Fall 2021

MEMS 411: P.O.T.T.E.R. Test Frame

Marie Drevets
Washington University in St. Louis

Kiersten Horton
Washington University in St. Louis

Tony Sancho
Washington University in St. Louis

Recommended Citation

Drevets, Marie; Horton, Kiersten; and Sancho, Tony, "MEMS 411: P.O.T.T.E.R. Test Frame" (2021). *Mechanical Engineering Design Project Class*. 162.
https://openscholarship.wustl.edu/mems411/162

FALL 2021 MEMS 411

Mechanical Engineering Design Project

P.O.T.T.E.R.: Professionally Oriented Testing Tool for Engineering Review

Assignment: Design Refinement

Group L

SANCHO, Tony
HORTON, Kiersten
DREVETS, Marie

Washington University in St. Louis

James McKelvey School of Engineering

FL21 MEMS 411 Mechanical Engineering Design Project

P.O.T.T.E.R: Professionally Oriented Testing Tool for Engineering Review

This should be a brief description of your whole project written for a general audience – the text should communicate to instructors, managers, non-technical co-workers, cost account managers, supply management personnel, etc. This should be approximately 200-300 words.

Our senior mechanical engineering design is a flexure test frame. At our university, third-year mechanical engineering students take a class called machine elements, in which the final project is a structural design competition. The students design a strong but lightweight object.

The P.O.T.T.E.R. device can be used to judge the structural integrity of students contest entries. The customer who commissioned this project is Dr. Potter, who teaches the machine elements class. The customer needs a portable test frame which can apply enough compressive force to fracture an object which is secured in the device. The test frame should also measure the fracture force (and possibly displacement) of the test specimens for comparison.

Based on the customer's needs, we have determined three performance goals for this prototype. First, the load applicator should travel 3 inches downward within 10 seconds. It should also apply at least 100lbs of compressive force. The frame should have reliable force and displacement measurements, with 0.1lb and 0.01 inch, respectively which is displayed clearly to the user.

To meet these performance goals, we have designed an aluminum frame with a steel base plate sitting on eight load cells and a linear actuator force applicator. The linear actuator is able to apply a load of 150 lbs and travel up to 6 inches at 1 inch/second. These specs exceed the first two performance goals. The base plate is supported by eight load cells, each rated at 20kg and 99.95% accuracy. These load cells meet the third goal. Additionally, to measure displacement, we have implemented a spool of string which should be secured to the specimen and can be measured before and after fracture. This string serves to measure the displacement of the specimen; its precision is determined by the precision of the measurement device.

Sancho,Tony
Horton, Kiersten
Drevets, Marie

Contents

List of Figures

List of Tables

1 Introduction

A major part of many small-scale building competitions is testing the load the structure can take before failing. A staple of nearly any mechanical engineering curriculum, these competitions grant bragging rights to the competitors who build the strongest structure. Therefore, it is of utmost importance that the fixture used to measure the load at failure is able to do so fairly to all competitors. Many current implementations require jerry-rigging and leave room to be desired in their ability to accurately and repeatedly measure the maximum load on the structure. Additionally, these solutions often fail to adequately protect the operator from shrapnel, and don't allow the end user to repeatedly fixture the specimens reliably. Our project aims to fill these deficits, where a wide variety of structures can be tested in a manner conducive to competitions.

2 Problem Understanding

2.1 Existing Devices

2.1.1 Existing Device #1: Uniflex 300 Flexural Frame

Figure 1: Uniflex 300 Flexural Frame (Source: Controls Group)

Link: https://www.controls-group.com/eng/flexural-testing-frames/universal-open-structure-f
php

Description: The Uniflex 300 flexural frame is a test frame designed to test the properties of concrete samples. The device has a strain gauge load cell that allows for accurate outputs. The load is applied vertically using a hydraulic press, and the device can withstand forces up to 300 kN. the upper bearers on the device can be adjusted to clamp objects from 80 to 500 mm, and the lower bearers can be adjusted to clamp objects from 80 to 1500 mm. The piston travels 110 mm. This device is not used individually, but must be used with a control console and other compatible accessories.

2.1.2 Existing Device #2: UTC-5610 Flexural Frame

Figure 2: UTC-5610 Flexural Frame (Source: UTEST)

Link: https://www.utest.com.tr/en/23430/Flexural-Frame-U-C-Type

Description: The UTC-5610 flexural test frame is meant to support versatile and easy testing. It has a maximum load capacity of 100 kN. The device has a ram travel of 100 mm, a vertical clearance of 435 mm, and a horizontal clearance of 870 mm. A load cell is used to measure the load that is on the test specimen. The load is applied by a ram, and the ram returns by way of a spring. This device can support tension, transverse, and compression testing with the proper accessories.

2.1.3 Existing Device #3: CBR/LBR and Marshall Automatic Load Frame

Figure 3: CBR/LBR and Marshall Automatic Load Frame (Source: Humboldt)

Link: https://www.humboldtmfg.com/cbr-lbr-and-marshall-automatic-load-frame.html
Description: This test frame has a 50 kN maximum load capacity, a 279 mm horizontal clearance, and a 659 mm vertical clearance. This one allows the machine to be used with a computer to read output. Load cells can be added to the device.

2.2 Patents

2.2.1 Method of Testing Additive Manufactured Material and Additive Manufactured Parts (US11054352B2)

This patent lays out a method for testing the material properties of AM parts by taking a sliver off of the part in question and running it through a series of non-destructive tests. Of more relevance is the computer logic used to take raw measurements and algorithmically convert them to meaningful quantities.

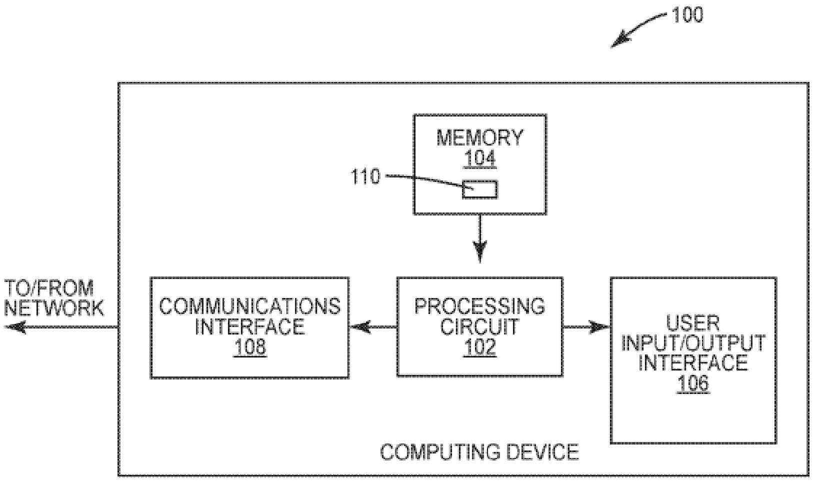


FIG. 8

Figure 4: Computer logic flowchart for testing apparatus

2.2.2 Strain Gage and Multi-Axis Force Sensor (US20200124486A1)

This patent depicts how the loading of a force applicator can be measured using dual Wheatstone bridges. These bridges, which are used to amplify and de-bias the raw voltage from the gauges, allow for accurate and precise measurement of axial and bending loads. The Wheatstone bridge described in this patent is applicable to other low-voltage sensors, such as thermocouples and load cells.

Fig. 2

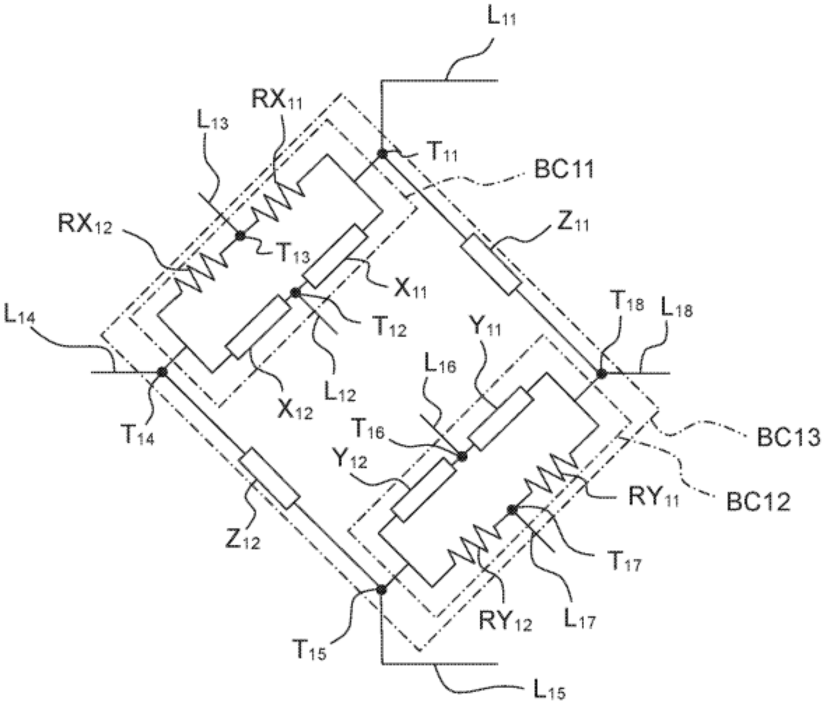


Figure 5: Electrical diagram of the strain gauge-Wheatstone bridge combination

2.3 Codes & Standards

2.3.1 Displacement Measurement (ASTM E2309)

Testing machines that apply and measure displacement are used in many industries. They may be used in research laboratories to determine material properties, and in production lines to qualify products for shipment. The displacement measuring devices integral to the testing machines may be used for measurement of crosshead or actuator displacement over a defined range of operation. The accuracy of the displacement value shall be traceable to the National Institute of Standards and Technology (NIST) or another recognized National Laboratory. Practices E2309 provides a procedure to verify these machines and systems, in order that the measured displacement values may be traceable. A key element to having traceability is that the devices used in the verification produce known displacement characteristics, and have been calibrated in accordance with adequate calibration standards. [1]

2.3.2 Standard Test Method for Compressive Properties of Rigid Plastics (ASTM D695)

Compression tests provide information about the compressive properties of plastics when employed under conditions approximating those under which the tests are made.

Compressive properties include modulus of elasticity, yield stress, deformation beyond yield point, and compressive strength (unless the material merely flattens but does not fracture). Materials possessing a low order of ductility may not exhibit a yield point. In the case of a material that fails in compression by a shattering fracture, the compressive strength has a very definite value. In the case of a material that does not fail in compression by a shattering fracture, the compressive strength is an arbitrary one depending upon the degree of distortion that is regarded as indicating complete failure of the material. Many plastic materials will continue to deform in compression until a flat disk is produced, the compressive stress (nominal) rising steadily in the process, without any well-defined fracture occurring. Compressive strength can have no real meaning in such cases.

Compression tests provide a standard method of obtaining data for research and development, quality control, acceptance or rejection under specifications, and special purposes. The tests cannot be considered significant for engineering design in applications differing widely from the load-time scale of the standard test. Such applications require additional tests such as impact, creep, and fatigue. [2]

2.4 User Needs

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Jolley 110, Washington University in St. Louis, Danforth Campus
Date: September 10^{th}, 2021
Setting: Conducted in lab with the other mini test frame group, took approximately 45 minutes. Primarily done using hand sketches on the whiteboard.

Interview Notes:
What are the typical uses of the device?

- Apply load to an test specimen in a contest or assignment to identify the max force and displacement the specimen can withstand before failing.

What are the most important aspects that should be included in the design?

- The test frame should be able to withstand a load of 150 lbs, take up no more than 1 cubic square foot, use an AC power supply, and digitally measure and display the force and displacement.

  What are current likes and dislikes of the product?

  - Dislike: We will have to add some type of shield to protect the user from flying fragments.
  - Like: The device will be designed to test and handle wood and 3D printed specimens, not metal.
  - Like: Measurement read-out will be digital and likely displayed on a computer.

2.4.2 Interpreted User Needs

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The test frame applies force precisely	5
2	The test frame has a bed which fits specimens	5
3	The test frame is portable	5
4	The test frame measures specimen displacement	3
5	The test frame is durable	4
6	The test frame applies consistent loads	5
7	Power is supplied to the test frame in a convenient way	3
8	The test frame can accommodate many specimen shapes/sizes with modular fixtures	3
9	The test frame is safe for the operator	5
10	the test frame applies a wide range of load magnitudes	4

2.5 Design Metrics

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Precision of load	lb	0.25	0.1
2	6	Number of identical measurements	score	9/10	10/10
3	2	Volume of bed	in^3	$6x6x6$	$8x8x6$
4	3	Footprint of device	in^3	$24x24$	$18x18$
5	3	Total weight of device	lb	> 30	> 15
6	4	Specimen displacement readout	–	scale indicator	digital
7	4	Precision of displacement measurement	in^3	1/8	1/16
8	5	Displacement of applicator during max load	in^3	1/32	0
9	5	Service life	tests	< 500	< 1000
10	7	Power supply	source	manual	AC power
11	8	Maximum motion of specimen during test	in	1/2	1/8
12	9	Impact, electrical, weight protection	binary	Pass	Pass
13	10	Load magnitude range	lb	0-85	0-150

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

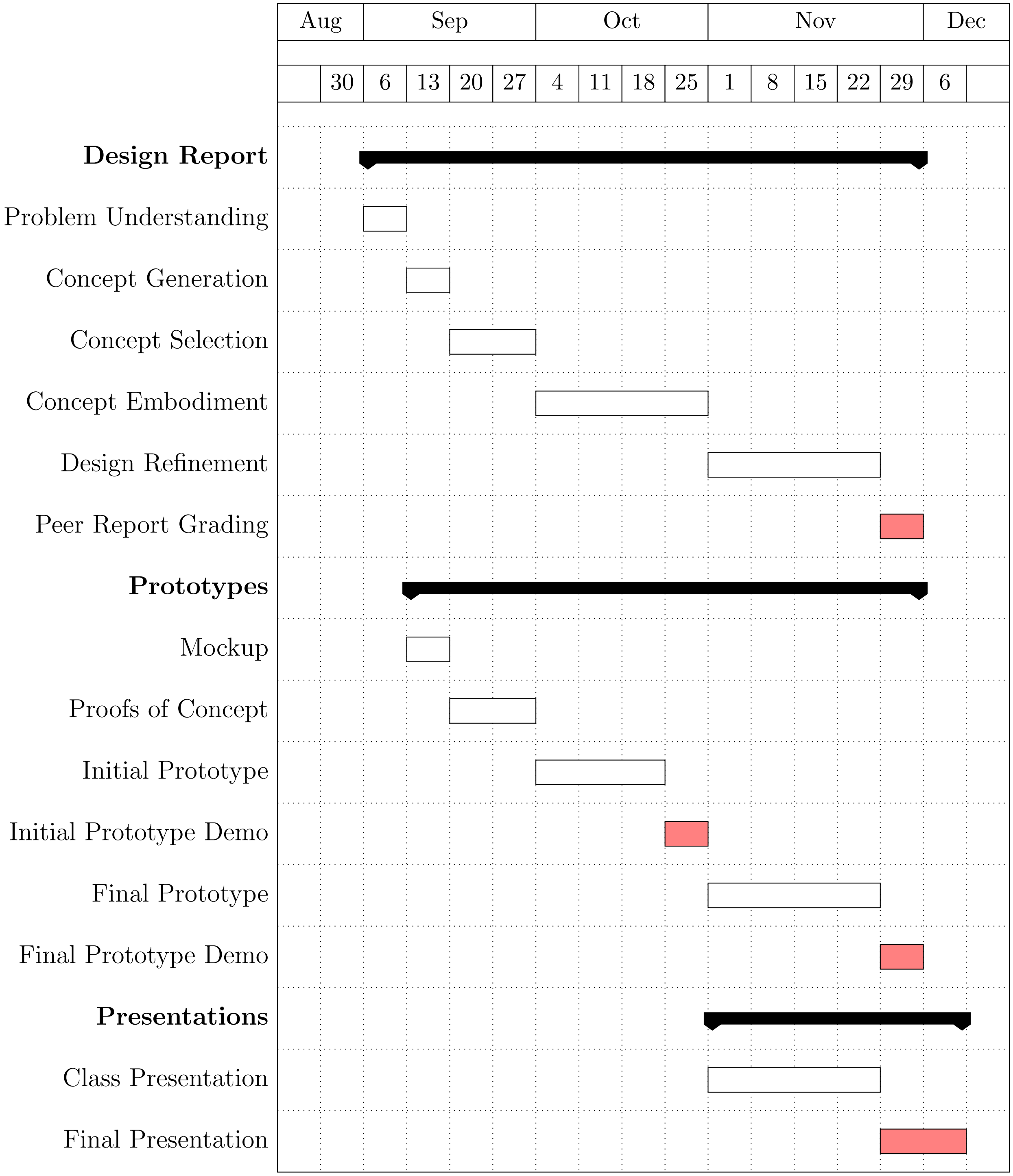


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

Our mockup was based around the electrically actuated and measurement concept, with a top mounted servo and ”lead screw” (made out of a dowel and pen markings), a control board connected to the servo, and a fixture plate at the bottom. During the construction of our mockup, we realized that fixturing the servo to the chassis would require some additional thought, and that we will really need to keep the chassis stiffness in mind to ensure accurate measurements. Another thing we realized was that the fixture plate will need additional clamps or other hardware (besides bolts) to hold down a generic test specimen that doesn’t exactly match the hole pattern.

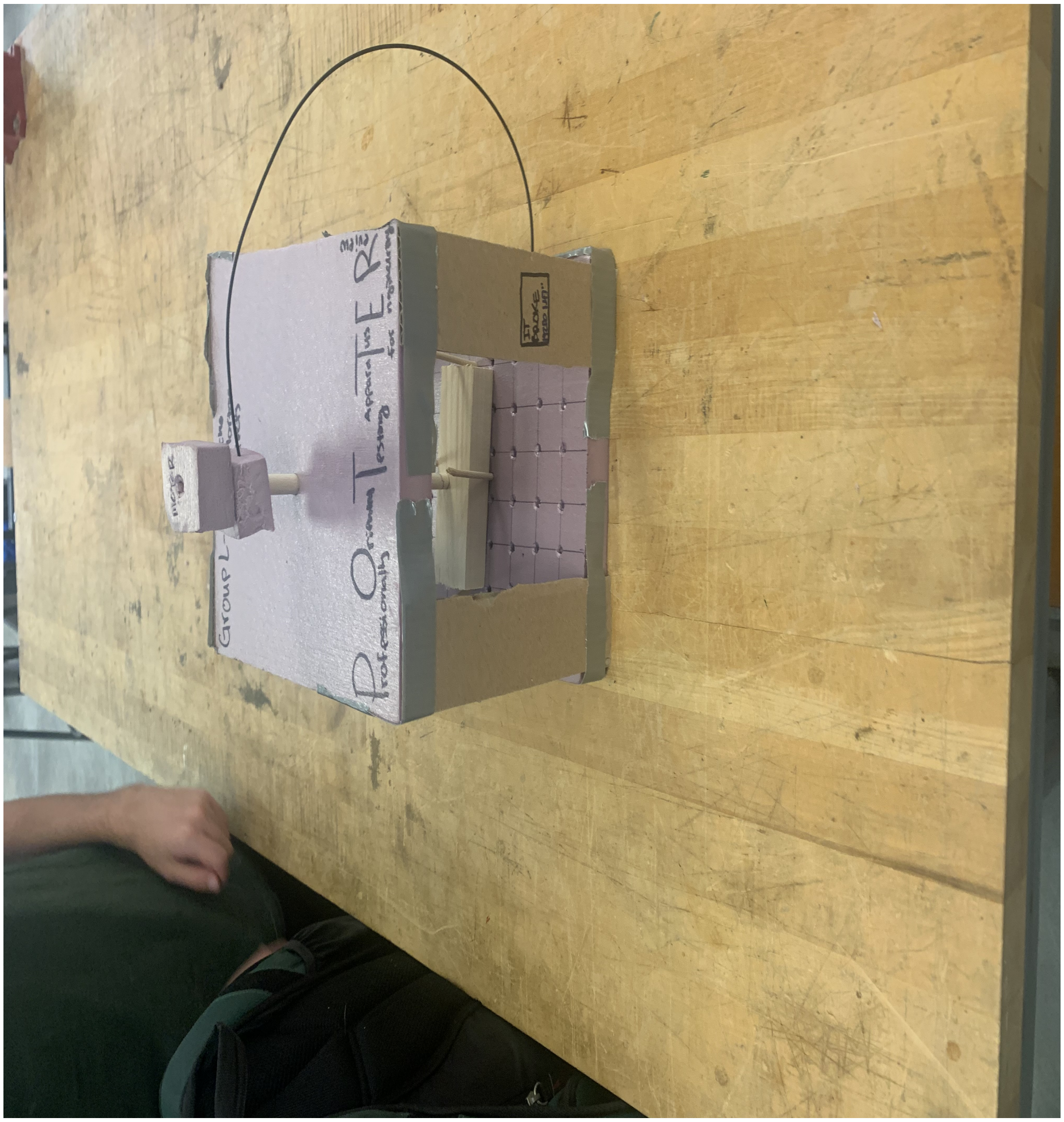


Figure 7: Front View of Mock Up

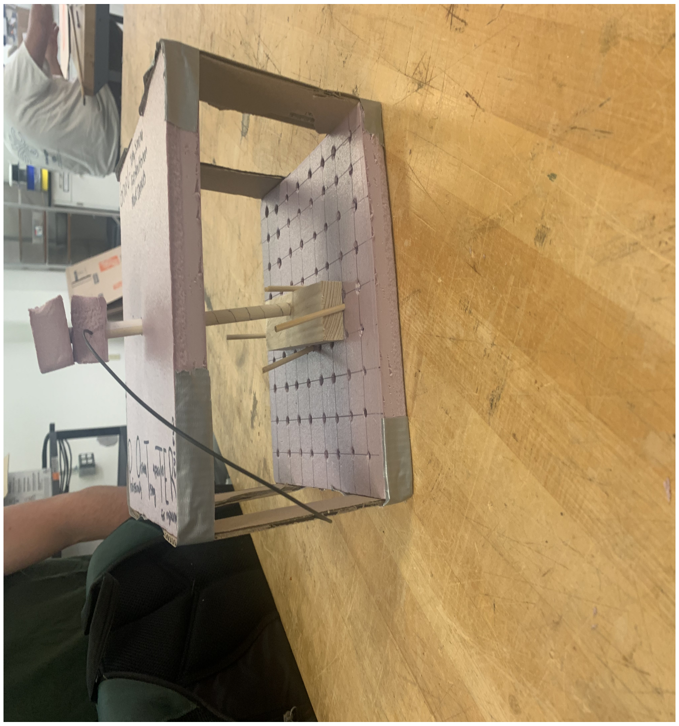


Figure 8: Side View of Mock Up

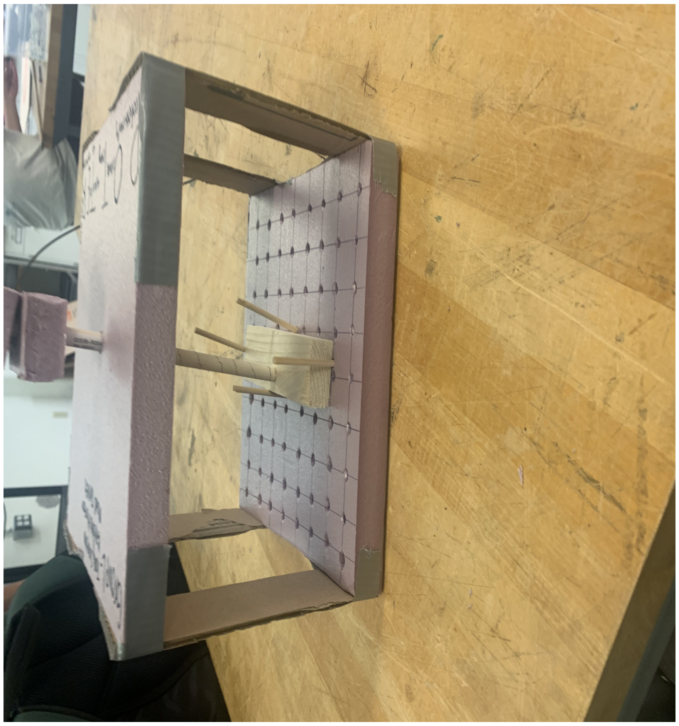


Figure 9: Side View of Mock Up

3.2 Functional Decomposition

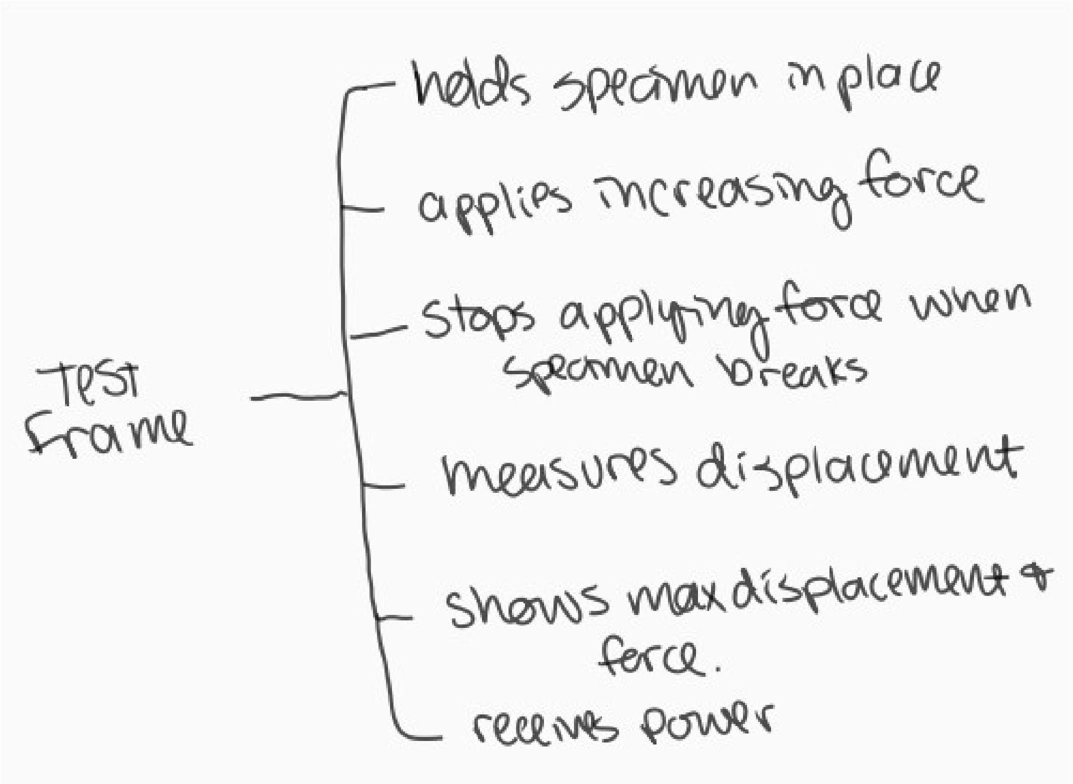


Figure 10: Function tree for Useless Box, hand-drawn and scanned

3.3 Morphological Chart

The morphological chart was created based on the function tree above. Several options to perform each function are pictured.

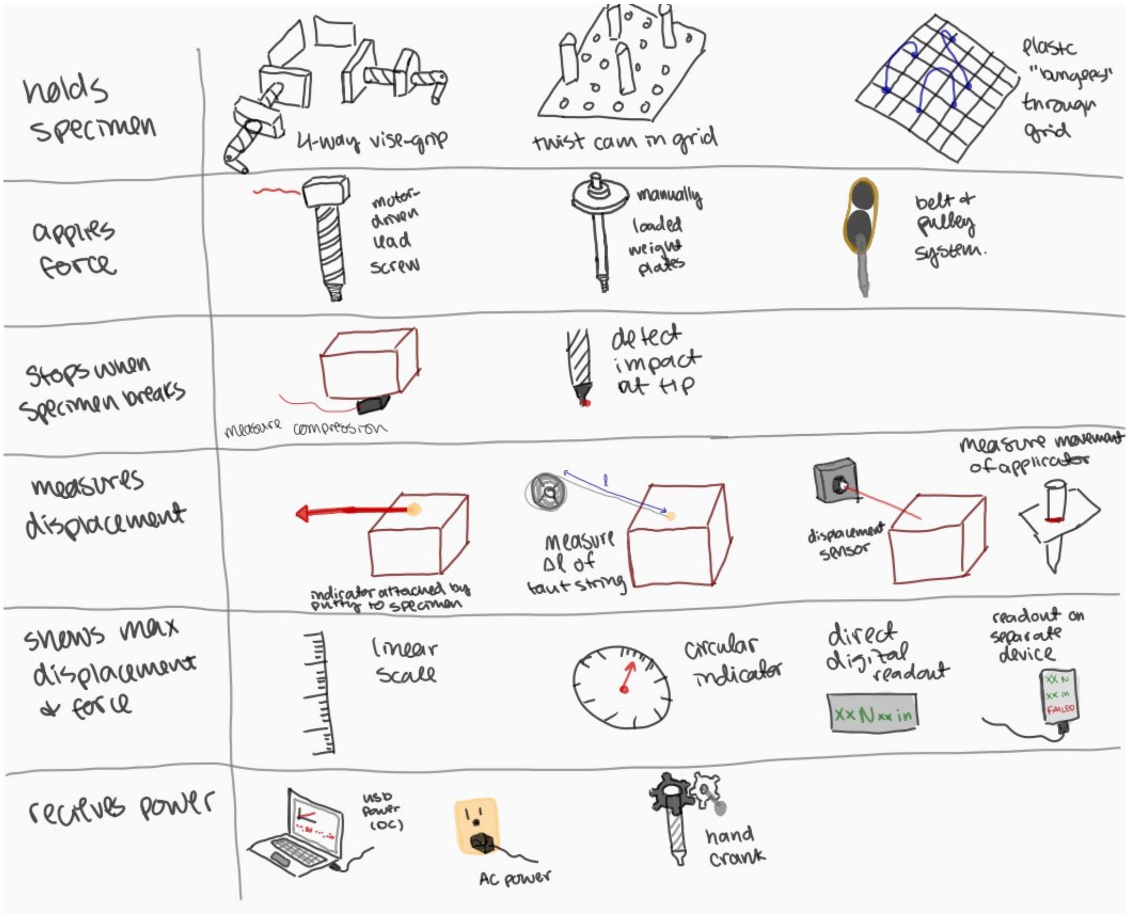


Figure 11: Morphological Chart for Test Frame

3.4 Alternative Design Concepts

3.4.1 Electric-Free (Marie Drevets)

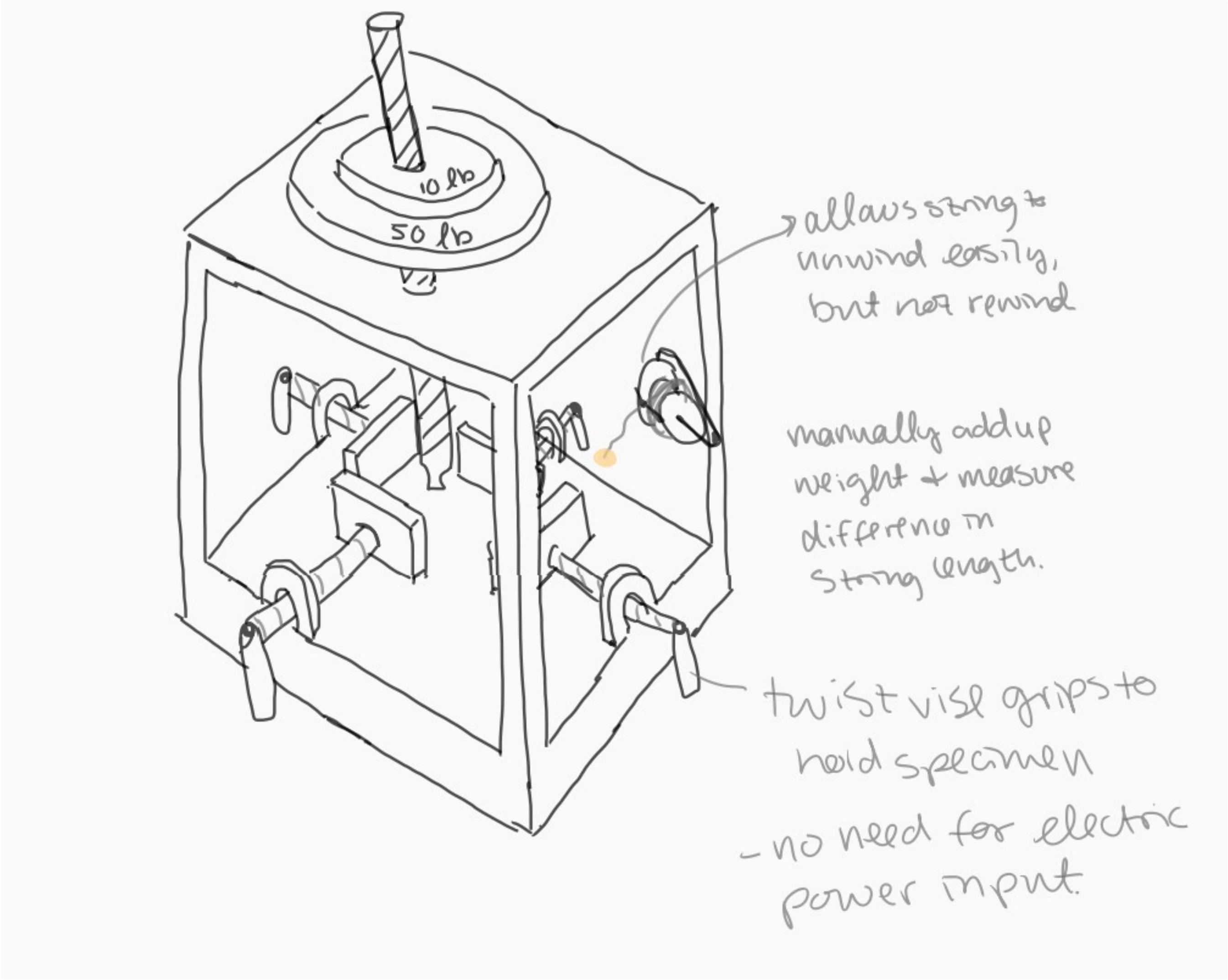


Figure 12: Sketches of Electric-Free concept

Solutions from morph chart:

1. 4-way vise grips
2. manually stack weight plates onto applicator pole
3. detect impact at tip - operator determined
4. measure length of a string
5. operator determined/linear scale
6. manual, doesn't need electric power

Description: The specimen is placed in the middle of the bed and secured by tightening 4 rotating vise-grips, and the displacement indicator string should be attached to the location of maximum deflection using putty. Then the operator stacks increasing weight onto the applicator pole until the specimen yields or passes. The displacement can be determined by measuring the change in length of the indicator string. The strength is simply the amount of weight at failure. Although this concept relies on the operator to perform most functions, it is convenient since it doesn't require electrical power.

3.4.2 Enclosed (Kiersten Horton)

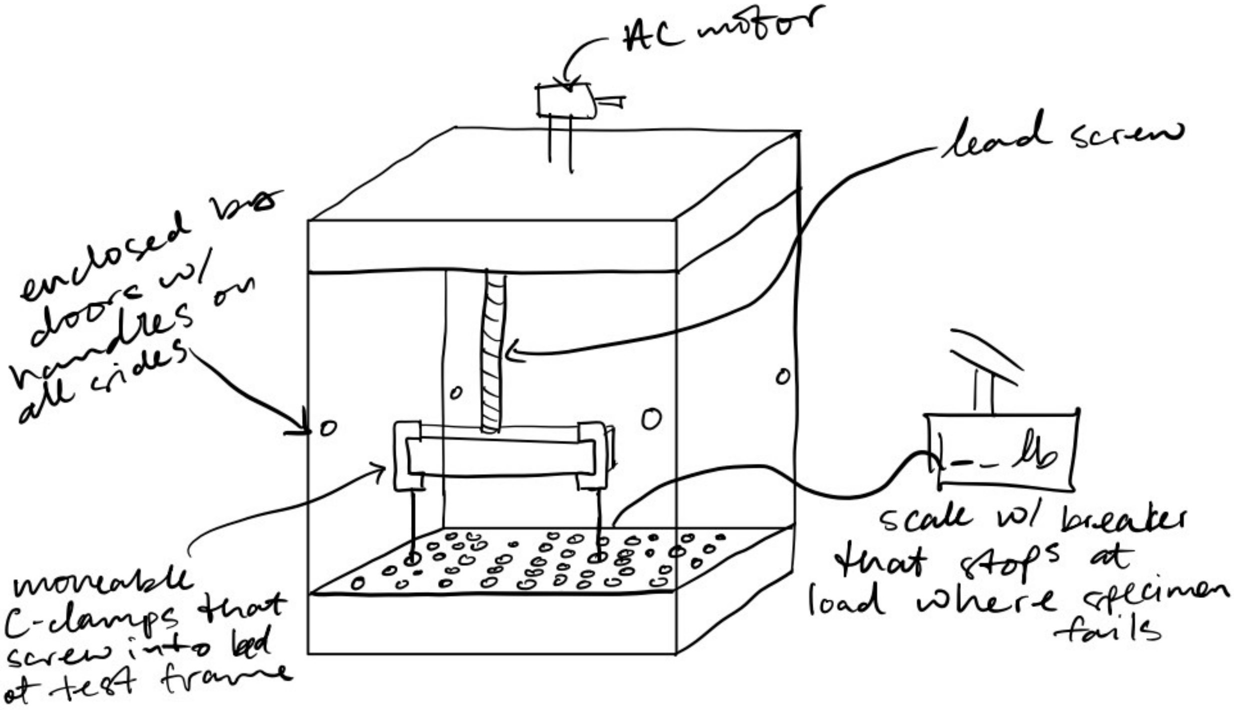


Figure 13: Sketches of AC Power and Lead-screw Concept

Solutions from morph chart:

1. Unit is portable
2. AC Motor applies force to leadscrew and thus the specimen
3. Move-able clamps
4. Scale stops when specimen fails
5. Doors surrounding the test specimen to protect user from fragments

Description: The specimen is loaded into c-clamps that can be adjusted to best support the specimen. The load is applied when an AC motor is powered and applies a force to a lead screw. The lead screw transfers the force to the specimen. When the specimen breaks, the scale will stop reading new values due to a circuit breaker. The specimen is enclosed by functional doors to contain fragments after the specimen fails.

3.4.3 Concept Three: Disco Ball (Tony Sancho)

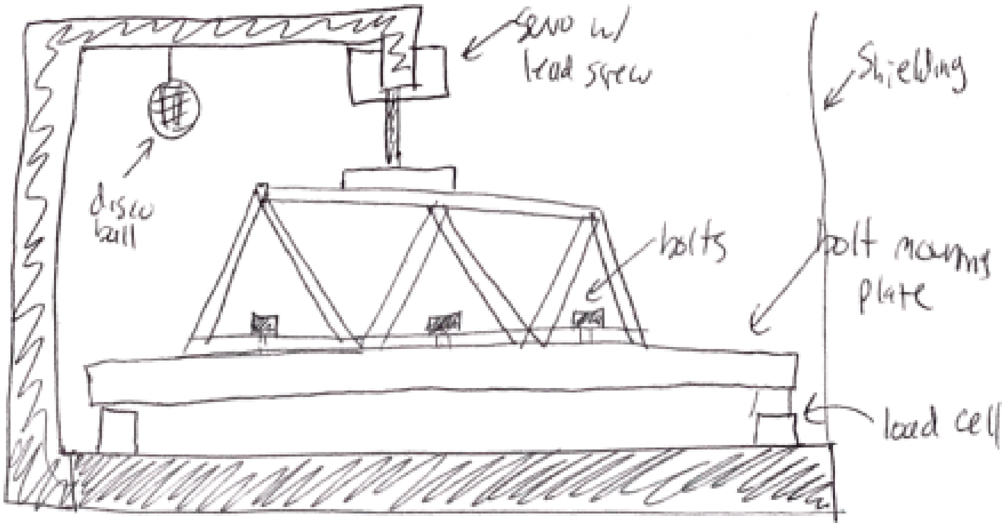


Figure 14: Sketch of load-cell based design

Solutions from morph chart:

1. Twist cam in grid
2. Motor-driven lead screw
3. Detect impact
4. Displacement sensor
5. Direct digital readout
6. AC Power

Description: A sturdy frame with redundant measurements for displacement and force ensures accurate and precise loading measurements. Electronic loading provides high resolution measurements as well. The fixture plate tightly fixtures the test specimen, and the splash shield makes sure that whatever isn't held down to the fixture plate won't injure the operator during structural failure.

4 Concept Selection

4.1 Selection Criteria

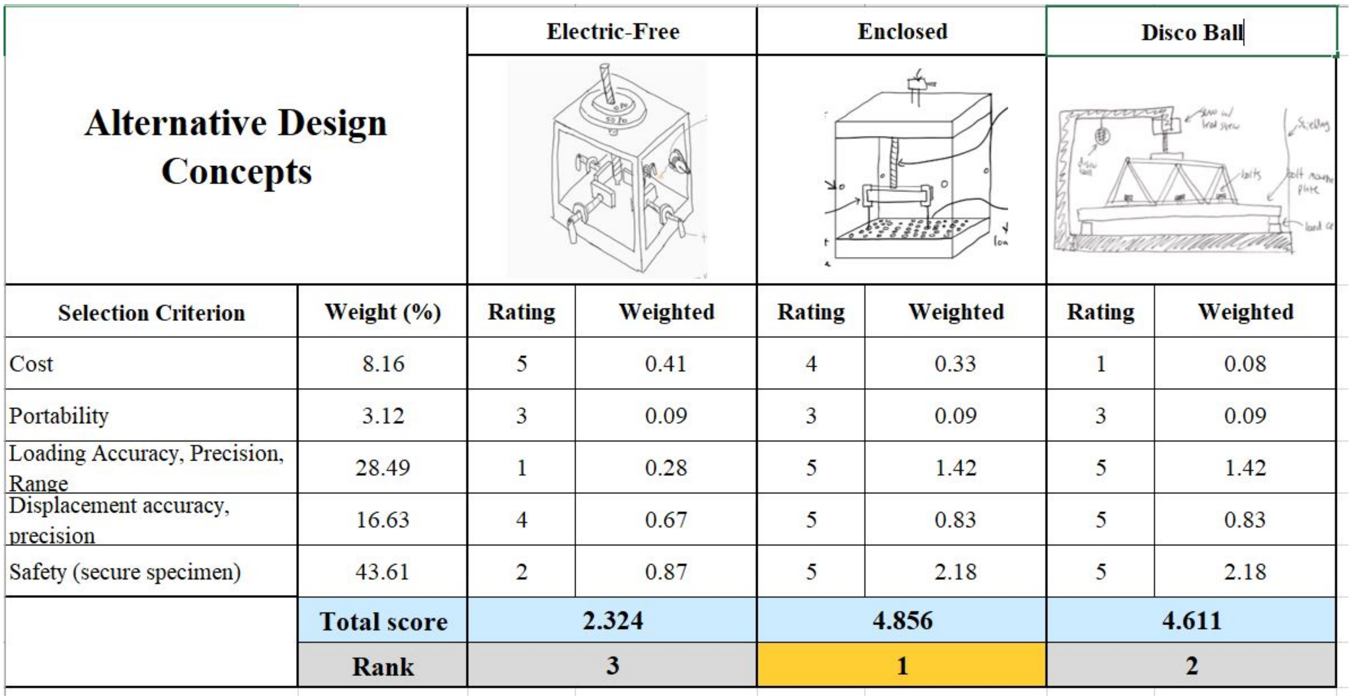
An analytical hierarchy chart was used to determine the weights of the selection criteria. These were chosen based on the customer interview, research, and desired specifications.

	Cost	Portability	Loading Accuracy, Precision, Range	Displacement accuracy, precision	Safety (secure specimen)	Row Total	Weight Value	Weight (%)
Cost	1.00	3.00	0.20	0.33	0.14	4.68	0.08	8.16
Portability	0.33	1.00	0.14	0.20	0.11	1.79	0.03	3.12
Loading Accuracy, Precision, Range	5.00	7.00	1.00	3.00	0.33	16.33	0.28	28.49
Displacement accuracy, precision	3.00	5.00	0.33	1.00	0.20	9.53	0.17	16.63
Safety (secure specimen)	7.00	9.00	3.00	5.00	1.00	25.00	0.44	43.61

Figure 15: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

For each criteria, the various concepts were given a rating 1-5, with 5 being the best and 1 the worst. From these ratings, a weighted average rating was calculated for each concept and used to rank them.



Alternative Design Concepts		Electric-Free		Enclosed		Disco Ball	
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Cost	8.16	5	0.41	4	0.33	1	0.08
Portability	3.12	3	0.09	3	0.09	3	0.09
Loading Accuracy, Precision, Range	28.49	1	0.28	5	1.42	5	1.42
Displacement accuracy, precision	16.63	4	0.67	5	0.83	5	0.83
Safety (secure specimen)	43.61	2	0.87	5	2.18	5	2.18
	Total score	**2.324**		**4.856**		**4.611**	
	Rank	**3**		**1**		**2**	

Figure 16: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The "Enclosed" concept was ranked the highest from the weighted scoring matrix, so it is the chosen concept. In terms of cost, it fairly inexpensive due to materials that would need to be purchased. This device uses an AC motor, lead screw, C-clamps, and plates (acrylic). It is a bit more expensive than the Electric-Free design, because that design focuses on manual load which are more cost-effective.

This device is most portable because all components are enclosed and can be easily moved as one unit. Weights do not have to be disassembled and everything is not left open like in the Disco Ball design.

The loading accuracy is highest here because a motor and lead screw is used to directly apply a force to the specimen. The load is applied by a lead screw with torque from an AC motor. The motor can be programmed, so there is no human error involved. The range of the load is determined by the torque rating of the motor, so it will have the correct range as long as an appropriate motor is installed. The force is then measured by load cells installed in the bottom plate to ensure accuracy in the scale reading. There are also load cells that give information to readout the max force before failure. The displacement is measured by data gathered from the load cell and the user. The user should know and input the stiffness of the material, so using Hooke's law, the system can identify the displacement because it knows the applied force.

The device is very safe, since it is completely enclosed. The user is protected from any flying pieces. The load is applied with electric power so the user is removed from any dangerous operations. All electrical components and wired will be covered and shielded so there is no chance of electrical shock.

4.4 Engineering Models/Relationships

4.4.1 Motor sizing

Variables used:

1. D_m: Pitch diameter of lead screw, m
2. F_{load}: Load applied to specimen, N
3. μ: Coefficient of friction
4. r_{screw}: 1/2 of the major diameter of the lead screw
5. T_{servo}: Required torque of servo motor
6. P: Pitch of lead screw

$$T_{servo} = \frac{F_{load}P}{2\pi r_{screw} + \mu D_m} \tag{1}$$

This model is used to determine the minimum servo torque based on the mechanical properties of the lead screw. Since finding hardware to interface a specific size of servo to a specific size of leadscrew is the most challenging part of this design, identifying the servo torque (different than the physical size) as a function of these properties makes sense.

4.4.2 Load cell rating

Variables used:

1. $F_{LC,i}$: Individual load cell force, N
2. $F_{LC,max}$: Minimum load cell force rating, N
3. $F_{app,max}$: Maximum applied force to test specimen, N
4. m_{plate}: Mass of fixture plate, kg
5. g: Acceleration due to gravity, $9.81\frac{m}{s^2}$
6. n_{LC}: Number of load cells
7. SF: Safety factor, typically 2

$$\sum_{i=1}^{n_{LC}} F_{LC,i} \geq m_{plate}g + F_{app,max} \tag{2}$$

$$F_{LC,max} = SF\frac{m_{plate}g + F_{app,max}}{n_{LC}} \tag{3}$$

This model is useful for determining the minimum load cell rating that can be used to measure loads on P.O.T.T.E.R.. The load cells see a constant load equal to the force of gravity acting on the fixture plate, and an additional load (that we want to measure) produced by the servo/linear actuator pushing on the test specimen. Load cells with too low of a force rating will either saturate or break, and load cells with too high of a force rating will have reduced resolution.

4.4.3 Hooke's Law

Variables used:

1. δ: Displacement of specimen
2. F: Force applied to the specimen
3. h: Height of specimen defined as the perpendicular distance from the base plate to where the lead screw makes contact
4. A: Cross-Sectional area of the specimen
5. E: Young's Modulus of the specimen's material

$$\delta = \frac{Fh}{AE} \tag{4}$$

This model is useful to determine the displacement of the specimen under the applied load. We can also use this model to choose a material to build the test frame from. It is important that the frame can withstand the maximum load applied by the lead screw so it doesn't break during testing.

5 Concept Embodiment

5.1 Assembly Drawings

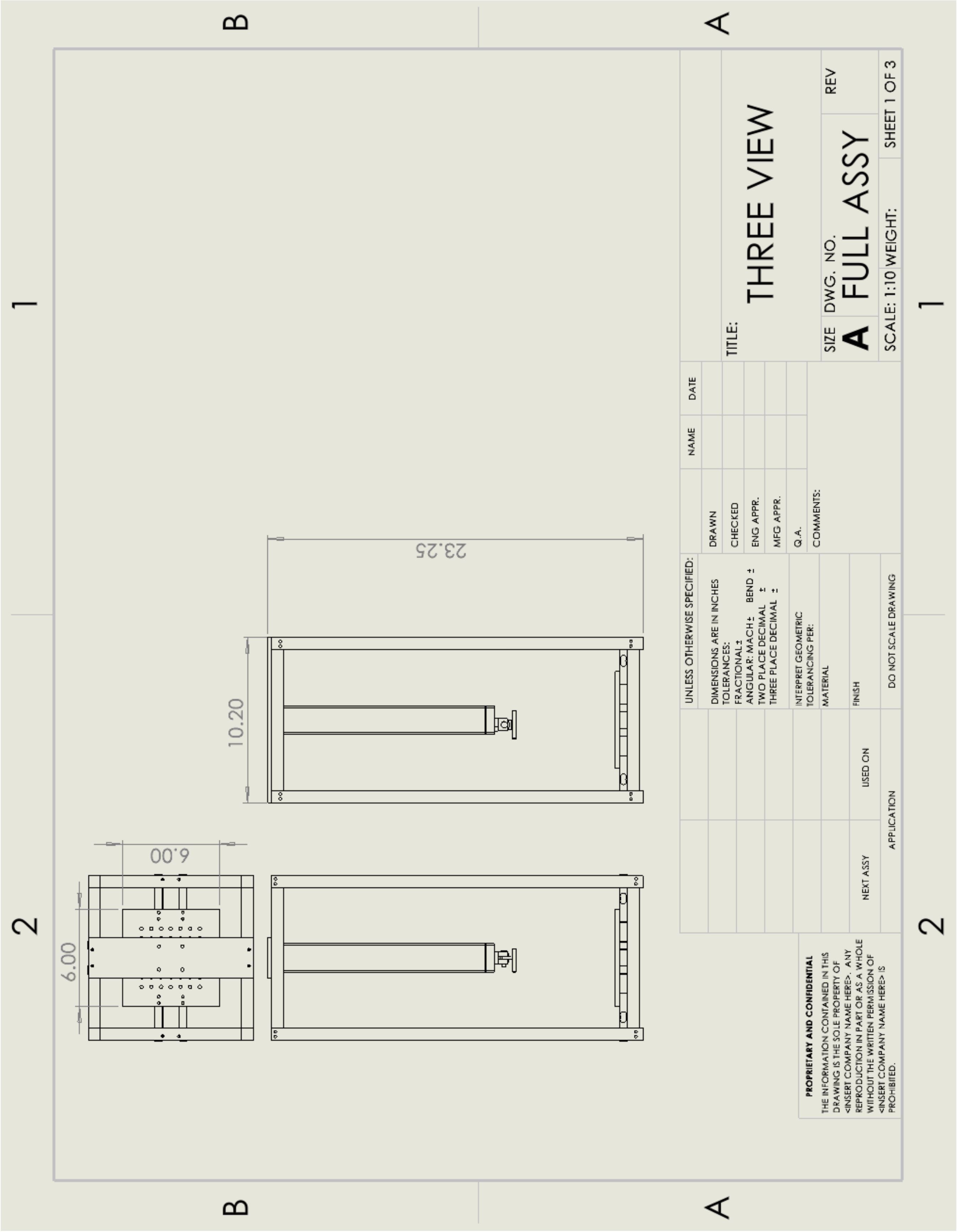
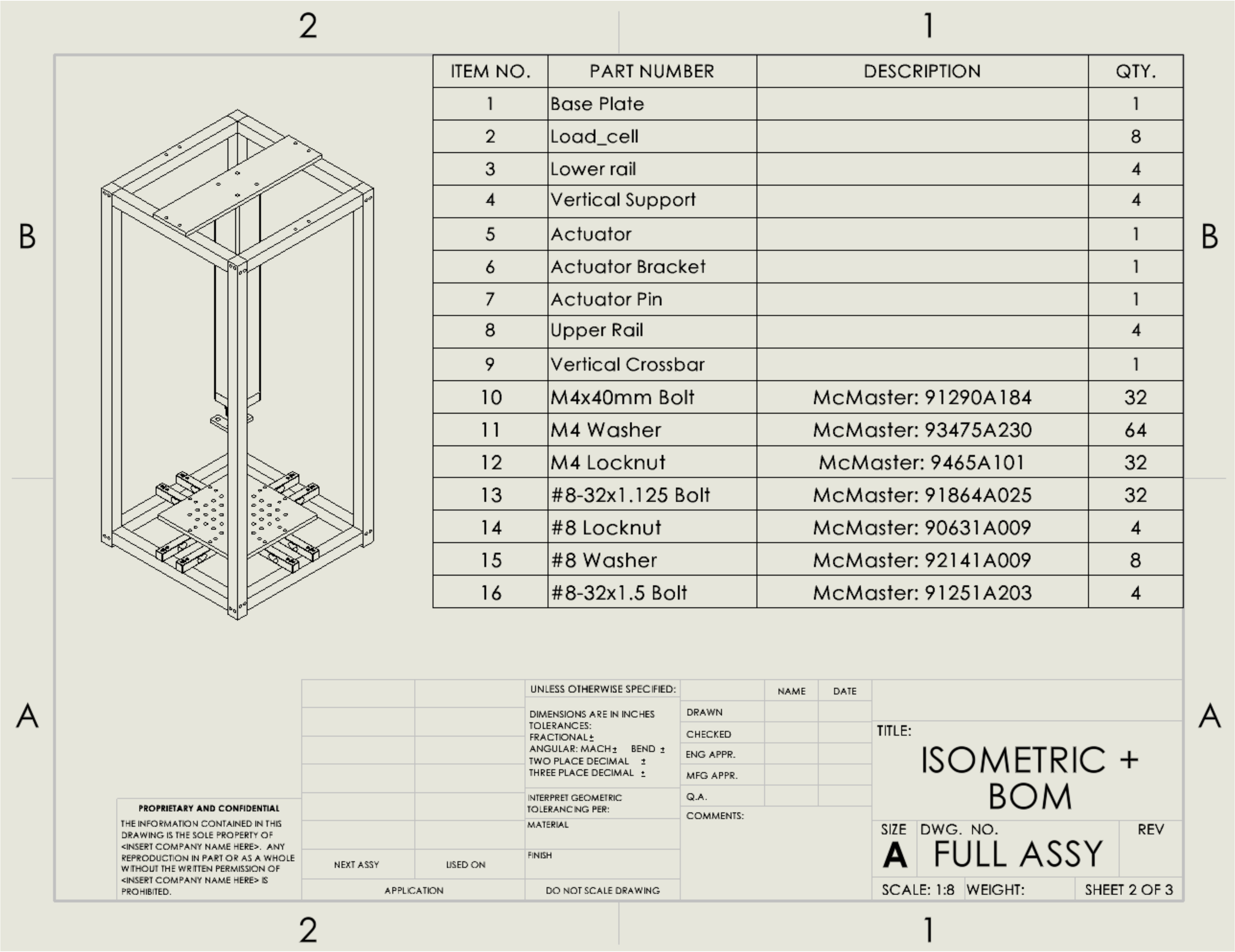


Figure 17: Assembled projected views with overall dimensions



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base Plate		1
2	Load_cell		8
3	Lower rail		4
4	Vertical Support		4
5	Actuator		1
6	Actuator Bracket		1
7	Actuator Pin		1
8	Upper Rail		4
9	Vertical Crossbar		1
10	M4x40mm Bolt	McMaster: 91290A184	32
11	M4 Washer	McMaster: 93475A230	64
12	M4 Locknut	McMaster: 9465A101	32
13	#8-32x1.125 Bolt	McMaster: 91864A025	32
14	#8 Locknut	McMaster: 90631A009	4
15	#8 Washer	McMaster: 92141A009	8
16	#8-32x1.5 Bolt	McMaster: 91251A203	4

Figure 18: Assembled isometric view with bill of materials (BOM)

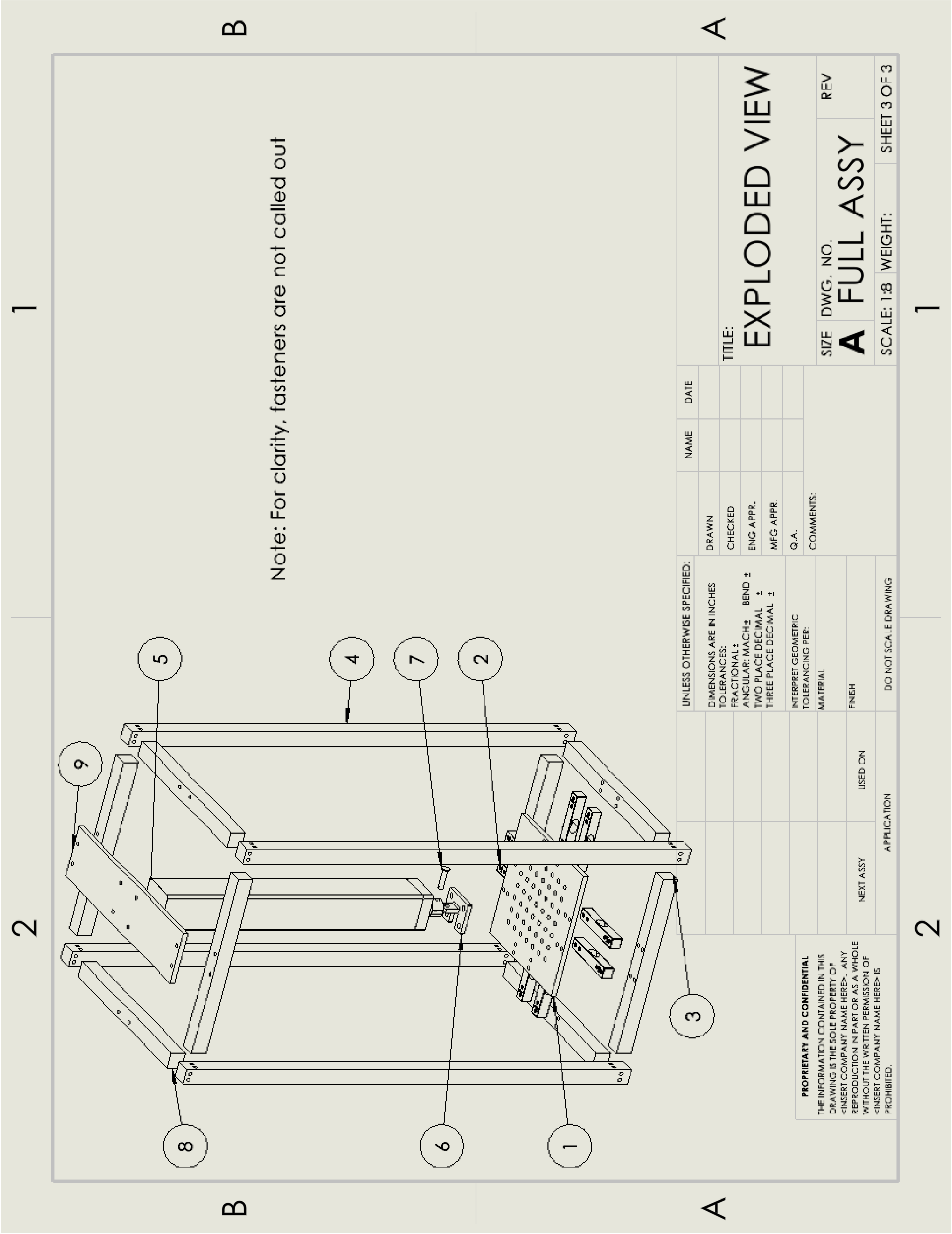


Figure 19: Exploded view with callout to BOM

5.2 Proofs-of-Concept

Due to the heavy loads which this test frame will apply, it needs to be made from metal, which takes up a big part of our budget. This project is not conducive to an intermediate prototype, so we are going directly from CAD modeling to the final product.

To make sure the steel base plate would be strong enough, we ran a static simulation with fixed edges and a 100lb force. From this study, we concluded that a 0.25" steel plate will be strong enough to withstand the loads.

5.3 Performance Goals

To measure the force, we have 8 load cells that are each rated at 20kg. Each side of the base plate will rest on two load cells. With this setup, the plate and load cells can support approximately 350lbs, which gives us a FOS of 2.3. The load cells measure the force with 99.95% accuracy, which will meet the goal of measuring the force within 0.1 lbs.

The actuator has a stroke of 6 inches, which meets our performance goal of exceeding 3 inches of displacement motion on our axis. Its speed is 1 inch/second, which exceed the performance goal of traveling 3 inches in 10 seconds. It can apply 150lbs of force, which exceeds the performance goal of applying 100lbs of force.

The displacement will be measured using a linear potentiometer measuring the length change of a string attached to the specimen. Using the diameter of a spool attached to the potentiometer, we will calculate the length change of the string. This will meet the performance goal of measuring the displacement within 0.01 in. The operator can check the displacement using their material and geometric parameters in Hooke's Law.

5.4 Design Changes

The main difference between the selected design concept and the current prototype is that we are using a linear actuator to apply the load instead of a lead screw powered by a motor. This change was made to simplify the design and reduce the number of components needed. It also eliminates the need for any shaft couplings.

We have also decided to leave the sides of the test frame open instead of covering them with acrylic. The main reason for this change is to save on the cost of material. In addition, leaving the sides open will make it easier for the operator to access their part to secure it.

We have decided to not use c-clamps. This choice was made so the device can be used for a variety of designs. Our device will have tapped holes that can allow different supports and structures to be screwed into place. This allows more flexibility for device orientation when applying a load. The plate can use c-clamps, three-pronged clamps, screws and elastics, and other securing methods.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Decision #1: Base Plate Thickness

We used an FEA model to determine the necessary thickness of the base plate so it wouldn't deflect under the highest possible load. This was before we had fully decided on all the part

Plate Thickness (in)	Max deflection (in)	Max Von Mises Stress (psi)	Part Weight (lbs)
0.5	0.00015	411.4	19.6
0.375	0.0003404	437.1	14.7
0.25	0.001115	980.3	9.8

Table 3: Results of base plate FEA

dimensions, so the model was a 12"x12" plate with a grid of 0.25" diameter holes spaced 1.25" apart. The bottom 4 outer edges were fixed and an evenly distributed load of 150lbs was applied to the top surface. The material used was plain carbon steel. The results are summarized in table 3 for 3 different thicknesses.

Based on the results of the simulation, it was decided that 0.25" was an acceptable thickness for the base plate. Although there is some deflection, it is very minimal, and a thicker plate weighs significantly more.

6.1.2 Decision #2: Number of Load Cells

In our model, there needs to be a way to output of the force the specimen can withstand. Regardless of how the specimen is loaded, the force is distributed over the entire base plate. After analyzing the distributed force of a 150 lb point force, we determined that we would use eight load cells to ensure a factor of safety of 2. Each load cell can withstand 20 kg or 44 lbs, so we would only need 4 load cells to successfully measure the 150 lb force from the linear actuator. To meet our factor of safety, we will use 8 load cells, and this allows an accurate load output up to 352lb, which exceeds the force directly from the linear actuator.

6.1.3 Decision #3: Metal Selection

One of the customer needs for our test frame is portability, and with that we wanted to find simple ways to minimize the weight. To withstand the force applied by the linear actuator, we chose to design the base plate using steel. However, other parts that don't receive such a concentrated, like vertical support beams, could be made of a softer and less expensive material, and we chose aluminum. These two decisions were supported by FEA modelling and simulations in SolidWorks.

6.2 Design for Safety

6.2.1 Risk #1: flying fragments

Description: small pieces could go flying into people's eyes or face if the specimen breaks
Severity: Critical
Probability: Likely
Mitigating Steps: put up an impact shield, make sure the specimen is secure, have the operator wear safety glasses

6.2.2 Risk #2: catching in actuator

Description: hair, jewelry or loose clothing could catch in the actuator and injure the operator
Severity: Catastrophic
Probability: Unlikely

Mitigating Steps: have the operator tie back all loose things

6.2.3 Risk #3: caught body part

Description: if someone is not careful, a finger could get caught between the specimen and load applicator and smushed by the load
Severity: Marginal
Probability: Seldom
Mitigating Steps: place a warning sign, impact shield can also prevent this, the applicator will move slowly so they have time to move the body part

6.2.4 Risk #4: electric shock

Description: if there are exposed electrical wires, someone could get shocked by touching them while the machine is operating
Severity: Marginal
Probability: Seldom
Mitigating Steps: do not have any exposed wires or electrical components

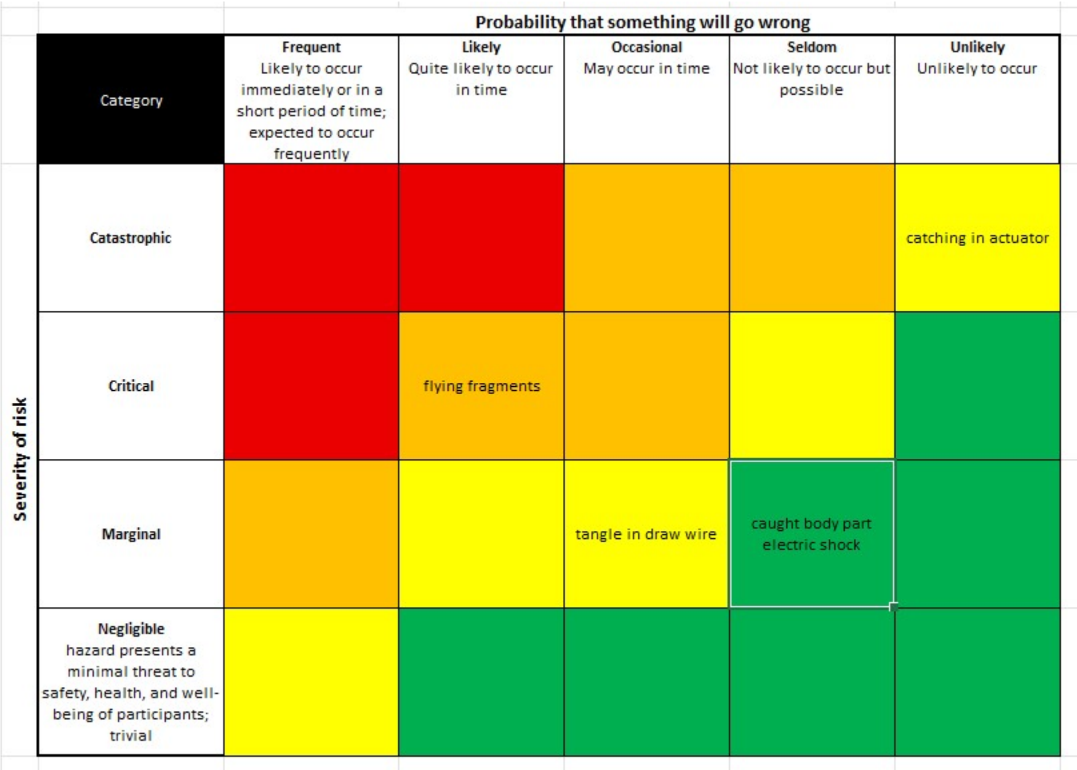
6.2.5 Risk #5: tangle in draw wire

Description: the draw wire from the displacement sensor could get tangled in someone's clothes, fingers, jewelry, or hair
Severity: Marginal
Probability: Occasional
Mitigating Steps: keep draw wire neatly wrapped around spool, do not pull it too hard or spin the spool to fast.

Based on the heat map, the highest priority risk is flying fragments since it is in the orange zone. There are no risks in the red zone, which is good. The second priority should be loose items catching in the actuator or string potentiometer. The lowest priority risks are body parts being smushed by the load and electric shocks. Ideally we would like to have a rigid plastic or wire mesh impact shield to prevent the top three risks. However, there was not enough money in the budget. We will instead instruct the operator on safe practices. They need to wear safety goggles, tie back any loose hair, sleeves, or jewelry, and keep hands clear of the device when load is being applied. These practices are not too difficult or inconvenient, so we can reasonably expect the operator to follow them and avoid risks.

6.3 Design for Manufacturing

Minimizing the number of machining operations was the design goal. All parts had to be machined on a mill. Therefore, to reduce machining operations, parts were designed to need no more than one swap out of the vice. This was done by prioritizing hole locations such that the sizing of the part and drilling of bolt holes could be done from the same orientation. Furthermore, aluminum was chosen for as many parts as possible due to it being significantly easier and faster to machine than steel. Fasteners and fastener locations were selected such that the frame can be built from the ”ground up”, not requiring any orientation changes to assemble.



		Probability that something will go wrong				
	Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Severity of risk	**Catastrophic**	🟥	🟥	🟧	🟧	🟨 catching in actuator
	Critical	🟥	🟧 flying fragments	🟧	🟨	🟩
	Marginal	🟧	🟨	🟨 tangle in draw wire	🟩 caught body part electric shock	🟩
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial	🟨	🟩	🟩	🟩	🟩

Figure 20: Heat map showing risks and with their severity and likelihood

6.4 Design for Usability

6.4.1 Vision Impairment

A vision impairment would make it difficult to use our device. First, it would be challenging to fixture the part without vision, but the components are simple and not too precise, so it should be doable. It would also be hard to read the results without vision. One possible way to fix this is having the option to plug into a laptop which could read the results aloud.

6.4.2 Hearing Impairment

Hearing impairment wouldn't get in the way of any of the major functions of our device. The only possibility would be that the specimen might make a sound when in fractures, but the operator should also be able to see the fracture visually.

6.4.3 Physical Impairment

Physical impairment would make it difficult to fixture the specimen. An operator with a physical impairment would probably need help bolting down the specimen since it requires fine motor control.

6.4.4 Control Impairment

Control impairment would make it dangerous to use our device. The operator could injure themselves if they do not stay clear of the device while it applies the load.

7 Final Prototype

7.1 Overview

The performance goals were all met or surpassed. The load applicator needed to travel 3 inches downward within 10 seconds and apply at least 100lbs of compressive force. The linear actuator is able to apply a load of 150 lbs and travel up to 6 inches at 1 inch/second. These specs exceed the first two performance goals. The frame should have reliable force and displacement measurements, with 0.1lb and 0.01 inch, respectively which is displayed clearly to the user. The base plate is supported by eight load cells, each rated at 20kg and 99.95% accuracy. We have calibrated the load cells to 0.05lb precision. These load cells meet the force part of third goal. To measure displacement, we have implemented a spool of string which should be secured to the specimen and can be measured before and after fracture. This string serves to measure the displacement of the specimen; its precision is determined by the precision of the measurement device.

7.2 Documentation

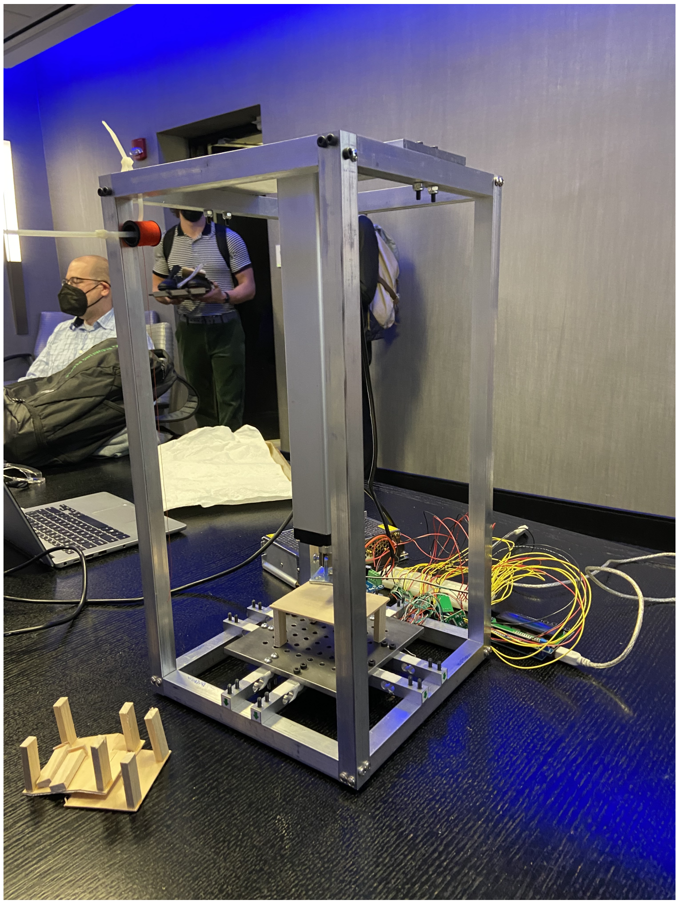


Figure 21: Final Project Submission

We surpassed all the performance goals. The displacement mechanism could be improved upon by implementing the original idea of a potentiometer. We were not able to implement that in this prototype because of time and electronic hardware limitations.

Bibliography

[1] ASTM International. *Standard Practices for Verification of Displacement Measuring Systems and Devices Used in Material Testing Machines*. 2020. URL: http://www.astm.org/cgi-bin/resolver.cgi?E2309E2309M.

[2] ASTM International. *Standard Test Method for Compressive Properties of Rigid Plastics*. 2015. URL: http://www.astm.org/cgi-bin/resolver.cgi?D695.