

Effects of Linear Notches and Copes on Timber Beams
Project ID: CEEEn_CPST_009

by

3d Engineers
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A Capstone Project Final Report

Submitted to

Dr. Johnn Judd

Department of Civil and Construction Engineering
Brigham Young University

April 10, 2023

Executive Summary

PROJECT TITLE: Effects of Linear Notches and Copes on Timber
PROJECT ID: CEEEn_CPST_009
PROJECT SPONSOR: Brigham Young University
TEAM NAME: 3d Engineers

The purpose of this report is to provide an introductory analysis of the effects of angular tapered notches and copes (circular notches) on Timber beams. While extensive research and analysis has been performed on rectangular notches cut at a 90 degree angle, little research has been done regarding these other notch types. While this is not meant to be an all inclusive analysis of the subject, it is a good starting point in the analysis of these notches.

In order to accomplish this we needed to obtain wood specimens, notch/cope them and then to test them in a lab. After completing the test we compiled the data and analyzed the data with hopes to find any notable patterns in the beams.

The project began in September of 2022 and was set to be completed in April of 2023. The results of this analysis will play an important role in determining whether or not more testing shall be pursued on the topic. The intended deliverable will be an analysis of general trends and data found in the test specimen.

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Introduction

A very important element of timber design includes the notching of beams. Extensive research has been done, and design equations made in order to account for the effects that a rectangular notch will have on a beam. However, there are other types of notches on a beam that are not so well known. The purpose of this project is to evaluate the effects of linear tapered notches and copes on the capacity of a Timber beam.

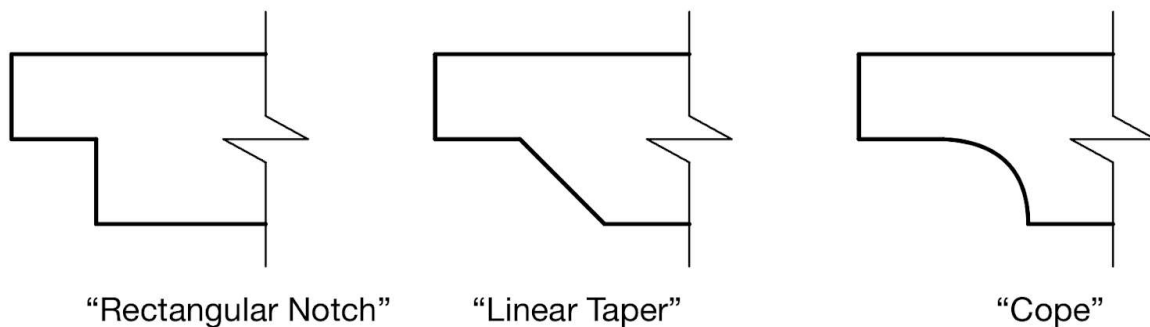


Figure 1 - Notch Type Comparison

Several tasks were required to be done in order to provide this analysis. Firstly it was important to look into other research that has been done on the subject matter. Several sources were reviewed prior to beginning analysis on the project. After reviewing previous literature on the subject, a preliminary analysis was to be performed. This assisted us in deciding which notch/copos to test, and what loads to expect in our testing. Once we had obtained anticipated loads from our preliminary analysis we moved on to design the testing apparatus. These three tasks were completed prior to January of 2023.

After these tasks were completed the wood specimens were obtained, cut, and tested. Data from the tests was compiled and analyzed, leading to several notable conclusions.

There were several key limitations that played an important role in the testing. Firstly was the budget. Because this is a Capstone project a smaller budget was used than what would have been used for a full fledged research project. Because of this the quantity of possible tests to be performed was relatively small. We also used wood that was donated. This resulted in more variability between specimens than would normally be used (for example, some specimens were DF #1 grade, and some were DF SEL. Additionally some had numerous cracks while others did not).

Another key limitation was the testing machine to be used. A Baldwin Universal testing Machine was used for the testing. We performed 16 tests in the specimens (with 4 different notch types). While the Baldwin was more than capable of handling the loads needed in order to perform testing on these specimens, and we did get the most important information needed for the analysis, other issues with the machine prevented any further testing that was intended to be done on the specimens.

Several assumptions and important conditions were to be met in this testing. In order to maximize testing, each timber beam was notched and tested on each side. It was assumed that the testing from one side would not propagate cracks or cause damage to the other side of the beam. For the most part this proved to be true. Another important condition was that each end was analyzed with a simple pinned connection. Other connection types are not included within the scope of this project and may need further research in order to obtain accurate estimations of strength.

While some inferences regarding the effects of linear tapers and copes on beams can be made, this project was not meant to be a full fledged analysis of the effects. Rather it was meant to be a starting point for future research and to provide some general patterns and inferences to work from. This project will help justify future research into the subject matter.

Design, Analysis & Results

Synopsis of Previous Research

The National Design Specifications for Wood Construction (NDS), section 4.4.3, gives design parameters for square notches at the ends of a solid-sawn beam over a support including a minimum notch depth of $\frac{1}{4}$ " the beam depth, and further clarification on how to calculate the shear given a rectangular notch. But in regards to tapered notches, section 3.2.3.1 only states that a gradual taper cut from the reduced depth of the member to the full depth of the member in lieu of a square-cornered notch reduces stress concentrations, however it fails to actually specify actual relations between various tapers and reductions to stress concentrations.

TFEC 1-2019 Standard Section 2.3 gives insight on how to calculate the effects of a tapered notch, and it also provides an approximation for coped notches. While it gives similar indication that stress concentrations can be reduced via coping, as compared to rectangular notches, little information is given on the matter.

This void of precise relations indicates that more research needs to be conducted to better understand and define the aforementioned relationships. Nicholas Thielson conducted a small scale research project aimed at helping to fill this void. Theilson's research was performed on 2x6 beams which, due to the small cross section, really limited the applicability of the research. However, Theilson did conclude on some minimum radii for radial tapers which were taken into account in the testing described in this report.

Preliminary Analysis

In order to determine how to notch the specimens and what loads to use in order to design the testing apparatus a preliminary analysis was required. Because the notch will occur at the ends of the beam it was inferred that the notch should have a notable effect on the shear capacity on the beam, and not on the flexural capacity. This assumption is supported in the analysis done by Thielsen. It should also be noted that the effects of rectangular notches are included in the The National Design Specification for Wood Construction (NDS) section 3.4.3.2, and implies that the effect of the notch primarily affects the shear strength of the beam, and not flexural strength. The same inference can be made in the Standard for Design of Timber Frame Structures Section 2.3 and the Eurocode 5 Design of Timber structures 1-1. Therefore it was concluded

that we should ensure that the tests are set up in a way that ensures shear failure to occur before flexural failure.

In order to ensure shear failure, calculations had to be performed. The max bending stress and shear stress equations were set equal to one another, and modified to show the distance from the support where the governing failure mode would transition from shear to flexural.

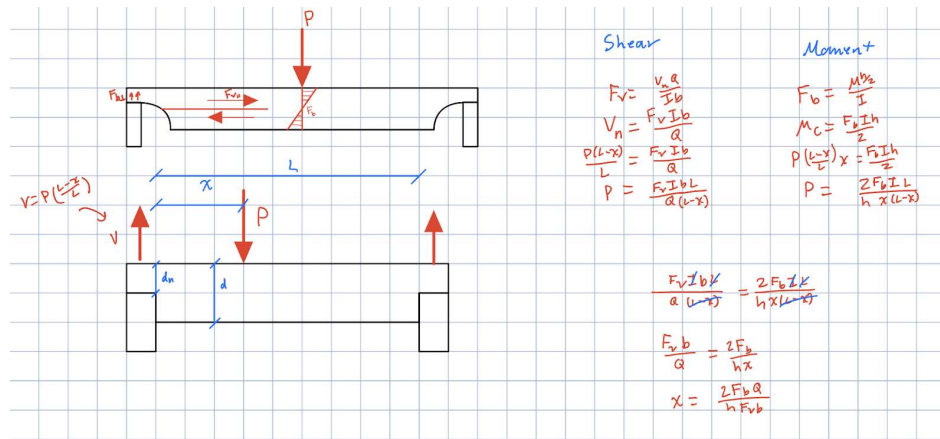


Figure 2 - Shear/Moment Transition Calculations

Analysis was done using LRFD analysis procedure and wood values were taken from the NDS Table 4D for DF #1 Grade wood. Applicable adjustment factors from NDS Table 4.3.1 were applied. Because values from the NDS Represent a very conservative capacity for the wood, the values were also multiplied by 3. In order to prevent crushing at the beam supports and at the point of loading this safety factor was not applied to the allowable compressive stress of the beam perpendicular to the grain of the wood.

Wood Design Values	
Design Parameter	Design Value (psi)
Allowable Bending Stress (F _b)=	8743
Allowable Shear Stress (F _v)=	1102
Allowable Compressive Stress (F _c ⊥)=	625

Table 1 - Wood Design Values

With these design values and the values in Table 1, it was determined that the applied load should be no more than 3.06' from the face of the support, and a bearing

area of 6.5 in² was required at each of the supports and 19.5 in² was needed at the loaded point.

Notch Selection

Previous research done by Thilsen used three different notch depths. These notch depths resulted in a notch ratio of 0.53, 0.44 and 0.36. The Notch Ratio is taken by dividing the remaining depth of the beam, and dividing it by the initial depth of a beam. For example a specimen with an initial depth of 5.5" with a 2.5" notch would result in 3" of remaining depth. The notch ratio (i) would be 3"/5.5"=0.52. It should be noted that the National Design Specification for Wood Construction (NDS) section 4.4.3.1 requires the notch ratio in a wood beam to be no less than 0.75. In order to magnify the effects of the copes and linear tapers on the beams it was determined that a more dramatic notch than what is recommended in the NDS should be used. Additionally in order to limit variables only one notch ratio was to be used in our testing. The notch ratio selected was 0.5.

Designation of Notches/Copes to be tested	
<u>Test Index</u>	<u>Taper Angle/Cope Radius</u>
1	30 Degrees
2	75 Degrees
3	9.25"
4	60"

Table 2 - Designation of Notches/Copes to be tested

When selecting the angle for the tapered notches and the radius of the copes we decided to do one that was relatively close to a typical 90 degree cut, and one that was significantly larger. The values selected, along with some cut sheets are shown in Table 2 and Figure 3.

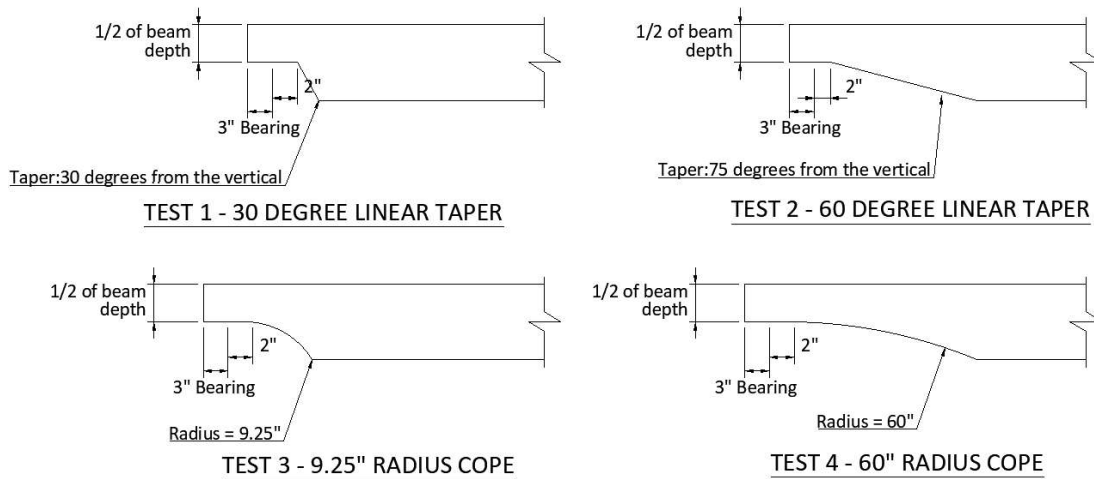


Figure 3 - Notch/Cope Cross Sections

Specimen Preparation

The Department of Civil Engineering obtained five 6"x10"x16' (nominal) timber beams from the Sunpro Corporation. After receiving the beams, we discovered that two beams were DF SELECT grade while the other three were DF #1 grade. After our preliminary analysis, we determined that we would cut each beam in half and notch each end of the cut beams to increase the number of test specimens, and to confine the coping (circular) notching to the DF SELECT grade and the linear tapered notches to the DF #1 grade specimens. This would inhibit comparisons between coped and linear tapered notches but would still allow for analysis within each notch type.



Figure 4 - Uncut Timber Beams

Because knots and cracks have a significantly negative effect on wood members, extra care was taken to place each notch where it would be least affected by these features. In some cases, it was impossible to completely avoid and thus the data from certain specimens may have been affected.



Figure 5 - Initial Wood Feature Inspection

After this decision, we proceeded to cut each beam in half with a large diameter circular saw. While this method was not ideal due to it requiring rotation of each beam to complete each bisecting cut, no deviations were large enough to impact the testing. A better method would have been to use a large jigsaw to avoid cut offsets caused by rotating each beam while still maintaining effectively straight cuts, however we were unable to acquire one.

After bisecting each beam, leaving us with a total of ten 6"x10"x8' (nominal) timber beams, we proceeded to notch each beam according to our preliminary analysis and testing matrix. As we did not have access to a large jigsaw, or other mean of making deep cuts in lumber, we decided that the best available option was the use of a large bandsaw on campus. As bandsaws are not mobile pieces of equipment, it became necessary for two people to participate for each cut. One person to ensure that the cut was made accurately, and another to maneuver each beam around the bandsaw's blade. This technique was difficult and far from precise. Thus, the decision was made that when an error was inevitable, we would choose to err on making the cut too shallow rather than too deep to avoid weakening the notch. Even so, several notches were cut deeper than intended, which may have impacted our test results.

After all the notches were prepared as best as possible on the bandsaw, we returned with an angle grinder equipped with a flap disc to remove excess material from the notches that required it. Again, this method was not optimal and may have introduced some minor errors which may have influenced the test data, though not to a significant degree.



Figure 6 - Prepared Specimens

Testing Apparatus Preparation

For our testing apparatus, we used a large hydraulic press to generate a point load at the location calculated to primarily load one end of the beam and to induce shear failure of the specimen before flexural failure. The hydraulic press was fitted with a large wide flange beam that was sized to eliminate effective deflection of the wide flange beam. Beam supports were mounted on the wide flange beam and equipped with steel plates sized to prevent crushing of the wood before shear failure of the beam. The support under the non-testing end of the beam was located before the notch to prevent failure on the wrong end of the specimen. The load point of the hydraulic press was also equipped with a steel plate sized to prevent crushing of the wood.



Figures 7 & 8 - Testing Apparatus (Full View & Beam)

The apparatus was equipped with a deflection sensor directly below the loading point, and the hydraulic press was equipped with integrated load sensors and time tracking. All of which output the required data for our analysis. In addition, we utilized a handheld moisture content sensor to monitor the moisture content of each notch directly after testing both ends of each beam.

Testing Process

For each test, we loaded a prepared beam into the testing apparatus and fastened the deflection sensor to the tension face of the beam, directly in line with the loading point. After confirming that all contact points were spaced correctly, we began loading the specimen. Loading continued until either significant shear failure occurred, or deflection exceeded acceptable code limits. In the case where deflection exceeded code limits, data was noted at that point, then loading continued until significant shear or flexural failure was achieved.



Figure 9 - Example of Significant Shear Failure

Each notch was labeled according to the following format: (Notch Type Number)(which beam of that notch type)-(left or right end of beam). Notch Type Numbers are 1, 2, 3 and 4, which represent a 30° taper, a 75° taper, a 9.25" diameter cope, and a 60" diameter cope respectively. Each notch type was tested four times, two tests per 8' beam, with the two beams being labeled A or B. Finally, we differentiate between the left and right ends of the beam with L and R, respectively. For example, specimen 1A-L refers to a 30° tapered notch, the first beam of that notch type, and the

left end of that beam. 1A-R would refer to the right end of that same beam and 2B-L would refer to a 75° tapered notch, the second beam of that notch type, and the left end of that beam.



Figure 10 - Testing Aftermath

<u>Spec ID</u>	<u>Test Type</u>	<u>Notch Radius /Taper Angle</u>	<u>Wood Type</u>	<u>Peak Load (lb)</u>	<u>Peak Disp.</u>
1A-L	Taper	30	DF #1	4302.21	1.128
1A-R	Taper	30	DF #1	11133.26	1.792
1B-L	Taper	30	DF #1	6882.12	1.879
1B-R	Taper	30	DF #1	9365.63	1.486
2A-L	Taper	75	DF #1	10450.27	1.468
2A-R	Taper	75	DF #1	12418.53	0.583
2B-L	Taper	75	DF #1	16534.97	0.646
2B-R	Taper	75	DF #1	10770.69	0.413
3A-L	Radial	9.25	DF Sel	19746.92	1.181
3A-R	Radial	9.25	DF Sel	19617.80	0.606
3B-L	Radial	9.25	DF Sel	14834.59	0.500
3B-R	Radial	9.25	DF Sel	22299.78	1.527
4A-L	Radial	60	DF Sel	12430.10	1.121
4A-R	Radial	60	DF Sel	17714.45	1.549
4B-L	Radial	60	DF Sel	7926.28	0.416
4B-R	Radial	60	DF Sel	21238.45	1.830

Table 3 - Individual Specimen Results

Testing Results

Results			
<u>Test Index</u>	<u>Notch Type</u>	<u>Wood Grade</u>	<u>Avg. Peak Load (kip)</u>
1	30 Degree Taper Angle	DF #1	7920.8
2	75 Degree Taper Angle	DF #1	12543.6
3	9.25 Inch Radius	DF Sel	19124.8
4	60 Inch Radius	DF Sel	14827.3

Table 4 - Average Peak Load of Specimens

The above table shows the tabulated results for each test type. It should be noted that coped tests were performed with DF SEL Grade wood, and linear tapered notches were performed with DF #1 Grade wood, so coped beam results should not be compared with the linear tapered notches. It was observed that on average the 30 degree tapered notches performed better than the 75 degree tapers. It was also observed that on average the 9.25" coped test performed better than the 60" coped tapers. See the following page for figures of the resulting point load maximum for the different notch types.

Variance in Specimen Results

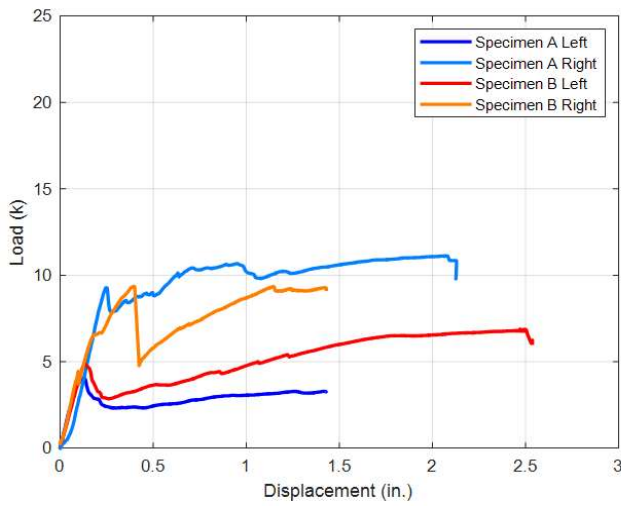


Figure 11: Test 1 Variance

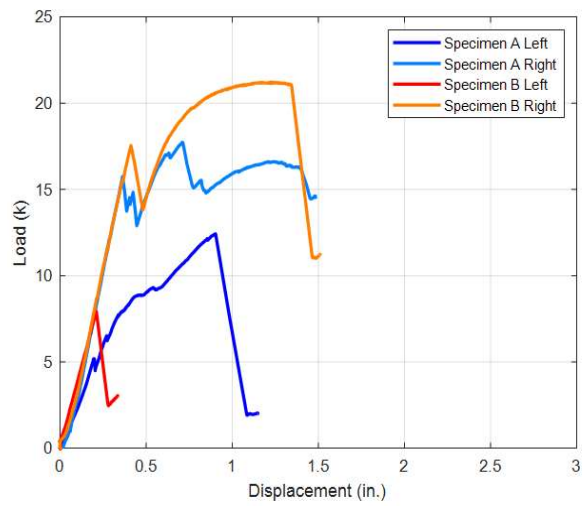


Figure 12: Test 2 Variance

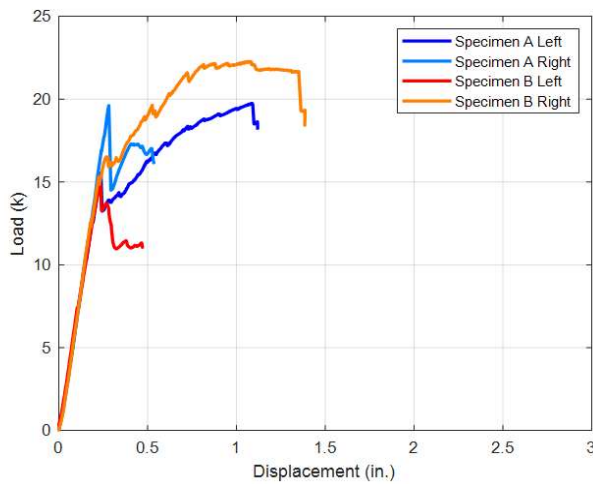


Figure 13: Test 3 Variance

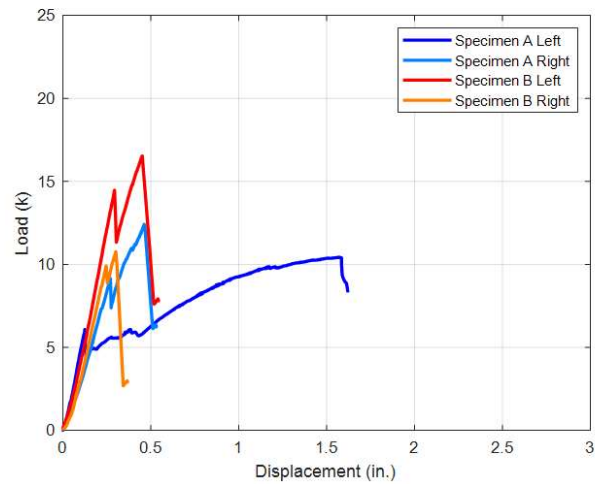


Figure 14: Test 4 Variance

Related Issues

Safety Factors

Understanding how various types of timber notches perform under stress has an immense impact on safety. As further testing is performed, standardized equations will be made available so that engineering design can be performed for linear tapered notches and copes in a standardized way. Performing engineering in a standardized way allows for predictability, and predictability is one of the largest influences upon overall safety.

Economic Factors

The reduction of stress via linear tapered notches and copes has the potential to allow for smaller cross sectional area beams to be used in construction. This reduction of beam size is directly correlated with a reduction in cost. Smaller beams typically cost less than larger beams. As standardized calculation standards become available for linear tapered notches and copes, companies will be able to start taking advantage of stress reduction opportunities and provide clients with more economically efficient designs. These savings, in one way or another, will eventually trickle down from companies and contractors to money saved in the pockets of house owners. An economically efficient design is one of the highest priorities a competitive engineering firm can have.

Global Factors

As seen in the Synopsis of Previous Research and the Preliminary Analysis sections at the beginning of this report, structural understanding is an international collaborative effort. The safety and economic benefits previously mentioned will be free for the international community to obtain as they continue to perform, analyze, and understand research regarding linear tapered notches and copes. Furthermore, the collaboration on this research and the implementation of the findings thereof will continue to help grow international collaboration on structural research. This may be due in part to the general sparsity of research that is able to be conducted on new and forthcoming structural optimisation opportunities. This sparsity forces those who have conducted research to seek out and collaborate with others who are conducting research in order to obtain a mutually beneficial pool of data from which proper inferences can be made.

Conclusions & Recommendations

While slight correlations can be drawn from the limited testing performed, more testing needs to be done in order to obtain enough data to make strong correlations between notch type and beam strength. Control beams should be tested as well to provide a good background to compare the notch tests against. Ideally, factors such as species and grade of wood should be kept consistent and % humidity should be kept as consistent between the specimens as possible. Essentially, all other influencing factors should be limited and or controlled so that the variation between notches can be observed with as little interference from outside factors as possible.

An important note as data from this report is analyzed is that peak Load (kip) as referenced in the various tables and figures is the average peak load in kips which was applied as a point load to the beam, not the reaction at the notched end of the beam.

Appendices

Appendix A - List of Tables and Figures

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Appendix B - Schedule

- Obtain and have milled five 6x10 timber beams sixteen feet in length by January 31st
 - Planned: ~ 15 hrs between communication with provider, delivery, and milling
- Designed and set up testing apparatus in the BYU structures lab by February 13th
 - ~ 7 hrs between design, set up, and welding
 - Actual: 39 hrs
- Begin testing of notched timbers, via the BYU structures lab, by February 13th
- Finish testing of notched timbers, via the BYU structures lab, by March 31st
 - Planned: ~ 30 hrs between positioning of timbers, testing, retrofitting, retesting, and clean-up
 - Actual: 35.5 hrs
- Create and submit poster by April 5th
 - Actual: 5.5 hrs
- Submit ruff draft of concluding report by April 8th
 - Planned: ~ 10 hrs between compiling, analyzing, discussing, and formatting the test results
 - Actual: 10.5 hrs
- Submit final draft of concluding report by April 19th
 - Planned: ~ 5 hrs between reviewing, corrections, discussing, and reformatting the test results

Appendix C - Resumes

DEXTER RODRIGUEZ

(385)-219-9612 | dexter.rodriquez2012@gmail.com

EDUCATION

Brigham Young University **2016-Present**

Bachelor of Science Civil Engineering: Emphasis in Structural Engineering

- Completed coursework: Statics, Engineering Drafting with CAD Applications, Computational Methods (VBA), Material Science, and Structural Analysis
- Current enrollment: Transportation Engineering, Hydraulics + Flow Theory, Soil Mechanics, and Reinforced Concrete Design
- Research Assistant for Dr. Taylor Sorensen studying concrete 3D printing **2021-current**

WORK EXPERIENCE

Home Renovation **2011-2016**

- Restored and remodeled residential homes, including plumbing, electrical, flooring, and framing

Oakleaf Landscaping **2011-2016**

- Dock construction, including framing, beachside foundations, and roofing
- Landscaping, including retaining wall construction, and excavation

Walgreens **2018-2019**

- Overnight store manager supervising coworkers and inbound shipments; resolving conflict with guests

Gordon's Ace Hardware

- Gave professional, courteous, and informed customer service and informed advice on home projects

Acute Engineering **2019-Present**

- Structural Engineering Intern
- Structural analysis and design of custom and production residential projects
- Training new interns in company protocol, program use, and engineering principles

SKILLS

- AutoCAD
- Revit
- Microsoft Office
- Excel
- Simpson Anchor Designer
- Enercalc
- Risa 2D and 3D

EXTRACURRICULAR EXPERIENCE:

- Officer of the American Society of Civil Engineers BYU Student Chapter, 2019
- Member of BYU Brazilian Jiu-Jitsu Club, 2016-Present
- Currently building a 5x8 ft concrete 3D printer

Mason G. Maxfield

Email: themaxfielder@gmail.com

Phone: (801) 882-2023

EDUCATION:

Bingham Young University

Pursuing a Bachelors Degree in Civil Engineering (structural emphasis)

Anticipated Graduation: April 2023

GPA 3.47 / 4.0

NOTEWORTHY COURSEWORK:

Business Ethics & Leadership, Reinforced Concrete Design, Structural Analysis, and Surveying

AWARDS:

Snow College's Dean's List: Fall 2018, Spring 2019, Fall 2019, Spring 2020.

5th place in Division 3 of the Snow College Mathematics Contest: 5 April, 2016.

Scholarship Math Contest 2015 Senior Winner: April, 2015.

WORK EXPERIENCE:

Acute Engineering, 3/01/21-Present

Positions Held: Engineer in Training

Skills Demonstrated: Ability to research, analyze, and improve iterations of structural plans; attention to detail; accountability; proactive communication; and dedication.

Notable Experience: Performed quality and timely engineering for one of the homes featured in the 2022 parade of homes.

Reinheit Landscaping & Maintenance, Inc., 5/25/20-3/01/21

Positions Held: Crew Member

Skills Demonstrated: Ability to efficiently work alone, manage a small crew, make precision measurements, cuts, and installments, plan ahead for materials and tools, and train others.

Notably Experience: Built decks, patios, and awnings.

7-Brothers Moving Co., 5/24/19-8/16/19

Positions Held: Crew Member, Asset Safety Expert, and Crew Lead.

Skills Demonstrated: Diligence, efficiency, and safety.

Notable Promotions: In a very short period of time, I was promoted from Crew Member to Asset Safety Expert based on my attention to detail and customer satisfaction.

Notably Experience: Provided detailed training, both on site and in company meetings, concerning maintaining and improving asset safety.

ADDITIONAL SKILLS:

SolidWorks

AutoCAD

Programming: C++

BlueBeam

Microsoft Office

ForteWEB

Nathan Chesnut

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Springville, Utah 84663
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Education

Brigham Young University

Provo Utah – December 2023

- Structures Emphasis
- Relevant Coursework completed
 - Mechanics of materials
 - Structural Analysis
 - Reinforced Concrete
 - Foundation Design
 - CAD and drafting applications
 - Materials (Concrete, Steel, Wood, etc.)
 - Math core (Calculus, Linear Algebra, Multivariable Calculus, Differential Equations)

Relevant Experience

Structures Intern-Acute Engineering

Orem, Utah – September 2020 - Present

- Analyze residential structures for gravity, seismic, and wind loads
- Collaborate with other students and licensed engineers to complete work in a timely manner.
- Implement finite element methods to design moment resisting frames in steel and wood (mostly work in RISA)
- Create dedicated structural plans from client drawings via AutoCAD

Structures Intern-Michael Baker International

Midvale, Utah - July 2020 - September 2020

- Learned the basics of bridge and culvert design from experienced engineers
- Set up drawings and applied engineering marks to plans using MicroStation (Connect and V8i editions) and Bluebeam Revu
- Inspected and reported on existing structures (such as culverts) via on-site inspections

Online Support Representative-Utah Community Credit Union

Provo Utah - December 2018 - July 2020

- Interacted with clients to resolve banking-related inquiries.
- Deescalated stressful interactions with clients in order to resolve their concerns
- Met hard deadlines

Relevant Skills

- MicroStation, Solid works and AutoCAD
- Excel and VBA coding
- RISA (2d, 3d, Connection)
- Familiarity with Building Code (IBC, IRC, NDS, ACI-318, etc.)
- Bluebeam Revu
- Revit
- Japanese