

Experimental Building Demonstration Model with Viscous Dampers

A Senior Project
presented to
the Faculty of the Architectural and Mechanical Engineering Department
California Polytechnic State University, San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Science

by

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June, 2016

Table of Contents

| | |
|--|-------|
| Introduction..... | 3 |
| Objective..... | 4 |
| Methods..... | 4 |
| Construction..... | 5 |
| Results..... | 7 |
| Analysis..... | 8 |
| Conclusion and Future Projects | 10 |
| Appendix A- Final Design | 11-16 |
| Appendix B- Initial Design Calculations | 17-42 |
| Appendix C- Matlab Earthquake Analysis | 43-53 |
| Appendix D- Material and Component Testing Analysis..... | 54-56 |
| Appendix E- Post Testing Analysis Calculations | 57-61 |
| Supplement 1- Mechanical Engineering Report | 61-92 |

Abstract

The Architectural Engineering major places a heavy emphasis on structural dynamics and the role of wind and seismic loading in building analysis and design. Buildings of high importance that are critical to community function, such as hospitals, often utilize supplemental damping devices like supplemental viscous fluid dampers or base isolators to reduce the overall demands on the structural system. The design and analysis of these dampers are typically not taught at the undergraduate level, and is frequently performed by mechanical engineers, in lieu of structural engineers.

To better understand and research building behavior with supplemental damping devices, our multi-disciplinary team designed and fabricated an interactive, reconfigurable, multi-story model of a building. This building structure was dynamically tested and analyzed using the ARCE Department's seismic shake table. The building model will be left with the university to serve as a model for undergraduate students enrolled in ARCE 483 and ARCE 412. Students worked together to test the structure under a variety of conditions and compare the findings with predictions from computer models. This model also has the potential to be used in core Mechanical Engineering courses, such as the Mechanical Vibrations course, ME 318.

Introduction

A 3-story, 7' tall model, with a 3' x 3'6" footprint was chosen for the model, to accommodate size limitations of the seismic shake table. Each floor has removable steel weights, with a capacity of up to 500 lbs per floor, to allow for experimentation with multiple mass configurations.

The model is intended to be used on the shake table located in the Architectural Engineering department's seismic lab. The shake table serves as a dynamic earthquake lab with unused potential, as it is mainly used only by the Earthquake Engineering Research Institute (EERI) club.

The table can move back and forth simulating various earthquake ground motions, as well as motions programmed by students. The seismic lab also has accelerometers and strain gauges that can be applied to the model to detect the real-time motions and forces of the members. The data from these devices was compiled and analyzed by students to interpret the effectiveness of the supplemental dampers when added to the model.



*Figure 1:
Shake Table*

Objectives

1. Construct a versatile building demonstration model
2. Leave the ARCE and ME departments with a lasting model that can be utilized by future students and integrate its use into ARCE courses
3. Predict structural behavior of buildings using supplemental damping devices
4. Determine critical variables in damper efficiency
5. Compare the actual behavior of the model under seismic loading with predicted behavior by common analysis techniques

Methods

Design

Design of the structure and dampers began in Fall 2015 and the project team enrolled in a three unit ARCE 400 course. The parameters of the shake table governed the majority of the design. After consulting the technician that was familiar with the table, the team determined a maximum weight of 2000 lbs for the entire model. Thus the list of design parameters is as follows:

- Must fit within 4'x 4' footprint of the table
- Maximum height of 8'
- Must resist max base shear from shake table (2g output force)
- Must have braced frame and moment frame lateral system capability
- Should have different stiffness in each direction of shaking
- Vibrations at full and half weight loading should be visible

Initial member sizes were chosen by iteration and testing, based on the flowchart shown in Figure 2. The students chose column sizes which would give ideal modal periods and deflections assuming 125-500lb loads at each floor. Modal properties were predicted using a MATLAB code developed by the students and double-checked with RISA and ETABS analysis. The code charted the response of the structure by inputting the moment of inertia of the columns, the height of the floors, Young's modulus, and the weights applied at each floor. See Appendix A for the code.

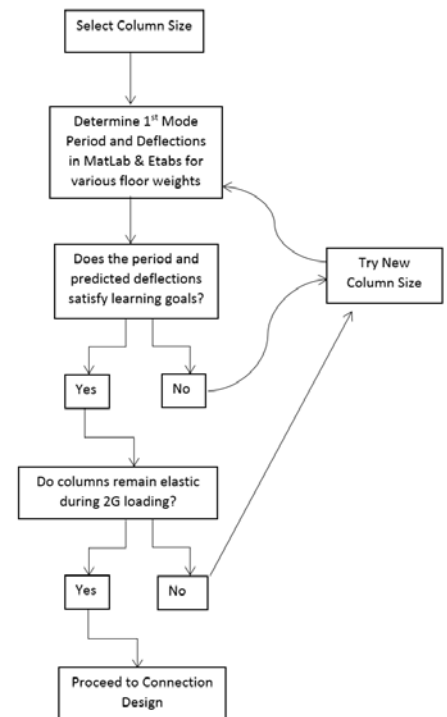


Figure 2:
Design Process

HSS 1.5" x 2" x 1/8" aluminum tubing was chosen for the beams and columns, 1/4" thick, bolted steel connections were chosen for the necessary "moment" connections, and clevises were chosen to simulate "pinned" connections. The model is connected to a 1/4" thick steel base plate, which bolts to the shake table. Viscous fluid dampers, were chosen for the supplemental dampers. The connections were designed to allow multiple bracing and damper configurations, spanning diagonally in each bay, for maximum versatility.

The columns were designed to be continuous to insure, should something fail, it would fail ductile manner instead of a sudden rupture. The structural members were designed to insure a strong column, weak beam connection to prevent structural damage to the model and to insure safety of the user.

Floor plates were designed with a grid of holes where additional steel plates can be bolted to the structure to increase the mass of each floor and allow additional versatility for future experiments. To insure the floor plates did not vibrate vertically during testing "leaning" columns were designed to only take axial load. The leaning columns were also critical to enable a braced frame configuration of the structure. They were designed as standard steel pipe members with a welded nut inside for the rod-ends to be threaded into the leaning column. Rod ends were chosen for the end of the members so that lateral load could not be transferred into them, and they could be true "pinned" connections. See Appendix A for final design and photos. See Appendix B for initial design calculations.

Mechanical Engineers were responsible for designing the connection from the column to the baseplate as well as specifying a damper or dampers that would provide the greatest decrease in deflections as possible within the budget provided. Their analysis and design methods can be seen in Supplement #1.

Construction

The construction phase of the project took place in the winter and spring quarter of the 2015-2016 academic year. In the spring quarter the project team enrolled in a three unit ARCE 453 course. Students fabricated most of the components using the machine shops on campus.



*Figure 3:
Rendering*

Before the connections were fabricated, the students tested similar connections using a hydraulic press, to verify their designs had the required strength. The designs were modified as required.

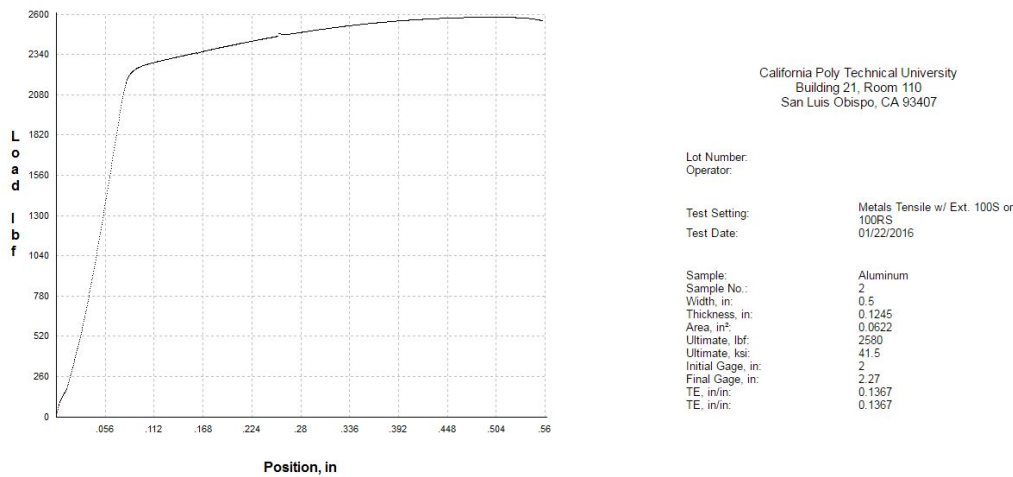
A one-story model was then constructed and tested to verify that the elements worked properly as a system, before constructing the entire model. After the one story model passed the tests, the students finished the remainder of the construction in June 2016.



Figure 4:
Moment Connection Test

Testing

Material testing was done to confirm that the material performed as expected. A tensile test was performed and the ultimate stress was confirmed to be 40 ksi as specified. A yield stress was conservatively determined to be 34 ksi. In addition, the material is ductile, with an elongation of about 17% before breakage as shown in figure 5. This means that deformations will be noticeable before the structure fails. This allows for users to stop the test if they see deformations occurring before more serious damage occurs should the structure be pushed past its capacity



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The one story model was tested to confirm that the designed values were within tolerance. A forced vibration test was performed to determine the structure's stiffness. In addition to this a snapback test was performed to determine the structures natural damping. These values were then compared to the previous design values from the analysis to determine if the difference was tolerable.

After the one story models design was deemed adequate, the three story model was constructed and similar testing was done on the three story model. Acceleration values were

recorded from different forcing functions to obtain the building stiffness and critical damping values. These values were compared to different configurations of dampers in the building to determine the effectiveness of the dampers and the degree of precision of the measuring instruments. The structural response was documented for various configurations of dampers engaged. The final testing phase of this project took place at the end of the spring quarter and involved forced vibration tests on the building using the shake table.

Results

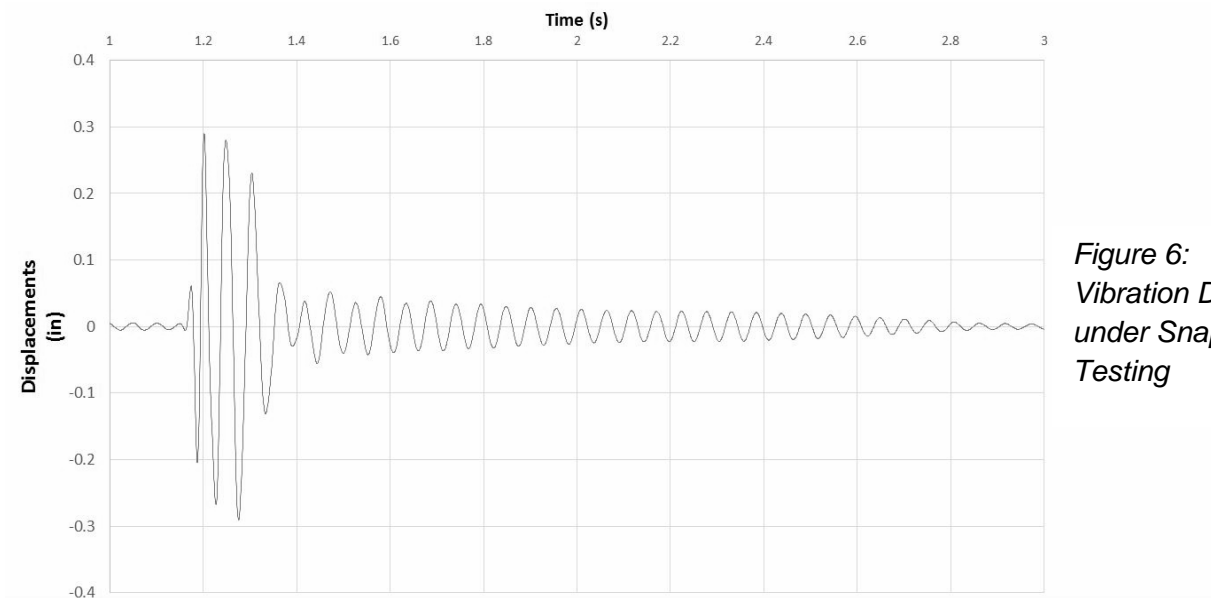
One story model

Two tests were performed on the one story model, a resonant frequency test and a snapback test. The stiffness of the one story model was determined to be 3.98 k/in which was within 10% of our predicted stiffness for the model. The stiffness was determined from the resonant frequency test from the following equation.

$$\omega = \sqrt{k/m} \rightarrow k = \omega^2 \times m$$

The natural damping of the one story model was determined from the snapback test using the logarithmic decay method outlined in section 2.2.3 of Chopra's dynamics of framed structures text. From the following equation, the natural damping of the one story structure was found to be 3.45%. Hand calculations of the following can be found in Appendix E.

$$u_i/u_{i+1} = 2\pi\xi/\sqrt{1 - \xi^2}$$



*Figure 6:
Vibration Decay
under Snapback
Testing*

Three story model

The testing of the three story model consisted of placing accelerometers on every floor and on the shake table itself. These accelerometers were used to track the vibration on every floor to determine the primary resonance frequency. From experimentation it was determined that the primary resonant frequency was 4.62 Hz compared to our expected 4.17 Hz, resulting in a 9.74% error.

In addition, after normalizing the building deflections under its first harmonic frequency for the values collected during experimentation and for the predicted deflections the error calculated was only 1.2% on the second floor and a 0.99% on the third floor. What this means is our design performed extremely close to as we expected it to be.

Testing of the first mode of vibration was conducted with and without dampers installed. The results showed that the first mode of vibration did not change with or without the dampers. This means the dampers do not add any additional stiffness to the structure. Additionally, we can determine the reduction in accelerations when the structure was shaken at its first mode of vibration without the supplemental dampers. The total peak accelerations were 199.4 mg at the first floor, 354.1 mg at the second, and 440.7 mg at the third. When tested with the supplemental dampers the accelerations per floor were, 169.75 mg, 303.94 mg, and 377.9 mg. This shows a decrease of 14.8 % at the first floor, 14.1% at the second floor and 14.2% at the third floor. We can apply these reductions to our expected displacements and expect a decrease in deflections of about 14% per floor.

Testing the dampers under various ground motions was not conducted due to time constraints. Future testing of the dampers will be conducted by graduate students in the ARCE department.

Analysis

Matlab

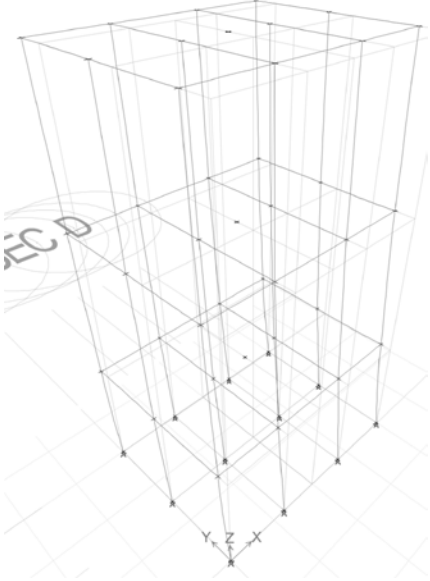
A numerical model of the structure was constructed using a matlab code that imports earthquake records, mass per floor, stiffness per floor, and natural damping, and outputs velocity, accelerations, and displacements per floor with and without the supplemental dampers. It was shown that the dampers decreased the deflections of each floor by about 5% when every floor has a half inch of steel plates. Compared the values that were received during the forced vibrations testing the reduction in deflections is very conservative compared to the values we received from experimentation. Code and output can be seen in Appendix C.

Risa

RISA was used in conjunction with our hand calculations to verify the adequacy of the model under ultimate loading. Risa was extremely beneficial in locating areas in the structure that may be insufficient for the desired loading and was an invaluable design tool. Loads were taken from hand calculations and placed into the program. Risa output can be found in Appendix B.

Etabs

Several ETABS models were constructed to verify calculations of the natural frequency, mode shapes, and pushover analysis. The model included the rigid end offsets from the beam-column intersection where it is reinforced with ¼ inch steel plates and ⅛ inch thick gusset plates. It should be noted that a greater amount of confidence was put into our calculations compared to our ETABS model due to the questionably large periods of vibration that ETABS provided as seen in figure 8.



*Figure 7:
Etabs Model Displacements
under First mode*

Modal Results

Table 5.8 - Modal Periods and Frequencies

| Case | Mode | Period sec | Frequency cyc/sec | Circular Frequency rad/sec | Eigenvalue rad ² /sec ² |
|-------|------|------------|-------------------|----------------------------|---|
| Modal | 1 | 0.434 | 2.302 | 14.462 | 209.1502 |
| Modal | 2 | 0.37 | 2.701 | 16.9693 | 287.9556 |
| Modal | 3 | 0.129 | 7.747 | 48.676 | 2369.3555 |

*Figure 8:
Etabs Modal output for natural frequencies and periods*

Conclusion and Future Projects

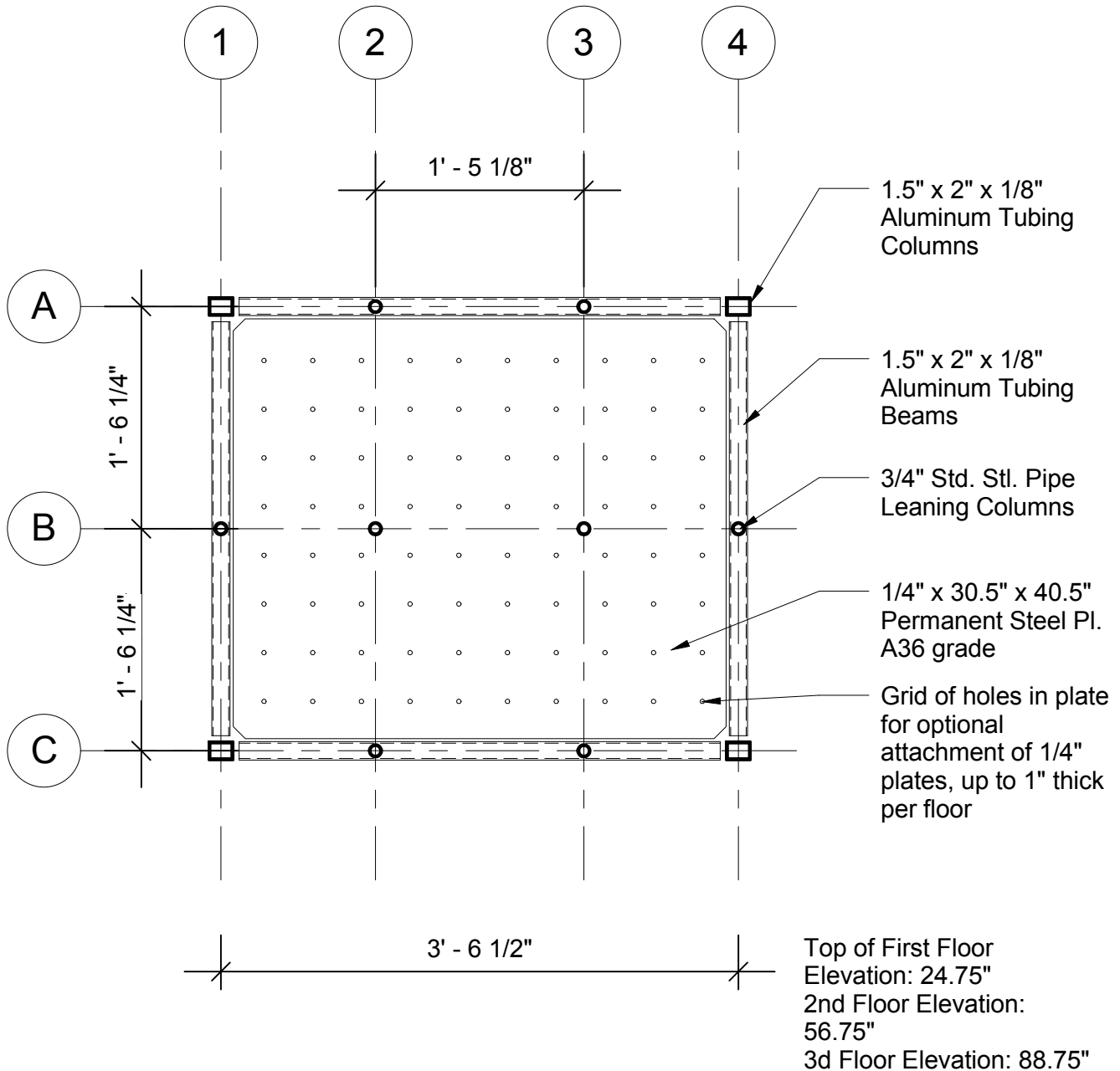
At the end of spring quarter, 2016, we were able to meet most of the objectives and complete basic testing of the structure, as described in the previous sections. However, there are a few things that we were unable to complete. Firstly, we were unable to fabricate supplemental beams and columns to be ready in the case that a member needed to be replaced. Drawings will be provided so that future students or faculty can fabricate the members. Secondly, we were unable to run earthquake ground motions through the structure due to time constraints with the students graduating. Future students in the ARCE department will be testing the structure by running various ground motions through the shake table and analyzing the performance in order to confirm the adequacy of the structure. Those experimental results will be compared with the calculations performed in appendix C to see how accurate our analysis was.

The list for future projects that can be tested on the model can be seen below. It should be noted that these are just project suggestions and this model was designed to give students creative freedom to experiment with the model and create other experiments as well.

- Suggested demonstrations for open house or courses:
 - Shaking at frequency
 - Shaking at various ground motions

- Suggested future testing includes:
 - Damper arrangement effectiveness
 - Actual base shear distribution per floor using strain gauges
 - Design base isolator system for model
 - Damage simulation by loosening bolts
 - Mass irregularities and their effect on the building lateral forces
 - Testing of various bracing system

Appendix A- Final Design



① Level 2
1" = 1'-0"



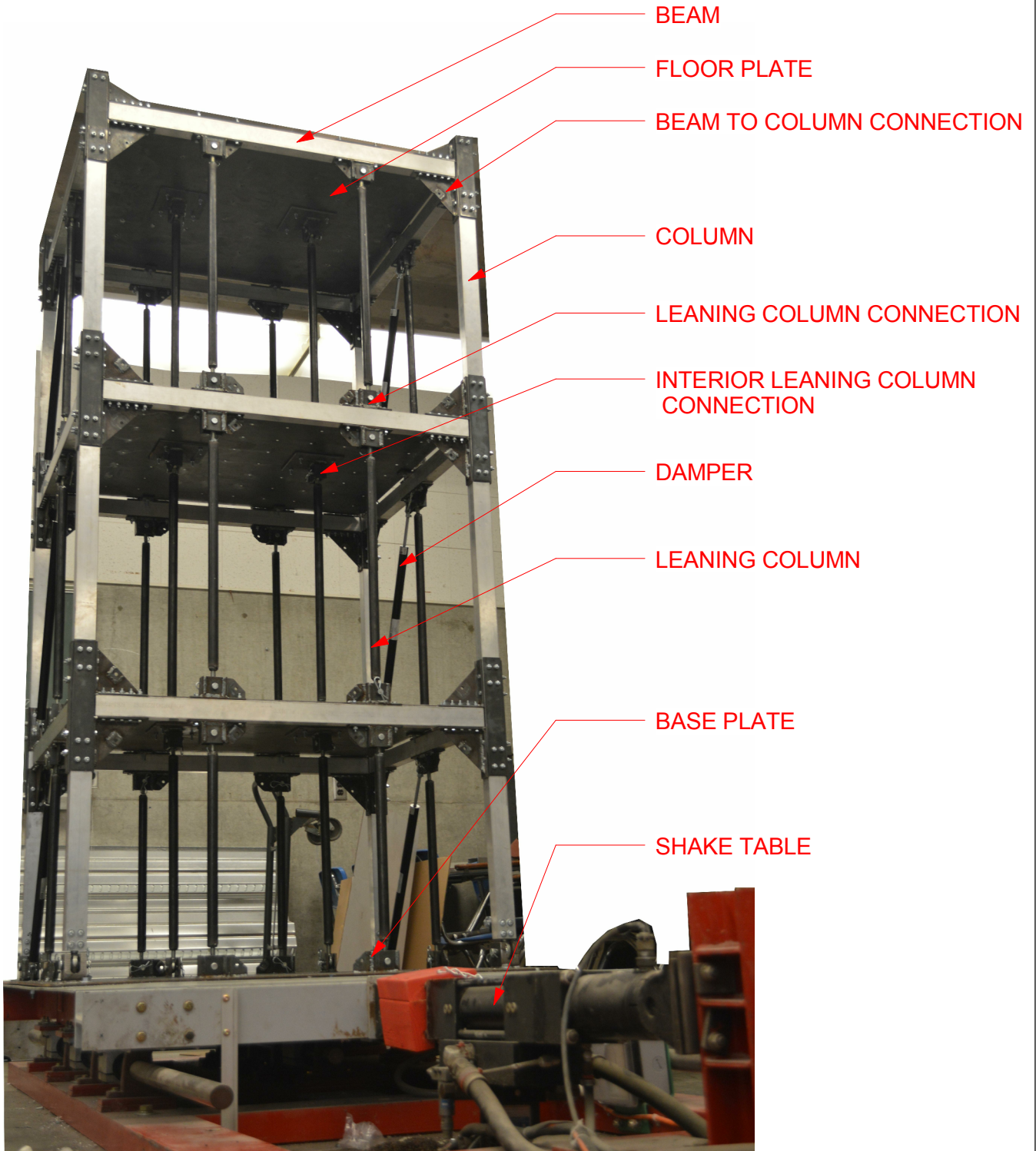
www.autodesk.com/revit

SENIOR
PROJECT

TYPICAL FLOOR PLAN

| | | |
|----------------|------------|--------------|
| Project number | 1 | S.1.0 |
| Date | 01/12/16 | |
| Drawn by | BTR | |
| Checked by | Checker | |
| Scale | 1" = 1'-0" | |

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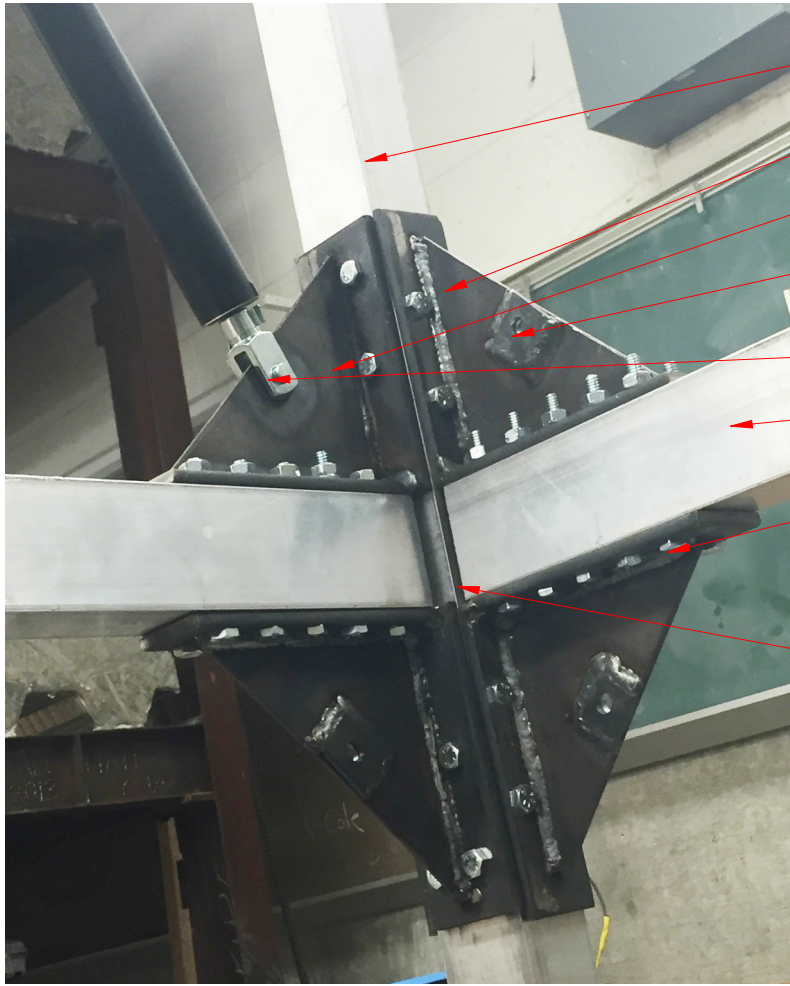
www.autodesk.com/revit

SENIOR
PROJECT

ANNOTATED PHOTO

| | | |
|----------------|----------|------------------|
| Project number | 1 | S.1.1 |
| Date | 01/12/16 | |
| Drawn by | Author | Scale 1" = 1'-0" |
| Checked by | Checker | |

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COLUMN

STRONG AXIS CONNECTION

WEAK AXIS CONNECTION

ATTACHMENT HOLE FOR DAMPER OR BRACE

DAMPER

BEAM

1/4" X 3" BOLT WITH LOCK WASHER, TYP.

1/4" GAP BETWEEN BEAM AND COL. TYP.

① Beam-Column Connection
1 1/2" = 1'-0"



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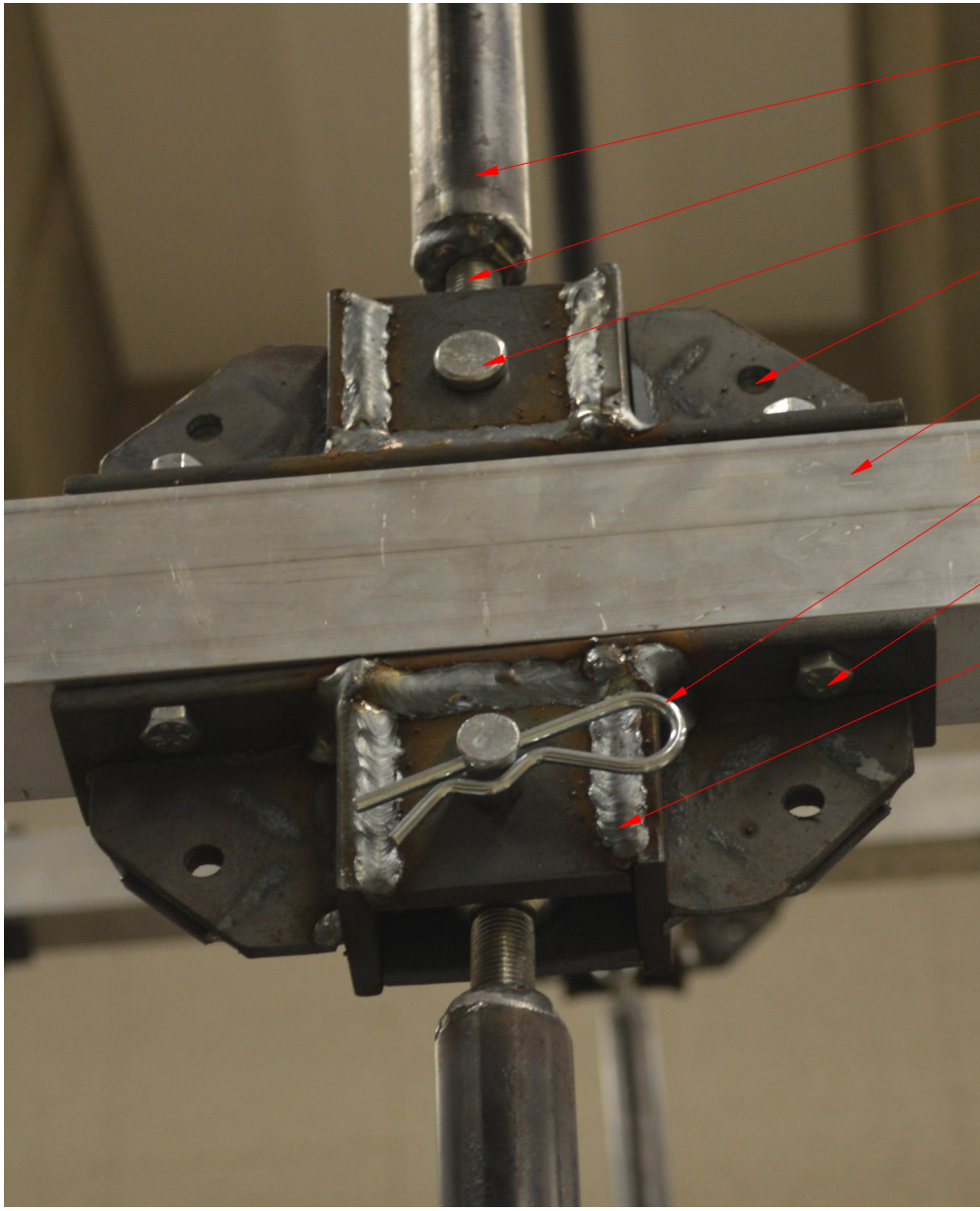
SENIOR
PROJECT

BEAM-COLUMN CONN.

| | |
|----------------|----------|
| Project number | 1 |
| Date | 01/12/16 |
| Drawn by | Author |
| Checked by | Checker |

S.1.2

Scale 1 1/2" = 1'-0"



LEANING COLUMN

1/2"-20 ROD END

CLEVIS PIN

ATTACHMENT HOLE FOR DAMPERS OR BRACES

BEAM

1/8" DIA. COTTER PIN

1/4"-20x3" BOLTS, TYP

LEANING COLUMN CONNECTION

① Leaning Column Connection
1 1/2" = 1'-0"



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SENIOR
PROJECT

LEANING COL. CONN.

| | |
|----------------|----------|
| Project number | 1 |
| Date | 01/12/16 |
| Drawn by | Author |
| Checked by | Checker |

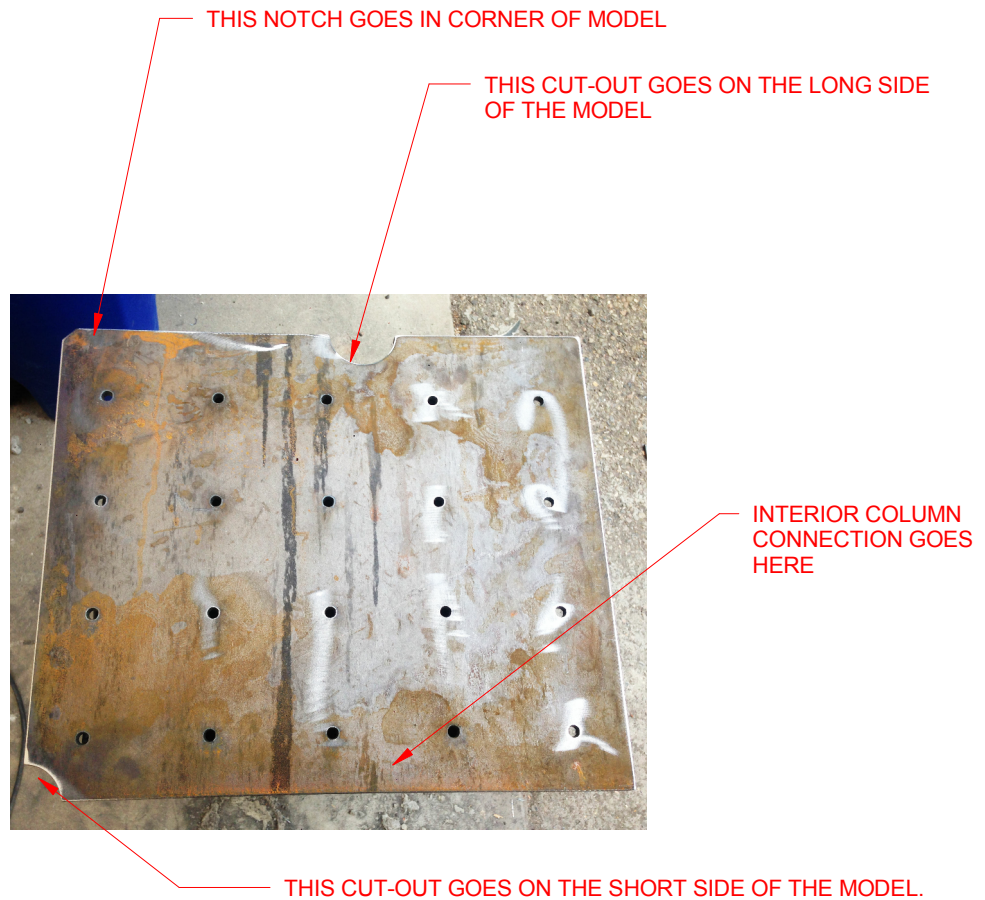
S.1.3

Scale 1 1/2" = 1'-0"


Adding weight plates

See Appendix A for part location.

1. Remove bolts for Interior Leaning Column Connection at desired floor. You can leave the bolts which attach it to the floor above.
2. Move leaning columns to the side.
3. Insert and rotate weight plates onto floor so that they align with the holes on the permanent plate.
4. Bolt the weight plate down at its corners. Use lock washers and tighten.
5. Twist Interior Leaning Column Connections so that the rod ends screw in enough to reattach connection to plates.
6. Bolt the Interior Leaning Column Connections to the weight plates.



① WEIGHT PLATE INSTALLATION 1 1/2" = 1'-0"

| | | | |
|---|---------------------------|-----------------------------|--------------------------------------|
|  AUTODESK | SENIOR PROJECT | WEIGHT PLATE INSTALL | |
| | | Project number 1 | S.1.4 Scale 1 1/2" = 1'-0" |
| Date 01/12/16 | | | |
| Drawn by Author | | | |
| www.autodesk.com/revit | PROJECT | Checked by Checker | Scale 1 1/2" = 1'-0" |

Appendix B- Initial Design Calculations

```

%Brianna Kufa
%Alumodel Sr. Project
%Modal Analysis Code- Analysis of periods etc. by changing I

format long
clear
clc

E=10100 %in ksi
I0=.1
t=(4)*3%stiffness modifier (4 cols) *__EI
g=386.4; %in in/s^2
A=2*g; %ground acceleration

L1=20%Height of each story
L2=32
L3=L2

L=[1;1;1]; % influence vector

Ts=1; %steel plate thickness
d=40.8; %density of steel in lb/ft^2in
W=12*d*Ts; %weight of steel per floor (lbs)
m1=W/386.4/1000*[1 0 0;0 1 0;0 0 1];% mass in k-s^2/in

for j=1:20 %varies column moment of inertia to generate graphs
    I=I0*j;
    k1=t*E*I/3/L1^3; %stiffness of each floor in k/in
    k2=t*E*I/L2^3;
    k3=t*E*I/L3^3;

    k=[k1+k2, -k2,0;-k2,k2+k3,-k3;0,-k3,k3];%in k, in

    [phi lam]=eig(k,m1); %solves for eigenvalues

    w1=(lam(1,1))^0.5; %solves for natural frequencies
    w2=(lam(2,2))^0.5;
    w3=(lam(3,3))^0.5;

    T1=2*pi/w1; %Solves for periods
    T2=2*pi/w2;
    T3=2*pi/w3;

    D1=A/(w1^2); %Max displacements,
    D2=A/(w2^2);
    D3=A/(w3^2);

    phil=phi(:,1);

```

```

phi2=phi(:,2);
phi3=phi(:,3);

gamma1=phi1'*m1*L; % finds modal participation factor
gamma2=phi2'*m1*L;
gamma3=phi3'*m1*L;

gamma=phi'*m1*L;

q1=D1*gamma1;%calcs q's
q2=D2*gamma2;
q3=D3*gamma3;

q=[q1 q2 q3];

u1=phi1*q1;%converts back to real modal displacements
u2=phi2*q2;
u3=phi3*q3;

i=1;% counter for u's
ulmax=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5;%Finds max displacement per mode
i=2;
u2max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5;
i=3;
u3max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5;

Umax=[ulmax;u2max;u3max];
MomentInertia(j,:)=[I];
period (j,:)=[T1];
displacement(j,:)=[u3max];

Vb=k1*ulmax; %Base shear in k
Vcol=Vb/4; %Base shear per column in k
Mcol=Vcol*L1; %Moment in k-in
    Dcol=1; %initial dimension of column for stress calc
    for q=1:9
        Depth=Dcol+(q-1)*.25; %depth of the column- increases from 1.5" to 3"
        Ccol=Depth/2; %c value in equation stress=M/I
        Stress(j,q)=Mcol*Ccol/I; %creates stress matrix with various column
depths, in ksi
    end
    Allowable (j,:)=35;
end

subplot (3,1,1)
plot (MomentInertia, period)
title('I (in^4) vs. Period- 1" plate')
xlabel('I (in^4)')
ylabel('Period (s)')

```

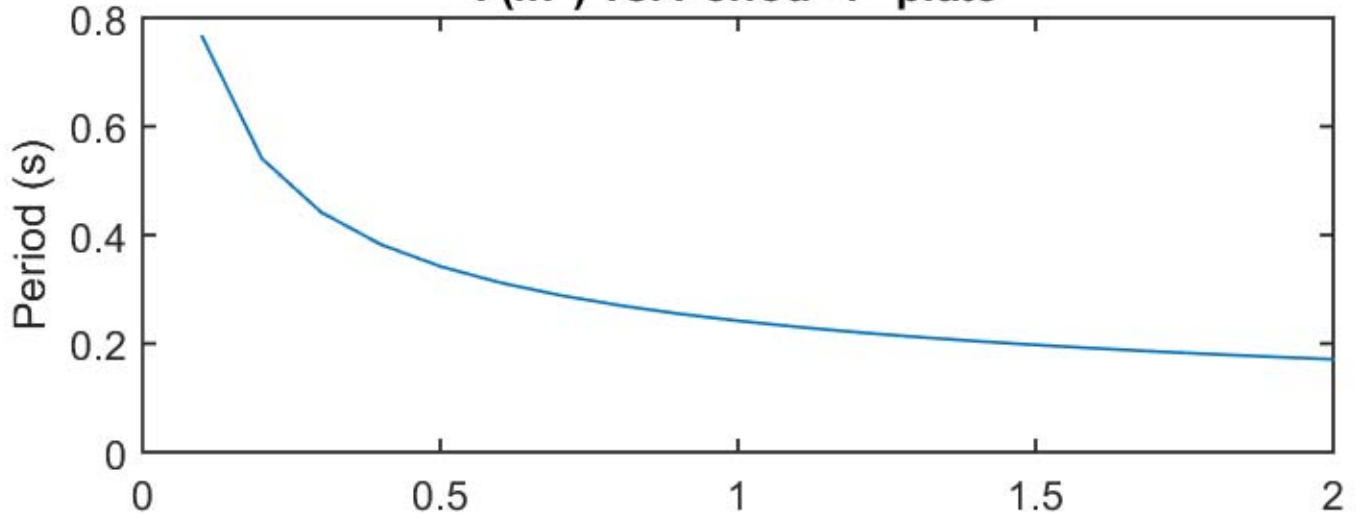
```
subplot (3,1,2)
plot (MomentInertia, displacement)
title('I (in^4) vs. Displacement')
xlabel('I (in^4)')
ylabel('Displacement (in)')

subplot (3,1,3)
plot (MomentInertia, Stress, MomentInertia, Allowable)
title('I (in^4) vs. Stress (ksi)')
xlabel('I (in^4)')
ylabel('Stress (ksi)')
legend('d=1.0', 'd=1.25', 'd=1.5', 'd=1.75', 'd=2', 'd=2.25', 'd=2.5', 'd=2.75', 'd=3')
%F=k*Umax;

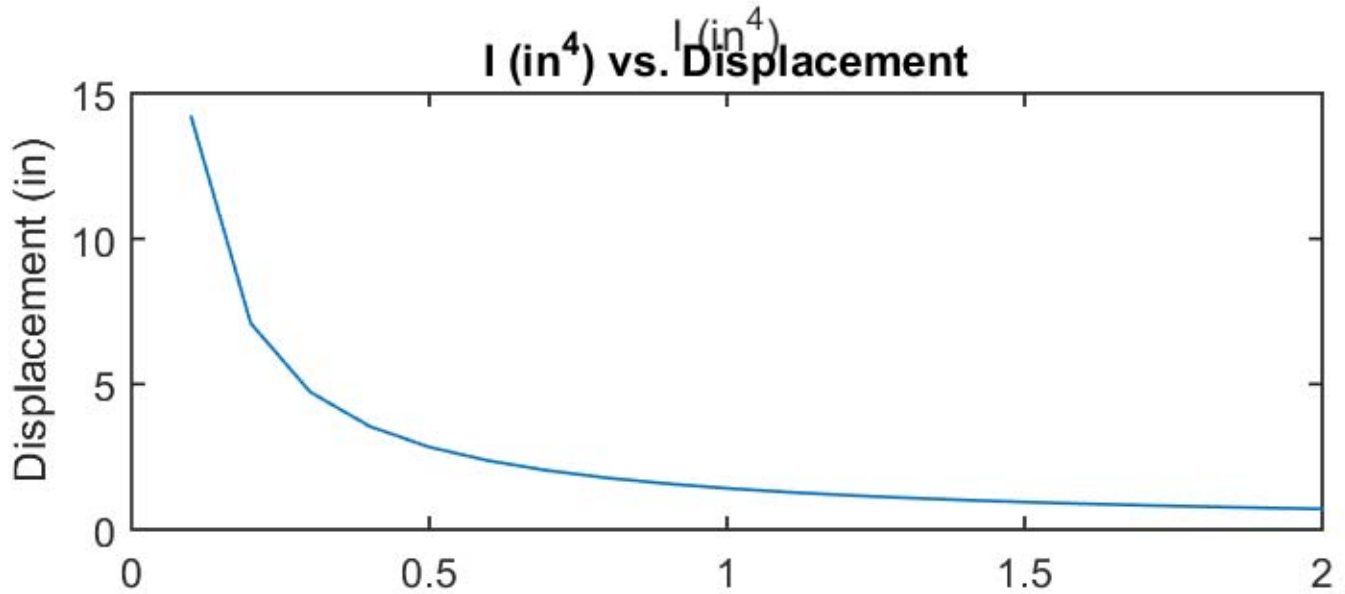
%v1=F(1,1)+F(2,1)+F(3,1)

%v2=F(2,1)
```

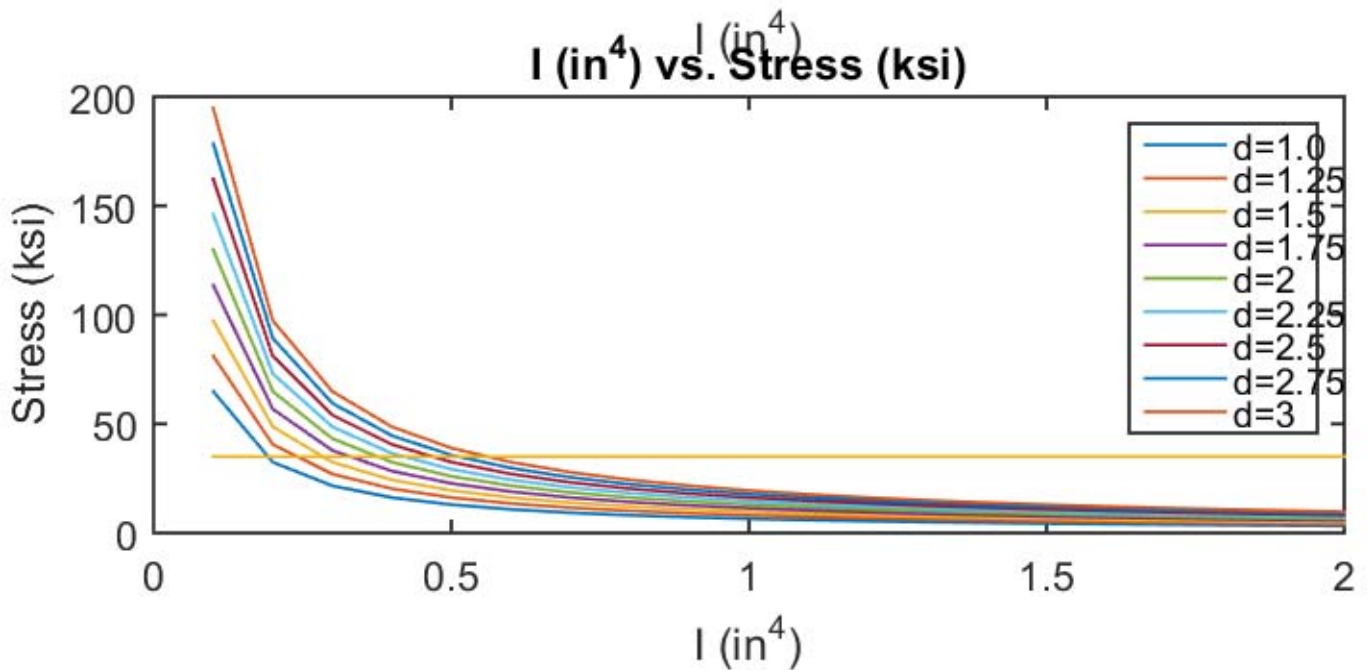
I (in⁴) vs. Period- 1" plate



I (in⁴) vs. Displacement



I (in⁴) vs. Stress (ksi)



```

%Brianna Kufa
%Alumodel Sr. Project
%Modal Analysis Code- periods by changing weight on each floor

format long
clear
clc

disp('Weak Axis, HSS 1.5" x 2" x .125"- 6061 T6 ')
E=10100 %in ksi
I=.244 %I for weak axis of HSS 2x1.5x1/8
t=(4)*3%stiffness modifier (4 cols) *__EI
g=386.4; %in in/s^2
A=2*g; %ground acceleration

L1=20%Height of each story
L2=32
L3=L2

k1=t*E*I/3/L1^3; %stiffness of each floor
k2=t*E*I/L2^3;
k3=t*E*I/L3^3;

k=[k1+k2, -k2,0;-k2,k2+k3,-k3;0,-k3,k3];%in k, in
L=[1;1;1]; % influence vector

Ts=.125; %steel plate thickness
d=40.8; %density of steel in lb/ft^2in

for j=1:8 %varies thickness of steel plate per floor to generate graph
    Tstl=Ts*j ;
    W=12*d*Tstl ;%weight of steel per floor (lbs)
    m1=W/386.4/1000*[1 0 0;0 1 0;0 0 1];% mass in k-s^2/in

    [phi lam]=eig(k,m1); %solves for eigenvalues

    w1=(lam(1,1))^0.5; %solves for natural frequencies
    w2=(lam(2,2))^0.5;
    w3=(lam(3,3))^0.5;

    T1=2*pi/w1; %Solves for periods
    T2=2*pi/w2;
    T3=2*pi/w3;

    D1=A/(w1^2); %Max displacements,
    D2=A/(w2^2);
    D3=A/(w3^2);

    phil=phi(:,1);

```

```

phi2=phi(:,2);
phi3=phi(:,3);

gamma1=phi1'*m1*L; % finds modal participation factor
gamma2=phi2'*m1*L;
gamma3=phi3'*m1*L;

gamma=phi'*m1*L;

q1=D1*gamma1;%calcs q's
q2=D2*gamma2;
q3=D3*gamma3;

q=[q1 q2 q3];

u1=phi1*q1;%converts back to real modal displacements
u2=phi2*q2;
u3=phi3*q3;

i=1;% counter for u's
ulmax=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5;%Finds max displacement per mode
i=2;
u2max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5;
i=3;
u3max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5;

Umax=[ulmax;u2max;u3max];
thickness(j,:)=Tst1;
period(j,:)=T1;
displacement(j,:)=u3max;
end
subplot(2,1,1)
plot(thickness, period)
title('Thickness vs. Period- Weak Axis, HSS 1.5" x 2" x .125"')
xlabel('Steel thickness (in)')
ylabel('Period (s)')

subplot(2,1,2)
plot(thickness, displacement)
title('Thickness vs. Displacement')
xlabel('Steel thickness (in)')
ylabel('Displacement (in)')

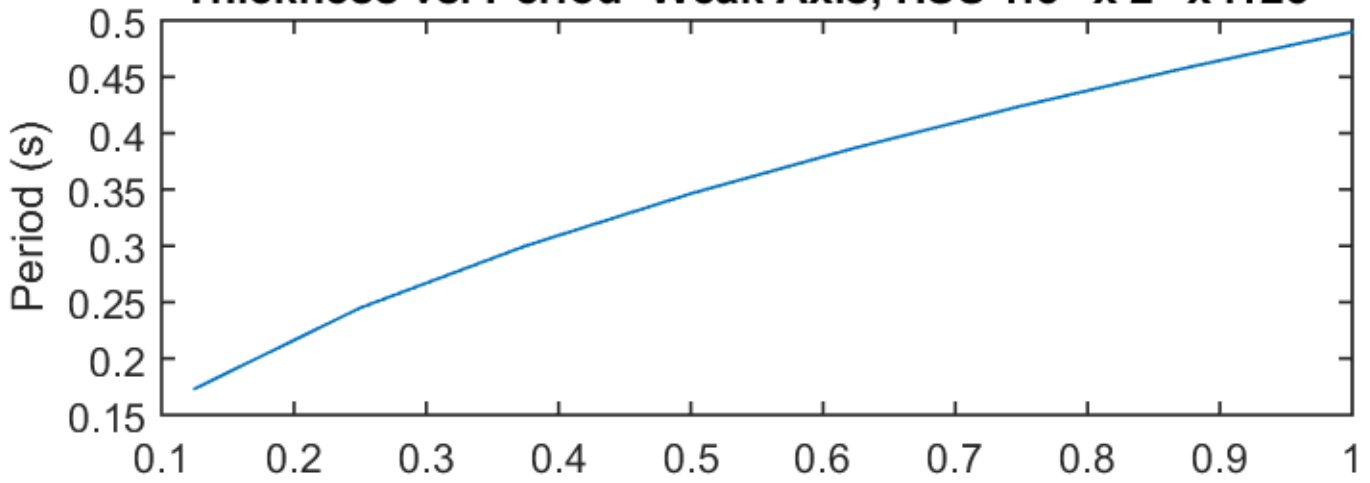
%F=k*Umax;

%v1=F(1,1)+F(2,1)+F(3,1);

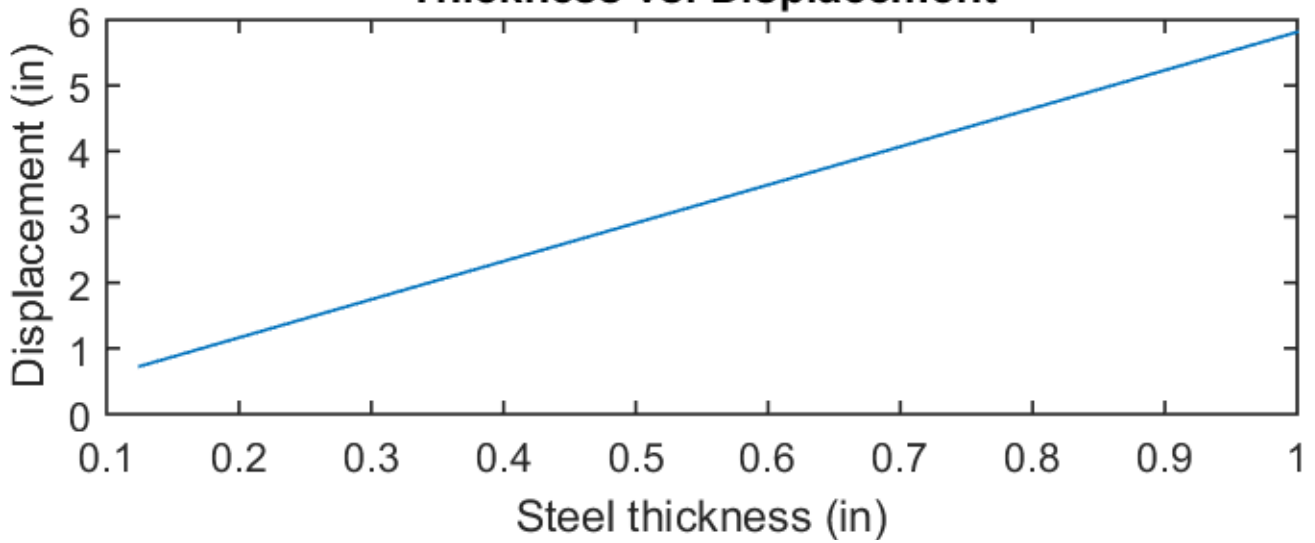
%v1=k1*ulmax;
%v2=F(2,1)

```

Thickness vs. Period- Weak Axis, HSS 1.5" x 2" x .125"



Thickness vs. Displacement




```
%Brianna Kufa
%Alumodel Sr. Project
%Modal Analysis Code

format long
clear
clc

disp('Strong Axis, HSS 1.5" x 2" x .125"- 6061 T6 ')
E=10100 %in ksi
I=.383%in^4
S=.383%in^3
Ts=1 %steel plate thickness (in)

g=386.4; %in in/s^2
A=2*g; %ground acceleration

t=4*3*E*I %temp variable for stiffness of columns. Now its 3EI/h^3 for 4 cols
L1=20 %first story ht
L2=32 %second story ht

k1=t/3/L1^3; %stiffness of first story
k2=t/L2^3;
k3=k2;

d=40.8; %density of steel in lb/ft^2in
W=12*d*Ts %weight of steel plate on each floor

k=[k1+k2, -k2,0;-k2,k2+k3,-k3;0,-k3,k3];% k, in
m1=W/386.4/1000*[1 0 0;0 1 0;0 0 1];% mass in k-s^2/in
L=[1;1;1]; % influence vector

[phi lam]=eig(k,m1); %solves for eigenvalues

w1=(lam(1,1))^0.5; %solves for natural frequencies
w2=(lam(2,2))^0.5;
w3=(lam(3,3))^0.5;

T1=2*pi/w1 %Solves for periods
T2=2*pi/w2
T3=2*pi/w3

D1=A/(w1^2); %Max displacements by mode
D2=A/(w2^2);
D3=A/(w3^2);

phi1=phi(:,1); %sets phi by mode
phi2=phi(:,2);
```

```

phi3=phi(:,3);

gamma1=phi1'*m1*L; % finds modal participation factor
gamma2=phi2'*m1*L;
gamma3=phi3'*m1*L;

gamma=phi'*m1*L;

q1=D1*gamma1;%calcs q's
q2=D2*gamma2;
q3=D3*gamma3;

q=[q1 q2 q3];

%Displacement Calcs
u1=phi1*q1 %Floor displacements by mode
u2=phi2*q2
u3=phi3*q3

u2_1=[u1(2,1)-u1(1,1) u2(2,1)-u2(1,1) u3(2,1)-u3(1,1)] %floor 2 displacements
relative to floor 1
u3_2=[u1(3,1)-u1(2,1) u2(3,1)-u2(2,1) u3(3,1)-u3(2,1)]%floor 2 displacements relative
to floor 1

i=1;% counter for u's
u1max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5%Finds max displacement per floor
i=2;
u2max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5
i=3;
u3max=((u1(i,1))^2+(u2(i,1))^2+(u3(i,1))^2)^.5

u2_1max=((u2_1(1,1))^2+(u2_1(1,2))^2+(u2_1(1,3))^2)^.5 %SRSS of floor 1-2 max
displacements
u3_2max=((u3_2(1,1))^2+(u3_2(1,2))^2+(u3_2(1,3))^2)^.5 %SRSS of floor 1-2 max
displacements

Umax=[u1max;u2max;u3max];

%Velocity Calculations
v1=w1*u1; %floor velocities mode 1
v2=w2*u2;%floor velocities mode 2
v3=w3*u3; %Floor velocities mode 3

VF1=[v1(1,1) v2(1,1) v3(1,1)] %Floor 1 velocities by mode (in/sec)
VF2=[v1(2,1)-v1(1,1) v2(2,1)-v2(1,1) v3(2,1)-v3(1,1)] %floor 2 velocities relative to
floor 1
VF3=[v1(3,1)-v1(2,1) v2(3,1)-v2(2,1) v3(3,1)-v3(2,1)] %floor 3 velocities relative to
floor2

V1srss=((VF1(1,1))^2+(VF1(1,2))^2+(VF1(1,3))^2)^.5 %SRSS of floor 1 velocities
V2srss=((VF2(1,1))^2+(VF2(1,2))^2+(VF2(1,3))^2)^.5 %srss of floor 2 velociites
V3srss=((VF3(1,1))^2+(VF3(1,2))^2+(VF3(1,3))^2)^.5 %srss of floor 2 velociites

```

```
Vb=((k1*u1(1,1))^2+(k1*u2(1,1))^2+(k1*u3(1,1))^2)^.5; %base shear

Vcol=Vb/4; %Base shear per column in k
Mcol=Vcol*L1; %Moment in k-in at top of bottom column

Stress=Mcol/S %stress at column
u3max

F=k*Umax; %Finds equivalent force on each floor
F/2;

%v1=F(1,1)
%v2=F(2,1)
```

Strong Axis, HSS 1.5" x 2" x .125"- 6061 T6

E =

10100

I =

0.3830000000000000

S =

0.3830000000000000

Ts =

1

t =

4.641960000000000e+04

L1 =

20

L2 =

32

W =

4.896000000000000e+02

T1 =

0.390953061239832

T2 =

0.142363653323813

T3 =

0.102029501529558

u2_1 =

1.512715353457626 -0.055996299577912 -0.074267434305227

u3_2 =

0.855137768570624 -0.217263445266564 0.053351486483184

u1max =

1.342353406613039

u2max =

2.848072786871932

u3max =

3.703590792274805

u2_1max =

1.515572161908212

u3_2max =

0.883917636997367

VF1 =

21.432963740262402 6.556573687740737 2.256635954462277

VF2 =

24.311539734841041 -2.471383099196639 -4.573540446959308

VF3 =

13.743309864508753 -9.588869456595688 3.285493616669508

V1srss =

22.526717449401030

V2srss =

24.861133741680455

V3srss =

17.076868910684809

Stress =

33.894423516979217

u3max =

3.703590792274805

>>

Modal Analysis summary for various sections- Weak Axis, from MATLAB

| | I | S | 1/2" Plates | | | | | 3/4" Plates | | | | | 1" Plates | | | | |
|------------------------|-------|-------|-------------|-------|-------|--------|-------|-------------|-------|-------|--------|-------|-----------|-------|-------|--------|-------|
| | | | T1 | T2 | T3 | Stress | Delta | T1 | T2 | T3 | Stress | Delta | T1 | T2 | T3 | Stress | Delta |
| HSS 2x 1.5 x 3/16 | | | 0.396 | 0.131 | | 21.9 | 3.6 | 0.485 | 0.16 | | 32.9 | 5.41 | 0.56 | 0.185 | | 43.9 | 7.22 |
| HSS2 1/2x1x3/16 | | | 0.59 | 0.19 | | 32.2 | 7.97 | 0.72 | 0.23 | | 48.45 | 11.96 | | | | | |
| HSS 2 1/2 x 1.5 x 3/16 | | | 0.353 | 0.116 | | 17.5 | 2.88 | 0.433 | 0.143 | | 26.2 | 4.32 | 0.5 | 0.165 | | 35 | 5.77 |
| HSS 2 1/2x1.5x1/4 | | | 0.332 | 0.109 | | 15.44 | 2.54 | 0.407 | 0.134 | | 23.2 | 3.81 | 0.47 | 0.16 | | 30.9 | 5.08 |
| HSS 2x1.5x1/4 | | | 0.341 | 0.112 | | 16.3 | 2.7 | 0.417 | 0.138 | | 24.4 | 4 | 0.481 | 0.159 | | 32.5 | 5.35 |
| HSS 1.5 x 3 x 1/8 | 0.355 | 0.474 | 0.288 | 0.105 | 0.075 | 13.69 | 2.017 | 0.353 | 0.128 | 0.092 | 20.54 | 3.02 | 0.408 | 0.148 | 0.106 | 27.38 | 4.03 |
| Etabs | | | | | | | | | | | | | 0.294 | 0.095 | 0.059 | | |
| HSS 1.5 x 2 x 1/8 | 0.244 | 0.325 | 0.346 | 0.126 | 0.09 | 19.97 | 2.9 | 0.424 | 0.154 | 0.111 | 29.95 | 4.36 | 0.49 | 0.178 | 0.128 | 39.94 | 5.81 |
| Etabs | | | | | | | | | | | | | 0.405 | 0.124 | 0.072 | | |

Selection

HSS 2" x 1.5" x 1/8", Thickness=1", weak axis

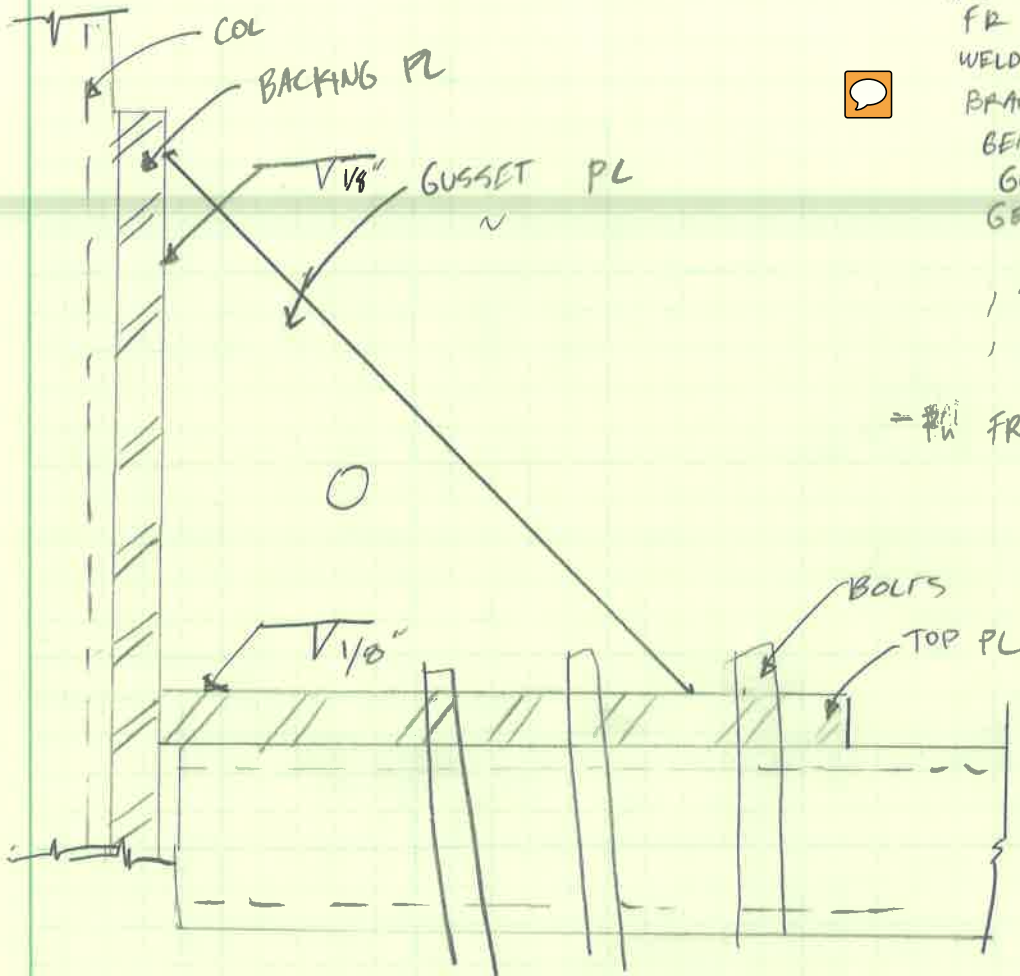
| | Mode 1 | Mode 2 | Mode 3 | SRSS |
|--------------------------------|---------------|---------------|---------------|-------------|
| Period (s) | 0.490 | 0.178 | 0.123 | - |
| Natural Frequency (1/s) | 2.04 | 5.62 | 8.13 | - |

| | | | | |
|----------------------------------|------|--------|--------|------|
| Floor 1 Displacement (in) | 2.09 | 0.233 | 0.057 | 2.11 |
| Floor 2 Displacement (in) | 4.47 | 0.145 | -0.059 | 4.47 |
| Floor 3 Displacement (in) | 5.81 | -0.196 | 0.024 | 5.81 |

| | | | | |
|---|------|--------|--------|------|
| Floor 1-2 relative displacement (in) | 2.37 | -0.088 | -0.117 | 2.38 |
| Floor 2-3 relative displacement (in) | 1.34 | -0.34 | 0.084 | 1.39 |

| | | | | |
|--------------------------------------|------|------|------|------|
| Floor 1 Velocities (in/s) | 26.9 | 8.21 | 2.83 | 28.2 |
| Floor 1-2 relative velocities | 30.5 | -3.1 | -5.7 | 31.1 |
| Floor 2-3 relative velocities | 17.2 | -12 | 4.1 | 21.4 |

FBD / DEMAND



- ASSUME MOMENT FR WILL GOVERN WELDS INSTEAD OF BRACED. BRACED GENERATES ~ 5K @ GUSSET. MOMENT GENERATES MUCH MORE



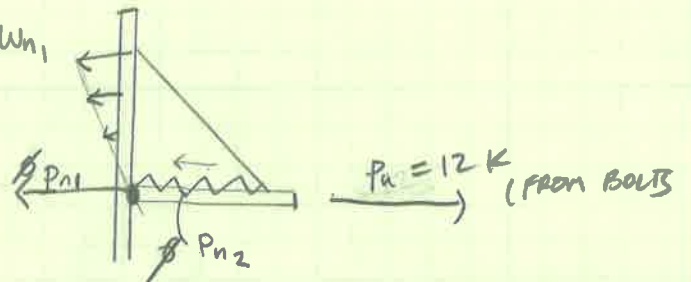
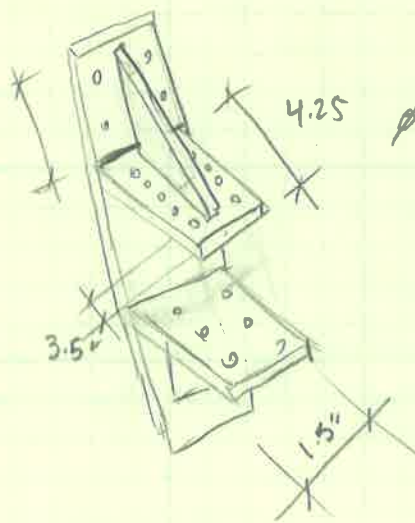
BRACE MOM

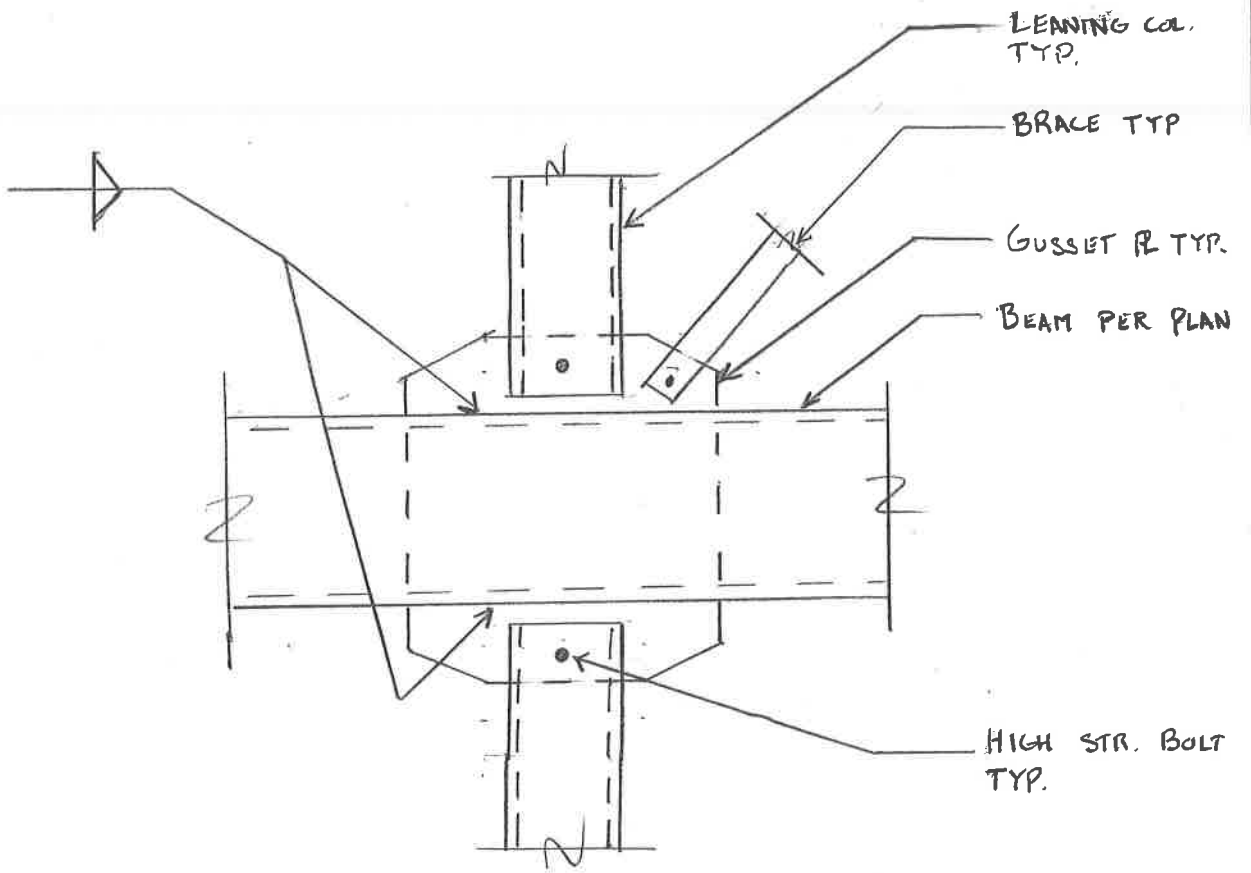


- P_u FROM BRACES ANALYSIS

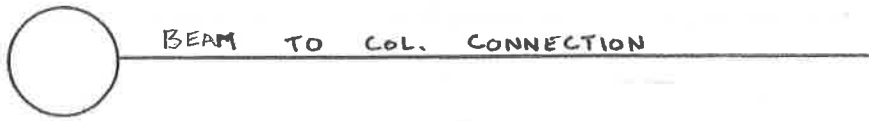
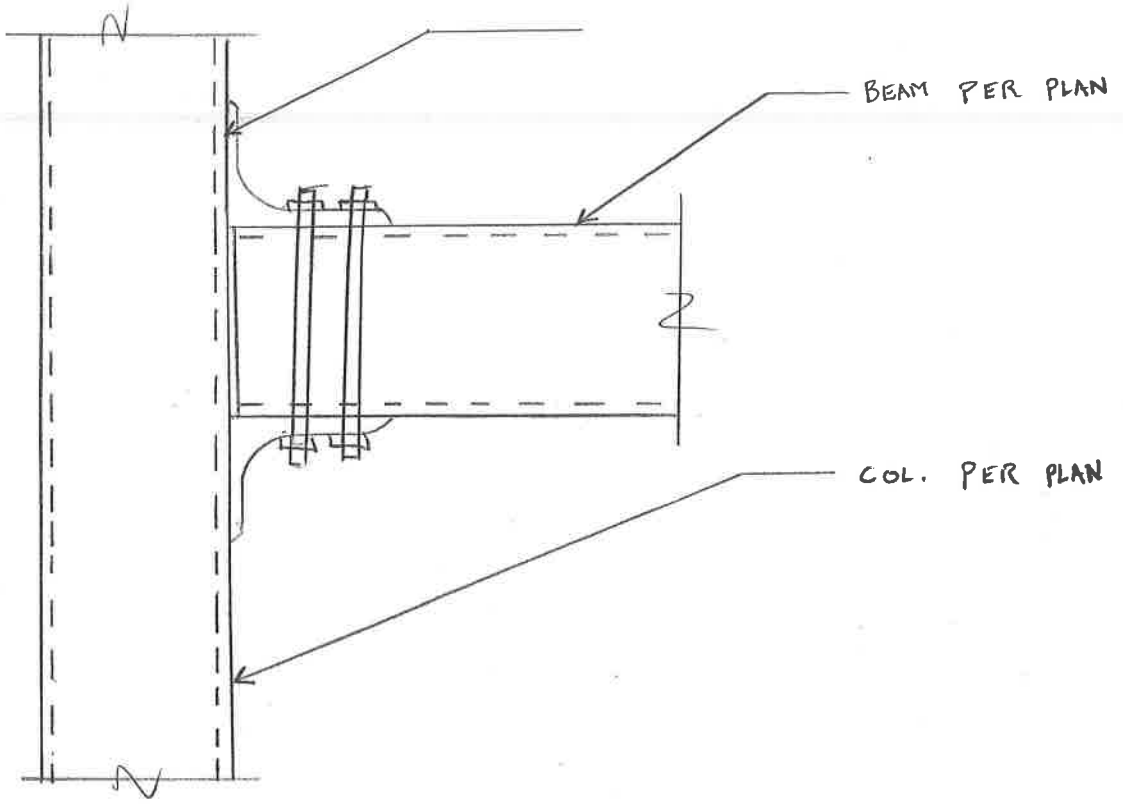
3D :

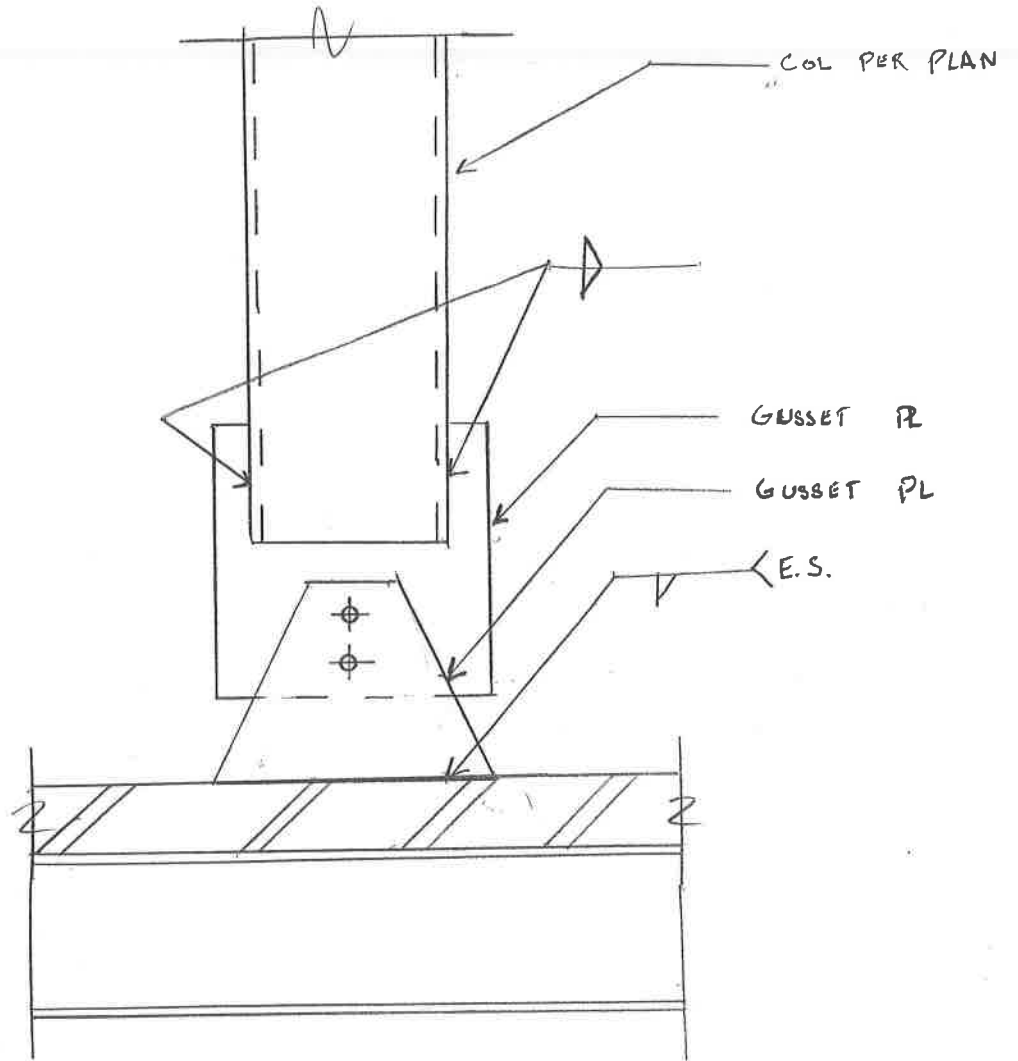
FBD





○ BEAM TO LEANING COL. CONNECTION





COL. TO BASE CONNECTION

STRENGTH OF ALUMINUM WELD PER LENGTH.

- ASSUME $F_y = 25 \text{ ksi}$ -- ALL WELDS ARE VERY WEAK

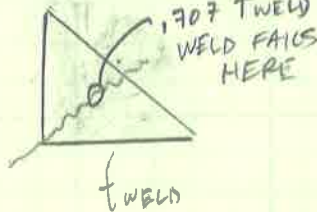
$$\phi R_n = F_n A_{WE} \phi$$

$$\phi = .75$$

$$F_n = .6 * F_y$$

← FACTOR FOR SHEAR FAILURE, ITS CONSERVATIVE. WE'LL ASSUME ALL WELDS IN TENSION HAVE THE SHR CAPACITY, EVEN THO ITS MORE

$$A_{WE} =$$



$$A_{WE} = .707 t_{WELD} * L$$

$$t_{WELD} = n * \frac{1}{16}''$$

$$n = \# \frac{1}{16} \text{ TH'S}$$

$$A_{WE} = .707 (n * \frac{1}{16}'') * L = .0442 n L$$

$$\phi R_n = \phi F_n A_{WE} \Rightarrow R_n = (.75 * .6 F_y) (.0442 n L)$$

$$\phi R_n = (.6 * 25 \text{ ksi}) * .0442 \text{ in} * n * L * .75$$

$$\phi R_n = .497 \text{ K/in} / \frac{1}{16}''$$

↓

$$\phi R_n = .5 \text{ K/in} / \frac{1}{16}'' \text{ WELD}$$

↓ 1/8" WELD

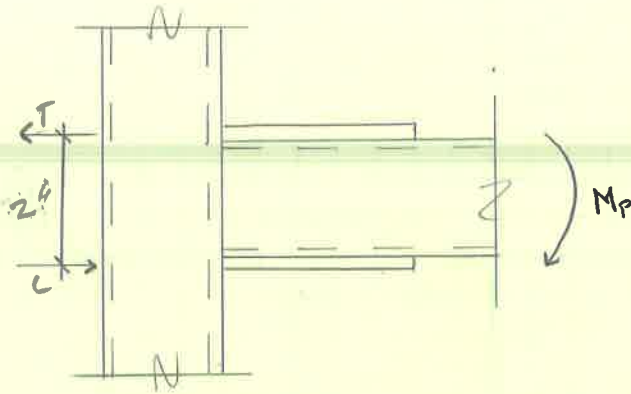
$$\phi R_n = .5 \text{ K/in} * (2) \frac{1}{16} \text{ TH WELD}$$

↓

$$\phi R_n = 1 \text{ K/in FOR } \frac{1}{8}'' \text{ WELD}$$

BLAKE REEVE

CAPACITY BASED DESIGN



$$Z_x = 0.816 \text{ in}^3$$

$$F_u = 48 \text{ KSI} \quad F_y = 35$$

$$\phi = 0.9$$

$$M_p = Z_x \cdot F_u \cdot \phi = 0.9 \cdot 48 \cdot 0.816 = 35.7 \text{ K-in}$$

$$\Omega = 1.2$$

$$M_p = 29.75 \text{ K-in}$$

$$T = C = \frac{29.75 \cdot 12}{2 \cdot 12} = 12.24 \text{ K}$$

$$T = C = 12.24 \text{ K}$$

USE $1/4"$ ϕ BOLTS

$$A_{\text{BEARING}} \cdot F_y \leq T$$

$$1/4 D \cdot 3 \cdot 35 \text{ KSI} = 4.16 \text{ K}$$

$$D_{\text{BOLT}} = .47"$$

$1/4"$ CAPACITY

$$= 1/4" \cdot 1/8" \cdot 35 \text{ KSI} = 1.09 \text{ K}$$

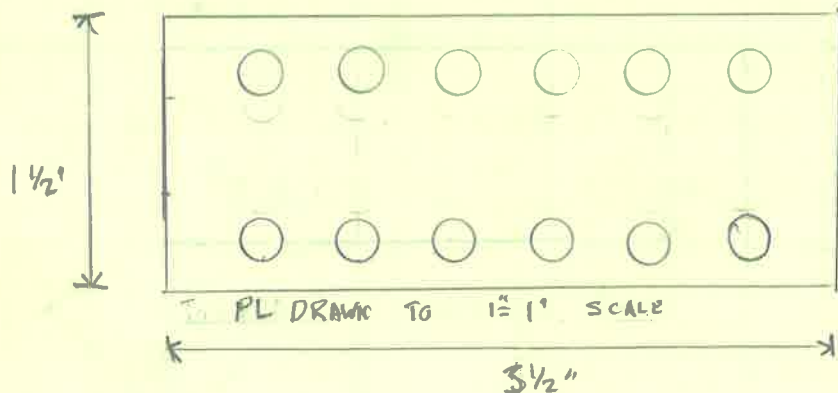
* BOLTS REQ.

$$\frac{12.24 \text{ K}}{1.09 \text{ K/bolt}} = 11.2 \text{ BOLTS} \rightarrow \text{USE 12 BOLTS}$$

PL THICKNESS CALC

$$(1.5 - 2(1/4" + 1/16")) \cdot t \cdot 48 \text{ KSI} \geq 12.24$$

$$t = 0.35" \approx 3/8"$$



Blake Reeve

4/29/16

HSS COL. - BM. MOMENT CONNECTION

$$Z_x = 0.475 \text{ in}^3$$

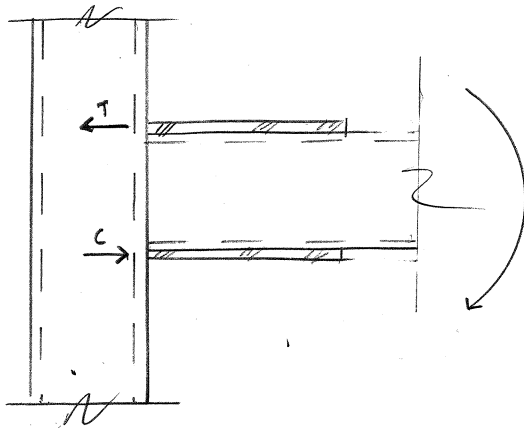
$$F_y = 35 \text{ ksi}$$

$$\Omega_o = 1.2$$

$$F_{ux} = 25 \text{ ksi}$$

$$f_u = 48 \text{ ksi}$$

$$M = Z_x \cdot F_y \cdot \Omega_o = 19.95 \text{ K-in}$$



DESIGN FOR BEARING

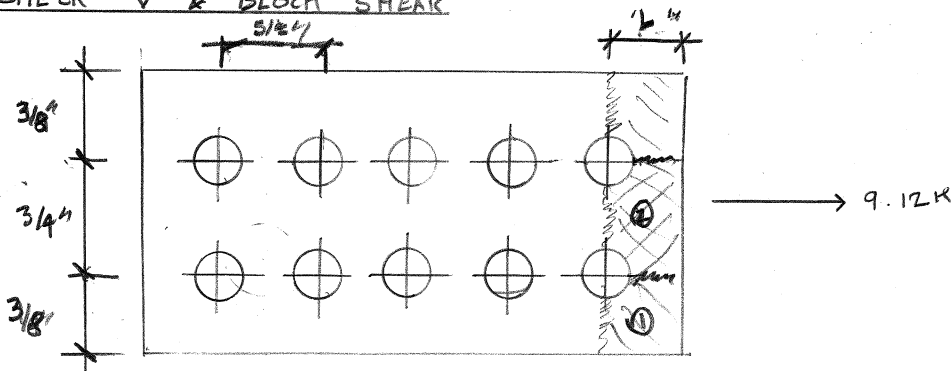
$$T = C = M/d = 19.95 \text{ K-in} / (2" + 3/16") = 9.12 \text{ K}$$

USE 1/4" Ø BOLTS

$$1/4" \cdot 1/8" \cdot \# \text{ BOLTS} \cdot 35 \text{ ksi} = 9.12 \text{ K}$$

$$\# \text{ BOLTS} = 8.3 \rightarrow \underline{10 \text{ BOLTS T \& B}}$$

CHECK V & BLOCK SHEAR



$$3/16" \cdot (2" - 2 \cdot (1/4" + 1/16")) \cdot 35 \text{ ksi} = 9.0 \text{ K} \approx 9.12 \text{ K}$$

BLOCK SHEAR

$$1/8" \cdot (2" - (1/4" + 1/16")) \cdot 2 \cdot 45 \text{ ksi} + 1/8" \cdot (3/4" - 1/4" - 1/16") \cdot (25 \text{ ksi}) = 9.12 \text{ K}$$

$$11.25 (2 - (1/4" + 1/16)) + 1.37 = 9.12 \text{ K}$$

LF 1"

42-381 50 SHEETS EYE-EASE® 5 SQUARES
 42-382 100 SHEETS EYE-EASE® 5 SQUARES
 42-383 200 SHEETS EYE-EASE® 5 SQUARES
 National Brand

CAPACITY - TO GUSSET PL + BACKING PL.

- USE $F_{WELD} = F_{WELD}$ FOR SHR
- $F_{WELD} = 1 \text{ k/in}$ FOR $1/8"$ WELD

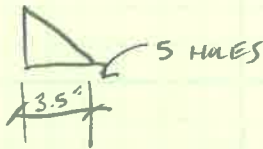
 ϕP_{n1}

$$\phi P_{n1} = F_{WELD} * L_{WELD} = 1 \text{ k/in} * 1.5 \text{ in} \Rightarrow \phi P_{n1} = 1.5 \text{ k}$$

 ϕP_{n2}

- DON'T WELD FOR $3/8"$ @ EACH HOLE

$$\therefore L_{WELD} = 3.5" - 3/8" * 5 \text{ HOLES} = 1.625" * 2 \text{ SIDES} = 3.25" \text{ WELD}$$



$$\phi P_{n2} = F_{WELD} * L_{WELD} = 1 \text{ k/in} * 3.25" = 3.25 \text{ k}$$

TOTAL

$$\phi(P_{n1} + P_{n2}) = 1.5 \text{ k} + 3.25 \text{ k} = 4.75 \text{ k} \ll P_u = 12 \text{ k}! \quad \text{FIND } L_{NEEDED} \text{ @ GUSSET}$$

DEMAND TO GUSSET

$$\phi P_{n2} = P_u - \phi P_{n1} = 12 \text{ k} - 1.5 \text{ k} = 10.5 \text{ k}$$

$$\phi P_{n2} = F_w L_w \Rightarrow L_w = \phi P_{n2} / F_w \Rightarrow L_w = \frac{10.5 \text{ k}}{1 \text{ k/in}}$$

$$L_{REQ} = 10.5 \text{ k.} \quad \text{OH NO. } \text{☹}$$

SOLUTION (POSSIBLY)

WE CAN MAKE $1/4"$ WELD @ P_1 , \checkmark + WELD BOTH SIDES
 SINCE BOTH PLATES $\geq 1/4"$ THK
 - USE $3/16$ GUSSET INSTEAD ϕ $3/16"$ WELD THERE

$$\phi P_{n1} = 0.5 \text{ k/in} / 1/16" * 4 \text{ } 1/16" \text{ TH'S} * 15" + 2 \text{ SIDES} \Rightarrow \phi P_{n1} = 6 \text{ k}$$

$$L_{REQ 2} = \frac{(12 \text{ k} - 6 \text{ k})}{0.5 \text{ k/in} * 3 \text{ } 1/16" \text{ TH'S} * 2 \text{ SIDES}} \Rightarrow L_{2 REQ} = 2" < L_{HAVE} = 3.25$$



BLAKE REEVE

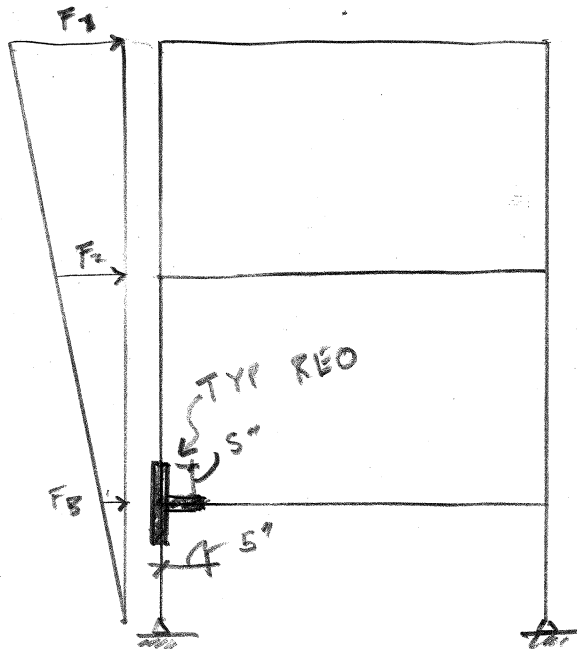
04/28/16

PUSHOVER

WEAK AXIS COL

$$F_2 = \frac{52}{84} F_1$$

$$F_3 = \frac{20}{84} F_1$$



$$Z_x = \frac{1.5 \cdot 2^2}{4} - \frac{1.25 \cdot 1.75^2}{4}$$

$$Z_x = 0.5429 \text{ in}^3$$

$$Z_y = \frac{2 \cdot 1.6^2}{4} - \frac{1.75 \cdot 1.25^2}{4}$$

$$Z_y = 0.44 \text{ in}^3$$

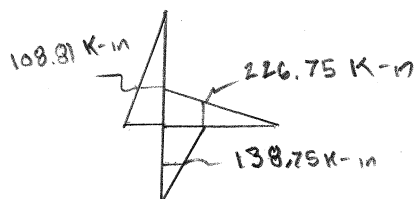
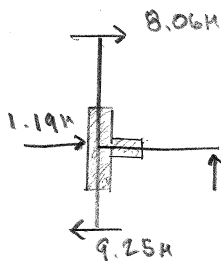
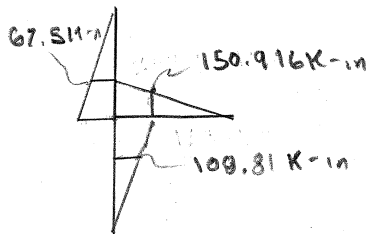
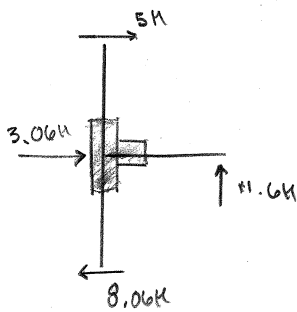
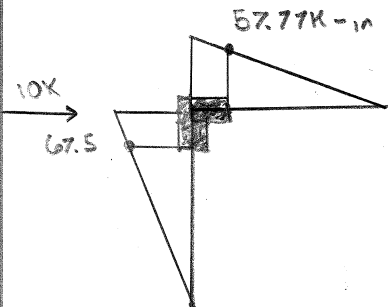
$$M_{px} = 30 \text{ ksi} \cdot 0.5429 \text{ in}^3$$

$$M_{px} = 16.287 \text{ K-in}$$

$$M_{py} = 30 \text{ ksi} \cdot 0.44 \text{ in}^3$$

$$M_{py} = 13.2 \text{ K-in}$$

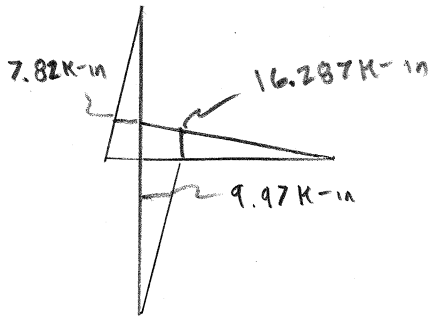
$$F_y \approx 30 \text{ ksi (FROM TESTING)}$$



42-391 50 SHEETS EYE-GLASS® - 5 SQUARES
 42-392 100 SHEETS EYE-GLASS® - 5 SQUARES
 42-393 200 SHEETS EYE-GLASS® - 5 SQUARES
 National Brand

SOLVE FOR V

FIRST FLOOR BM YIELDS FIRST BY INSPECTION



$$V = \frac{9.97K-in}{20"} = 0.4985K$$

$$V_{TOT} = 0.4985K \cdot 4 \text{ COL} = \underline{1.994K}$$

NOTE: ROOF COL WILL YIELD BEFORE BEAM

LAST YIELD

$$\sum M \ominus = \sum P \Delta$$

$$84 \cdot F \cdot \cancel{\phi} = 2 M_p \cancel{\phi} \longrightarrow F = 0.314K$$

$$F \cdot \frac{52}{84} \cdot \cancel{\phi} = 2 M_p \cancel{\phi} \longrightarrow F = 1.012K$$

$$F \cdot \frac{20}{84} \cdot \cancel{\phi} = 2 M_p \cancel{\phi} \longrightarrow F = 6.84K$$

$$\sum F = 8.165K$$

Appendix C- MATLAB Earthquake Analysis

```

% Peter Laursen
% Modified by Blake Reeve
% MDOF response history analysis

clear all
clc
format compact
format short

disp('FVT Research, 3 story frame 3 Dof, mdof solver, EQ ground motion')
g = 386.4; %in/s2

if 1==1
    load elcentro.dat %load El Centro record
    uddg = [elcentro']*g;
    deltt = 0.02
    t = 0:deltt:deltt*(length(uddg)-1);
else
    uddg0 = 0.5*g
    deltt = 0.1
    t = 0:deltt:1
    uddg = uddg0*sin(2*pi()*t) %single sine wave
end

if 1==1
% 3 story moment frame 3 DOF, CM
    n = 3
    L1=23.5 %first story height
    L2=32 %2nd and 3rd story height
    E=10100 %in ksi
    I=.438%in^4

    stiff=4*3*E*I %placeholder for stiffness calculation
    k1=stiff/3/L1^3; % First floor stiffness
    k2=stiff/L2^3; % second floor stiffness
    k3=k2; % 3rd floor stiffness)

    K=[k1+k2,-k2,0;
        -k2,k2+k3,-k3;
        0,-k3,k3]
    Ts1=.5; %steel plate thickness Floor 1
    Ts2=.5; %steel plate thickness Floor 2
    Ts3=.5; %steel plate thickness Floor 3
    d=40.8; %density of steel in lb/ft^2in
    g=386.4; %in in/s^2
    W1 = 12*d*Ts1 %floor 1 weight
    W2 = 12*d*Ts2;%floor 2 weight
    W3 = 12*d*Ts3; %floor 3 weight
    Wtotal = W1+W2+W3;
    M = zeros(n,n);

```

```

M(1,1) = (W1/g);
M(2,2) = (W2/g);
M(3,3) = (W3/g);
L = [1;1;1]
else
    % 5 story shear building (Chopra)
    n = 5
    m = 100/g;
    M = m*eye(5)
    k = 100;
    K = k*[ 2 -1 0 0 0;
           -1 2 -1 0 0;
           0 -1 2 -1 0;
           0 0 -1 2 -1;
           0 0 0 -1 1]
    L = [1;1;1;1;1]
end

[Phi omega] = eig(K,M);
for i = 1:n
    wn(i) = sqrt(omega(i,i));
end
% sort modeshapes by order of lowest to highest frequency
[wn iwn] = sort(wn);
Phi = Phi(:,iwn);
for i = 1:n
    T(i) = 2*pi()/wn(i);
    f(i) = 1/T(i);
end
Phi, wn, T, f

%Rayleigh damping of modes q and r
% NOTE: C may be comprised by any combination of modal, Rayleigh and
% discrete damping.
zeta = 0.039
q = 1;
r = 2;
a0 = zeta*(2*wn(q)*wn(r))/(wn(q)+wn(r));
a1 = zeta*(2)/(wn(q)+wn(r));
Cdamp=[1,0,0;
       0,1,0;
       0,0,1]
C = a0*M + a1*K
%Cn = Phi'*C*Phi

% mdof modal analysis with non-classical damping
%input
p = -M*L*uddg;
u0 = zeros(n,1);
ud0 = zeros(n,1);

```

```
% solve problem by newmarks method (average 1/2 & 1/4; linear 1/2 & 1/6
modes = 3 %number of lowest modes considered, use total dof for small problems
gamma = 1/2
beta = 1/4
[u,ud,udd,D] = newmark_mdof_modified(M,C,K,p,delt,u0,ud0,Phi,modes,gamma,beta);
%q,u

%peak values
for i = 1:n
upeak(i,1) = max(abs(u(i,:)));
udpeak(i,1) = max(abs(ud(i,:)));
end
upeak

close all
figure(1)
hold on
for i = 1:n
subplot(n,1,i)
hold on
plot(t,u(i,:), 'linestyle','- ', 'color','black')
v = [0 max(t) 0 0];
plot([v(1) v(2)], [v(3) v(4)], 'k-'); % plot the horizontal line through y = 0
%plot([v(1) v(2)], [0 0], 'k-'); % plot the horizontal line through y = 0
titletext = ['u' num2str(i) ' modes 1-' num2str(modes) ' of ' num2str(n)];
title(titletext, 'FontSize',12, 'FontWeight', 'bold', 'Color', 'black')
xlabel('t [sec]')
ylabel('u [in or rad]')
end
%{
figure(2)
hold on
for i = 1:modes
subplot(modes,1,i)
hold on
plot(t,q(i,:), 'linestyle','- ', 'color','black')
v = [0 max(t) 0 0];
plot([v(1) v(2)], [v(3) v(4)], 'k-'); % plot the horizontal line through y = 0
%plot([v(1) v(2)], [0 0], 'k-'); % plot the horizontal line through y = 0
titletext = ['q' num2str(i) ' modes 1-' num2str(modes) ' of ' num2str(n)];
title(titletext, 'FontSize',12, 'FontWeight', 'bold', 'Color', 'black')
xlabel('t [sec]')
ylabel('q [-]')
end
%}
```

```

% Peter Laursen
% Modified by Blake Reeve
% MDOF response history analysis
% Newmark Linear/Average Acceleration method
%*** Input
% M, C, K: real stiffness, damping and stiffness matrices
% NOTES: M, C, K are constant
%       C may be fully populated (non-classical damping)
% p, delt: real load vector, time step
% u0, ud0, real initial displacement and velocity vectors
% Phi, modes: Mode shape matrix
% modes: number of modes to be considered for analysis (1 to modes)
% gamma/beta: average 1/2 & 1/4; linear 1/2 & 1/6
%*** Output
% u, ud, udd: real displacement, velocity and acceleration response vectors
% q, qd, qdd: modal displacement, velocity and acc response vectors

function [u, ud, udd,D] = newmark_mdof(M,C,K,p,delt,u0,ud0,Phi,modes,gamma,beta)
[dof,n] = size(p); %number of elements in load vector
Phin = Phi(:,1:modes); %reduced number of modes considered

%modal stiffnes, damping and mass matrices
Mn = M;
Cn = C;
Kn = K;

u = zeros(dof,n); %initialize variables
ud = zeros(dof,n);
udd = zeros(dof,n);

d = zeros(dof,n);
q(:,1) = M*u0; %initial conditions
qd(:,1) = M*ud0;
Pn0 = p(:,1); %load at t = 0
u(:,1) = u0;
ud(:,1) = ud0;
udd(:,1) = inv(Mn)*(Pn0 - Cn*ud(:,1) - Kn*u(:,1));

D(:,1)=u0;

a1 = Mn/(beta*delt^2) + gamma*Cn/(beta*delt);
a2 = Mn/(beta*delt) + ((gamma/beta)-1)*Cn;
a3 = ((1/(2*beta))-1)*Mn + delt*((gamma/(2*beta))-1)*Cn;
Kh = Kn + a1;
Khin = inv(Kh);

for i = 1:n-1

    D1 = Damper(55,12*(ud(1,i))); %Damper Force output on First Floor
    D2 = Damper(60,12*(ud(2,i)-ud(1,i))); %Damper Force output on Second Floor
    D3 = Damper(60,12*(ud(3,i)-ud(2,i))); %Damper Force output on Third Floor

```

```
d(1,i)= D2-D1;
d(2,i)= D3-D2;
d(3,i)= D3;
Ph = p(:,i+1) - d(:,i) + a1*u(:,i) + a2*ud(:,i) + a3*udd(:,i);
u(:,i+1) = Khinv*Ph;
ud(:,i+1) = (gamma/(beta*delt))*(u(:,i+1)-u(:,i))+(1-(gamma/beta))*ud(:,i)+delt*(1-
(gamma/(2*beta)))*udd(:,i);
udd(:,i+1) = (1/(beta*delt^2))*(u(:,i+1)-u(:,i))-(1/(beta*delt))*ud(:,i)-((1/
(2*beta))-1)*udd(:,i);
```

end

end


```
function [ F ] = Damper( theta,ud )
% Blake Reeve
% Damper Output Force determination
% To Be Used With Newmark Linear/Average Acceleration method
%*** Input
% Angle Damper is Set At,Relative Horizontal Velocity per Floor
%*** Output
% Horizontal Force Output By the Damper "F"

Fmax = 667.7/1000;           %max output force from damper guide in kips

V=(cosd(theta)^2)*ud;      %finds velocity along damper

if(V<0)                    %implys the damper is in compression

    if(V<55.1)             %checks to be sure the damper doesnt reach its max output
force
        F = ((0.4715*abs(V)^2)-1.6203*abs(V))/1000;
        if (F<0)          %ensures the damper cannot add force to the structure
            F=0;
        end
    else
        F = Fmax;
    end
end

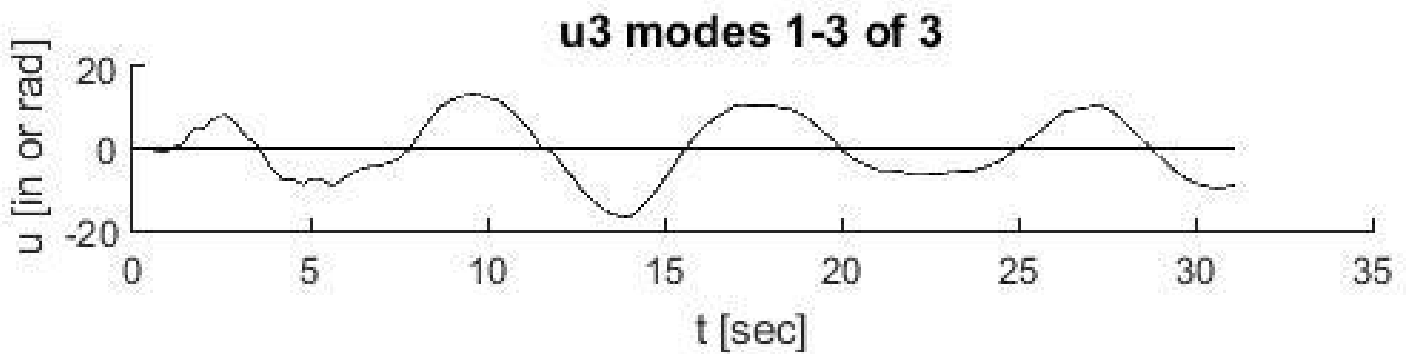
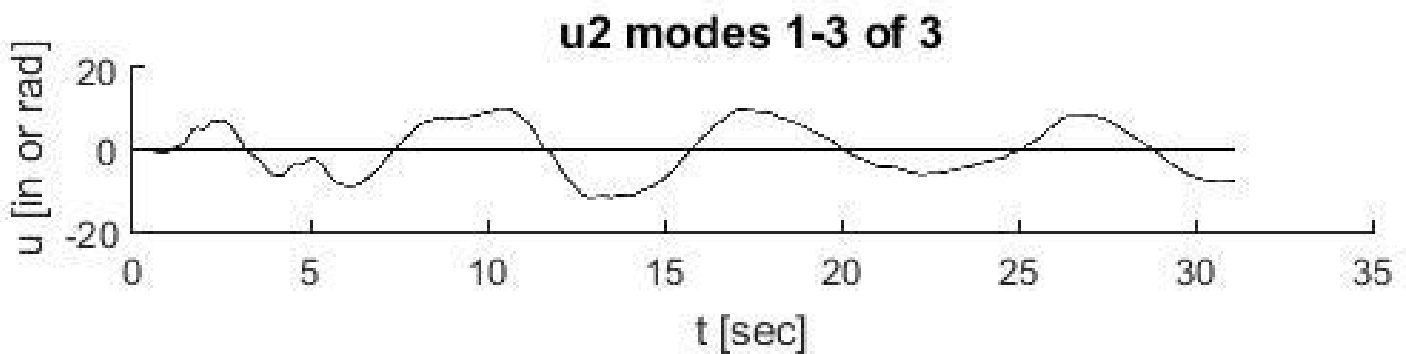
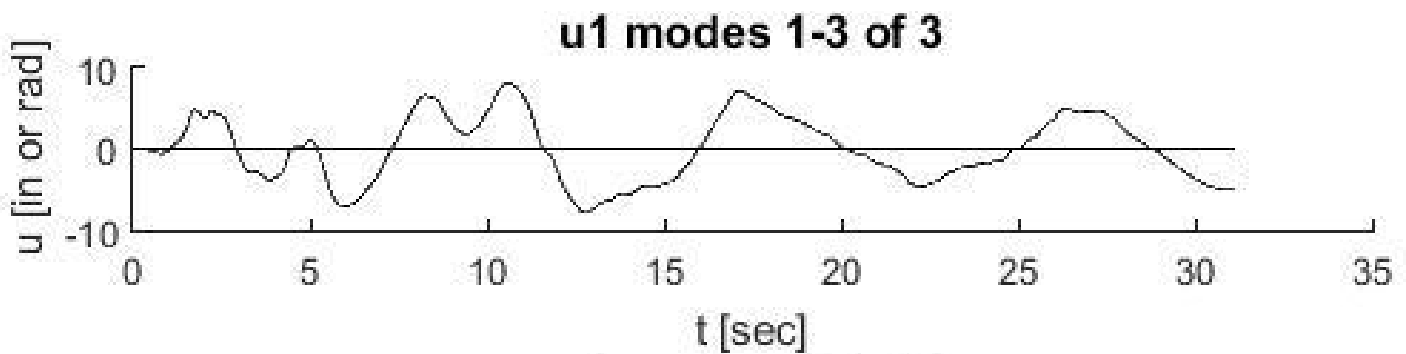
if(V>=0)                  %implys the damper is in tension
    if(abs(V)<39.37)       %checks to be sure the damper doesnt reach its max output
force
        F = ((0.2331*abs(V)^2)-0.7486*abs(V))/1000;
        if (F<0)         %ensures the damper cannot add force to the structure
            F=0;
        end
    else
        F = Fmax;
    end
end
end
```

FVT Research, 3 story frame 3 Dof, mdof solver, EQ ground motion

```
delt =
    0.0200
n =
    3
L1 =
    23.5000
L2 =
    32
E =
    10100
I =
    0.4380
stiff =
    5.3086e+04
K =
    2.9835   -1.6200     0
   -1.6200    3.2401   -1.6200
     0   -1.6200    1.6200
W1 =
    244.8000
L =
     1
     1
     1
Phi =
   -0.4479    0.9414   -0.7011
   -0.7445    0.3523    0.9487
   -0.9074   -0.7537   -0.4323
wn =
    0.6776    1.9371    2.8582
T =
    9.2732    3.2436    2.1983
f =
    0.1078    0.3083    0.4549
zeta =
    0.0390
Cdamp =
     1     0     0
     0     1     0
     0     0     1
C =
    0.1138   -0.0483     0
   -0.0483    0.1215   -0.0483
     0   -0.0483    0.0731
modes =
     3
gamma =
    0.5000
beta =
    0.2500
```

Output Without
Dampers

```
upeak =  
    8.5307  
   12.3362  
   17.9024  
>>
```

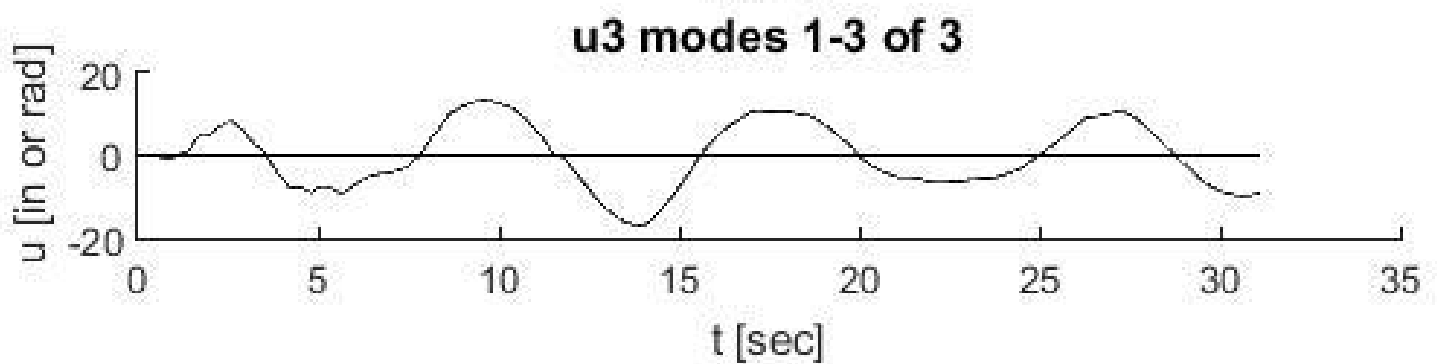
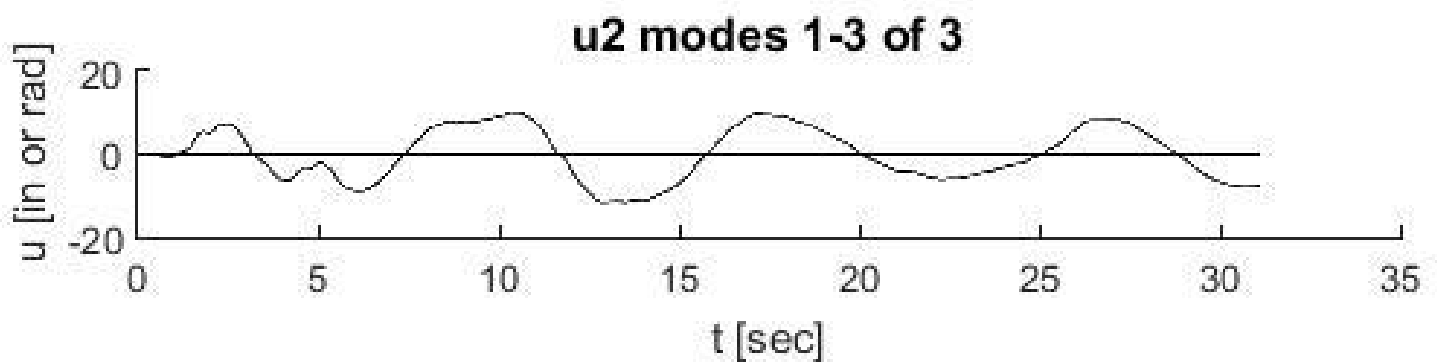
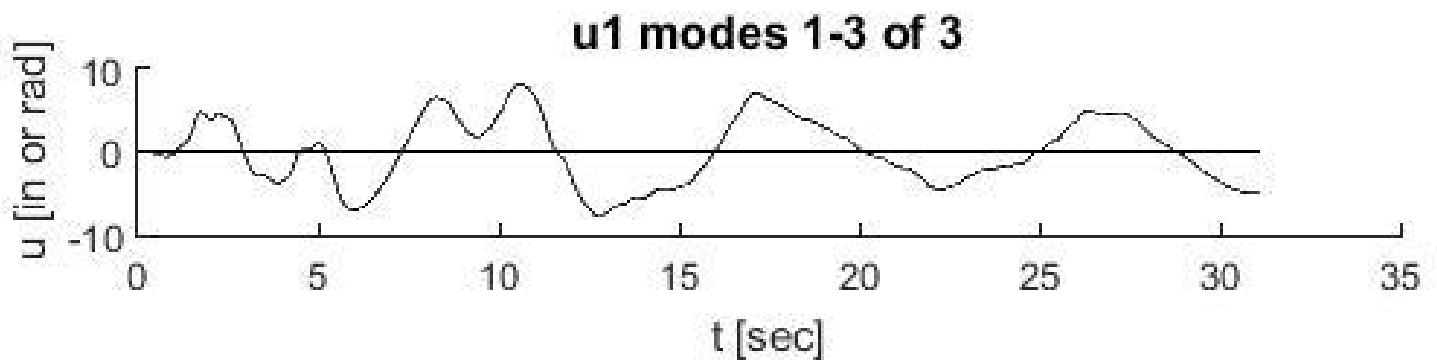


FVT Research, 3 story frame 3 Dof, mdof solver, EQ ground motion

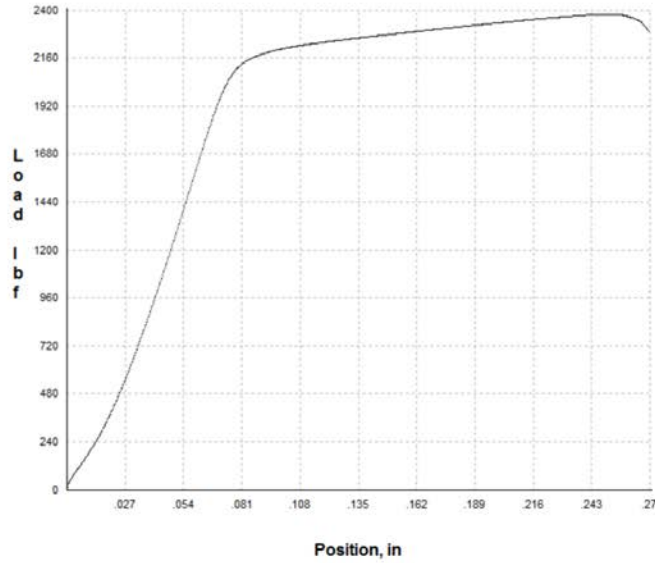
```
delt =
    0.0200
n =
    3
L1 =
    23.5000
L2 =
    32
E =
    10100
I =
    0.4380
stiff =
    5.3086e+04
K =
    2.9835   -1.6200     0
   -1.6200    3.2401   -1.6200
     0   -1.6200    1.6200
W1 =
    244.8000
L =
     1
     1
     1
Phi =
   -0.4479    0.9414   -0.7011
   -0.7445    0.3523    0.9487
   -0.9074   -0.7537   -0.4323
wn =
    0.6776    1.9371    2.8582
T =
    9.2732    3.2436    2.1983
f =
    0.1078    0.3083    0.4549
zeta =
    0.0390
Cdamp =
     1     0     0
     0     1     0
     0     0     1
C =
    0.1138   -0.0483     0
   -0.0483    0.1215   -0.0483
     0   -0.0483    0.0731
modes =
     3
gamma =
    0.5000
beta =
    0.2500
```

Output With
Dampers

```
upeak =  
    8.1635  
   11.6338  
   16.8953  
>>
```



Appendix D- Material and Component Testing Analysis



California Poly Technical University
 Building 21, Room 110
 San Luis Obispo, CA 93407

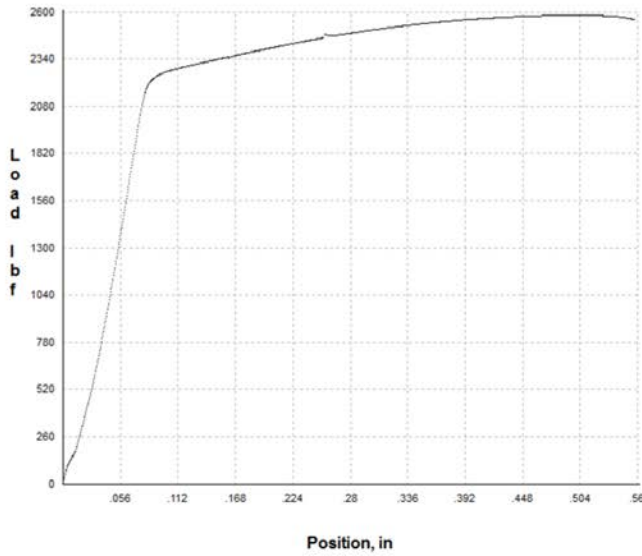
Lot Number:
 Operator:

Test Setting: Metals Tensile w/ Ext. 100S or 100RS
 Test Date: 01/22/2016

Sample: Aluminum
 Sample No.: 1
 Width, in: 0.501
 Thickness, in: 0.122
 Area, in²: 0.0611
 Ultimate, lbf: 2380
 Ultimate, ksi: 38.9
 Initial Gage, in: 2
 Final Gage, in: 2.1
 TE, in/in: 0.0481
 TE, in/in: 0.0481

Jan 22, 2016 3:46:41 PM SN: 217965-R0 V7 02 06

Aluminum Materials Testing:



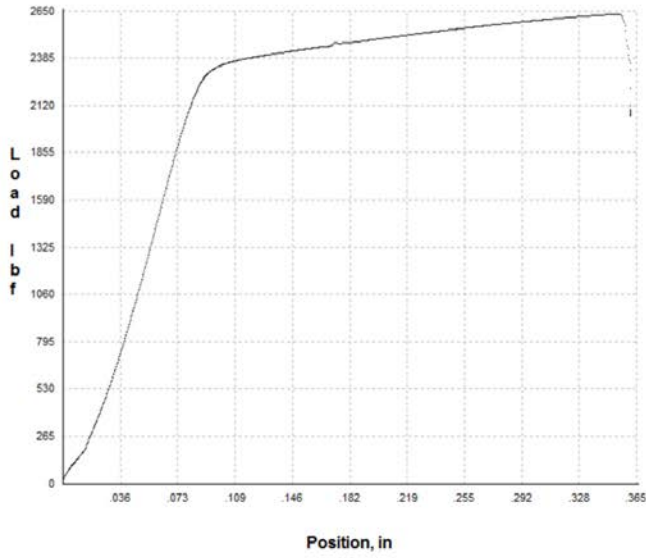
California Poly Technical University
 Building 21, Room 110
 San Luis Obispo, CA 93407

Lot Number:
 Operator:

Test Setting: Metals Tensile w/ Ext. 100S or 100RS
 Test Date: 01/22/2016

Sample: Aluminum
 Sample No.: 2
 Width, in: 0.5
 Thickness, in: 0.1245
 Area, in²: 0.0622
 Ultimate, lbf: 2580
 Ultimate, ksi: 41.5
 Initial Gage, in: 2
 Final Gage, in: 2.27
 TE, in/in: 0.1367
 TE, in/in: 0.1367

Jan 22, 2016 3:54:55 PM SN: 217965-R0 V7 02 06

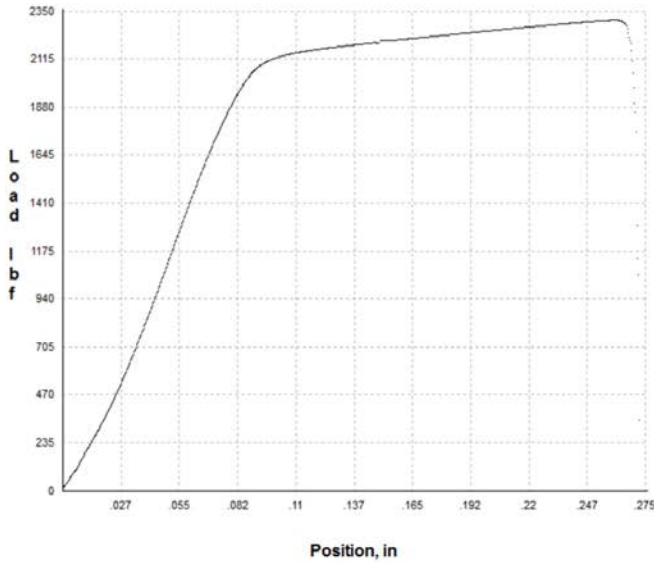


California Poly Technical University
 Building 21, Room 110
 San Luis Obispo, CA 93407

Lot Number:
 Operator:

Test Setting: Metals Tensile w/ Ext. 100S or 100RS
 Test Date: 01/22/2016

Sample: Aluminum
 Sample No.: 3
 Width, in: 0.506
 Thickness, in: 0.125
 Area, in²: 0.0632
 Ultimate, lbf: 2630
 Ultimate, ksi: 41.6
 Initial Gage, in: 2
 Final Gage, in: 2.13
 TE, in/in: 0.0672
 TE, in/in: 0.0672

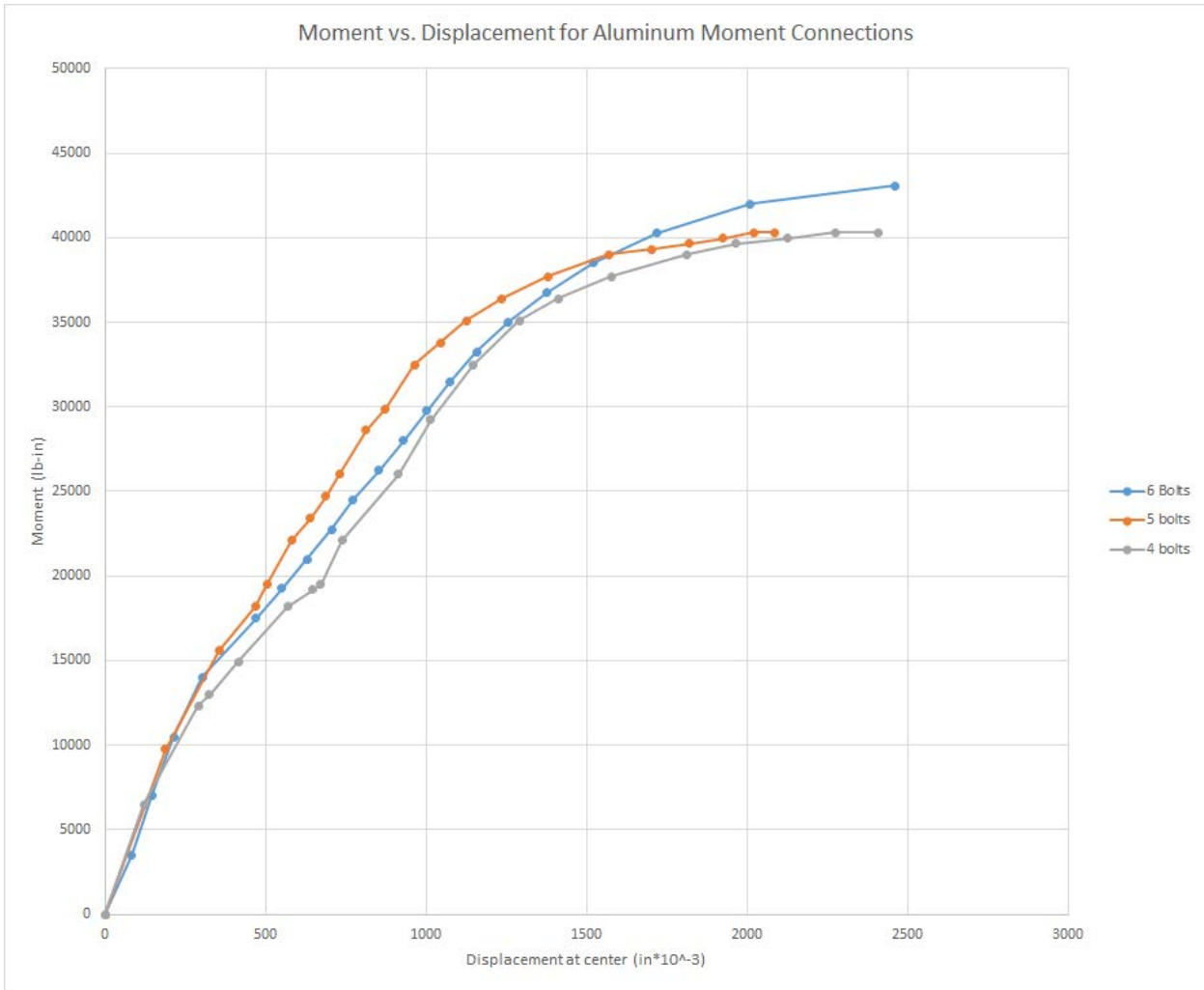


California Poly Technical University
 Building 21, Room 110
 San Luis Obispo, CA 93407

Lot Number:
 Operator:

Test Setting: Metals Tensile w/ Ext. 100S or 100RS
 Test Date: 01/22/2016

Sample: Aluminum
 Sample No.: 4
 Width, in: 0.485
 Thickness, in: 0.115
 Area, in²: 0.0558
 Ultimate, lbf: 2310
 Ultimate, ksi: 41.4
 Initial Gage, in: 2
 Final Gage, in: 2.09
 TE, in/in: 0.0437
 TE, in/in: 0.0437



Test data for bolted moment connection capacities:

Appendix E- Post Testing Analysis Calculations

BLAKE REEVE

04/29/16

1 STORY STIFFNESS

$$K_{\text{EXPECTED}} = 4.4238 \text{ K-IN}$$

SNAPBACK

$$\omega_{\text{EXPERIMENTAL}} = 17.9 \text{ HZ}$$

$$M = 175 \text{ lbs} / (1000 \cdot 386.4) = 4.5289 \times 10^{-4}$$

$$\omega = \sqrt{K/M} \longrightarrow 17.9 \text{ HZ} = \sqrt{K/M}$$

112.5 RAD/S

$$K_{\text{EXP}} = 5.73 \text{ K/IN} \longleftarrow \text{FROM SNAPBACK}$$

SHAKE TABLE

$$\omega_{\text{EXPERIMENTAL}} = 14.92 \text{ HZ}$$

$$M = 4.5289 \times 10^{-4}$$

$$\omega = \sqrt{K/M} \longrightarrow 93.745 \text{ RAD/S} = \sqrt{K/M}$$

$$K = 3.980 \text{ K/IN} \longleftarrow \text{FROM SHAKING}$$

$$\frac{K_{\text{EXP}} - K_{\text{PRE}}}{K_{\text{EXP}}} = 0.100 \approx 10\% \text{ ERROR}$$

OK TO PROCEED

SNAP BACK TEST DID NOT RECEIVE LARGE DISP.
 USE SIN SWEEP FROM TABLE TO DET. K &
 SNAPBACK TO DET. EFFECTIVE DAMPING

BLAKE REEVE

04/29/16

E CALC

SEE SECTION 2.2 PG 50 OF CHOPRA

$$T_D = \frac{T_n}{\sqrt{1-E}}$$

$$T_n = 0.0670 \leftarrow \text{FROM TABLE}$$

$$T_D = 0.0558 \leftarrow \text{FROM SNAB BACK}$$

$$0.0558 = \frac{0.0670}{\sqrt{1-E^2}}$$

$$1.2007 = \sqrt{1-E^2}$$

$$1.4917 = 1-E^2$$

$$\sqrt{-.4917} = E \rightarrow E = 0.664? \quad \underline{\text{DOESNT MAKE SENSE}}$$

SECTION 2.2.3 CHOPRA

$$\ln \frac{U_1}{U_2} = \frac{2\pi E}{\sqrt{1-E^2}} \quad \text{EQ 2.2.10}$$

$$U_1 = 0.065817 \quad \Rightarrow \quad T = 1.3635$$

$$U_2 = 0.052584 \quad \Rightarrow \quad T = 1.4715$$

$$\ln \left(\frac{0.065817}{0.052584} \right) = \frac{2\pi E}{\sqrt{1-E^2}}$$

$$0.035724917 = \frac{E}{\sqrt{1-E^2}}$$

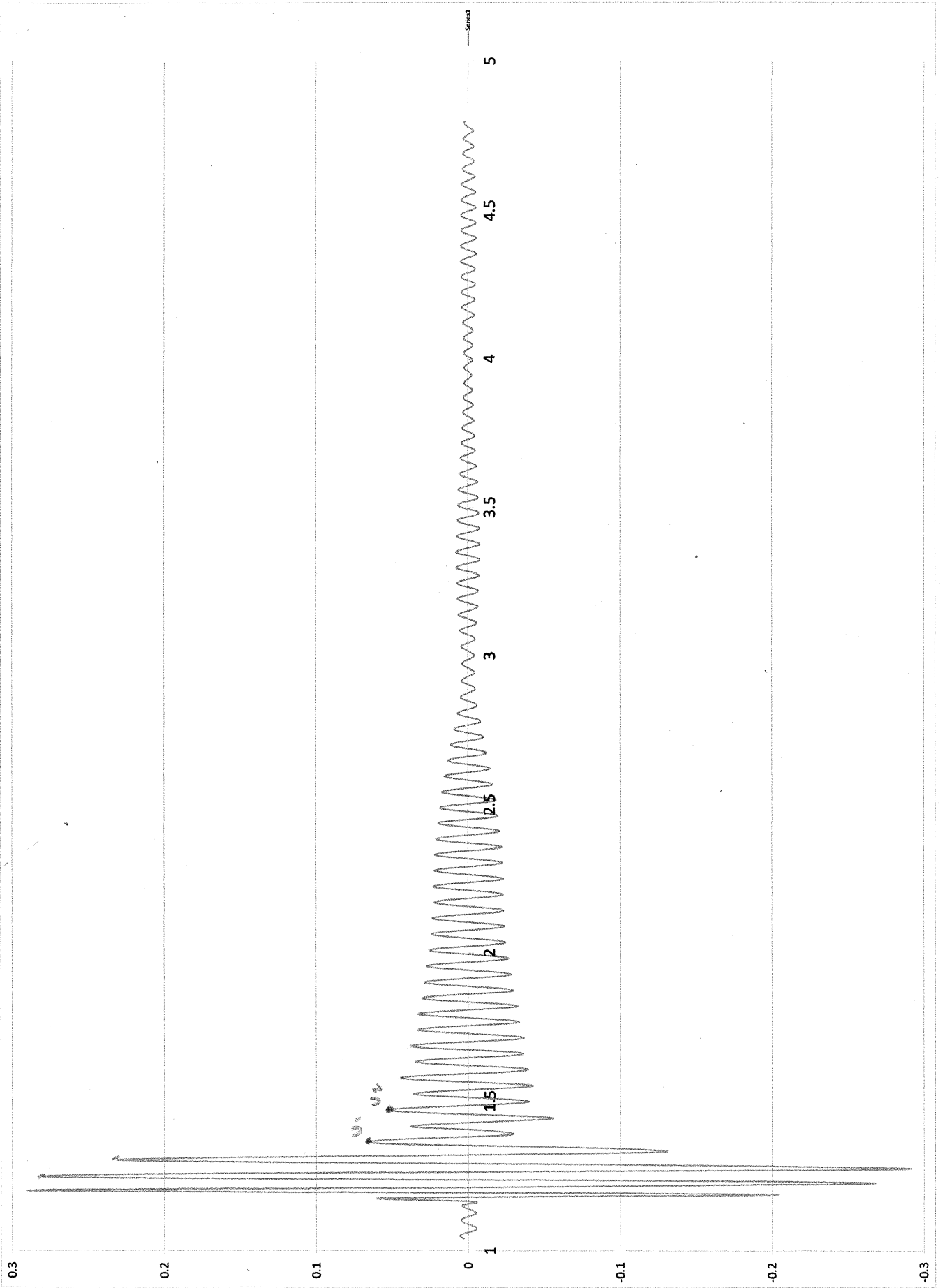
$$1-E^2 = \left(\frac{E}{0.035724917} \right)^2$$

$$1 = \left(\frac{E}{0.035724917} \right)^2 + E^2$$

$$1 = \frac{E}{0.035724917} + E$$

$$1 = 28.99 E$$

$$E = 0.0345 \rightarrow 3.45\%$$



Blake Reeve

06/08/16

3 STORY STIFFNESS

$K_{\text{expected}} = 1.26 \text{ K/in}$
GLOBAL

MODE SHAPE EXPECTED
(1st only)

| |
|------|
| 1 |
| 1.65 |
| 2.01 |

EXPECTED FREQUENCY = 4.17 Hz

EXPERIMENTAL FREQUENCY = 4.62 Hz =

| ACCELERATION VALUES | 1st FLOOR | 242.91 m |
|---------------------|-----------|----------|
| | 2nd | 397.07 m |
| | 3rd | 483.89 m |

note: m = milli g

NORMALIZED MODE SHAPE
(1st only)

| MODE SHAPE | 1st | 2nd | 3rd |
|------------|-----|-------|--------|
| | 1 | 1.63 | 1.99 |
| % ERROR | 0 | 1.2 % | 0.99 % |

FREQUENCY ERROR = 9.74 %

ADDITIONAL TESTING REQUIRED TO OBTAIN STIFFNESS

Supplement #1- Mechanical Engineering Report

A Damped Interactive, Reconfigurable, Multi-Story Model
A Multidisciplinary Senior Project



Design & Development Process of the Components Engineered by the Team's Mechanical Engineers

Aden Malek Stephanians
Sophie Ratkovich
Advisor: Dr. Andrew Davol
3/15/2016

Senior Project: Design & Development Process of the Components Engineered by the Team's Mechanical Engineers

1. Introduction
2. System Description
3. Manufacturing
4. Calculations & Analysis
5. Appendices
 - Appendix A: Damper Excel Sheet
 - Appendix B: Clevis Fatigue Hand Calculations
 - Appendix C: Clevis Fatigue Matlab Calculations
 - Appendix D: Exterior Clevis Detail Drawing
 - Appendix E: Interior Clevis Detail Drawing
 - Appendix F: FEA of Exterior Clevis
 - Appendix G: Interior Rod End Detail Drawings
 - Appendix H: Exterior Rod End Detail Drawings
 - Appendix I: Plug Calculations
 - Appendix J: Plug Detail Drawing
 - Appendix K: Interior Clevis Calculations

Senior Project

FALL QUARTER OBJECTIVES COMPLETED

Mechanical Engineering:

- Design and selection of passive viscous damping device

Architectural Engineering:

- Design.
- Bolted moment frame connection design.
- ETABS model creation.
- Performed pushover analysis using ETABS supplemented by hand calculations
- Risa 2D model creation to confirm member stresses remain elastic.
- MatLab calculations to confirm ETABS results and RISA 2D results.
- Revit model creation to provide floorplans.

WINTER QUARTER OBJECTIVES COMPLETED:

Mechanical Engineering:

- Design and manufacture of clevises for leaning column connections.
- Design and manufacture of clevises for exterior column connections.
- Design and selection of rod ends for leaning column connections.
- Design and selection of rod ends for exterior column connections.
- Fatigue analysis of clevises for infinite life prediction

Architectural Engineering:

- Baseplate thickness and connection calculations.
- Bolted moment frame connection testing.
- Perform tensile test on aluminum section to confirm yield and ultimate stresses
- Fabrication of Model.
- MatLab calculations including damping matrix.
- Update Etabs model to include damping devices.

Introduction

To better understand and research building behavior with supplemental damping devices, our multi-disciplinary team plans to design and fabricate an interactive, reconfigurable, multi-story model of a building. This building structure will be dynamically tested and analyzed using the ARCE Department's seismic shake table. Students will work together to test the structure under a variety of conditions and compare the findings with predictions from computer models.

A 3-story, 7' tall model, with a 3' x 4' footprint was chosen for the model, to accommodate size limitations of the seismic shake table. Each floor will have removable steel weights, with a capacity of up to 500 lbs per floor, to allow for experimentation with multiple mass configurations. The table has a single horizontal degree of freedom that can simulate various earthquake ground motions, as well as motions programmed by students. The seismic lab also has accelerometers and strain gauges that can be applied to the model to detect the real-time motions and forces in the members. The data from these devices will be compiled and analyzed by students to interpret the effectiveness of damping the model.

Aluminum tubing was chosen for the majority of the structural elements, bolted steel connections were chosen for the necessary "moment" connections, and clevises were chosen to simulate "pinned" connections. The model will be connected to a steel base plate, which will bolt to the shake table. Viscous fluid dampers, were chosen as the supplemental dampers. The connections are being designed to allow multiple bracing and damper configurations, spanning diagonally in each bay, for maximum versatility.

System Descriptions

Dampers

The purpose of the dampers is to reduce the structure's vibration to aid in the building performance when confronted with transient vibrations. This is meant to prevent the resulting damage of a seismic shock by dissipating the energy produced. The maximum acceleration the structure will ever see is twice the force of gravity (2gs). The Architectural Engineers modeled the structure using MatLab and Etabs programs, providing the Mechanical Engineers with a modal and velocity analysis. This data was used to do a vibrations analysis in Excel and to find the maximum forces the dampers would see and the damping constant. The tables used for these calculations are attached in **Appendix A**.

The damping constants presented in the tables of appendix B were calculated using the equation:

$$\text{Damping Constant } (C) = 2 * \zeta * \omega * \text{mass}$$

Where zeta (ζ) is the percent damping we want to achieve, ω is the frequency produced by the shake table, and the mass is the mass of the floor. Using the damping constant we are able to calculate the damping force the damper can produce by using the equation:

$$\text{Force} = \text{Damping Constant } (C) * \text{Floor Velocity } (v)$$

We were given the values for the floor velocities from the Architectural Engineers who obtained them using Etabs from a modal analysis on the building.

While these values could be correct in theory, they will be different during experiments. The issue stems from the over simplification of our damping model. To fully understand how our dampers will impact the structure we would have to construct a complicated mass damper model. The model would take into account the behavior of the different materials used to build the structure and how they interact with one another and with the damper. In our case we assumed the dampers would directly provide the percent damping we calculated to our building. In practice this percent damping will depend on the materials used, the impact of one floor weight on another, the orientation, angle and number of dampers on each floor. Another point to consider is the addition of torsion, which we neglected in our calculations, that will be produced when the structure is excited. While the goal was to make every part of the building the same, there will be sections that weigh more than another causing the structure to experience torsional deformation.

Clevises

Clevises were designed to be used with spherical rod ends at the base of the columns as pinned connections. The interior leaning column base connections will see a maximum vertical force of 5000 lbf. The interior columns are connected to clevises made from A36 steel and welded to the base plate. These clevises are made from plates of steel welded together to form the clevis. Detailed drawings of the plates are found in **appendix E** and the completed interior clevises can be seen in figure 1 below. These welds were $\frac{1}{4}$ " fillet welds using an E70xx electrode. A fatigue analysis of the welds is provided in **appendix K**.



Figure 1: Completed interior clevis welded to the baseplate.

The exterior column base connections will see a maximum horizontal force of 750 lbf in addition to the maximum vertical force of 5000 lbf. A fatigue analysis was done by hand to determine infinite life of the clevises with a factor of safety of 5. The exterior corner clevises are machined from A 36 steel. The hand calculations are attached as **Appendix B**. These calculations show that with a factor of safety of 5, the exterior clevises are not sufficient. Matlab was used to reanalyze the clevises with factors of safety of 3. At a factor of safety of 3, the exterior clevises can last infinite life at full loading. As mentioned before, our calculations were extremely conservative even before adding the safety factor of 5, so a safety factor of 3 was a reasonable change to make to the design requirements.

The Matlab code is attached as **Appendix C**. The textbook Shigley's Mechanical Engineering Design was referenced to do this infinite life fatigue analysis. For all the analyses we made extremely conservative assumptions for the calculations, for example, the fatigue analysis for the exterior clevises was calculated assuming all four exterior clevises would experience the maximum vertical and horizontal forces at once, which will likely never be the case. Detailed drawings of both the interior and exterior clevises can be found in **Appendix D** and **Appendix E**.

The fatigue-life analysis of the exterior clevises was calculated at the interior corners of the clevises which are the areas that we know to be the most likely to fail and will experience the most stress. Using notch sensitivity and the geometric stress concentration factor, an allowable stress was calculated

and compared to the yield strength of the material. The strength-life curve derived from the MatLab analysis is provided in figure 2 below.

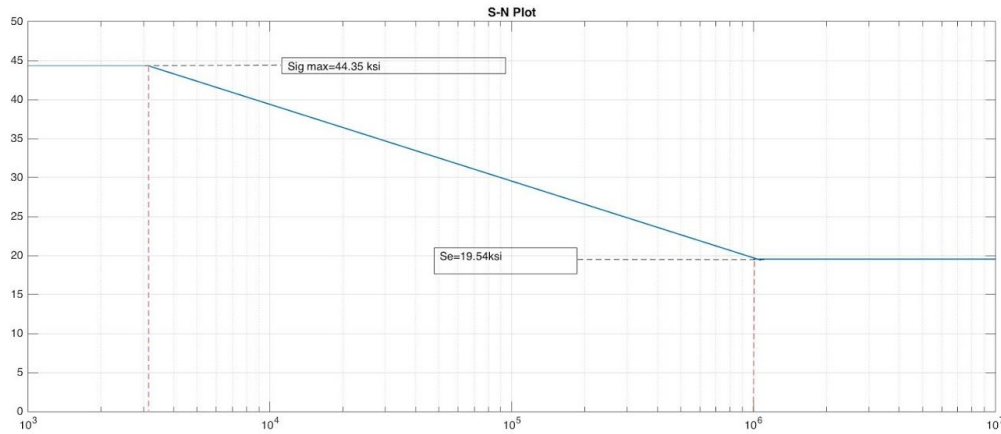


Figure 2: S-N Plot for Exterior Clevis Fatigue Analysis

Rod Ends

The spherical rod ends were designed and selected from the McMaster-Carr selection of spherical rod ends. The rod ends chosen needed to be small, male threaded rod ends that will be connected to the column ends and pinned to the clevises with a clevis pin. The interior leaning columns have 1/2" rod ends and the exterior corner columns have 3/4" rod ends at the base. The detail drawings for each rod end are attached in **Appendix G** and **Appendix H**.

Plugs

The 3/4" rod ends connected to the exterior clevises needed to be secured to the base of the exterior columns. A steel insert or "plug" was designed for this purpose. The steel insert was machined out of stock A36 steel bars and slipped into the base of the exterior aluminum columns. The steel insert was secured to the column with six 3/8" bolts. The bottom face of the plug is threaded with a 3/4"-16 thread, 1 3/4" long for the exterior rod end to be secured. The plug design is shown in **appendix J**. A bearing stress analysis was completed to determine the diameter and number of bolts required to support the load and the steel plugs in the aluminum columns. This analysis is attached in **appendix I**.

Manufacturing

Plugs

Although the plugs were of a simple design, manufacturing them was perhaps the cause of the largest set backs on the mechanical side of this project. Initially we had planned for two days of machining for the plugs. It took about 4 full days. The final plug design can be seen in appendix J. The plugs were to be manufactured from an A36 steel bar with dimensions 18"x1.75"x1.5". The stock for the clevises was the exact same aside from a small difference in dimensions. The bar stock for the clevises was 18"x2.0"x3.0". On the first day machining, we decided it would be easiest to cut the material for the clevises in half to more easily machine the parts. We used a vertical band saw to cut the bar stock down the center and began facing one side of the material down to size. It wasn't until about an hour into using the mill to face the material that we realized we were machining the plug material, not the clevis material. This could have been a huge disaster and a very careless mistake. Luckily we needed to face that exact side of the material anyway for the plug design, so we spent the rest of the first day on the plugs. We continued facing the same side of the bar stock to ultimately bring the 1.5" height down to the necessary 1.25" for the design. The plan was to face the material dimension down to 1.25" and slice the bar stock into 2" sections to achieve the 2.0" x 1.75" x 1.25" plug dimension. We used a large 0.5" diameter end mill to face the steel material. Due to the size of the cutter and the strength of the material, the mill needed to run at a slow speed of approximately 480 IPM and we could only cut 0.05" depth per pass.

Our production came to a grinding halt when we noticed an issue with the steel that had been machined. Due to a worn out tool bit, coupled with incorrect clamping, the part ended up coming out tapered. The tool bit was not properly secured and began to slip out of the collet causing the machine to face the steel at a slope leaving a small taper. The taper caused our parts to be uneven and while still useable, they were outside of our tolerance. Once we noticed this issue, we consulted a shop tech for guidance.

After the shop techs informed us what had happened, we again ran into another issue when trying to replace the tool bit. The Bridgeport mill uses a motor to clamp and secure the collet and when the shop techs tried to disengage the collet it wouldn't budge. The mechanism in the mill was jammed and wouldn't allow the collet to be removed so they had to disassemble it from the top. It took the shop techs nearly an hour to remedy this issue, as seen in figure 3 below, adding onto our total time machining.



Figure 3: Shop Tech repairing Bridgeport Mill

After facing the steel, we calculated the total time it took for us to finish the first phase of machining the plugs and we discovered that it took us over 6 hours. When planning our time to work in the machine shop we didn't account for everything that comes with working in the shop. Certain unaccounted measures such as low cutting speeds, setup and cleanup time, and both machine and operator caused complications ended up adding close to 4 hours to our total machining time.

After machining, our next step was to measure out how much we needed to part off and took it to the vertical band saw. Due to the unevenness that was produced in our previous operation, it became a challenge to properly clamp it in the vertical band saw. This led to a few uneven cuts, but again the parts that were produced were still useable. This can be seen in figure 4 below.

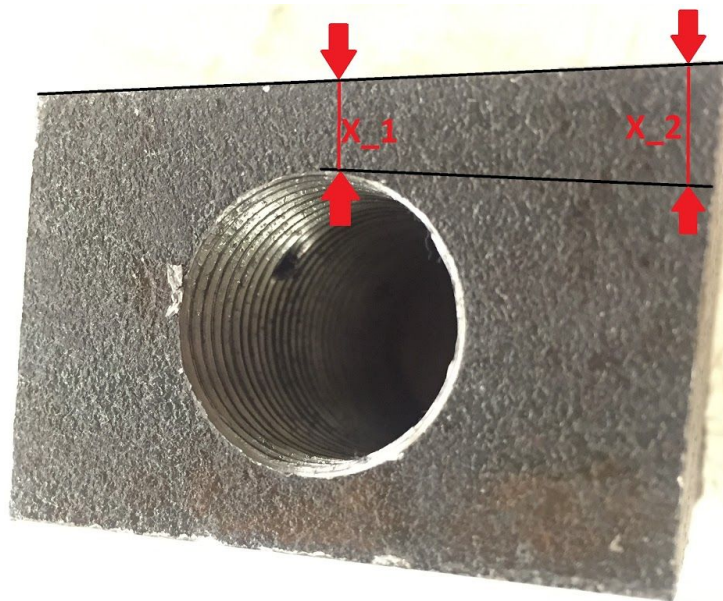


Figure 4: Angled plug caused by uneven cutting where $X_2 > X_1$

Our next step was to create the $\frac{3}{4}$ " tapered through hole on each plug. To have a $\frac{3}{4}$ " tapered hole we had to drill a smaller hole using a $\frac{11}{16}$ " drill bit so that the $\frac{3}{4}$ " taper wouldn't fall through. Using the centering probe, we were able to zero the X direction to the edge of each solid block. After establishing our zeros, we positioned the bit to the correct coordinates using the electronic readout of the mill and began drilling the holes. The slanted sides of a few of the plugs made it difficult to touch off with the probe properly on the mill, making it very difficult to establish a correct coordinate system from which to drill the $\frac{11}{16}$ " holes. After drilling, we manually threaded the holes with a $\frac{3}{4}$ " tap from the shop.

Originally, when we designed the plugs, we had planned to slip them into the columns with very little play so that we can use the drill press to create the No. 7 drill bit holes that would go straight through the column and into the plugs insuring proper alignment. This didn't end up being the case since the slanted sides of the plug caused there to be quite a bit of play inside the column. There were gaps that varied in size between the plug sides and the interior walls of the columns which would cause a problem when trying to screw the parts in.

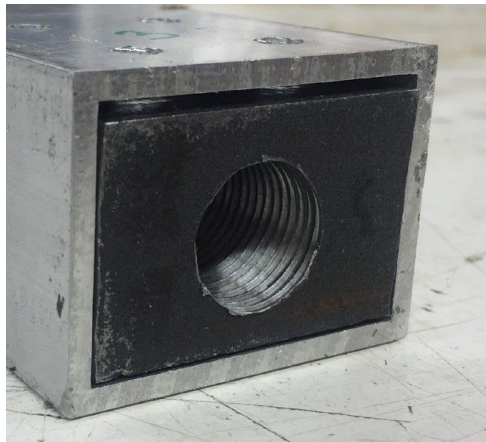


Figure 5: Gap between plug and column

We tried to remedy this issue by first piloting the holes in the columns without the plugs, then inserting the plugs and using a No. 7 drill bit to simultaneously drill through the column and pilot the holes in the plugs. The plugs were then removed and the No. 7 drill bit holes were drilled separately. Because we had to add extra steps to a simple process it exponentially extended our total process time by an extra 4 hours.



Figure 6: Having to remove plug to drill holes

After drilling the hole in the plugs we had to hand tap each hole with a $\frac{1}{4}$ " tap. This started to become tedious as we had to slowly tap all 24 small holes as to not damage the tap or the threads we were making. Ultimately once we finished taping all the small holes in each plug, we paired the correct plug with the column with hole locations only matched its pair. The columns and plugs were successfully machined but were not of the quality we hoped them to be. Even so, the plugs were usable and we handed them over to the Architectural Engineers.

After a few weeks, we were informed that the ARCEs had some trouble with the plugs we had manufactured. There was some miscommunication between the two sides regarding the condition of the plugs which led to further delays in production. By the time we came to an understanding of the situation at hand, we had put ourselves behind schedule. We came to the conclusion as a whole that the plugs were unable to be used, due complications during installation, and we needed to manufacture a new set.

With only 5 weeks left in the quarter, we did not have enough time to manufacture the plugs again but we did have money in our budget to outsource the machining. We got in contact with the machinists in Mustang 60 in hopes that they would be able to help us and within a week they were able to manufacture a new set of plugs.

Exterior Clevises

Initially we had planned to machine the clevises on the mill ourselves. After machining the plugs and understanding the amount of time needed to simply face A36 steel, let alone machine a 2.0" x 1.55" x 0.55" channel down the center of the material, we realized milling this part would take weeks and it was not efficient nor effective to use the mill. The Haas CNC mill would take far less time and machine a much more precise clevis. The CNC can only be used by an authorized licensed user, so we worked with the technicians in the shop at Mustang 60 to develop a plan. The shop technicians developed a machining

plan from our clevis design and created a code to be used in the CNC machine. This took a total of 4 hours in the CNC machine. The machinist took the steel bar stock and machined out the channel and the holes for the clevis pin.

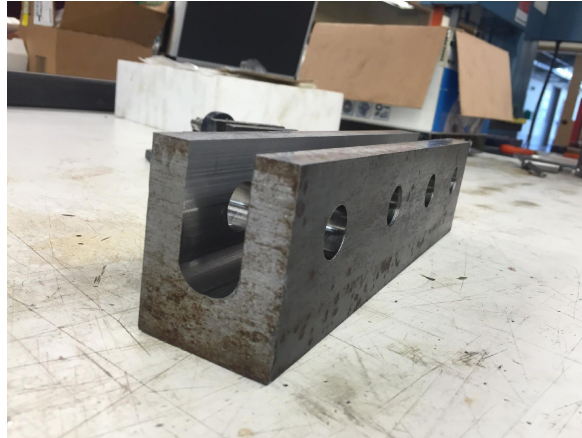


Figure 7: CNC machined Clevises

When the material was removed, all that was needed to be done was to slice the material into 4 clevises. The material was marked with a pencil and a band saw was used to cut the clevises. While using the vertical band saw we ran into an issue. Due to the strength and thickness of our clevises the band saw had trouble making a clean cut all the way through the part. The saw didn't have much issue cutting through the sides of the clevis, but it struggled once it reached the thickest part. The saw would come to a stop halfway through cutting the bottom of the clevis and we would have to lift it up and reset it before we can cut again. Resetting the band saw and making a second cut made it difficult to keep a straight line which resulted in the clevises having curved bottoms instead of a flat surface. We aren't sure as to why this kept happening, but we assumed that the strength of our steel overloaded the blade when cutting the thicker section causing the machine to shut down. Another reason would be to assume that the blade has been dulled over time and would need to be replaced if it's to make difficult cuts. Even with this issue, we believe it will not affect the performance of the clevises since we over designed it with a high factor of safety. If we are ever faced with a similar challenge in the future, it will be wise to consider blade condition and machinability of our steel selection.

After we had completed our clevises and delivered them to the ARCEs, we were informed that there were some fitment issues. We had designed the rod ends to be close to a press fit within the clevises, but when we tried to assemble them, they wouldn't completely fit. After investigating the issue, we discovered that the channels inside the clevises were at a slight angle. This caused the distance from the centerline of the channel to the bottom of the inside wall of the clevis to be about 0.006" shorter when compared to the distance from the centerline of the channel to the top of the inside wall of the clevis. After consulting with the shop techs we discovered that the discrepancy between the top and bottom of the channel was caused during the CNC process. When the tool started to go deeper into the part to create the channel it produced a larger moment causing the tool to deflect ever so slightly. In most cases this wouldn't be a problem, but since we had designed for a near press fit, it led to a fitment issue the further into the clevis the rod end was inserted.

To remedy this issue we had to remove the excess material from both the rod ends and the clevises. Since the amount of metal we needed to remove was so small we decided to use a grinder instead of a mill. We used a belt grinder to grind down the round ends of the clevises and a hand grinder for the interior walls of the clevises. Ultimately, we were able to remove enough material so that rod ends were able to easily split into the channel. Since we were using grinders we would only have an estimation to how much material we removed so the rod ends weren't a press fit but, the play within the channel was small enough that it wouldn't impact the performance of our parts.

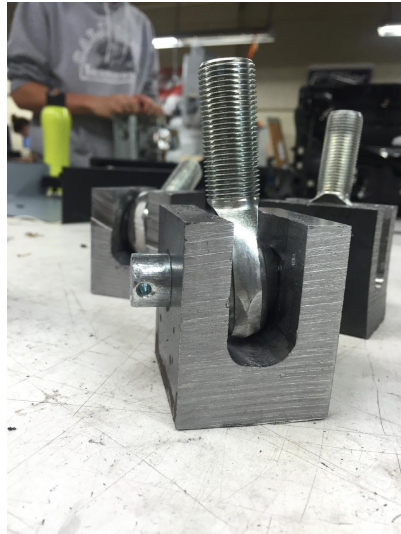


Figure 8: Grinded clevises and rod ends assembled

Interior Clevises

The interior columns are connected to clevises made from A36 steel and welded to the base plate. These clevises are made from plates of steel welded together to form the clevis. We had initially considered machining these clevises as we had the exterior clevises, but after considering time, cost, and strength requirements, it was determined that creating the clevises by welding steel plates together would take less time, cost less, and fulfill the strength requirements necessary. The architectural engineers suggested this option, as one of them is conveniently a professional welder. The weld will make the connection material even stronger, as the structure of the metal will become finer from the heat and cooling process. Detailed drawings of the plates are found in **appendix F**. These welds were $\frac{1}{4}$ " fillet welds using an E70xx electrode. A fatigue analysis of the welds is provided in **appendix K**.

Calculations & Computer Modeling

Appendix F (FEA)

To help visualize the loads that our clevis would see, we decided to construct an assembly in Solidworks using our clevis and the rod end, from McMaster-Carr, we were planning on using. After constructing the assembly, we would be able to use the Finite Element Analysis (FEA) software within Solidworks to determine the stress and deflection our clevis would experience under the prescribed loads.

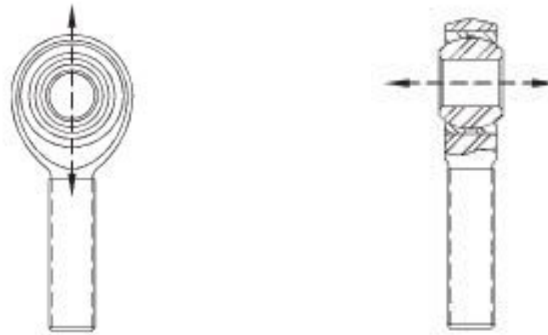


Figure 9: Visualization of Radial (left) and Axial (right) load application

We know that this software takes a very simplified approach, so we wanted to make sure we were as conservative as possible with the loads we used within the model. We know that our clevis, during a full cycle, would experience forces alternating between both the positive and negative directions axially and radially. To help simplify our model, we decided to look at the clevis through half a cycle and see how it would react.

We were given max loads of 5000 lbs applied radially, in tension and compression, and 750 lbs applied axially. To begin, we had to first simplify the radial load distribution that would be applied to the holes of our clevis via the pin that held the rod end in place. To achieve this goal, we applied a load only to one hole (right side) of the clevis. Erring on the side of caution, we decided to be conservative with our model and applied 60% of the 5000 lb load. With that in mind, along with the factor of safety of 3, we arrived at an upward load of 9000 lbs which was applied to the hole on the right side of the clevis. We then applied an axial load, with a factor of safety of 3, of 2250 lbs around the outer edge of the same hole we applied the radial load to.

After constraining the assembly and applying the loads, we ran the FEA software on Solidworks to determine the max deflection and the location of the stress concentrations of our clevis. We paid close attention to the locations with the highest stress concentrations so that we can determine where the clevis could deform or fail. Before we ran the FEA, our predictions were that the interior radii of the clevis would yield the highest stress concentration. After running the FEA, we arrived at a max displacement of 0.00129 inches and confirmed our predictions on the location of the highest stress concentration.

From fig. 1 in **appendix F**, we can see that the max displacement of our clevis occurs is at the top. We were extremely pleased with the results as we were able to achieve a previous goal of designing a sturdy body with minimal deflection.

Looking at fig. 2 in **appendix F**, the stress is actually highest around the pin hole and along the side of the clevis. These results are misleading because the high stresses at those locations stem from how our model was constructed for the analysis. Since the loads were placed in and around the pin hole, it skews the results thus allowing us to mostly neglect the high stresses in those regions. The next highest stress concentration, ~12,000 psi, can be found on the inside radii, confirming our predictions.

References

- (1) Budynas, Richard G., J. Keith. Nisbett, and Joseph Edward. Shigley. *Shigley's Mechanical Engineering Design*. New York: McGraw-Hill, 2011. Print.
- (2) Bickford, John H., and Sayed Nassar. *Handbook of Bolts and Bolted Joints*. New York: M. Dekker, 1998. Print.
- (3) Taylor, Douglas P., President. *BUILDINGS: DESIGN FOR DAMPING*. July 1999. Technical paper about damping devices. Taylor Devices, Inc., 90 Taylor Drive, North Tonawanda, NY.

APPENDIX A

| Analysis Of 1st Mode Of 1st Floor | | |
|-----------------------------------|---------------------|----------------------|
| Zeta (ζ) % damping | Damping Constant | F _d (lbf) |
| 0.10 | 204 | 457 |
| 0.11 | 224 | 503 |
| 0.12 | 245 | 549 |
| 0.13 | 265 | 594 |
| 0.14 | 286 | 640 |
| 0.15 | 306 | 686 |
| 0.16 | 326 | 732 |
| 0.17 | 347 | 777 |
| 0.18 | 367 | 823 |
| 0.19 | 388 | 869 |
| 0.20 | 408 | 915 |
| 0.21 | 428 | 960 |
| 0.22 | 449 | 1006 |
| 0.23 | 469 | 1052 |
| 0.24 | 490 | 1098 |
| 0.25 | 510 | 1143 |
| 0.26 | 530 | 1189 |
| 0.27 | 551 | 1235 |
| 0.28 | 571 | 1280 |
| 0.29 | 592 | 1326 |
| 0.30 | 612 | 1372 |
| 0.31 | 632 | 1418 |
| 0.32 | 653 | 1463 |
| 0.33 | 673 | 1509 |
| 0.34 | 694 | 1555 |
| 0.35 | 714 | 1601 |
| 0.36 | 734 | 1646 |
| 0.37 | 755 | 1692 |
| 0.38 | 775 | 1738 |
| 0.39 | 796 | 1783 |
| 0.40 | 816 | 1829 |
| 0.41 | 836 | 1875 |
| 0.42 | 857 | 1921 |
| 0.43 | 877 | 1966 |
| 0.44 | 898 | 2012 |
| 0.45 | 918 | 2058 |
| 0.46 | 938 | 2104 |
| 0.47 | 959 | 2149 |
| 0.48 | 979 | 2195 |
| 0.49 | 1000 | 2241 |

APPENDIX A

| Analysis Of 1st Mode Of 2st Floor | | |
|-----------------------------------|---------------------|----------------------|
| Zeta (ζ) % Damping | Damping Constant | F _d (lbf) |
| 0.10 | 408 | 1037 |
| 0.11 | 449 | 1141 |
| 0.12 | 490 | 1244 |
| 0.13 | 530 | 1348 |
| 0.14 | 571 | 1452 |
| 0.15 | 612 | 1556 |
| 0.16 | 653 | 1659 |
| 0.17 | 694 | 1763 |
| 0.18 | 734 | 1867 |
| 0.19 | 775 | 1970 |
| 0.20 | 816 | 2074 |
| 0.21 | 857 | 2178 |
| 0.22 | 898 | 2281 |
| 0.23 | 938 | 2385 |
| 0.24 | 979 | 2489 |
| 0.25 | 1020 | 2593 |
| 0.26 | 1061 | 2696 |
| 0.27 | 1102 | 2800 |
| 0.28 | 1142 | 2904 |
| 0.29 | 1183 | 3007 |
| 0.30 | 1224 | 3111 |
| 0.31 | 1265 | 3215 |
| 0.32 | 1306 | 3318 |
| 0.33 | 1346 | 3422 |
| 0.34 | 1387 | 3526 |
| 0.35 | 1428 | 3630 |
| 0.36 | 1469 | 3733 |
| 0.37 | 1510 | 3837 |
| 0.38 | 1550 | 3941 |
| 0.39 | 1591 | 4044 |
| 0.40 | 1632 | 4148 |
| 0.41 | 1673 | 4252 |
| 0.42 | 1714 | 4355 |
| 0.43 | 1754 | 4459 |
| 0.44 | 1795 | 4563 |
| 0.45 | 1836 | 4667 |
| 0.46 | 1877 | 4770 |
| 0.47 | 1918 | 4874 |
| 0.48 | 1958 | 4978 |
| 0.49 | 1999 | 5081 |

APPENDIX B

EXTERIOR COLUMN CLEVIS FATIGUE ANALYSIS

A36 STEEL

Sut = 58000 PSI, SHIGLEY'S

$$c = d/2, d = 0.5''$$

$$t = 2.5'' \text{ (DEPTH / THICKNESS)}$$

$$P = 5000 (5)(0.6) = 15000 \text{ lb}$$

$$M = 750 (5)(0.6)(11) = 2250 \text{ in-lb}$$

$$t/d = 2.5/0.5 = 5'' \quad \frac{P}{d} = 3125/0.5 = 6250$$

$$I = \frac{t \cdot d^3}{12} = \frac{(2.5)(0.5^3)}{12} = 0.02604167 \text{ in}^4$$

$$A = (5)(2.5) = 1.25 \text{ in}^2$$

$$S_e' = 0.5 S_u t = 29000 \text{ PSI}$$

$$K_a = (2.7)(58)^{(-0.265)} = 0.9206$$

$$d_e = 0.808 (h_b)^{1/2} = 0.808 \sqrt{(2)(.5)} = .808$$

$$K_b = (.879)(.808)^{-1.07} = 0.8993$$

$$K_c = 1; \text{ BENDING}$$

$$K_e = 0.814; \text{ DUE TO 99\% RELIABILITY}$$

$$f = 0.9$$

$$q = 0.8 \text{ [SHIGLEY'S, FIG 6-20]}$$

$$K_L \approx 1.4$$

$$K_f = 1 + q(K_L - 1) = 1.32$$

$$S_e = S_e' K_a K_b K_c K_e = 19.54 \text{ ksi}$$

$$\sigma_0 = \frac{M C}{I} + \frac{P}{A} = \frac{(2250 \text{ in-lb})(.5)}{0.02604167} + \frac{15000 \text{ lb}}{1.25 \text{ in}^2} = 33.6 \text{ ksi}$$

$$\sigma_{\max} = K_f \sigma_0 = (1.32)(33.6 \text{ ksi}) = 44.35 \text{ ksi}$$

$$a = \left(\frac{f S_u}{S_e} \right)^2 = \frac{(.9)(58)^2}{19.54} = 139.45 \text{ ksi}$$

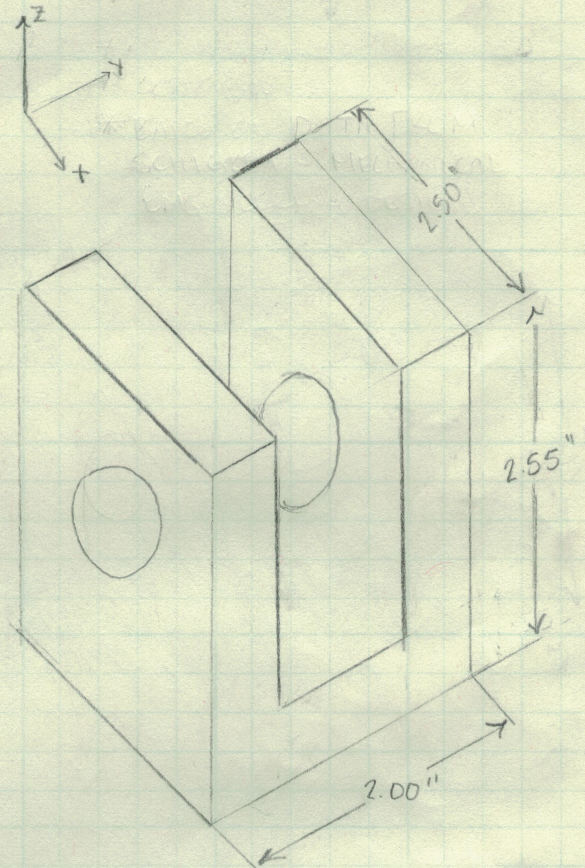
$$b = -\frac{1}{3} \log \left[f \frac{S_u t}{S_e} \right] = -0.1423$$

$$\text{@ } N = 10^6 \quad S_f = S_e = a N^b = 19.53 \text{ ksi}$$

$$\text{@ } N = 10^3 \quad S_f = 0.9 S_u t = 52 \text{ ksi}$$

REFERENCE: SHIGLEY'S MECHANICAL ENGINEERING DESIGN

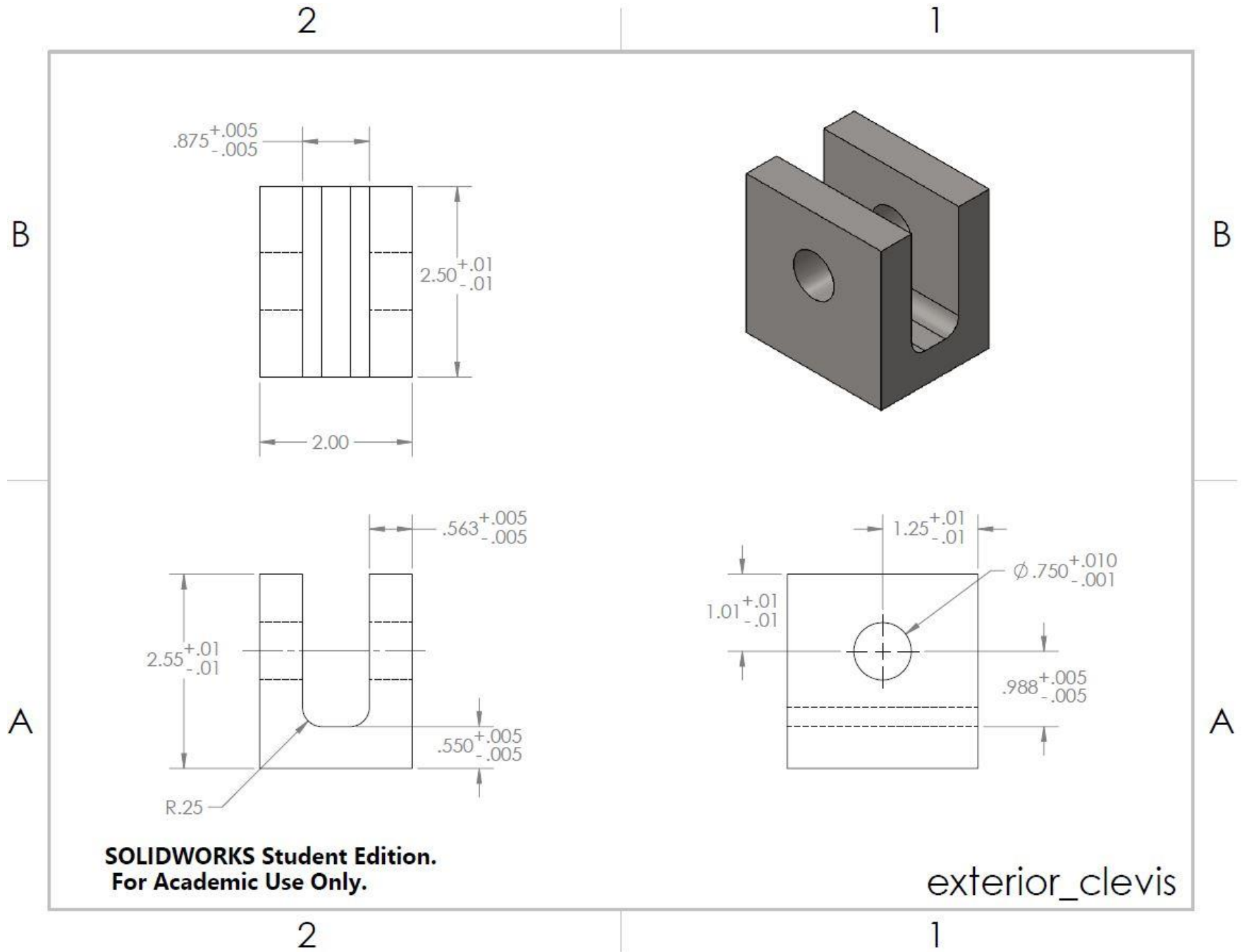
ASSUME FULLY REVERSED LOADING



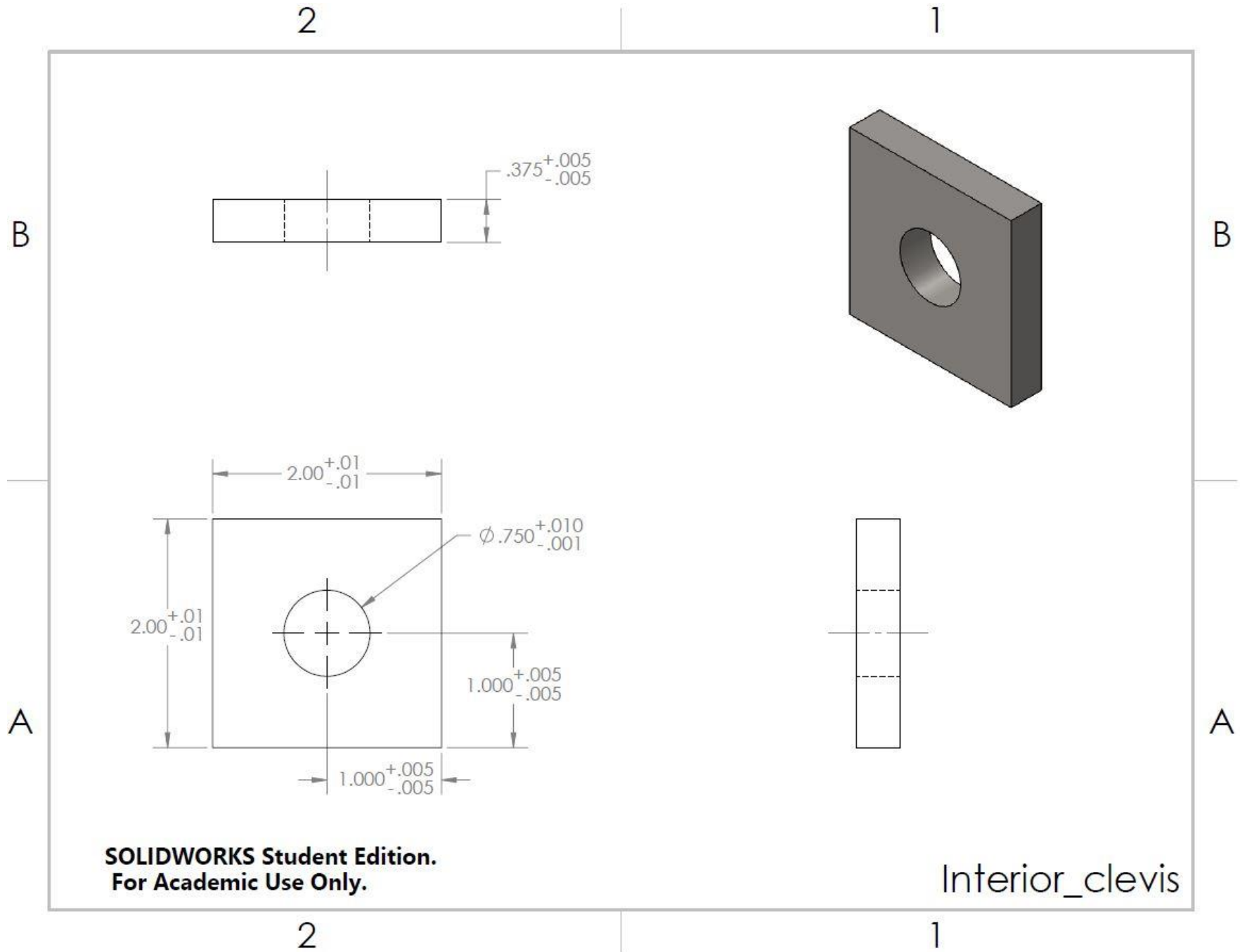
APPENDIX C

```
%Clevis Fatigue Analysis
%Material is A36 steel
FOS=5; %factor of safety
%Assuming fully reversed loading
Sy=36; %[kpsi] Yield strength
Sut=58; %[kpsi] Ultimate tensile strength
Se1=0.5*Sut; %[kpsi] Endurance Limit Se'
w=2; %[in] base width
d=0.5; %[in] base thickness
c=d/2;
t=2.5; %[in] base depth
I= t*(d^3) /12;
Ax=(d*t); %Cross sectional area
de=0.808*sqrt(d*w); %[in^3]Moment of Inertia
%Sf=a*(N^b); %N=cycles to failure, Sf=fatigue strength
%N=(Sf/a)^(1/b);
ka=2.7*(Sut)^(-.265); %surface condition mod factor
kb=.879*(de^(-.107)); %Size
kc=1; %bending
kd=1; %temp mod factor
ke=0.814; % at 99% reliability
q=0.8; %Notch sensitivity Fig (6-20)
Kt=1.4; %geometric stress-concentration factor
M=750*FOS*(0.6)*(1); %Bending Stress
P=5000*FOS*(.6); %Axial, 0.6 is overlapping assumption
Kf= 1 + q*(Kt-1); %fatigue stress concentration factor
Sig_a=(5000*2*0.6)/(0.5*(3/8)); %Sigma Allowable
Se=ka*kb*kc*kd*ke*Se1; %[kpsi]
Sig_max= (1/1000)*((M*c/I) + (P/Ax)) * Kf; %ksi
f=0.9;
a=((f*Sut)^2)/Se;
b=-log10((f*Sut)/Se)/3;
N=[10^3.5 10^4 10^5 10^6];
Sf=a*(N.^b);
figure (1);
%loglog(N,Sf);
semilogx(N,Sf);
xlim manual
ylim ([0 50]);
axis([1000, 10000000, 0 ,50]);
title('S-N Plot');
hold on
line([10^3 10^3.5],[Sig_max Sig_max], 'Color', 'r');
line([10^6 10^7],[Se Se], 'color', 'b');
grid on
hold off
```

Appendix D



Appendix E



Appendix F

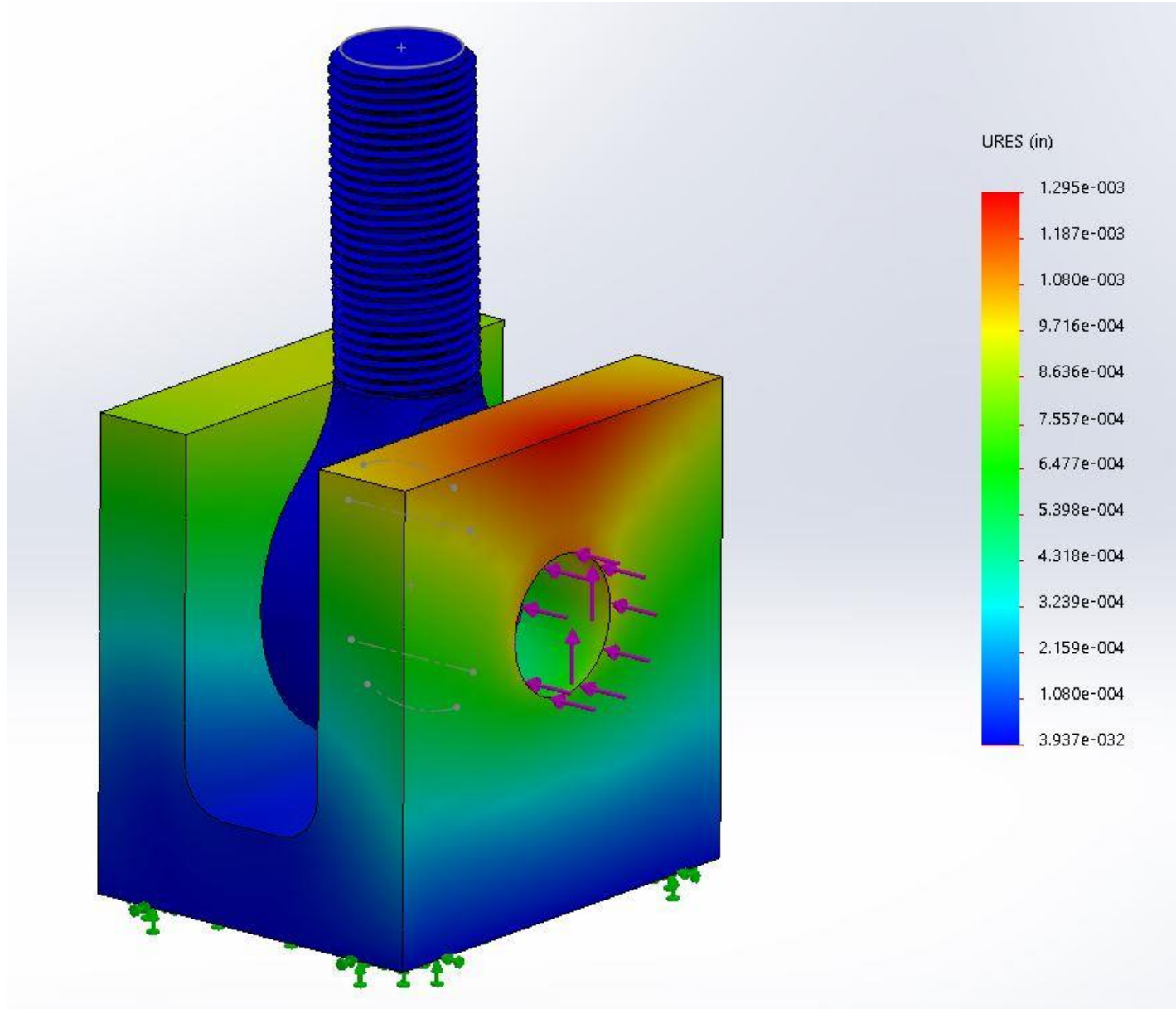


Fig. 1: Displacement under prescribed loads

Appendix F

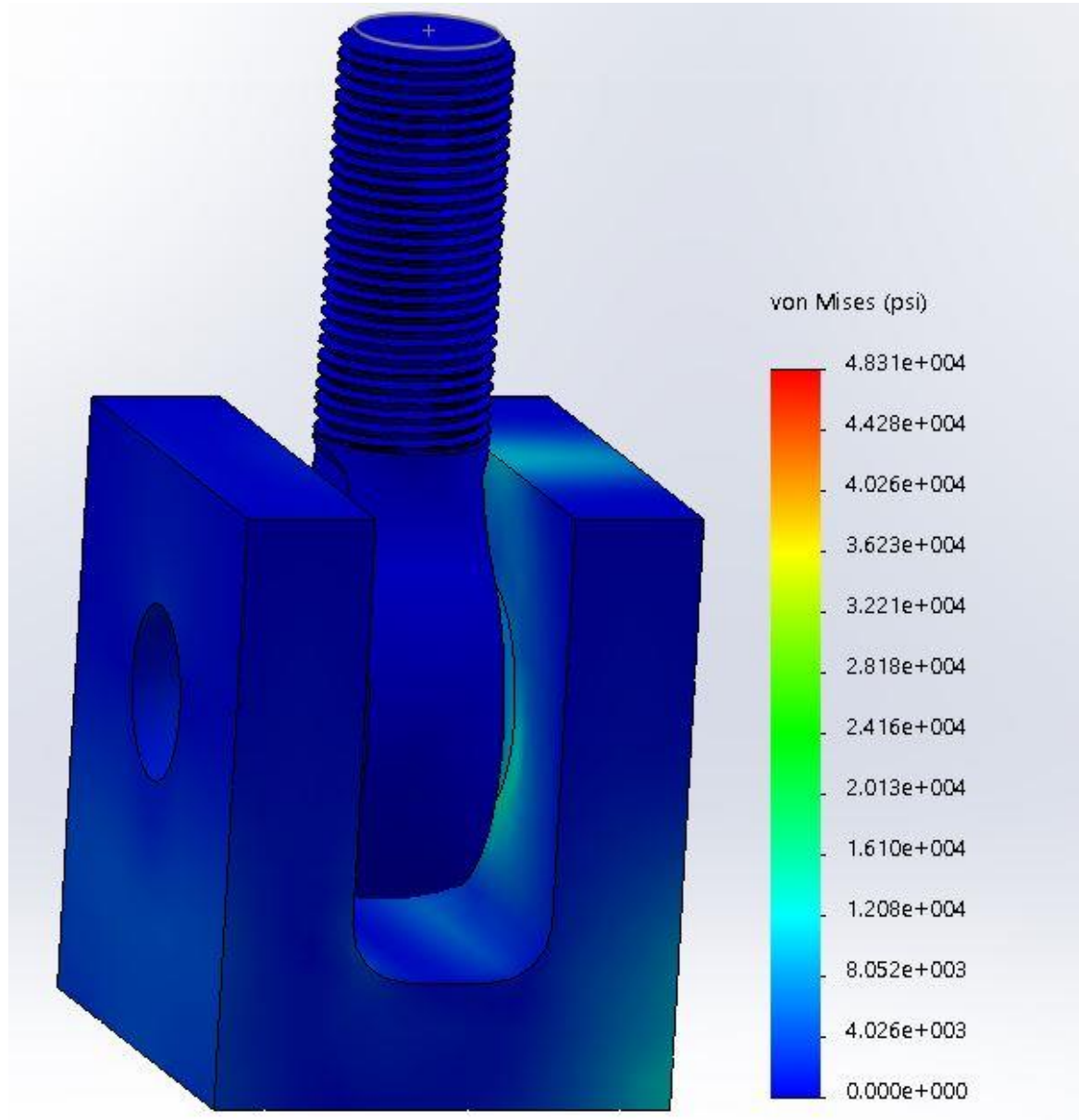


Fig. 2: von Mises Stress under prescribed loads

Appendix F

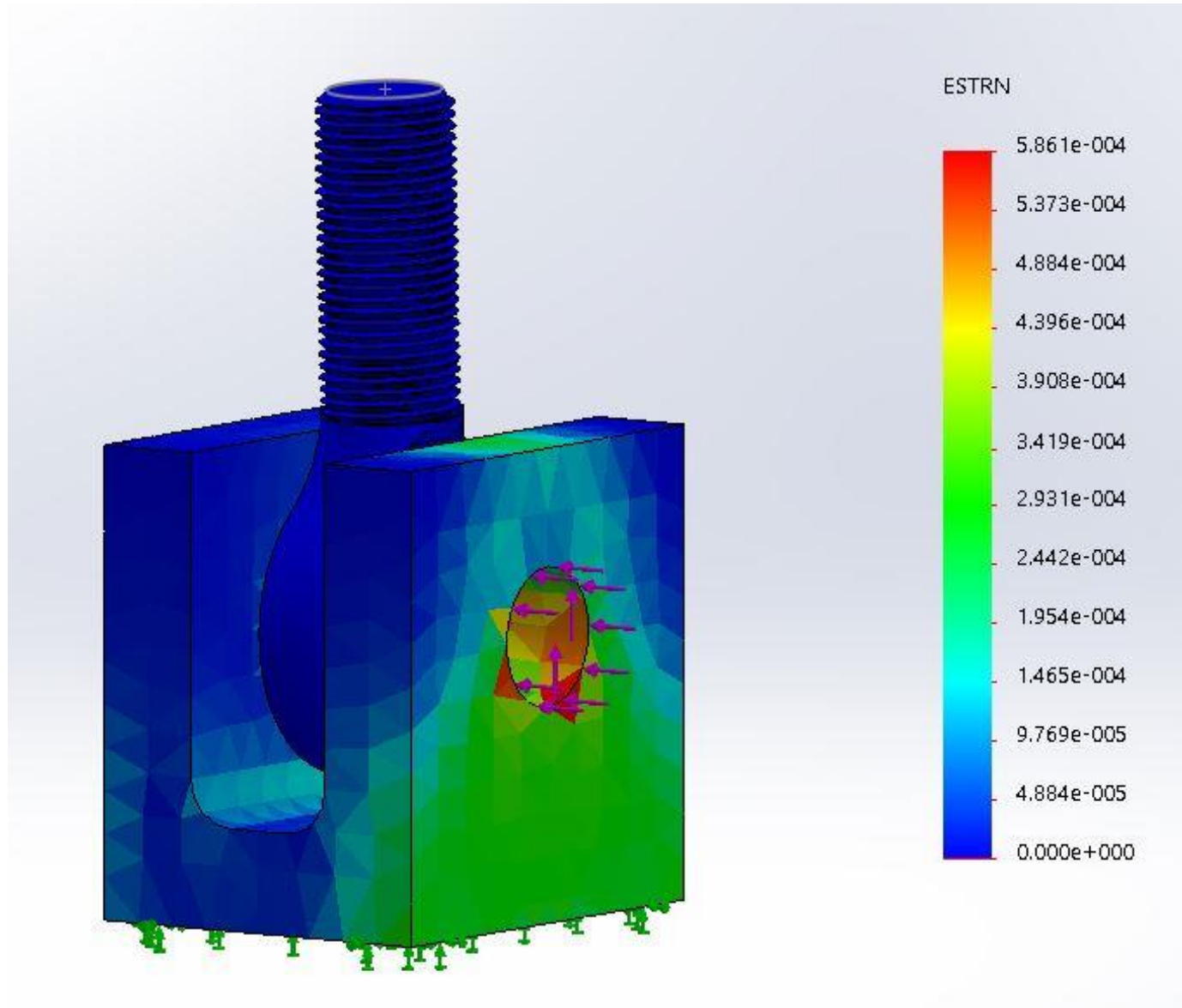
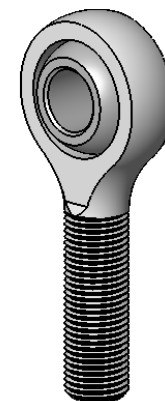
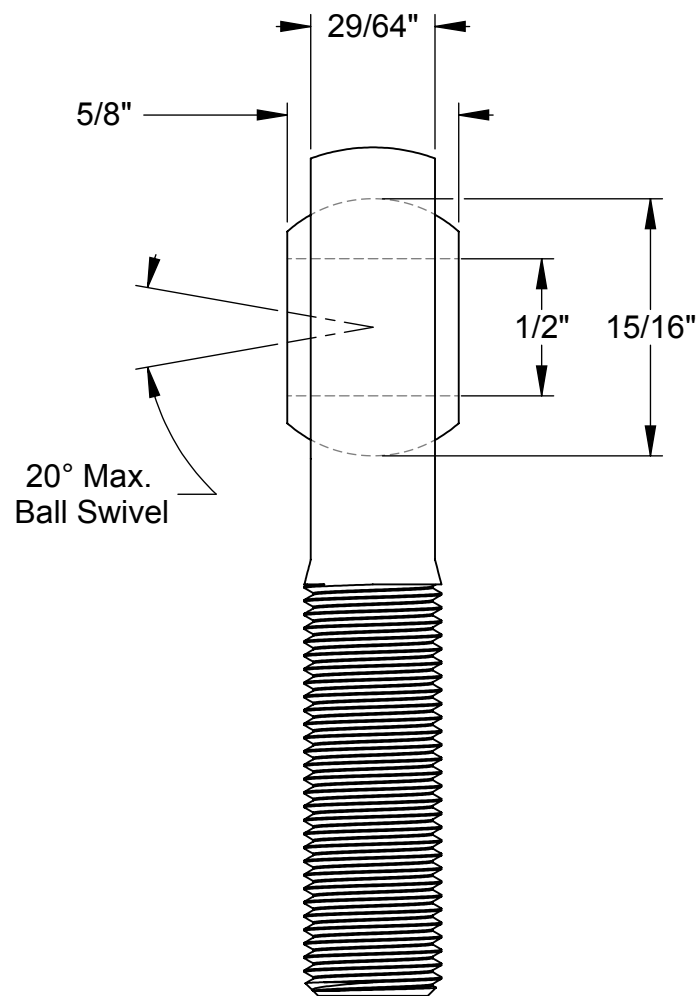
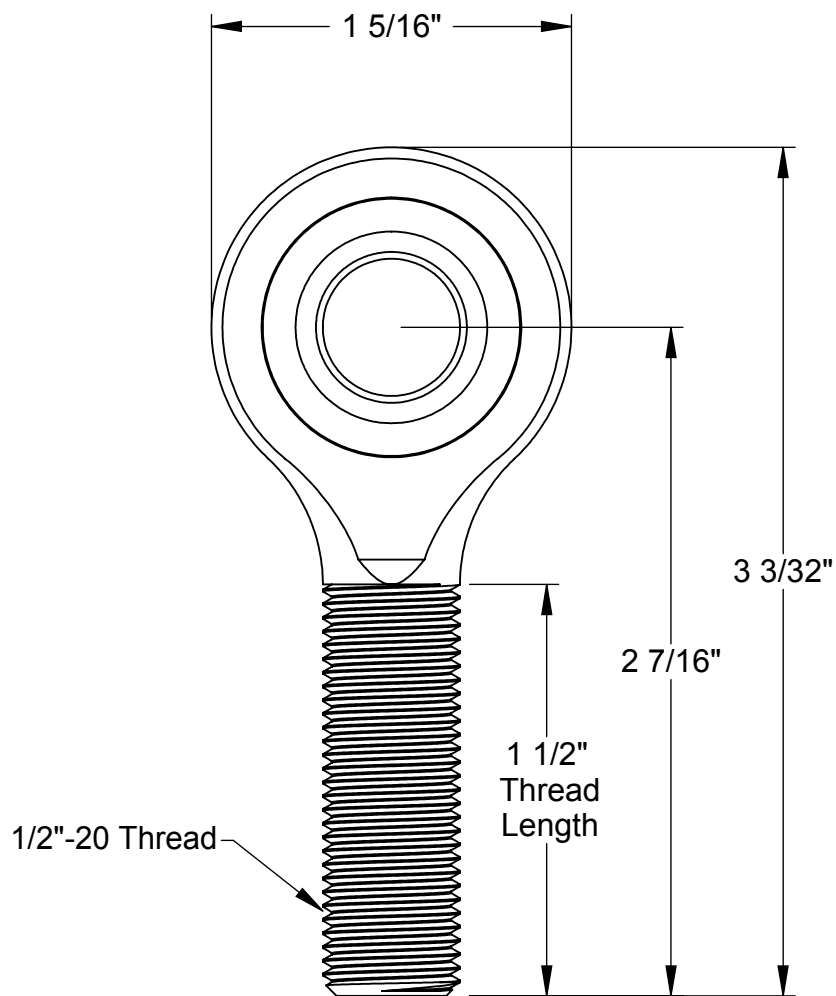


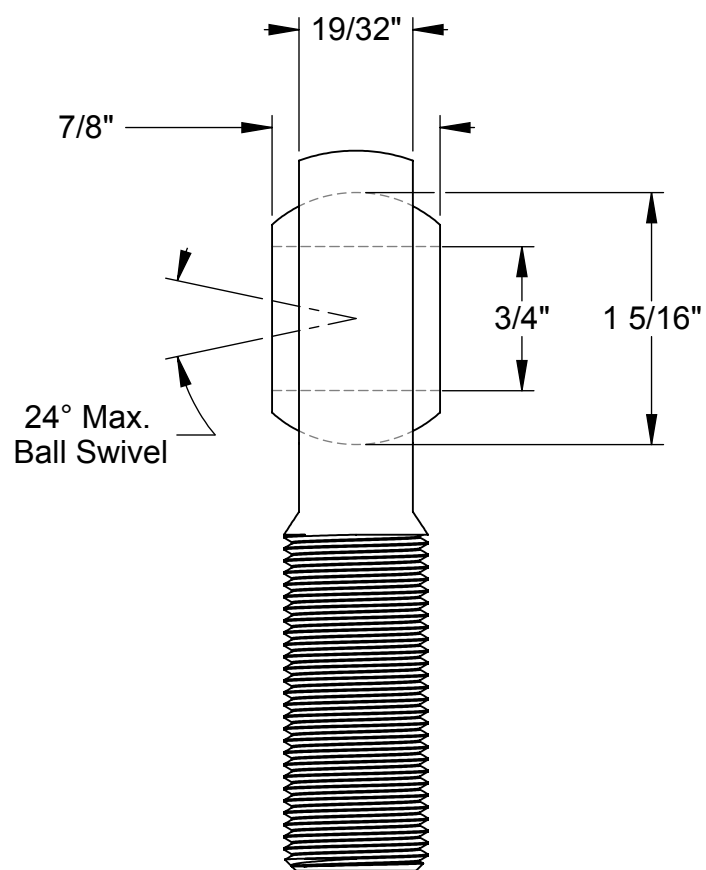
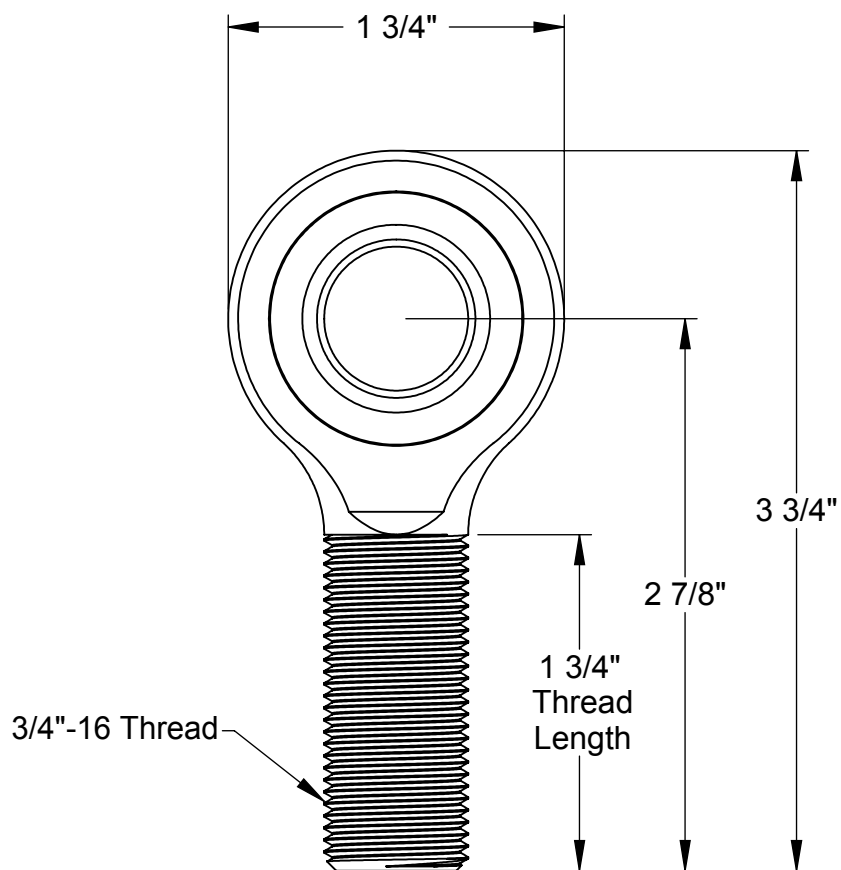
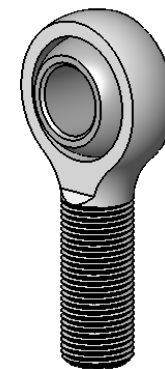
Fig. 3: Strain under prescribed loads

APPENDIX G



Notes:
 Zinc-Plated Steel Housing
 Chrome-Plated Steel Ball

| | | |
|---|-------------|---|
| McMASTER-CARR <small>CAD</small> | PART NUMBER | 60645K161 |
| http://www.mcmaster.com | | Right-Hand Thread |
| © 2013 McMaster-Carr Supply Company | | Ball Joint Rod End <small>88/92</small> |
| Information in this drawing is provided for reference only. | | |



Notes:
 Zinc-Plated Steel Housing
 Chrome-Plated Steel Ball

McMASTER-CARR CAD PART NUMBER **60645K181**

<http://www.mcmaster.com>
 © 2013 McMaster-Carr Supply Company

Right-Hand Thread
 Ball Joint Rod End 89/92

Information in this drawing is provided for reference only.

APPENDIX I

PLUG BEARING STRESS ANALYSIS

PLUG

A 36 STEEL

$S_u = 42,000 \text{ psi}$ [ULTIMATE TENSILE STRENGTH] (1)

$$(1.5)(S_u) = \frac{5000(3)}{d(0.125")n}$$

↑ ALUMINUM BEARING STRESS

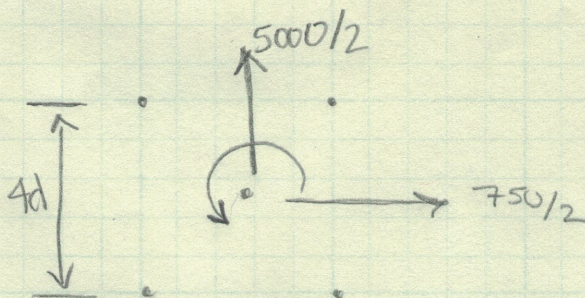
$n = \# \text{ bolts}$

$d = \text{bolt diam (in)}$

$0.125" = \text{thickness of ALUMINUM}$

(1) REFERENCE: SHIGLEY'S
MECHANICAL EN. DESIGN, 9E

(2) HANDBOOK OF BOLTS
& BOLTED JOINTS



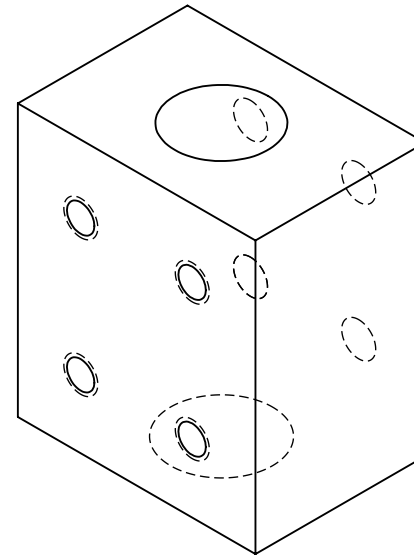
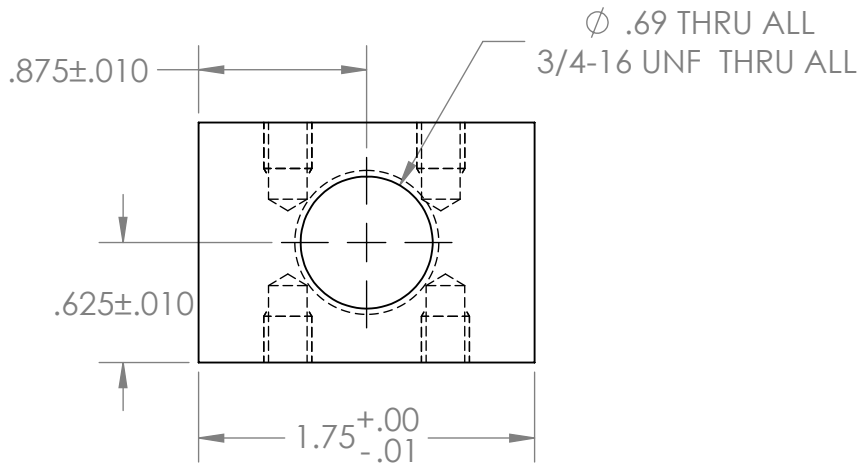
$$M = \frac{750(a)}{2}$$

$a = \text{distance from pin center to center of bolt group}$

IF $d = 0.25"$

$$n = \frac{5000(3)}{(0.25")(0.125")(S_u)(1.5)}$$

$$n = 8, \underline{8 \text{ bolts}}$$

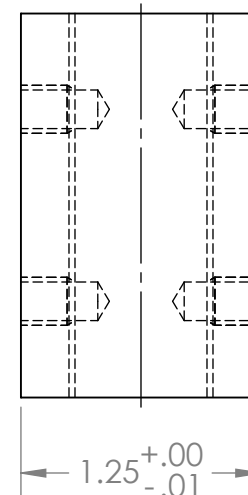
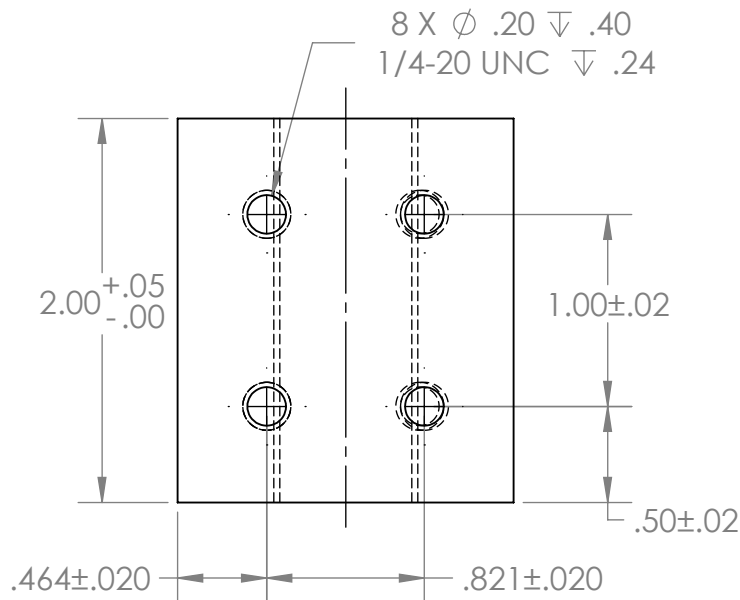


B

B

A

A



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Plug

APPENDIX K

INTERIOR CLEVIS WELD FATIGUE ANALYSIS

REFERENCE: SHIGLEY'S M.E. DESIGN, 9th e., ch. 9 *SEE APPENDIX F
 GIVEN VALUES

USE GOODMAN APPROACH

MATERIAL: A36 STEEL

$S_{ut} = 58 \text{ ksi}$, $S_y = 36 \text{ ksi}$

INTERIOR CLEVISES SEE ONLY A DOWNWARD
 MAXIMUM FORCE OF 5000 lbf

WELD: $h = .25 \text{ in}$

PARTIAL PENETRATION $\frac{1}{4}$ " FILLET WELD

ELECTRODE: E70XX

$S_{ut} = 70 \text{ ksi}$

$S_y = 57 \text{ ksi}$

$\sigma_{all} = 18 \text{ ksi}$ Table 9.6

$f = 3.18$

SHIGLEY'S 9e, ch 9-2; 9-4
 FILLET WELD IN COMPRESSION

$$\sigma = \frac{F}{A}, A = .707hd$$

$F = 5000 \text{ lbf}$,

$h = \text{Weld size}$

$d = 2"$, length of each weld = l

$$A = .3535 \text{ in}^2$$

$$\sigma = \frac{F}{A} = \frac{5000 \text{ lbf}}{.3535 \text{ in}^2} = 14.144 \text{ ksi}$$

ACCORDING TO TABLE 9-6

$$F = 3.71l = 3.71(2 \text{ in}) = 7.42 \text{ kip}$$

THE

$5 \text{ kip} < 7.42 \text{ kip} \therefore \text{WELD METAL STRENGTH IS SATISFACTORY}$

TABLE 9-4,

$$\sigma_{all} = 0.60 S_y = 0.60(36 \text{ ksi}) = 21.6 \text{ ksi}$$

$$\underline{\underline{\sigma < \sigma_{all}}}$$

