | D | **0.0000** | 0.0000 | -0.743 |
| N002 | D | **1.0000** | **0.0019** | -0.305 |
| N003 | D | 0.9957 | **-0.0023** | **-0.292** |
| N004 | D | 0.0000 | -0.0000 | **-0.745** |

### Member Extreme Results

| Member | Fx (lc) lb | Vy (lc) lb | Mz (lc) lb-in |
|---|---|---|---|
| BmX001 | -353.902 ( 1) | **-373.748 ( 1)** | **-33974.561 ( 1)** |
| BmX001 | -353.902 ( 1) | -321.816 ( 1) | 32799.577 ( 1) |
| COL001 | 295.849 ( 1) | 341.662 ( 1) | -0.00 ( 1) |
| COL001 | **2892.484 ( 1)** | 341.662 ( 1) | 32799.577 ( 1) |
| COL002 | **-399.715 ( 1)** | **353.902 ( 1)** | -0.00 ( 1) |
| COL002 | 2196.920 ( 1) | 353.902 ( 1) | **33974.561 ( 1)** |



**Appendix Figure 17: VA Print out #6**

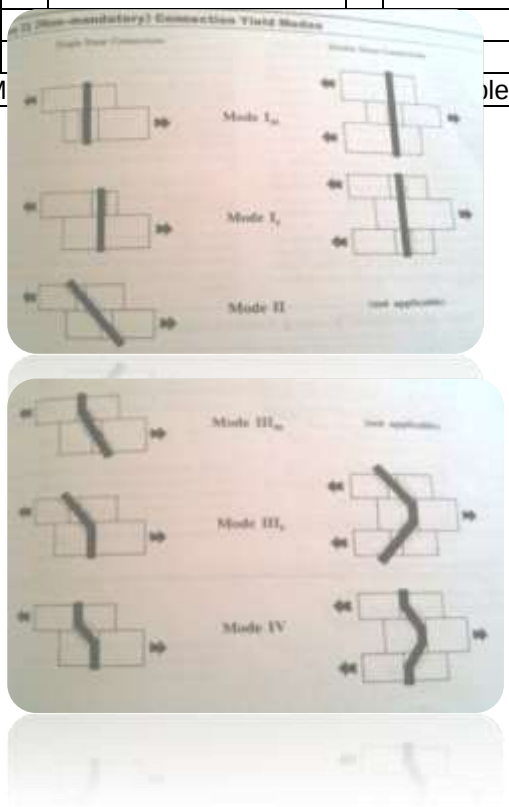
**Appendix Table 29: Specific Gravity Check**

| Specific Gravity of OSB Gusset Plate | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| length (in) | width (in) | thickness (in) | weight (g) | Volume (in^3) | Volume (cm^3) | Volume water cm^3 | Weight water (g) | Weight Oven Dry (g) | Density g/cm^3 | SG |
| 2.988 | 2.9835 | 1.036 | 94.86 | 9.24 | 151.34 | 22.7 | 22.7 | 72.2 | 0.48 | 0.48 |
| 2.987 | 2.979 | 1.036 | 96.28 | 9.22 | 151.07 | 22.7 | 22.7 | 73.6 | 0.49 | 0.49 |
| 2.9685 | 2.977 | 1.038 | 94.31 | 9.17 | 150.32 | 22.5 | 22.5 | 71.8 | 0.48 | 0.48 |
| 2.9795 | 2.979 | 1.038 | 97.22 | 9.21 | 150.98 | 22.6 | 22.6 | 74.6 | 0.49 | 0.49 |
| 2.953 | 2.969 | 1.03 | 93.09 | 9.03 | 147.98 | 22.2 | 22.2 | 70.9 | 0.48 | 0.48 |
| 2.972 | 2.963 | 1.0295 | 93.59 | 9.07 | 148.56 | 22.3 | 22.3 | 71.3 | 0.48 | 0.48 |
| | | | | | | | | | Average | .48 |

Note: Specific Gravity is based on oven dried specimens so in this calculation the water content was known to be 15% so the weight of the water was just subtracted from the total weight.

## Appendix Table 30: Future Design Yield Mode Calculations for Hollow Fasteners

| Capacity of CherryMate Rivets for iJoist with 1in Gusset Plates | | | | |
|---|---|---|---|---|
| | | | | |
| D | 0.24999 | 1/4 | in | (see 11.3.6 Reduction term Table 11.3.1B) |
| theta | 45 | degrees | (maximum angle to grain 0-90 Table 11.3.1B) | |
| Kth | 1.125 | | | |
| lm | 0.44 | | main member dowel bearing length in | |
| ls | 1 | | side member dowel bearing length in | |
| Gm | 0.61 | | specific gravity of main member table 11.3.2A P74 | |
| Gs | 0.5 | | specific gravity of side member table 11.3.2A P74 | |
| Fyb | 18500 | | NDS p160 psi | For nails |
| MMO | 0 | | Is the main member stress orientation; =0 for perpendicular; =1 for parallel; =Degree orientation if neither | |
| | | | | |
| SMO | 0 | | Is the side member stress orientation; =0 for perpendicular; =1 for parallel; =Degree orientation if neither | |
| | | | | |
| | | | | |
| Rd1 | 2.9999 | | | |
| Rd2 | 2.9999 | | | |
| Rd34 | 2.9999 | | | |
| | | | | |
| Fem | 6685.209 | | Main M | ble 11.3.2 |
| Fes | 4636.742 | | | |
| | | | | |
| Re | 1.44179 | | | |
| Rt | 0.4375 | | | |
| k1 | 0.365235 | | | |
| k2 | 1.687543 | | | |
| k3 | 0.958296 | | | |
| | | | | |
| ZImDS | 243.73 | lb | | |
| ZIsDS | 772.7851 | lb | | |
| ZIIIsDS | 310.2244 | lb | | |
| ZIVDS | 242.1096 | lb | | |
| ZImSS | 243.73 | lb | | |
| ZIsSS | 386.3926 | lb | | |
| ZIISS | 141.124 | lb | | |
| ZIIImSS | 105.9086 | lb | | |
| ZIIIsSS | 155.1122 | lb | | |
| ZIVSS | 121.0548 | lb | | |
| | | | | |
| Min DS | 242.1096 | | | |
| Min SS | 105.9086 | | | |
| | | | | |



**Appendix Table 31: Future Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis**

| Web Bearing Strength 1 row | | | |
|---|---|---|---|
| G | 0.5 | | |
| D | 0.25 | in | see P73 NDS |
| t | 0.375 | | |
| R connection | 3.875 | | |
| | | lb | |
| Max Moment | 12500 | in | |
| Fe | 4650 | psi | |
| Abearing | 0.09375 | | |
| Dowel Capacity | 435.9375 | lb | |
| Dowel Moment | 1689.258 | | |
| # Dowels | 8 | | |
| | | | |
| min spacing | 1.7391 | OK | |
| | | | |
| Fastener Capacity | | | |
| Dowel Capacity | 242.1096 | lb | |
| Dowel Moment | 938.1748 | | |
| # Dowels | 14 | | |

| Web Bearing Strength 2 row | | | |
|---|---|---|---|
| G | 0.5 | | |
| D | 0.25 | in | see P73 NDS |
| t | 0.375 | | |
| R1 connection | 3.875 | | |
| R2 Connection | 3.375 | | |
| | | lb | |
| Max Moment | 12500 | in | |
| Fe | 4650 | psi | |
| Abearing | 0.09375 | | |
| Dowel Capacity | 435.9375 | | |
| Dowel Moment2 | 1471.289 | | |
| Dowel Moment1 | 1689.258 | | |
| # Dowels Per Row | 4 | | |
| # Dowels total | 8 | | |
| | | | |
| min spacing 1 | 3.0434 | OK | |
| min spacing 2 | 2.6507 | OK | |
| | | | |
| Fastener Capacity | | | |
| Dowel Capacity | 242.1096 | | |
| Dowel Moment1 | 938.1748 | | |
| Dowel Moment 2 | 817.12 | | |
| # Dowels Per Row | 8 | | |
| # Dowels total | 16 | | |

**Appendix Table 32: Future Design Calculations for Bearing Strength and Capacity for Yield Mode Analysis Cont.**

| Web Bearing Strength 3 row | | | |
|---|---|---|---|
| | | | |
| G | 0.5 | | |
| D | 0.25 | in | see P73 NDS |
| t | 0.375 | | |
| R1 Connection | 3.875 | | |
| R2 Connection | 3.375 | | |
| R3 Connection | 2.875 | | |
| | | lb | |
| Max Moment | 12500 | in | |
| Fe | 4650 | psi | |
| Abearing | 0.09375 | | |
| Dowel Capacity | 435.9375 | | |
| Dowel Moment1 | 1689.258 | | |
| Dowel Moment2 | 1471.289 | | |
| Dowel Moment3 | 1253.32 | | |
| # Dowels Per Row | 3 | | |
| # Dowels total | 9 | | |
| | | | |
| min spacing 1 | 4.0579 | OK | |
| min spacing 2 | 3.5343 | OK | |
| min spacing 3 | 3.0107 | OK | |
| | | | |
| Fastener Capacity | | | |
| Dowel Capacity | 242.1096 | | |
| Dowel Moment1 | 938.1748 | | |
| Dowel Moment 2 | 817.12 | | |
| Dowel Moment 3 | 696.0651 | | |
| # Dowels Per Row | 6 | | |
| # Dowels total | 18 | | |