Universal Testing Machine Frame Deformation

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Abstract:

Concerning the Universal Testing Machine, this thesis aims to develop an alternative frame model for bending test. The design needs to be simple, increase the operator safety and fulfill criteria of bending standards.

The frame was designed in SolidWorks software, and built using AISI 4340 steel sheets. Laser cutting was used to prepare all parts of the frame, followed by welding to permanently join them into one single entity.

ASTM D790 and E2309 limit the frame strain to 0.0005, and maximum displacement to 1% of specimen deformation. Finite Element Analysis and Euler – Bernoulli theory were applied to simulate bending tests, to compute stress and deformation of the frame. Hooke's law was for the calculation of strain and the largest force the frame can withstand corresponding to its strain limit.

As a result, the model was proved to be lighter, more affordable and safer than the traditional frame. The developed frame model fulfills ASTM D790 and Class A of E2309 until 13.7 kN. It fulfills D790 and Class B – E2309 to 14.38 kN for 20-mm span, to 22.01 kN for 30-mm span, and to 30 kN for the range from 50 – 400 mm span.

Keywords:	Universal Testing Machine, bending test, frame, Finite Element Analysis. Hooke's law, Euler – Bernoulli.
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1 INTRODUCTION

Bending test is a mechanical testing method commonly used to define the flexural strength of a material. Its fundamental steps include subjecting a force to a specimen and measuring the specimen deflection. However, not only does the force deform the specimen but it also displaces the whole testing system to some degree during the operation [1]. Thus, in order to achieve the correct deflection of the specimen, the displacement of the testing system need be minimized and removed from the total measured value. This calls for an evaluation of the frame displacement during bending test, from which understands and ensures the accuracy of the test result, as well as aim to propose a new frame design that is affordable and performs accurately in university.

The testing method was applied within the valid range of bending tests, Hooke's Law, Euler-Bernoulli beam theory, Finite Element Analysis, ASTM and ISO standards.

1.1 Objective - two criteria for frame testing

This thesis aims to design a bending frame that is simple, increases the operator safety and ensures the accuracy of the test results. In order to ensure the result accuracy, the frame need to fulfill two criteria of displacement: frame strain limit of 0.0005, and maximum frame displacement of 1% specimen deflection.

1.1.1 Criterion 1

ASTM E2309 is a standard outlining the procedures for displacement verification of universal testing machines:

Classification	Error not to Exceed the Greater of:	
	Absolute Error [mm]	Relative error [% of displacement]
Class A	±0.025	±0.5
Class B	±0.075	±1.0
Class C	±0.125	±2.0
Class D	±0.25	±3.0

Table 1: ASTM E2309 accuracy classification criteria

In which,

$$\text{Relative error} = \frac{A-B}{B} \quad (1)$$

$$\text{Absolute error} = \mathrm{A} - \mathrm{B} \quad (2)$$

A	displacement measured by the machine.
B	correct value of the specimen deformation

- According to ASTM E2309 Class B, the maximum displacement measuring error is 1%.
- Meanwhile, ASTM D790 states that the maximum specimen strain is 5%.

If the displacement measuring error is limited to 1%, the frame cannot deform more than 1% during the 5% strain test. In other words, the frame displacement shall not exceed 1% of 5% during bending test. Therefore, strain limit of the frame is $\boxed{\varepsilon = 0.01 \times 0.05 = 0.0005}$

1.1.2 Criterion 2

According to ASTM D790, the specimen maximum strain is ε = 5% (section 4.2), and the maximum frame displacement is 1% of the specimen deflection. (section 6.1), meaning that

$$\varepsilon_{specimen} = 0.05 \quad (3)$$

$$y_{frame} = 0.01 \cdot y_{specimen} \quad (4)$$

- For three-point bending, $y_{specimen} = \frac{\varepsilon L^2}{6h}$ [2] (5)
- For four-point bending, $y_{specimen} = \frac{\varepsilon(3L^2-4a^2)}{12h}$ [3] (6)

In which,

$y_{specimen}$	maximum deflection of specimen [mm]
y_{frame}	maximum frame displacement [mm]
$\varepsilon_{specimen}$	strain limit of the specimen [mm/mm, %, or dimensionless]
L	support span [mm]
h	beam thickness [mm]
a	distance from support point to loading point [mm]

According to D790, the specimen length and thickness are such that $h = \frac{1}{16}L$ (7)

According to ASTM D6272, ASTM D7264 and ISO 14125, the load span is either one-half or one-third of the support span. Therefore, the distance from support point to loading point $a = \frac{1}{3}L$ or $a = \frac{1}{4}L$ (Figure 1) (8)

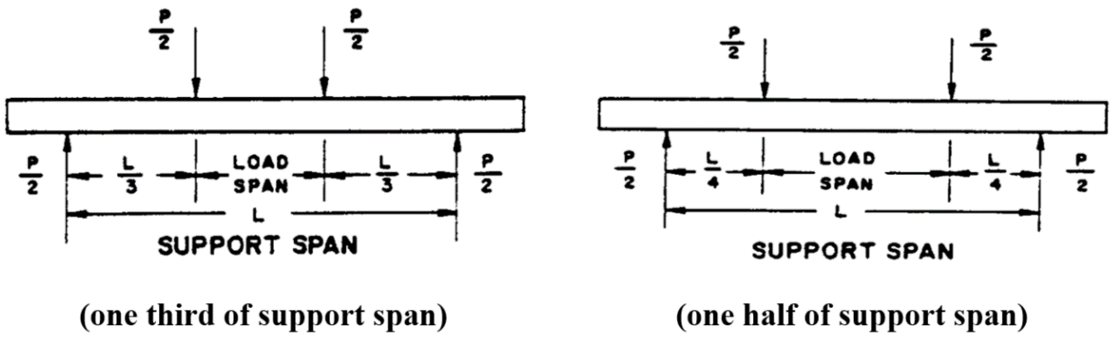


Figure 1: Four-point bending – Load span [4]

Combine equations (3), (4), (5) and (7), we have

$$y_{frame-3point} = 0.01 \times \frac{0.05L^2}{6 \times \frac{1}{16}L} = \frac{L}{750}$$

Combine equations (3), (4), (6), (7) and (8), we have

$$y_{frame-4point-one-third} = 0.01 \times \frac{0.05\left(3L^2 - \frac{4}{9}L^2\right)}{12 \times \frac{1}{16}L} = \frac{23L}{13500}$$

$$y_{frame-4point-one-half} = 0.01 \times \frac{0.05(3L^2 - \frac{4}{16}L^2)}{12 \times \frac{1}{16}L} = \frac{11L}{6000}$$

To sum up, maximum frame displacements are calculated as:

Three-point bending [mm]	**Four-point bending [mm]**	
	One third	**One half**
$\frac{L}{750}$	$\frac{23L}{13500}$	$\frac{11L}{6000}$

Table 2: Frame displacement formula

1.2 Bending test

Bending test, also called flexural test, is a combination of tension and compression tests used to study the strength of materials under loading. It directly measures the applied force and maximum deflection of the specimen, from which determine the flexural strength and select the right material for specific application. The materials can be metal, plastic, wood, and ceramics, and are commonly made into rectangular or cylindrical beams. [5]

Bending tests are conducted by a universal testing machine using either three-point or four-point fixture. Three-point bending involves two support points and one loading point while four-point bending requires two support points and two loading points (Figure 2).

In three-point bending, the force is concentrated and applied vertically downwards at the beam center, while in four-point bending, the force is separated into two loading points, equally distant from the center. Therefore, larger portion of the specimen is exposed to stress, leading to the maximum flexural stress spreads over the beam section between two loading points in four-point bending, and yet occurs at the beam center in three-point bending. [5]

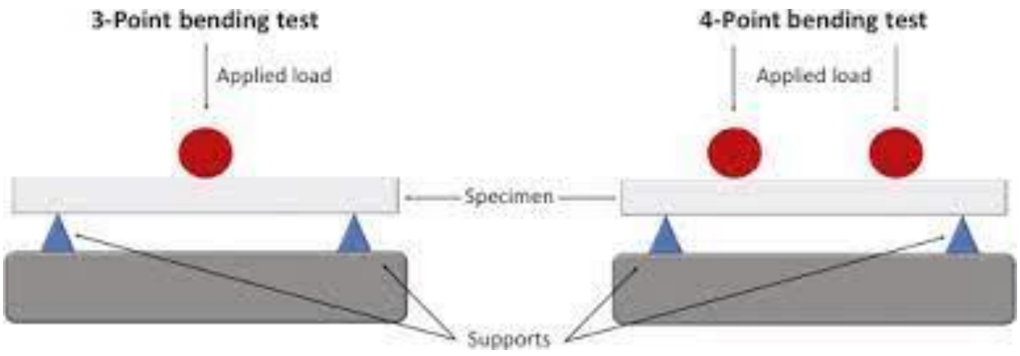


Figure 2: Three-point bending and four-point bending tests arrangement. [6]

Bending moment causes normal stress in the beam, particularly compressive stress at the top and tensile stress at the bottom surfaces, which develops an area of transverse shear stress acting along the midline. If the specimens are short, especially sandwich structure element that comprises a core of a less stiff material, the shear stress can dominate the normal stress and affect the bending results. Therefore, the specimen needs to be prepared so that the support span is large enough compared to its thickness. [5]

According to the ASTM D790, the support span-to-depth ratio of 16 is generally recommended to minimize the shear effect and ensure that the specimen failure is only because of the bending moment; for composites and laminated materials, this ratio shall be larger and can increase to 32:1, 40:1 or 60:1. [2]

1.3 Universal testing machine

Universal Testing Machine (UTM) is a testing device used to measure the compressive and tensile strength of a material. The machine is also called a tensile tester, or a universal tester since it can carry out a wide range of mechanical tests relating to tension, compression, bending, torsion, peeling, puncture resistance, slip properties and texture of the materials. [7]

Depending on the frequently tested materials and their maximum load capacity, consumers shall invest in a machine model which has either single, dual or four columns, floor standing or tabletop, and electromechanical or hydraulic system. A typical UTM will have a load frame, a load cell, an actuator, an extensometer and a control system [8]:

- Load frame defines the maximum load capacity of the machine. It consists of a base, support columns, a fixed and a moving crosshead. The frame can be supported by either one, two or four columns. Each support column comprises a guiding column and a ball screw. The fixed crosshead is placed either at the top or at the bottom of the frame while the moving crosshead is mounted on the guiding columns and the ball screws. The ball screws rotate, and thus drive the movable crosshead up and down.
- Load cell is a sensor device that converts pressure into electrical signal, therefore, measures the value of force. It is attached to either the fixed or the movable crosshead and calibrated periodically.
- Extensometer is used to measure the specimen elongation or deflection under stress. The name comes from two words “extension” and “meter”.

- Control software plays an important role in monitoring the test, setting up specifications, displaying and analyzing the test results.
- A UTM also has an actuator, which is a device converting electrical, air or hydraulic energy into motion.

Besides, the machine is equipped with some external accessories such as grips, fixtures and plates for wider testing applications; with a conditioning chamber to control the temperature, pressure and humidity of the testing environment. [8]

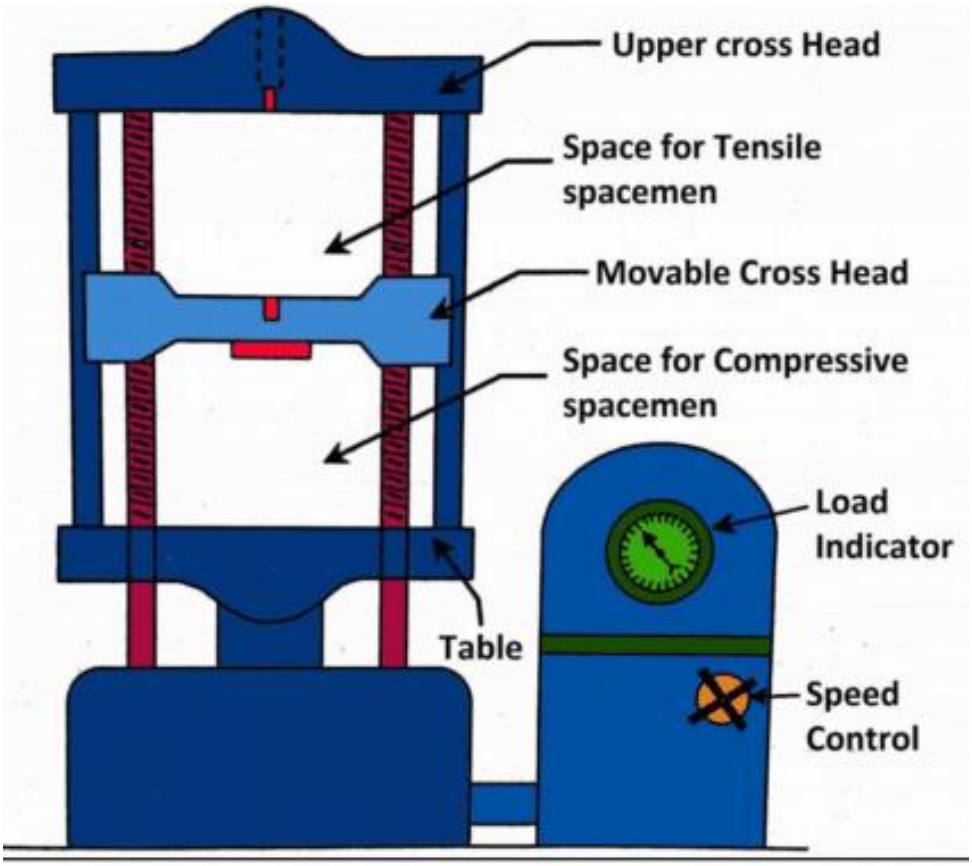


Figure 3: Universal testing machine diagram [9]

2 LITERATURE REVIEW

2.1 Essential components of UTM machine

Although universal testing machines vary according to manufacturers and testing demands, it aims to measure the force and the specimen deflection. Essential parts of the machine are [8]:

- A load frame with support columns, fixed and moving crossheads
- A load cell measures the applied force, in Newton [N]
- An extensometer measures the specimen deflection, in millimeter [mm]
- An actuator to produce force
- A control software

2.2 CAD design of traditional frame

The 3D design of the existing frame was modelled in SolidWorks 2020 software, and based on *Universal Testing Machine – SL series* of Tinius Olsen [10]. The traditional frame below comprises one base, one top plate, 4 support columns, 2 ball screws and one movable cross-head.

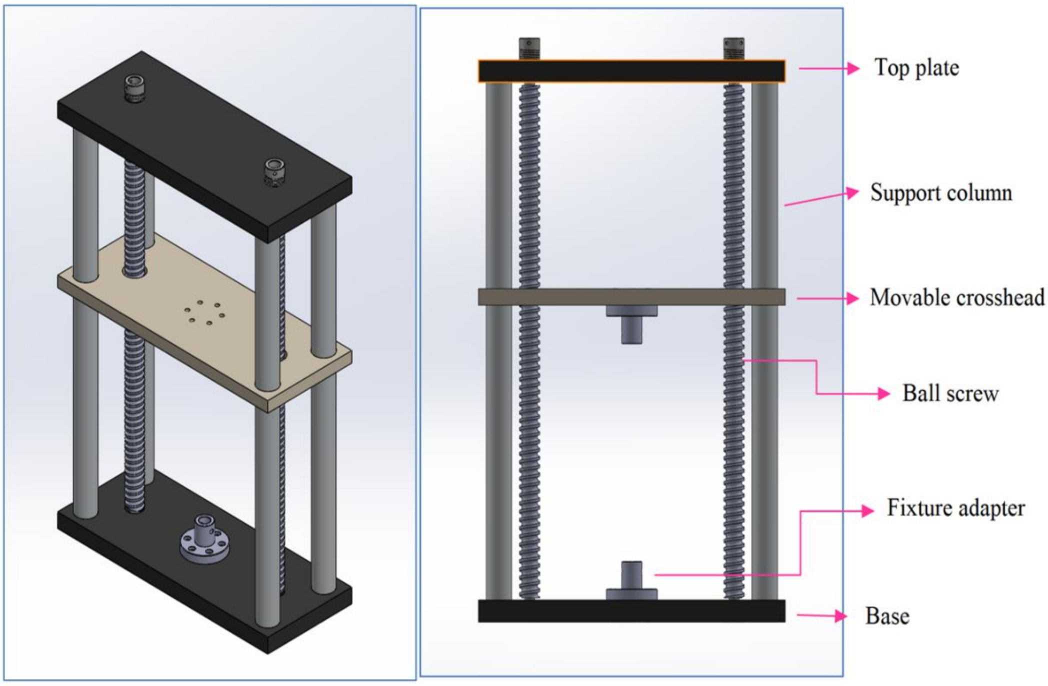


Figure 4: 3D model of traditional bending frame

2.3 Manufacturing process of traditional frames

Before comparing the traditional to alternative approach, it is necessary to understand the traditional processes. This chapter demonstrates the traditional frame structure manufacturing process, based on the book *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*, by Mikell P. Groover.

As described in Chapter 2.2 of this thesis, base plate, top plate, movable crosshead, support columns and ball screws are essential parts of a machine frame. They are manufactured as:

- The base, top plate and movable crosshead can be formed by casting, in which the molten metal is poured into a mold and afterwards solidified in the shape of the mold cavity. Next, milling, drilling and tapping are applied to trim the edges and create threaded holes to connect them with the support columns and ball screws.

  Casting is a solidification process yet also a term to describe the final part that is achieved from the operation. [11]

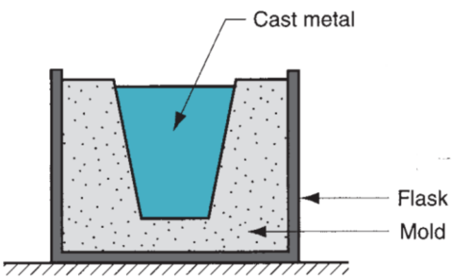
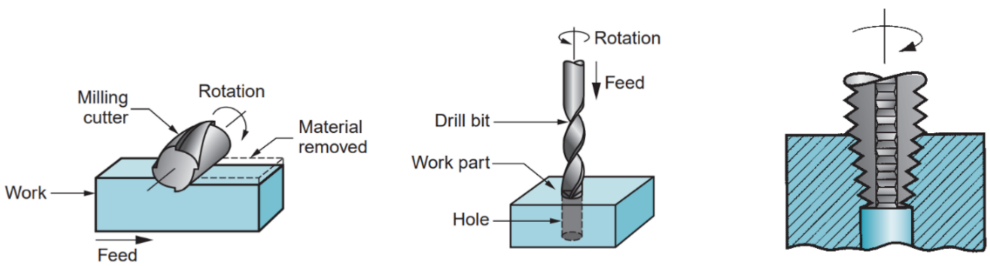


Figure 5: Open-mold casting [11]



a. b. c.

*Figure 6: **a.** Milling, **b.** Drilling, and **c.** Tapping [11]*

- Support columns and ball screws are generated by casting six cylindrical bars in which four bars are turned and polished to make support columns, while the other two are turned and thread cut to create ball screws.

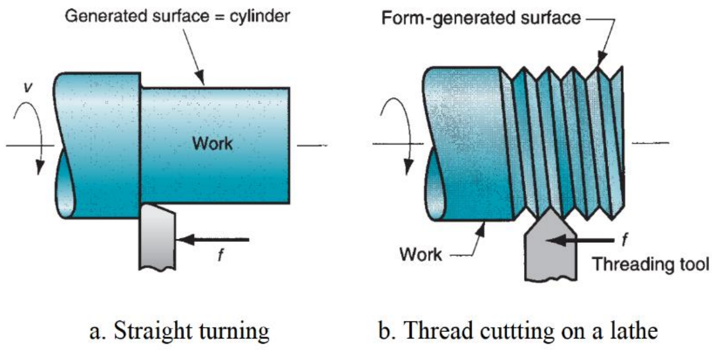


Figure 7: Turning and Thread cutting [11]

All parts are then either joined permanently by welding or assembled by mechanical fasteners.

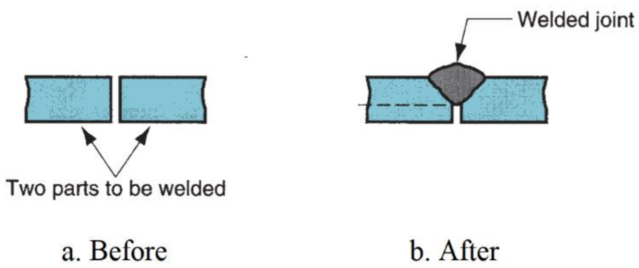


Figure 8: Before welding and finished weldment [11]

Weldment is the welded assembly. [11]

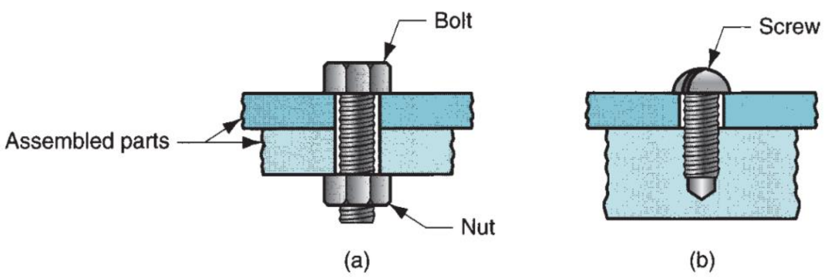


Figure 9: Mechanical fasteners - assemblies using bolt and nut ***(a)****, and screw* ***(b)*** *[11]*

2.4 UTM frame standards

ASTM E1012 - Practice for Verification of Test Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application.

ASTM E2309 – Standard Practices for Verification of Displacement Measuring Systems and Devices Used in Material Testing Machine.

2.5 Bending test standards

Some commonly used ISO and ASTM standards are:

- ISO 178: Plastics - Determination of Flexural Properties.
- ISO 7438: Metallic Materials – Bend Test.
- ISO 14125: Fibre-Reinforced Plastic Composites - Determination of Flexural Properties.
- ASTM D790: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.
- ASTM D6272: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending.
- ASTM D7264: Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials.
- ASTM C393: Standard Test Method for Flexural Properties of Sandwich Constructions.
- ASTM C1609: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete.
- ASTM C1161: Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature.
- ASTM C158: Standard Test Method for Strength of Glass by Flexure.
- ASTM E290: Standard Test Method for Bend Test of Material for Ductility.
- ASTM E190: Standard Test Method for Guided Bend Test for Ductility of Welds.

2.6 Hooke's law

Hooke's law, also known as law of elasticity, is named after a British physicist Robert Hooke in 17^{th} century. Hooke's law states that the force applied to deform a spring, or a body is proportional to its displacement, as long as the load does not exceed the elastic limit of the material. [12]

> Elasticity is the ability of a body to return to its original shape and dimension after the load causing deformation is removed. [13]

For linear springs, the applied force *F* is proportional to the extension or compression displacement *x*, by the spring constant *k*. Value of *k* depends on the material elasticity, shape and dimensions. The law is mathematically described as below: [12]

$$F_{spring} = -kx \tag{9}$$

Where:

F_{spring}	restoring force or spring force, equal in magnitude yet in opposite direction to the applied force. [N]
x	the displacement or change in length [m]
k	spring constant [N/m]
$-$	means the direction of spring force is opposite to that of the applied force and the displacement.

Besides springs, any object or material that obeys this law of elasticity is also called linear-elastic material, or Hookean material.

Hooke's law also indicates the relationship between stress and strain, in which stress is linearly proportional to strain, and is expressed as: [14]

$$\sigma = E\varepsilon \tag{10}$$

$$\sigma = \frac{F}{A} \tag{11}$$

$$\varepsilon = \frac{L-L_0}{L_0} = \frac{\Delta L}{L_0} \tag{12}$$

Where:

σ	stress, is the applied force per unit area [N/m^2, Pa, MPa]
ε	strain, is the relative deformation of material caused by stress [dimensionless or %]
E	Young modulus or modulus of elasticity, this value is specified for each type of material. Unit of E is often expressed in MPa or GPa.

$$1\ \text{Pa} = 1\ \text{N/m}^2$$

$$1\ \text{MPa} = 10^6\ \text{Pa}$$

$$1\ \text{GPa} = 10^9\ \text{Pa}$$

F	applied force [N]
A	cross-sectional area [m^2]
L_0	the original length of the object [m or mm]
L	the final length of the object after deformation [m or mm]
ΔL	$= L - L_0$, is the change in length [m or mm]

2.7 Euler – Bernoulli equation for beams

Euler – Bernoulli theory is an elementary method for analyzing the deformation of the beam under loading. It was introduced by two Swiss mathematicians and physicists Leonhard Euler and Danial Bernoulli in 1750. [15]

The theory was improved by adding the effect of rotatory inertia by Lord Rayleigh in 1877 and the shear deformation by Stephan Timoshenko in 1921, when applying for high frequency or short wavelength vibration. [15]

2.7.1 Euler – Bernoulli theory assumption

Euler – Bernoulli beam theory assumes that:

- The beam is homogenous and isotropic.
- The applied force acts on the plane of symmetry and perpendicular to the neutral surface.
- The beam axis bends but does not extend.

- The plane sections remain perpendicular to the x axis and does twist during the deformation, meaning that the shear stress and shear deformation are negligible compared to axial stress and bending moment.
- The deformation is within the beam elastic limit and satisfying Hooke's law.
- The deflection is much smaller than the beam length.

[16]

2.7.2 Euler – Bernoulli beam equation

Consider a beam with below coordinate system:

- x-axis, is the longitudinal axis, passing along the beam lengthwise.
- y- axis, is the axis of symmetry, a vertical line dividing the cross section into two symmetrical halves.
- z-axis is a line passing through the neutral axis of cross section.
- x-z plane is neutral surface containing the neutral axis of the cross section and perpendicular to y-axis.
- x-y plane is plane of symmetry, going across the axis of symmetry and perpendicular to the neutral surface.

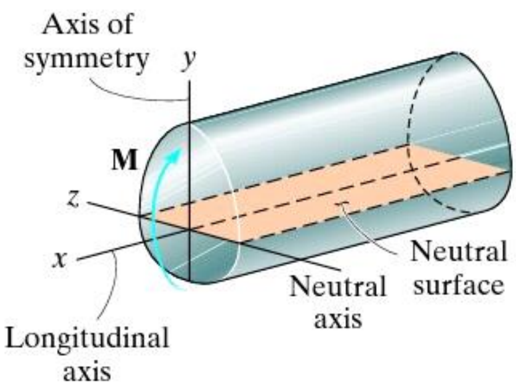


Figure 10: Axes of beam [17]

Euler – Bernoulli equation defines the correlation between the beam deflection and the applied force [18]:

$$\boxed{\frac{d^2}{d^2x}\left(EI\frac{d^2w}{dx^2}\right) = q} \tag{13}$$

In which

w(x)	external deflection of beam centroid in y direction at position *x* [m or mm]
q	distributed load, is the force per unit length [N/m]
E	the modulus of elasticity [Pa, GA]
I	the moment of inertia, about the neutral axis of the beam cross-section [m^4 or mm^4]

EI is called the flexural rigidity [$N.m^2$] and often a constant, hence, equation (5) can be simplified as

$$EI\frac{d^4w}{dx^4} = q \tag{14}$$

Or

$$EIw^{(4)}(x) = q(x) \tag{15}$$

Besides the external load, relationship between the beam deflection and slope of the elastic curve, bending moment and shear force can also be expressed as [19]:

$$\theta = w'(x) = \frac{dw}{dx} \tag{16}$$

$$M(x) = EI\, w''(x) \tag{17}$$

$$Q(x) = EIw'''(x) \tag{18}$$

$$\varepsilon_x = -yw''(x) = -\frac{y}{\rho} = -ky \tag{19}$$

Where:

θ	deflection slope [rad]
M	internal moment at location *x* [N.m]
Q	shear force [N]
ε_x	axial strain [dimensionless or %]
ρ	radius of the curvature [rad]

$k = \frac{1}{\rho}$ the beam curvature [m^{-1}]

y distance from the concerned point or line to the neutral surface [mm, m]

Then values of slope, deflection, shear force and bending moment can be obtained by applying boundary conditions into above equations.

In this thesis, Euler – Bernoulli theory is applied via Finite Element Analysis to determine the stress and deformation of the bending frame under loading.

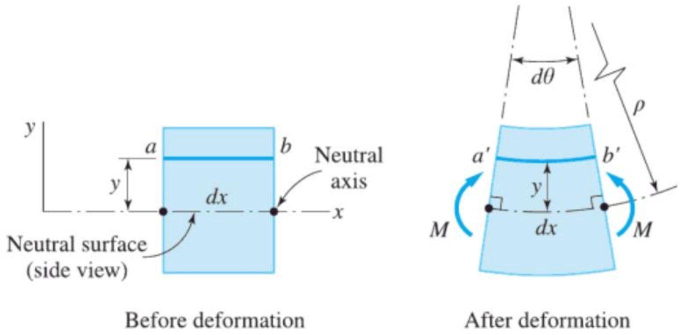


Figure 11: Deformation of beam segment [16]

3 METHOD

3.1 Finite Element Analysis (FEA)

Finite element analysis, or finite element method, is a numerical method utilized to examine and predict how a product will respond to the real-life world, in order to optimize the design, ensure the safety and function, as well as quality of the product throughout its lifetime. [20]

The method starts by using a computer to build a model of an object, in which the overall shape of the object is represented as "geometry", while its properties are represented as "material". Secondly, the model is divided into several smaller and manageable units, also known as elements, by a finite element tool called a mesh. These elements can be one-dimensional, two-dimensional or three-dimensional, meaning that they can be lines, squares, pyramids or blocks to depict different sides of the object. Thirdly, specific boundary conditions, such as force, pressure and temperature, are applied and mathematical equations are formed and solved to predict how each element behaves under these environmental effects, and subsequently envisage the behavior of the whole object. [21]

With the use of this analysis, instead of making and damaging a physical object, manufacturers could create and verify its representative model using finite element analysis. Although this process sometimes requires a considerable amount of computing power to handle complicated cases, Finite Element Analysis is much more economical and faster to use than doing physical tests, which is of great advantage. [21]

FEA is utilized in a variety of fields such as mechanical/civil/aerospace/automotive engineering, structure analysis, fluid flows, electromagnetics and even human body in biomechanics. [20]

The Finite Element Analysis in this thesis was carried out by COMSOL Multiphysics software. Basic steps of a COMSOL simulation include: [22]

1. Set up the model environment,
2. Create or import the geometry,
3. Define the material properties,
4. Assign physics and boundary conditions,
5. Build the mesh,
6. Perform the simulation,
7. Post-process the solutions.

There are many various types of Finite Element Analysis in the field of mechanics to simulate different aspect of the real world, such as static, dynamic, vibration, heat, fatigue and flow analyses. Since deformations studied in the test frame are at the magnitude of 0.0005, the frame material is assumed completely linear elastic, this thesis would focus on linear static deformation analysis.

> "Linear" means that the applied force is proportional to the stress response [23]. For example, if we apply a load of 1N on an object and get a stress response of x MPa, then if we apply 100N, this will result in a response of $100x$ MPa.
>
> "Static" means that the system does not depend on time and the force is applied slowly, slow enough so that we can omit the inertia loads and other dynamic properties of the object. [23]

Below is an example using COMSOL Multiphysics to model a cantilever beam and study its stress and deflection under loading. Given that the beam is 200mm long, 10mm wide, 2mm deep and made of Steel AISI 4340. It is fixed at one end; the other end is subjected to a 1N concentrated load. The mesh is set up as 3D tetrahedral shape, finer size.

3.1.1 Environment set-up

Right after opening COMSOL Multiphysics software, a new window appears with two options to create the model environment. Selecting the Model Wizard option to set up the model dimension, physics and types of the study.

The beam was a three-dimensional object; thus, **3D** was chosen on the **Select Space Dimension** window.

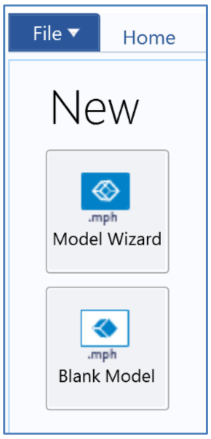


Figure 12: Model Wizard

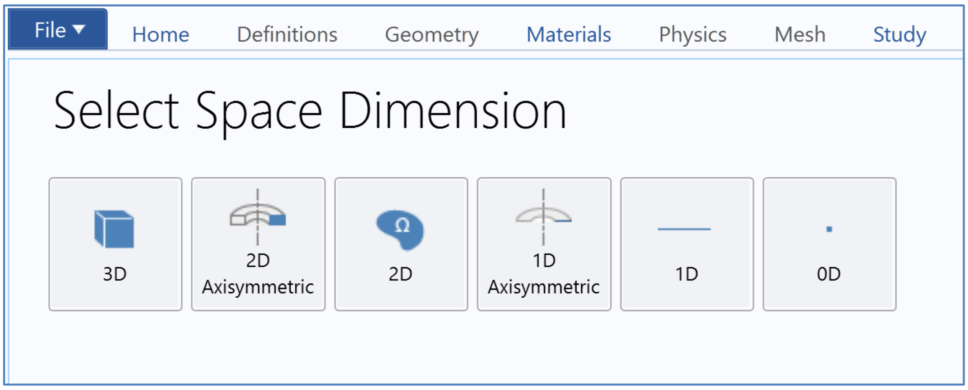


Figure 13: Space Dimension

Select Physics:

To analyze the mechanical behavior of the beam, extend Structural Mechanics → Solid Mechanics, followed by Add and Study.

Select Study:

Under General Studies branches, choose Stationary, and press Done

Stationary was preferred over other types of study as it is used determine the stress and deflection of the beam at static equilibrium.

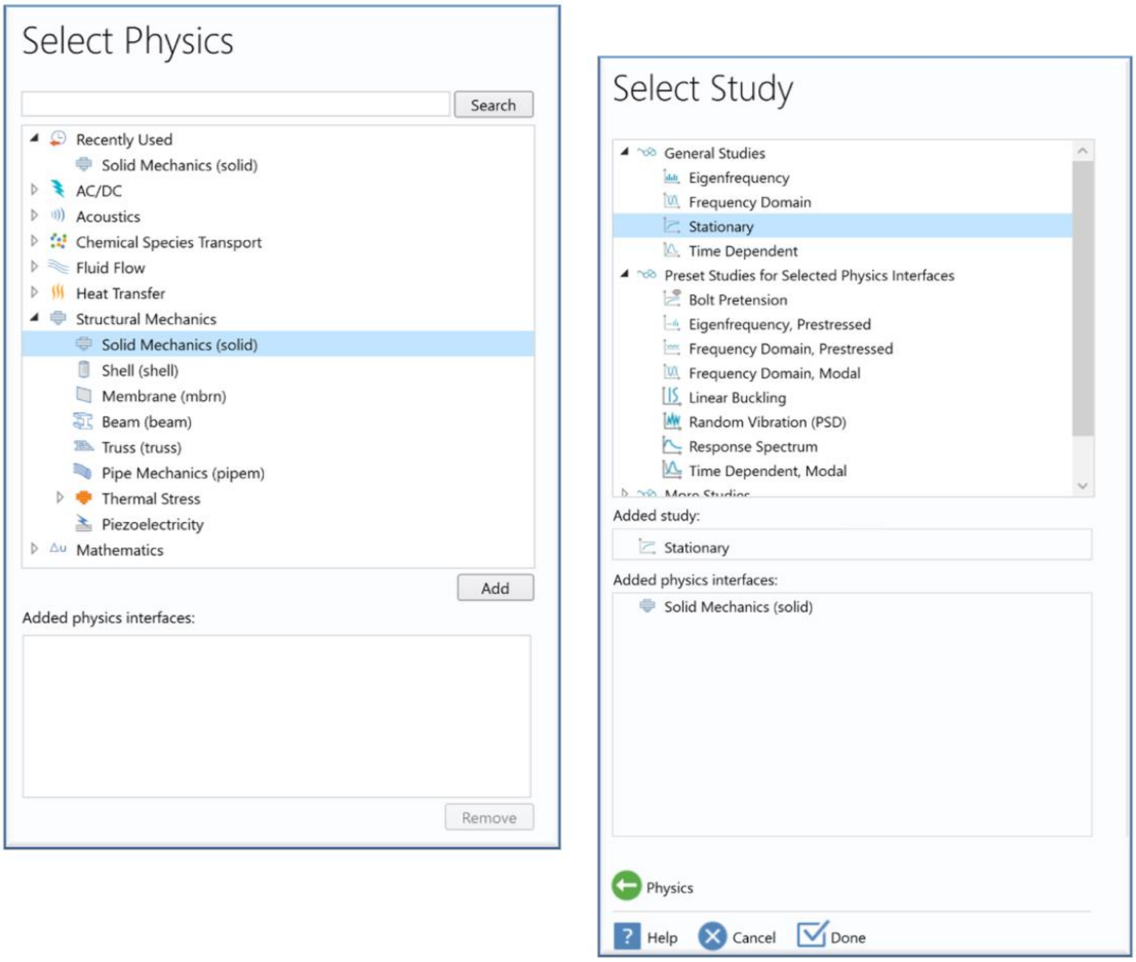


Figure 14: Physics and Study

3.1.2 Geometry creation

In the Geometry toolbar, select Block button to add a beam model to the Graphics window.

In the Settings window, all given dimensions of the beam were converted from millimeter to the default unit meter, thus, insert 0.01 for Width, 0.002 for Depth, 0.2 for Height, and click Build Selected. (Figure 15)

Next step is adding material to define the object properties. In the Add Material window on the right side of the COMSOL desktop, extend the Built-In branch, choose Steel AISI 4340 and select Add to Component. Steel AISI 4340 can also be found through the Search bar. (Figure 16)

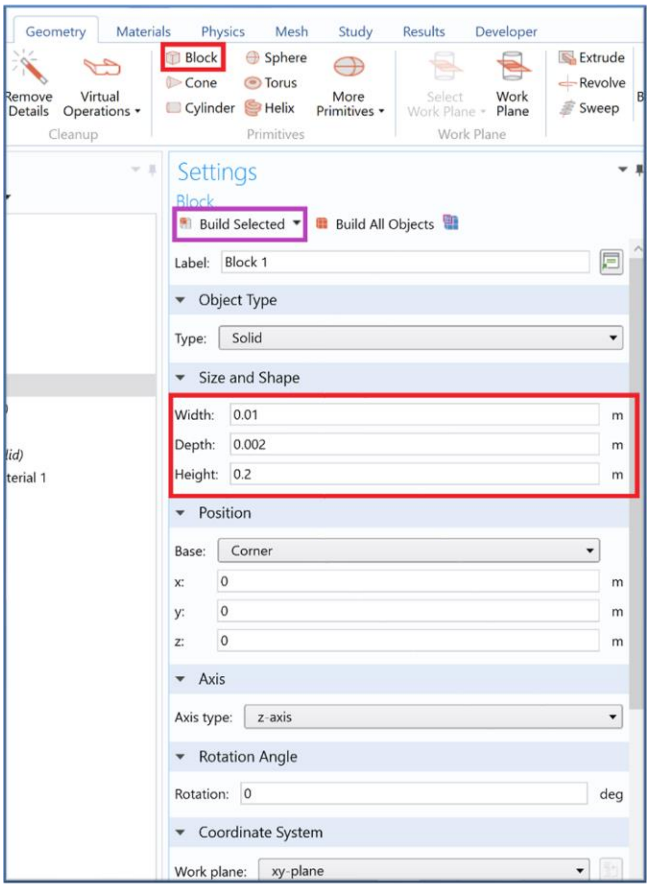


Figure 15: Building geometry.

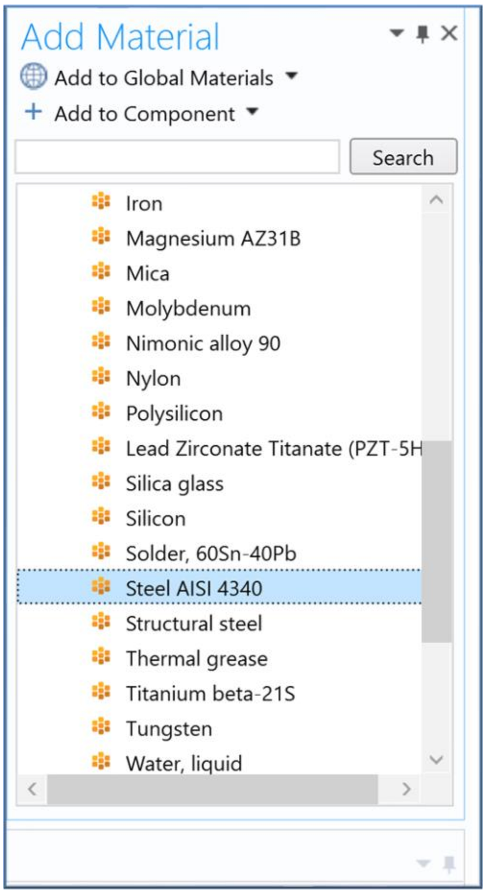
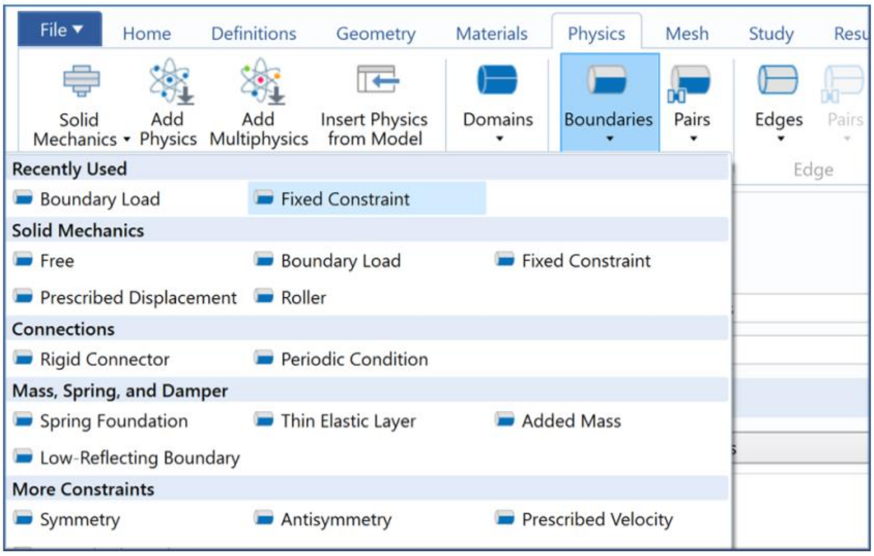


Figure 16: Material selection

3.1.3 Physics boundary conditions

In Physics tab, extend Boundaries → Fixed Constraint and select the purple surface as shown in below Graphics window to fix one end of the beam.



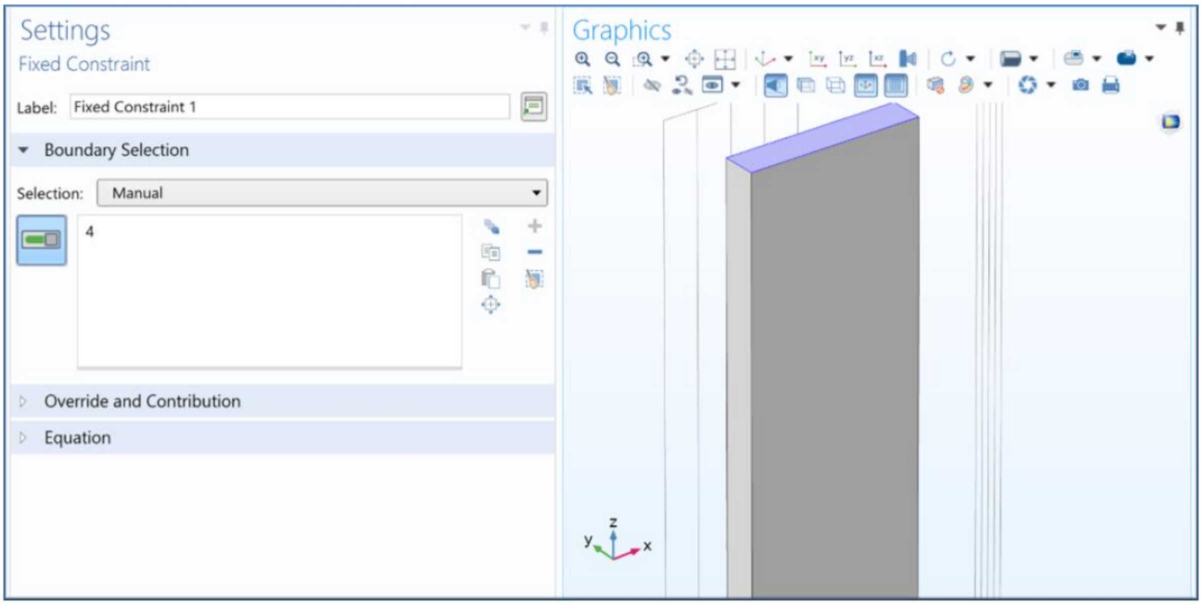


Figure 17: Fixed Constraint: fixing one end of the beam

Similarly, select Boundaries → Boundary Load.

In Force Settings window, select the other end of the beam to apply the boundary load, choose Total Force type and edit 1N in y-direction.

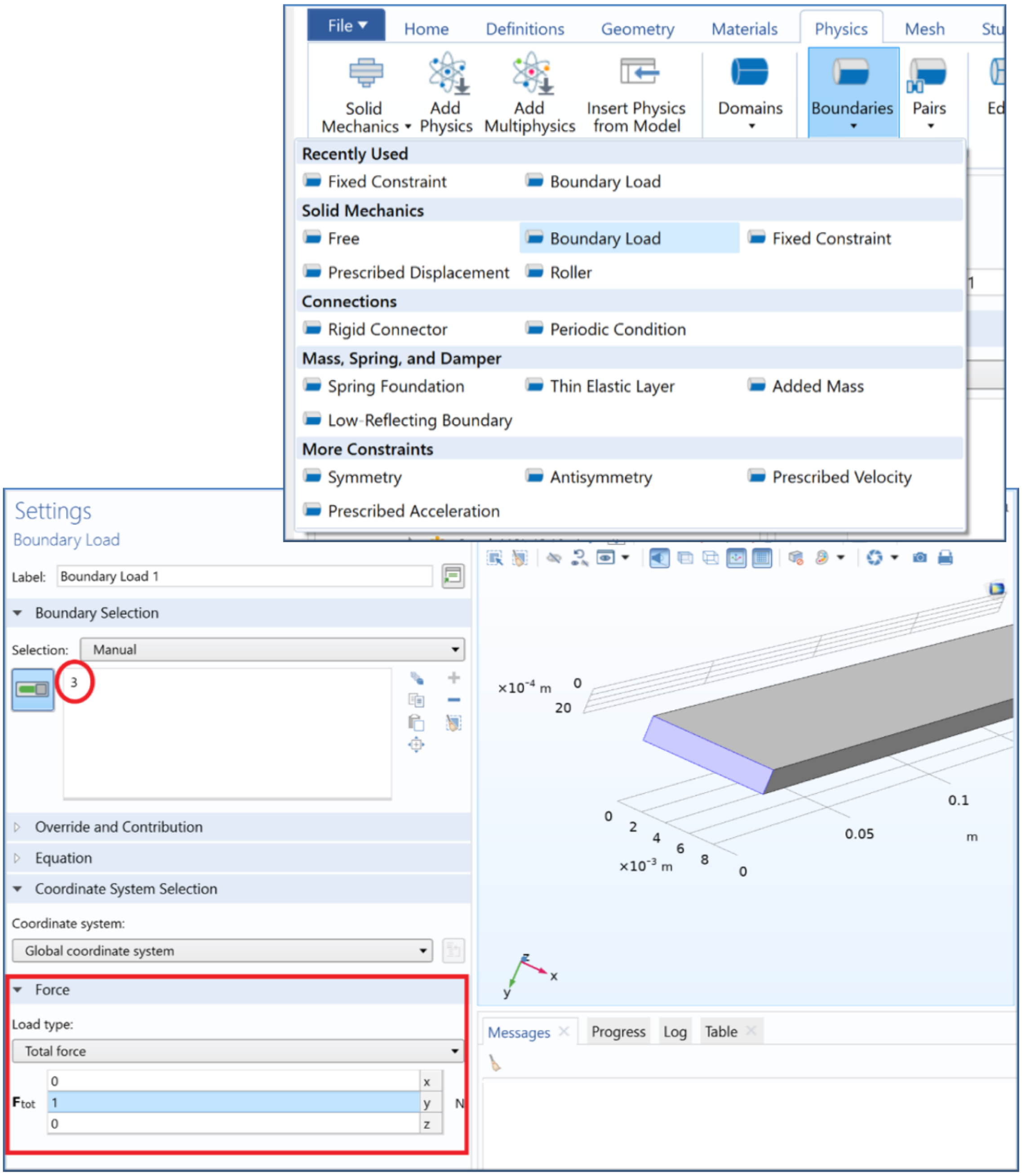


Figure 18: Boundary Load.

3.1.4 Mesh generation

Under Mesh tab, choose Free Tetrahedral mesh shape → Build All.

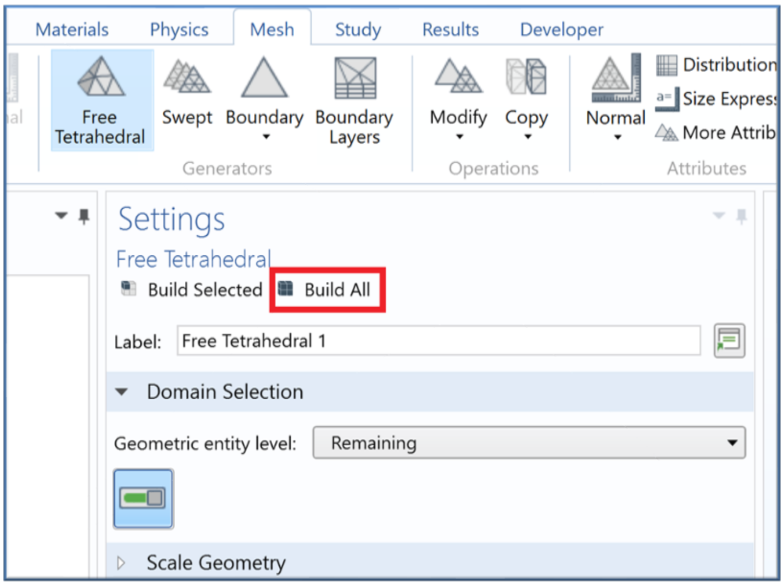


Figure 19: Mesh generation

In Model Builder window, under Mesh 1 node, select Size. In the Settings window, choose the Finer size and press Build All.

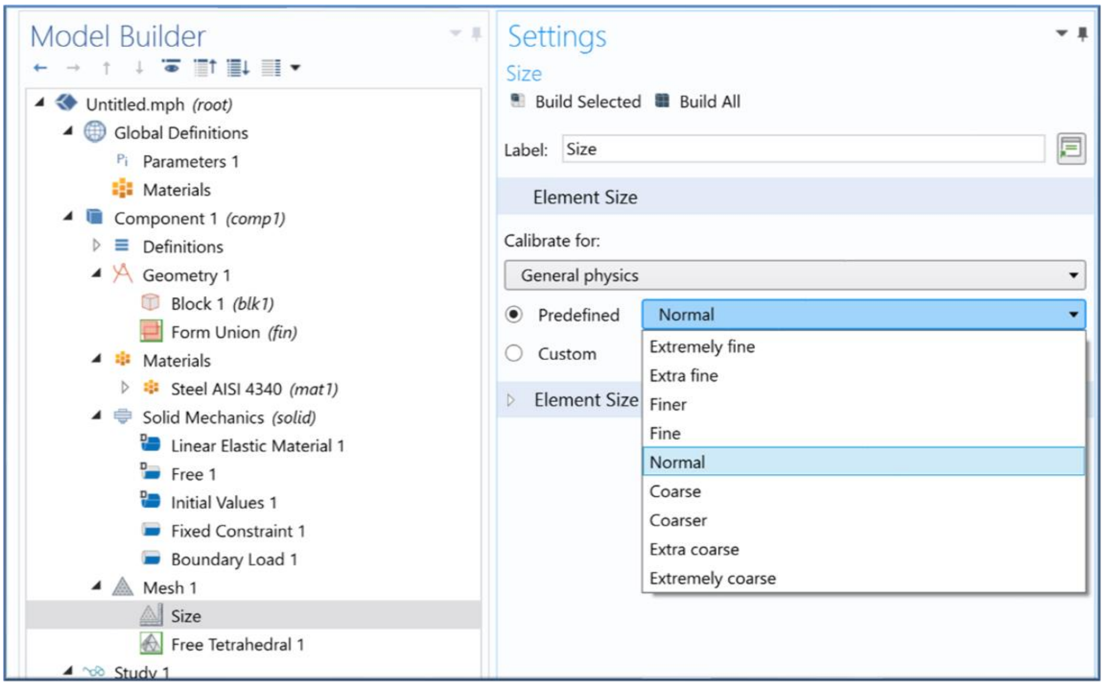


Figure 20: Mesh size

3.1.5 Computer simulation

In the Model Builder window, right click Study 1 node and select Compute to run the simulation. Next, in the Settings window of the Stress result, under Color Legend section, tick Show maximum and minimum values and Show units. As be shown in the Graphics window below, maximum stress is located at the fixed end of the beam and equal to 3.10^7 N/m^2.

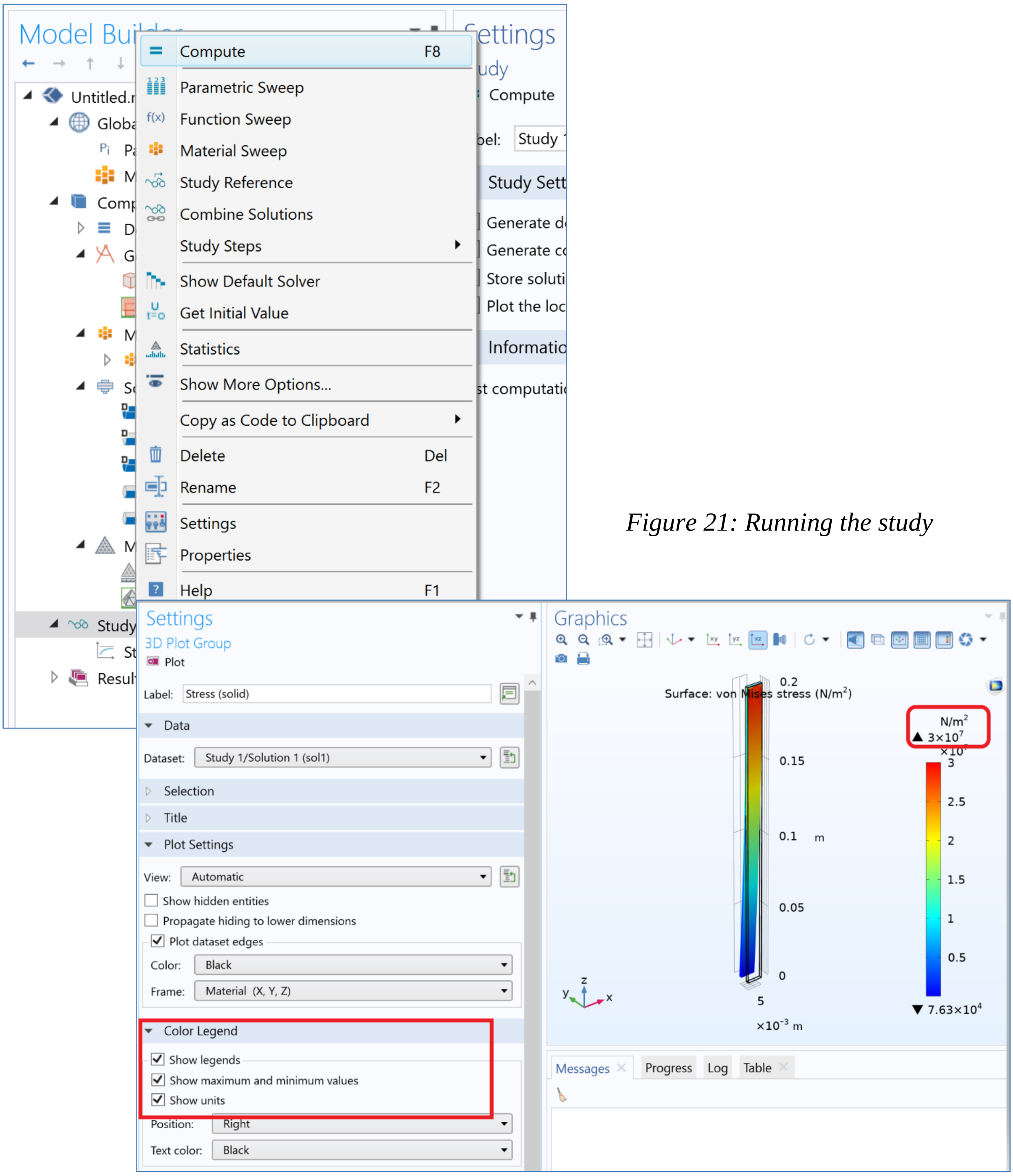
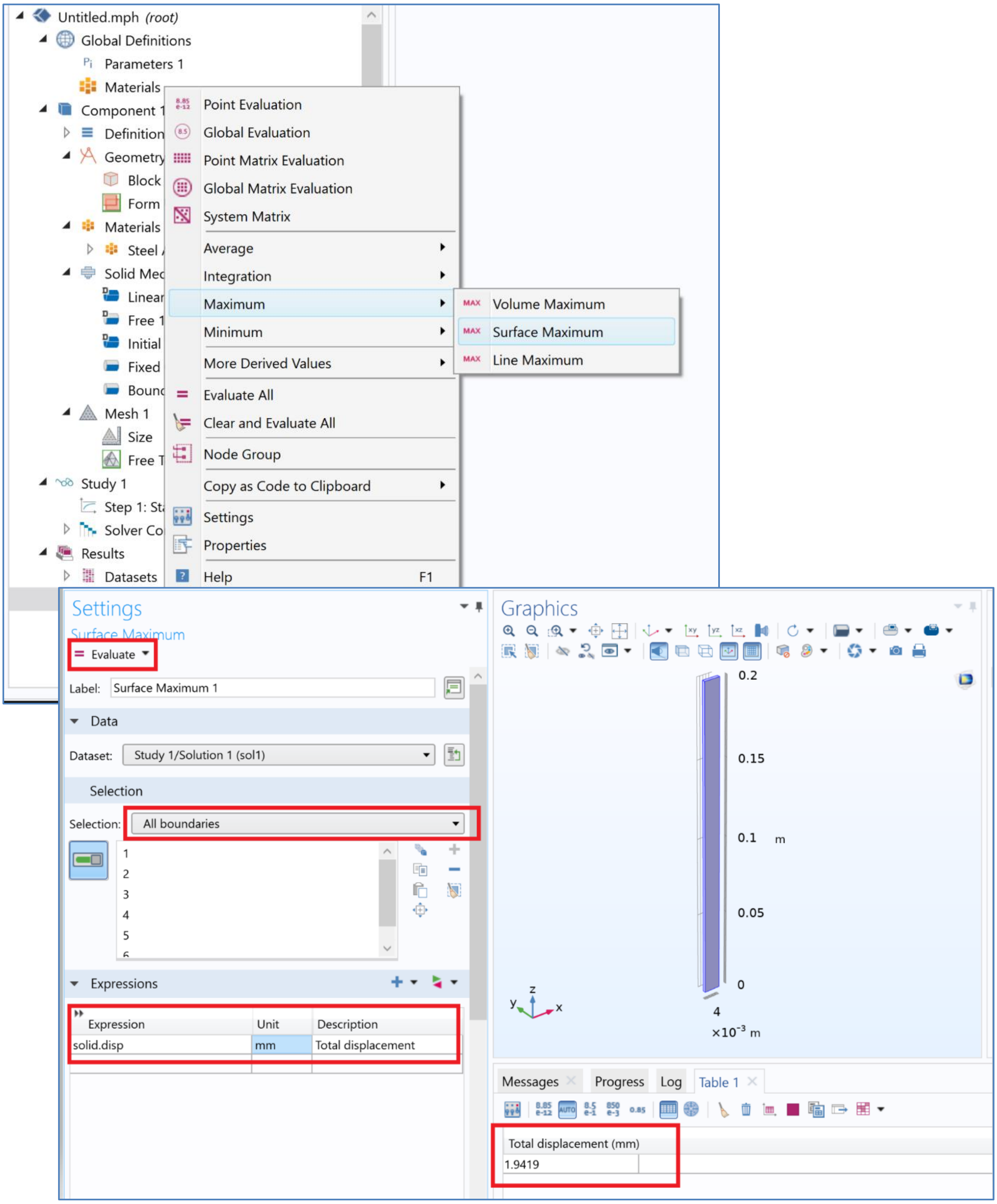


Figure 21: Running the study

To find the beam maximum deflection, right click Derived Value in the model tree, select Maximum → Surface Maximum.

In the Settings window, select All Boundaries, insert "solid.disp" in Expression column and "mm" in Unit column. Press Evaluate. As a result, the maximum deflection was shown in the Table window at the bottom of the COMSOL desktop, which is 1.94mm.

Figure 22: Computing total displacement



3.1.6 Post-processing results

The results achieved from COMSOL were:

Maximum stress, at fixed end: $\sigma_{FEA} = 3 \times 10^7 \ N/m^2$

Maximum deflection, at unsupported end: $w_{FEA} = 1.9419 \ mm$

When repeating the simulation with normal mesh size, the results became:

$$\sigma_{FEA\_normal\ mesh} = 2.95 \times 10^7 \ N/m^2$$

$$w_{FEA\_normal\ mesh} = 1.9401 \ mm$$

Resolving the problem above using Analytical Method:

Given: Cantilever beam supported at one end.

Length L= 0.2 m, Width b = 0.01 m, Thickness t = 0.002 m.

Elastic Modulus $E = 205 \times 10^9 \ Pa$

Load at unsupported end F = 1 N. Find the maximum stress and maximum deflection

Solve:

Second moment of inertia $I = \frac{1}{12} bt^3$ (20)

Maximum stress $\sigma_0 = \frac{FLt}{2I}$ [24] (21)

$$\sigma_0 = \frac{1 \times 0.2 \times 0.002}{2 \times \frac{1}{12} \times 0.01 \times 0.002^3} = 3 \times 10^7 \ \frac{N}{m^2}$$

Maximum deflection $w_0 = \frac{FL^3}{3EI}$ [24] (22)

$$w_0 = 1 \times \frac{0.2^3}{3 \times 205 \times 10^9 \times \frac{1}{12} \times 0.01 \times 0.002^3}$$

$$= 1.9512 \times 10^{-3} \ m$$

$$= 1.9512 \ mm$$

Calculating relative errors:

Relative error in stress = $1 - \frac{\sigma_{FEA}}{\sigma_0} = 0$ for finer mesh size

$= 1.67\ \%$ for normal mesh size

Relative error in deflection = $1 - \frac{w_{FEA}}{w_0} = 0.476\ \%$, for finer mesh size

$= 0.569\%$, for normal mesh size

Therefore, the finer the mesh is, the more accurate the results obtained from COMSOL will be.

4 RESULTS

4.1 Bending frame design

4.1.1 SolidWorks modeling

The idea was to design a new frame for bending test that is affordable and can be easily built in-house from accessible metal sheets. The frame was modeled using SolidWorks 2020 software while its physical performance was simulated using Finite Element Analysis, to make sure that it conforms the frame standard, and can perform safely and accurately in university.

The design was inspired by a frame model of supervisor Rene Herrmann, as depicted in Figure 23. The specimen will be placed from the sides of the frame instead of from the front as in traditional models. Since the front and back of the frame are metal plates, they work as two protective shields against flying debris from violent failure of the specimen and provide safety for the operator and the surrounding environment.

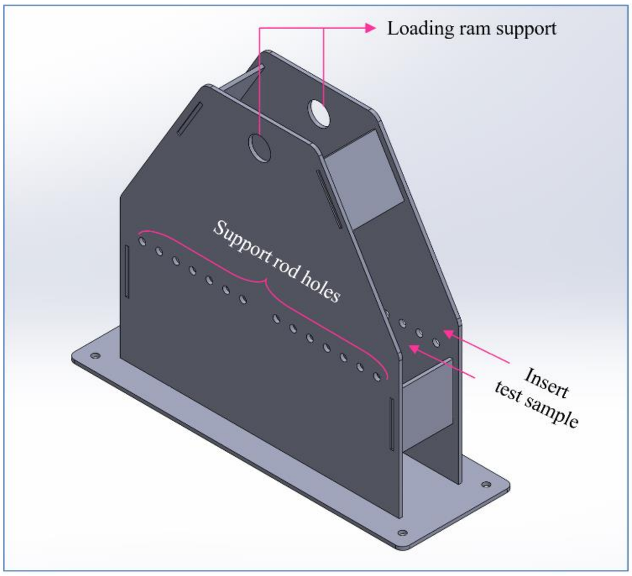


Figure 23: Frame model of supervisor Rene Herrmann

Frame design.

The unit system is MMGS (millimeter, gram, second).

Designing the frame is a process of trial and error, and the final frame consists of one base plate, one top plate, one front plate, one back plate, and 4 support side plates. The base plate is identical to the top plate while the front plate is identical to the back plate.

The frame assembly weighs 64.43 kg, and needs a working area of (560×180×440) mm. (Figure 24)

Raw material needed for all parts of the frame includes (Figure 25):

- One steel sheet (1000× 500×10) mm for 4 support side plates, front and back plates.
- One steel sheet (560×360×20) mm for the top and base.

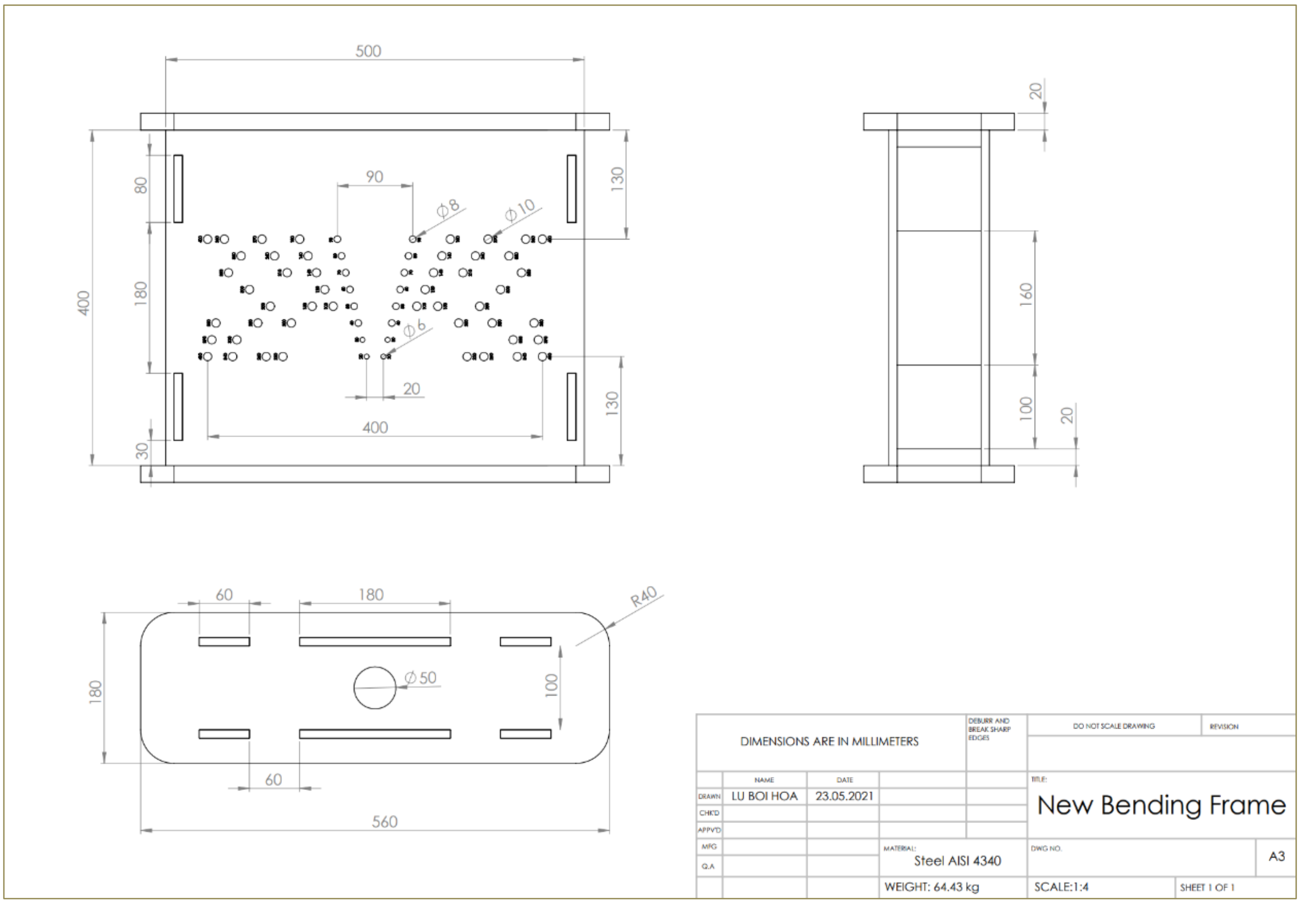


Figure 24: 2D drawing of the bending frame.

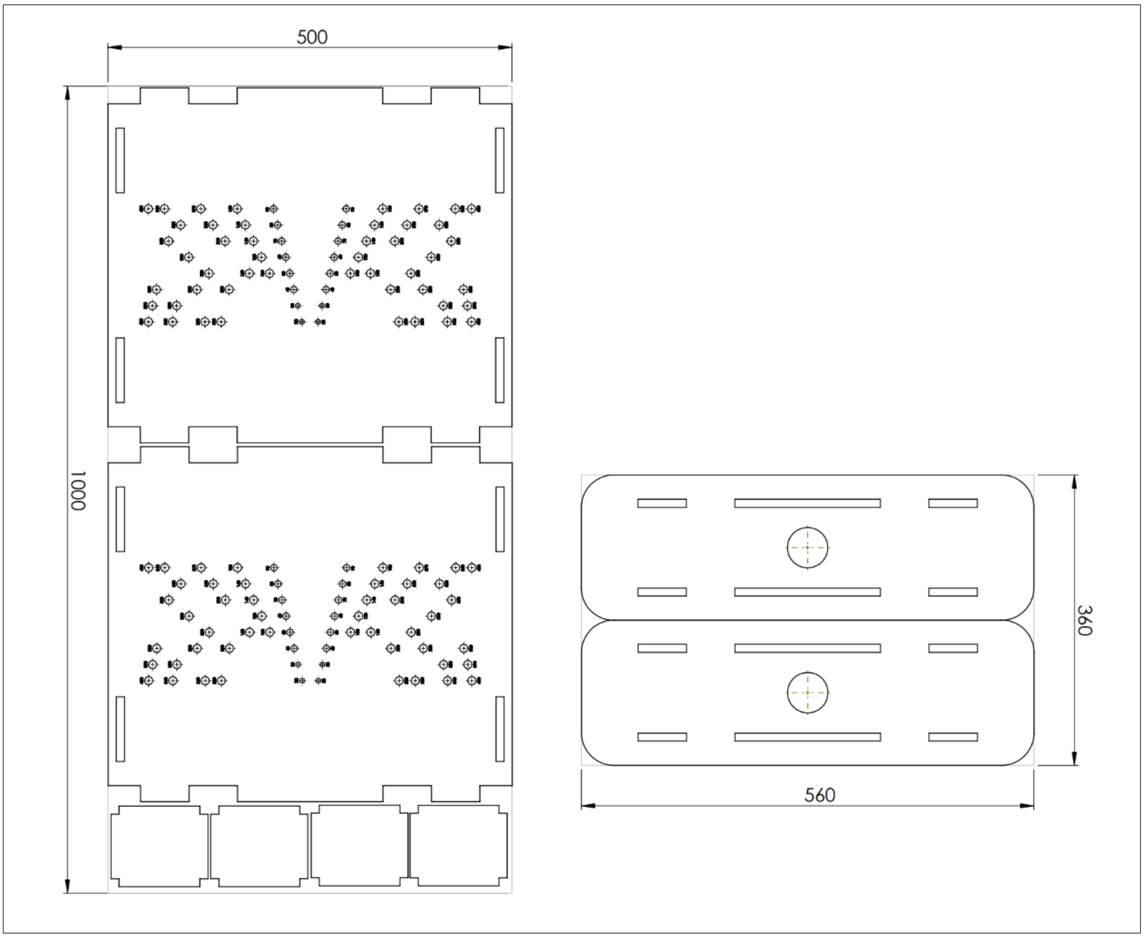
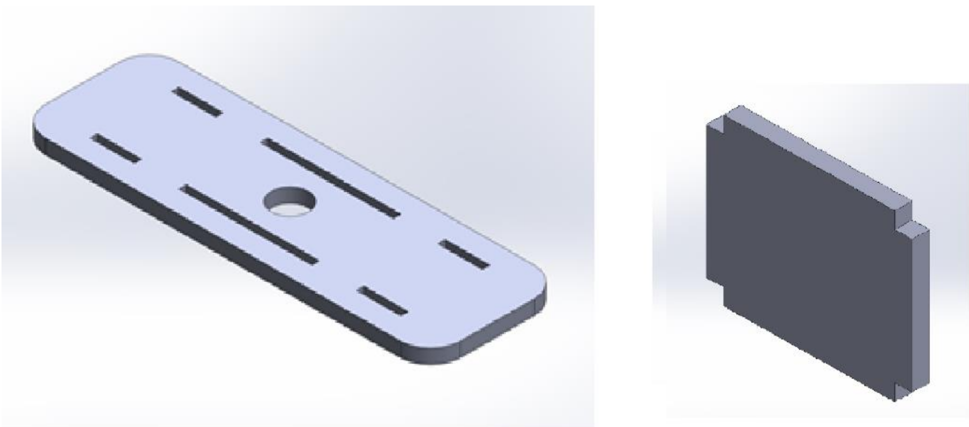


Figure 25: Steel sheets (1000× 500×10) mm and (560×360×20) mm

Below are models of the top and support side plates:



a. b.

*Figure 26: **a.** Base-Top plate, and **b.** Support side plate*

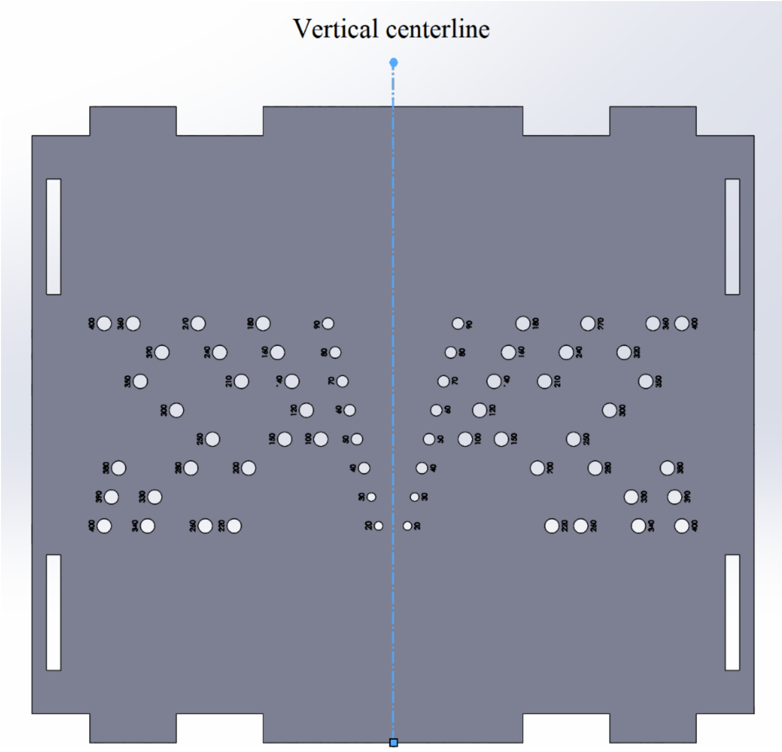


Figure 27: Front and back plates

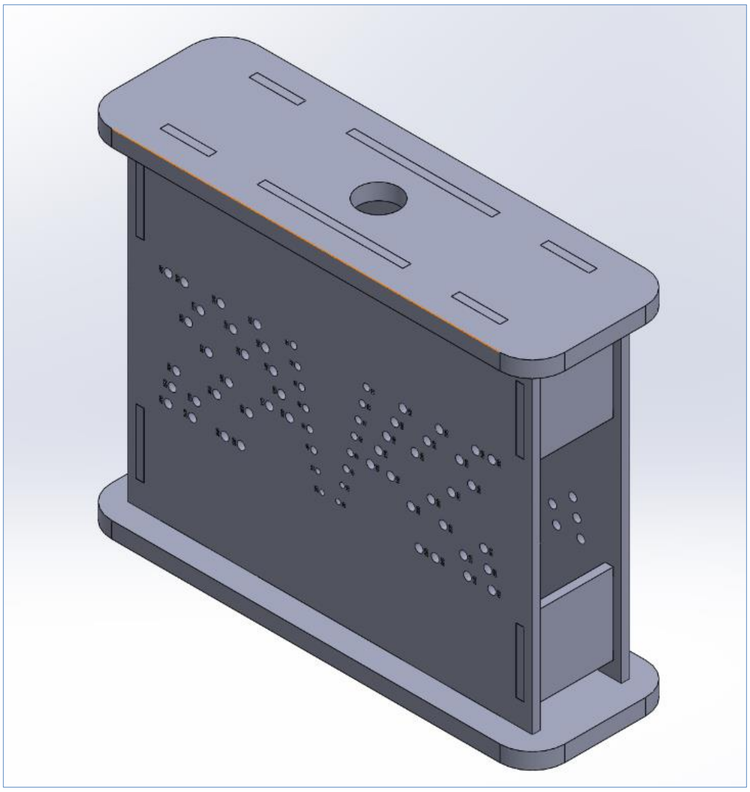


Figure 28: Frame assembly

In Figure 23, the model has one base plate and no top plate, the force is only distributed to the front and back plates. Whereas in Figure 28, the force is distributed not only to the front and back plates, but also to the top and the welded joints between the top and the front-back plate. Therefore, how strong the frame is depends on the welding techniques and quality of the filler metal.

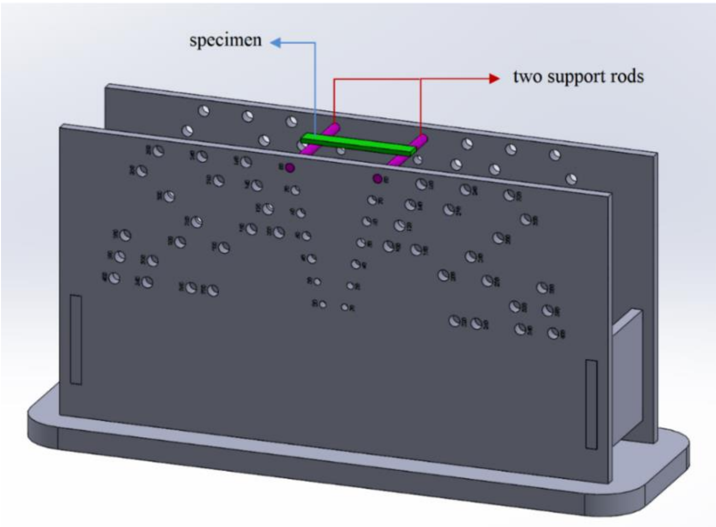


Figure 29: Position of support rods and specimen when the frame is in use

4.1.2 Hole creation on front and back plates

There are 32 pairs of holes representing 32 cases of support distance. Their values are multiples from 20 to 400 of 20, 30, 40, 50, 60, 70, 80 and 90 (Table 1).

- Duplicate values are removed (Table 3, grey cell)
- Remaining multiples of 20 are grouped in a row named row2. Similarly, remaining multiples of 30, 40, ..., 90 are grouped in row3, row4, …, row9. (Table 4)
- 380 is a multiple of 20 but it was moved to row4. Because 380 and 400 holes can overlap each other if they are on the same row.
- 400-mm hole was duplicated in row9 (Table 4 and Figure 30) to compare its bending results between row2 and row9.

All support holes are created on the frame and will beautifully form in a butterfly pattern in Figure 27 and 30.

Since the distance between the front and back plates is 100 mm, the maximum specimen width is 100 mm. Span L is the distance between two supports. Recommended diameter of support rods and support span would be shown in detail in Chapter 3.3.

	Multiples from 20 to 400 of							
	20	**30**	**40**	**50**	**60**	**70**	**80**	**90**
	20	30	40	50	60	70	80	90
	40	60	80	100	120	140	160	180
	60	90	120	150	180	210	240	270
	80	120	160	200	240	280	320	360
	100	150	200	250	300	350	400	
	120	180	240	300	360			
	140	210	280	350				
	160	240	320	400				
	180	270	360					
	200	300	400					
	220	330						
	240	360						
	260	390						
	280							
	300							
	320							
	340							
	360							
	380							
	400							
Number of remaining multiples	6	3	3	4	3	4	4	4
Total	31							

Table 3: Multiples from 20 to 400 of 20, 30, 40, 50, 60, 70, 80, 90

Row	Support span [mm]					Number of pair per row	Total
2	20	220	260	340	400	5	32
3	30	330	390			3	
4	40	200	280	380		4	
5	50	100	150	250		4	
6	60	120	300			3	
7	70	140	210	350		4	
8	80	160	240	320		4	
9	90	180	270	360	400	5	

Table 4: Support span values

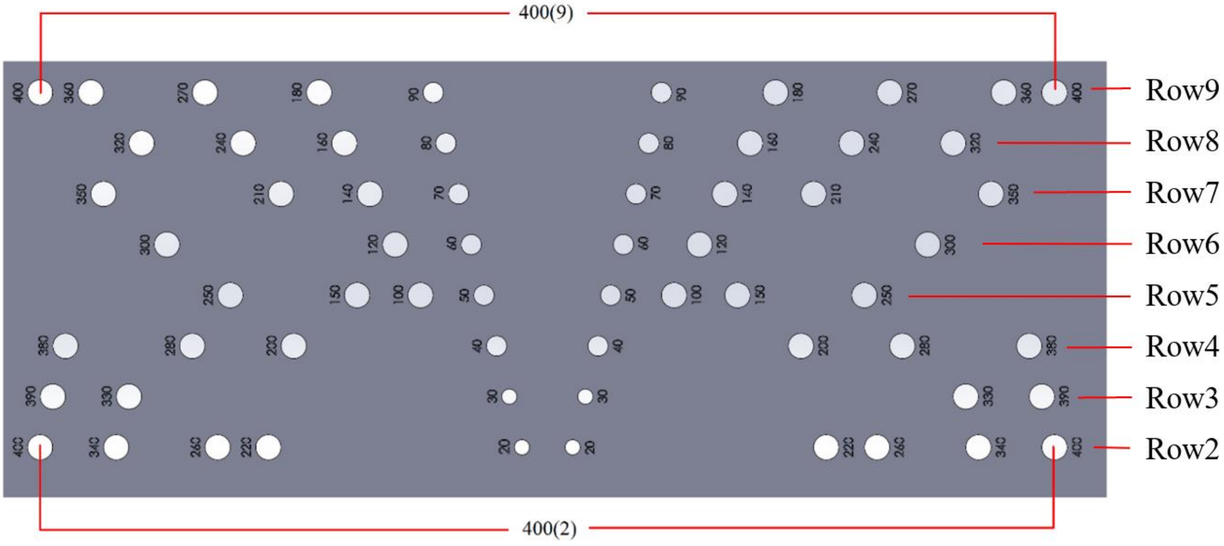


Figure 30: 400(2) and 400(9)

Ratios of support span and thickness of the specimen according to ASTM and ISO bending standards are summarized in Table 5.

Bending standard	**Support span L [mm] and specimen thickness h [mm]**
ASTM D790 ASTM D6272	L ≥ 16h, overhang on each end shall be at least 10% of support span.
ASTM D7264	L = 32h
ISO 178	L ≥ 16h. Preferred h = 4 mm
ISO 7438	$L = (3h + D) \pm \frac{1}{2}h$, D = diameter of the loading nose
ISO 14125	L/h = {16; 20; 40} for three-point bending L/h = {16.5; 22.5; 40.5} for four-point bending
ASTM C393	L > 20h
ASTM C1609	L = 3h
ASTM C1161	L = {20; 40; 80}
ASTM C158	L = 200 mm
ASTM E290	$L = 3h + 2r \pm \frac{1}{2}h$, r = radius of the loading nose
ASTM E190	L = 60 mm

Table 5: Bending standard – support span L

4.1.3 Frame material

Steel AISI 4340 is an alloy steel comprising nickel, chromium and molybdenum. It is heat treated at 830°C to achieve high strength and toughness, along with ideal resistance to stress and atmospheric corrosion [25].

Although steel manufacturing process demands a lot of heating energy, contributes to global warming and pollution by releasing carbon dioxide (CO_2) into the air and other iron-making byproducts, the finished product is durable and can benefit the environment in long-term. Besides, by using magnetic separation, iron and steel are 100% recyclable and can maintain their essential properties even after several recycling circles. [26]

For these reasons, AISI 4340 was accordingly chosen as the material for all parts of the frame assembly.

Steel AISI 4340 composition

Element	Symbol	Weight percentage (%)
Iron	Fe	95.195 – 96.33
Nickel	Ni	1.65 – 2.00
Chromium	Cr	0.70 – 0.90
Manganese	Mn	0.60 – 0.80
Carbon	C	0.37 – 0.43
Molybdenum	Mo	0.20 – 0.30
Silicon	Si	0.15 – 0.30
Sulfur	S	0.04
Phosphorous	P	0.035

Table 6: Steel AISI 4340 composition [27]

Material properties

Property	Value	Unit
Elastic modulus	190 – 210	GPa
Shear modulus	80	GPa
Poisson's ratio	0.27 – 0.3	N/A
Tensile strength	745	MPa
Yield strength	470	MPa
Elongation at break	22	%
Machinability	50	%
Thermal conductivity	44.5	W/(m·K)
Specific heat capacity	475	J/(kg·K)
Density	7850	kg/m^3
Melting point	1427	ºC

Table 7: Steel AISI properties [27]

4.2 Bending frame manufacturing

The purpose of this chapter is to show that the alternative frame structure studied is not only safer for the operator and fulfills the deformation limits but is also cheaper and faster to manufacture and assemble.

The UTM currently used in Arcada is Testometric M350-5CT, which weighs 146 kg and has a load capacity of 5 kN [28]. Like other generic UTM frames, Testometric M350-5CT is built using turning and milling which are two types of mechanical cutting. Although mechanical cutting and laser cutting complete each other and are two versatile and efficient methods used in the manufacturing industry, in the case of sheet metal, laser cutting shows great advantage of precision (± 0.1 mm), speed, cost-effectiveness, fewer waste and smooth finishes [29], and therefore was chosen to prepare parts and texts for the new frame.

After laser cutting, parts of the frame are permanently joined together into a single entity by welding, which is an economical joining technique and requires a skilled welder for proper and safe operation [11].

4.3 Bending frame deformation

COMSOL software was utilized to simulate bending test on the frame and generate Euler – Bernoulli equations to compute the maximum stress and frame deformation. Below is a table of recommended support span, support rod diameter, boundary load, maximum stress, maximum strain and maximum frame displacement.

Note:

- Boundary load = applied force F_o = 1N. Mesh setup is finer size.
- Maximum stress and frame displacement were obtained from COMSOL.
- Young's modulus of Steel AISI 4340 E_{steel} = 200 GPa
- From E_{steel} and maximum stress, maximum strain of the frame when applied a load of 1N is:

$$\varepsilon_{max} = \frac{E_{Steel}}{\sigma_{max}}$$

(Hooke's law, was rewritten from equation (2))

- According Chapter 1.1.1, strain limit of the frame is 0.01×0.05 = 0.0005. Based on Hooke's law, the applied force is proportional to the frame displacement. Then we have:

When applying F_o = 1N, the frame has ε_{max}.

If we apply F_{max}, the frame will reach its strain limit of 0.0005.

→ This gives $$F_{max} = \frac{0.0005 \times 1N}{\varepsilon_{max}} \quad (23)$$

Table 8: Bending frame deformation

No.	Span L [mm]	Support rod diameter [mm]	Applied force [N]	σ_{max} [Pa]	ε_{max}	F_{max} [N]	Frame Displacement at 1N [10^{-6} mm]	Frame Displacement at 30 kN [mm]
1	20	6	1	3327.5	1.664E-08	30052.6	1.854	0.05562
2	30	6	1	3322.1	1.661E-08	30101.4	1.817	0.05451
3	40	8	1	3314.3	1.657E-08	30172.3	1.770	0.0531
4	50	8	1	3305.1	1.653E-08	30256.3	1.734	0.05202
5	60	8	1	3293.2	1.647E-08	30365.6	1.699	0.05097
6	70	8	1	3277.9	1.639E-08	30507.3	1.661	0.04983
7	80	8	1	3258.0	1.629E-08	30693.7	1.621	0.04863
8	90	10	1	3231.4	1.616E-08	30946.3	1.574	0.04722
9	100	10	1	3301.9	1.651E-08	30285.6	1.711	0.05133
10	120	10	1	3290.0	1.645E-08	30395.1	1.682	0.05046
11	140	10	1	3275.7	1.638E-08	30527.8	1.651	0.04953
12	150	10	1	3301.1	1.651E-08	30292.9	1.710	0.0513
13	160	10	1	3258.9	1.629E-08	30685.2	1.624	0.04872
14	180	10	1	3239.6	1.620E-08	30868.0	1.600	0.048
15	200	10	1	3310.2	1.655E-08	30209.7	1.734	0.05202
16	210	10	1	3281.4	1.641E-08	30474.8	1.674	0.05022
17	220	10	1	3322.2	1.661E-08	30100.5	1.772	0.05316
18	240	10	1	3272.2	1.636E-08	30560.5	1.668	0.05004
19	250	10	1	3304.6	1.652E-08	30260.8	1.730	0.0519
20	260	10	1	3322.8	1.661E-08	30095.1	1.778	0.05334
21	270	10	1	3265.3	1.633E-08	30625.1	1.672	0.05016
22	280	10	1	3313.2	1.657E-08	30182.3	1.759	0.05277
23	300	10	1	3301.0	1.651E-08	30293.9	1.737	0.05211
24	320	10	1	3287.8	1.644E-08	30415.5	1.727	0.05182
25	330	10	1	3320.0	1.660E-08	30120.5	1.789	0.05182
26	340	10	1	3324.3	1.662E-08	30081.5	1.805	0.05182
27	350	10	1	3299.7	1.650E-08	30305.8	1.760	0.05182
28	360	10	1	3287.4	1.644E-08	30419.2	1.754	0.05182
29	380	10	1	3317.4	1.659E-08	30144.1	1.799	0.05182
30	390	10	1	3322.0	1.661E-08	30102.3	1.818	0.05182
31	400 (2)	10	1	3325.3	1.663E-08	30072.5	1.829	0.05487
32	400 (9)	10	1	3295.1	1.648E-08	30348.1	1.790	0.05371

From Table 8:

- Difference between 400(2) and 400(9) spans is acceptable and was described as follows:

Equation	σ_{max} [Pa]	ε_{max}	F_{max} [N]	Frame displacement [10^{-6} mm]
$400(2)_{value} - 400(9)_{value}$	30.2	0.015E-08	-272.6	0.039
$\frac{400(2)_{value} - 400(9)_{value}}{400(9)_{value}} \times 100$ [unit: %]	0.91	0.91	-0.89	2.1

- The maximum load the frame can handle for all span cases is 30000 N = 30 kN.
- 20-mm span had the largest displacement 1.854×10^{-6} mm when applied a load of 1N.
- As the FEA used in this study is linear static deformation method, if the force reaches 30 kN, 20-mm span will also show highest displacement among 32 cases. The displacement can be either obtained by COMSOL or calculated as follows:

$$1.854\times10^{-6} \times 30000 = 0.0556 \text{ mm}.$$

- Figure 32 shows that 30-kN load causes a maximum surface deformation anywhere on the frame of no more than 0,0556 mm. Additionally, notice in Figure 31, the maximum principal strain is lower than 0.0005, which therefore satisfies the small strain assumption and indicates that the frame material is still within its elastic region.

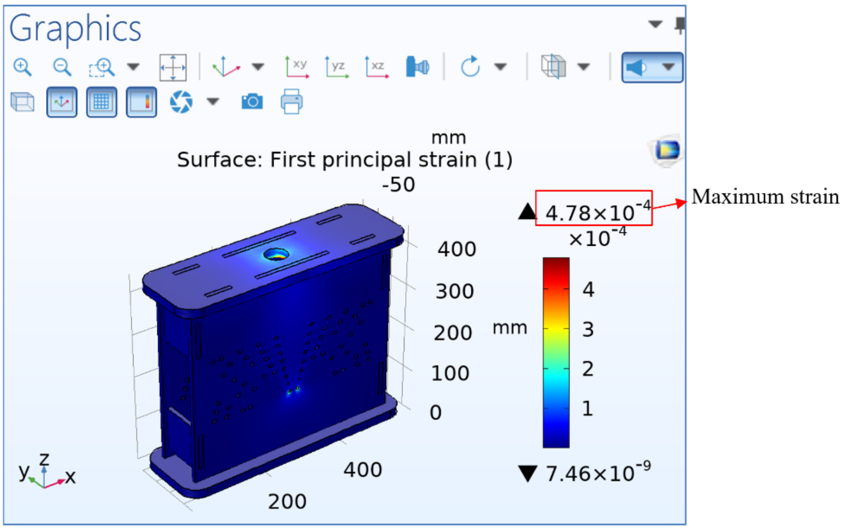


Figure 31: First Principal Strain – 20-mm span at 30 kN

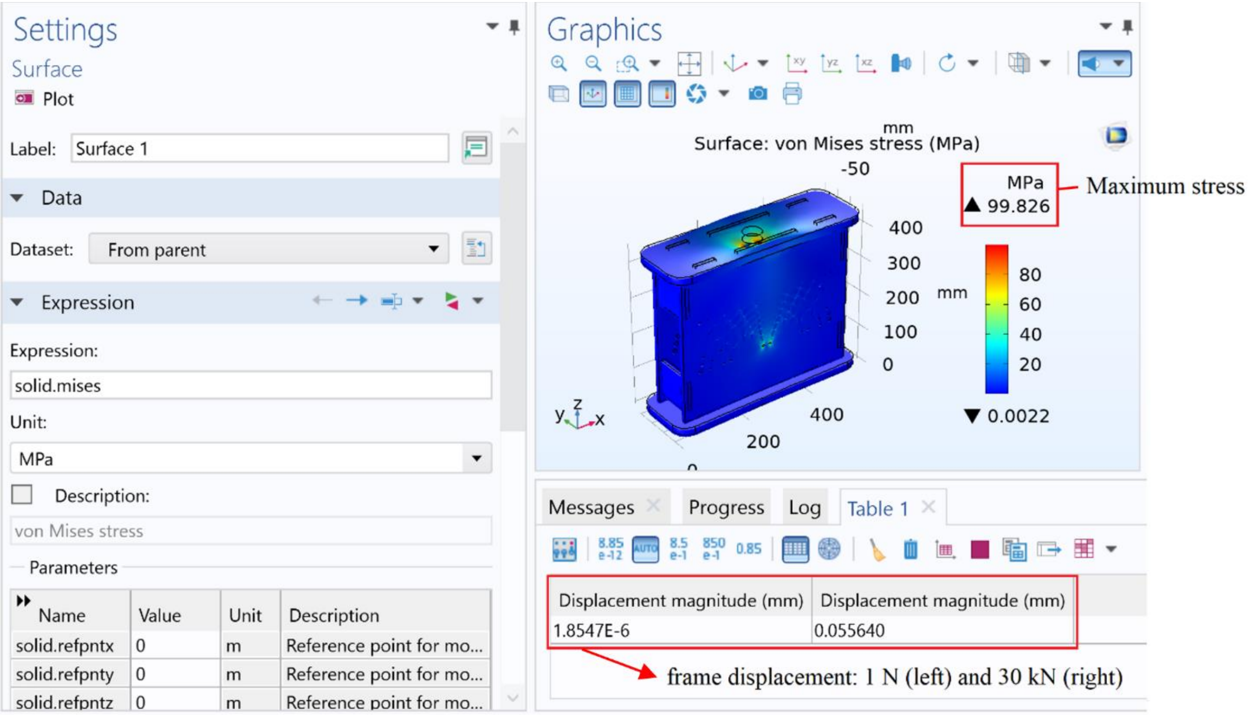


Figure 32: Frame displacement – 20-mm span

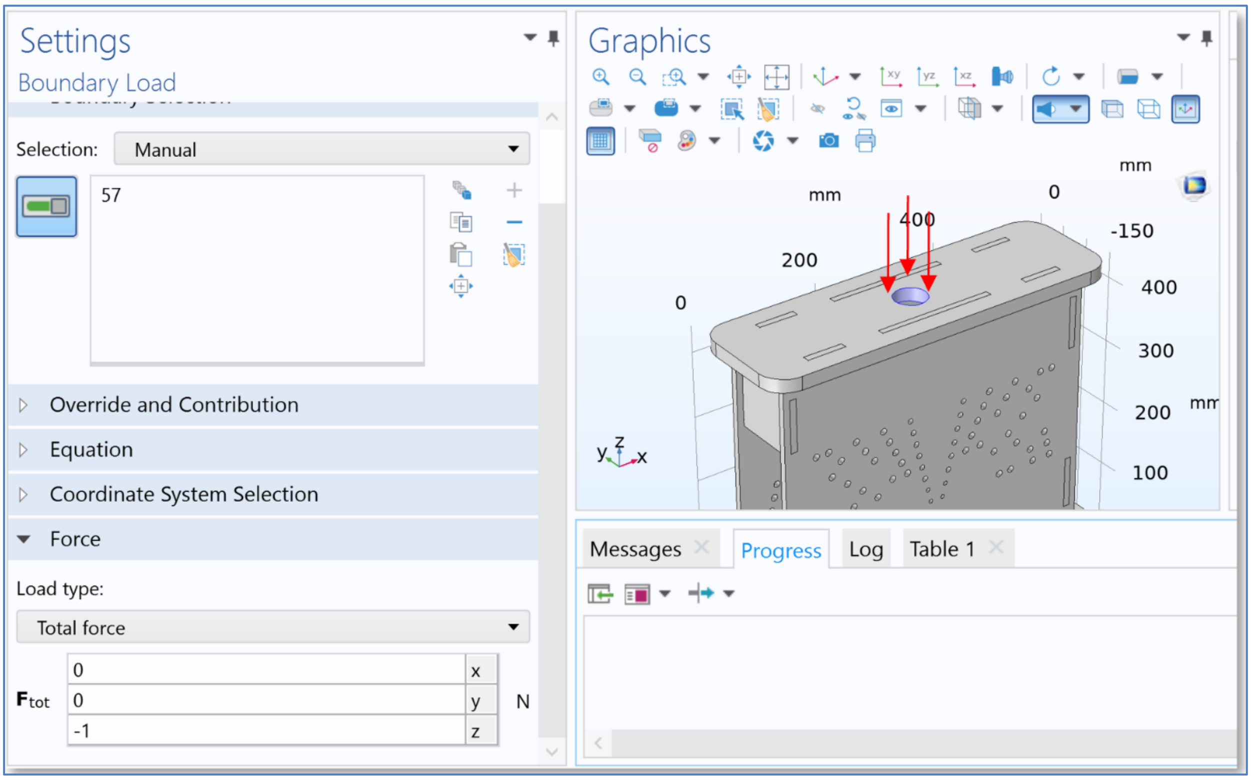


Figure 33: Boundary Load: force value and placement

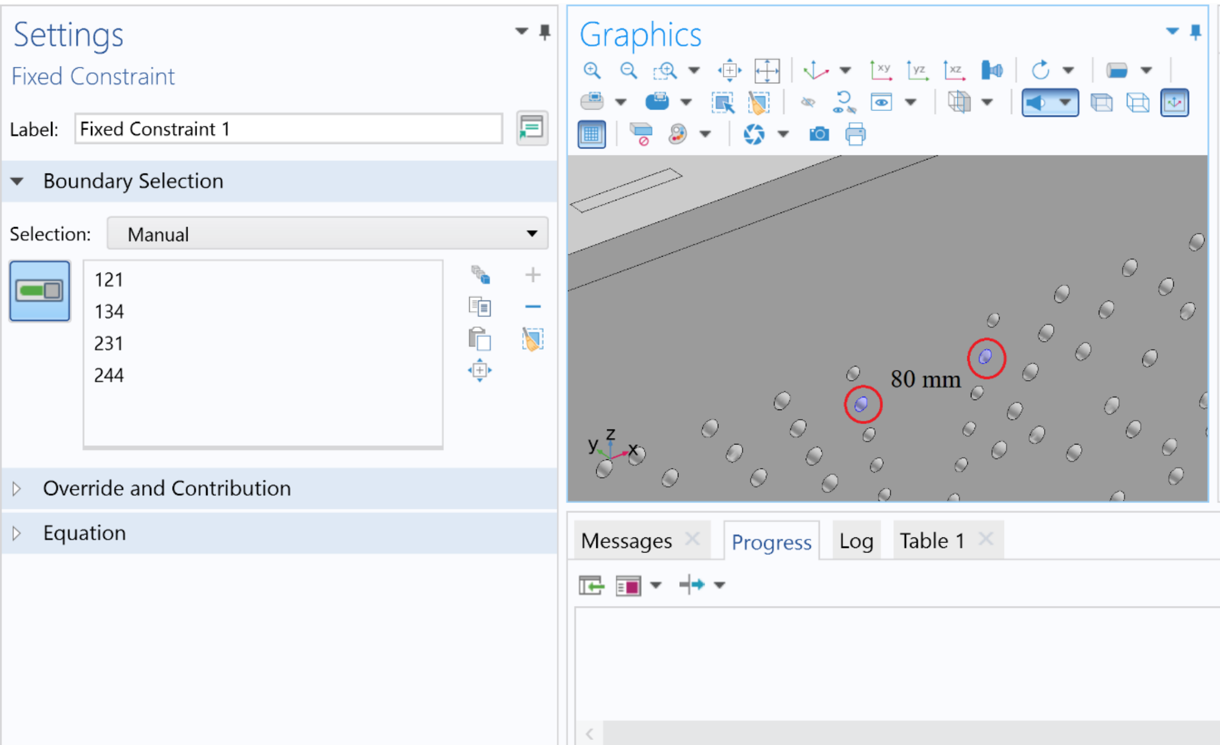


Figure 34: Fixed Constraint: 80-mm span

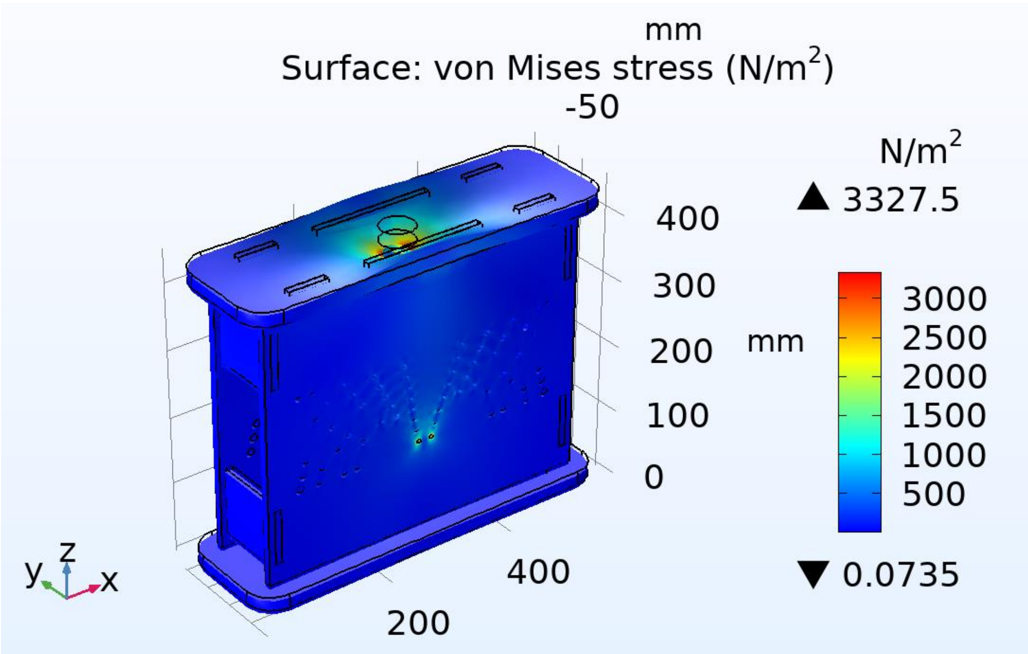


Figure 35: COMSOL simulation of bending frame

4.3.1 Criterion – 1 assessment

Comparing the maximum frame displacement to Absolute Error in Table 1 of Chapter 1.1.1 to see if the frame can fulfill the first criterion.

Classification	Error not to Exceed the Greater of:	
	Absolute Error [mm]	Relative error [% of displacement]
Class A	±0.025	±0.5
Class B	±0.075	±1.0
Class C	±0.125	±2.0
Class D	±0.25	±3.0

As calculated in FEA, the new bending frame has a load capacity of 30 kN and a maximum displacement of 0.05564 mm.

The maximum displacement 0.05564 mm lies within the range from 0.025 to 0.075 mm, meaning that the frame satisfies Class B of the criteria: maximum allowable frame displacement of ±0.075 mm or 1% of the specimen deformation, and thus complies with ASTM E2309 standard.

In order to satisfy Class A, load capacity of the frame need to be:

$$\frac{0.025 \times 30}{0.05564} = 13.7 \text{ kN}$$

4.3.2 Criterion – 2 assessment

Create a table of frame displacements, in which

- **Criterion1 Class B - 30 kN** column was taken from Table 8 – Frame displacement at 30 kN. Let's assume A is value in this column.
- **Criterion 2** columns was calculated based on Table 2 in Chapter 1.1.2.
  Similarly, assume B is value in column **3-point bending,** C and D are values in columns **One third** and **One half.**
- **F_{max} that satisfies two criteria** column was created in such that:
  If A is the lowest displacement of A, B, C and D, the load equals 30 kN.

  Otherwise, the load equals $\frac{the\ lowest\ of\ (A,B,C,D)\times 30}{A}\ [unit: kN]$

No.	Span L [mm]	Frame displacement [mm]				F_{max} that satisfies two criteria [kN]
		Criterion 1 Class B - 30kN A	Criterion 2			
			3-point bending $B = \frac{L}{750}$	4-point bending		
				One third $C = \frac{23L}{13500}$	One half $D = \frac{11L}{6000}$	
1	20	0.0556	0.0267	0.0341	0.0367	14.38
2	30	0.0545	0.0400	0.0511	0.0550	22.01
3	40	0.0531	0.0533	0.0681	0.0733	30
4	50	0.0520	0.0667	0.0852	0.0917	30
5	60	0.0510	0.0800	0.1022	0.1100	30
6	70	0.0498	0.0933	0.1193	0.1283	30
7	80	0.0486	0.1067	0.1363	0.1467	30
8	90	0.0472	0.1200	0.1533	0.1650	30
9	100	0.0513	0.1333	0.1704	0.1833	30
10	120	0.0505	0.1600	0.2044	0.2200	30
11	140	0.0495	0.1867	0.2385	0.2567	30
12	150	0.0513	0.2000	0.2556	0.2750	30
13	160	0.0487	0.2133	0.2726	0.2933	30
14	180	0.0480	0.2400	0.3067	0.3300	30
15	200	0.0520	0.2667	0.3407	0.3667	30
16	210	0.0502	0.2800	0.3578	0.3850	30
17	220	0.0532	0.2933	0.3748	0.4033	30
18	240	0.0500	0.3200	0.4089	0.4400	30
19	250	0.0519	0.3333	0.4259	0.4583	30
20	260	0.0533	0.3467	0.4430	0.4767	30
21	270	0.0502	0.3600	0.4600	0.4950	30
22	280	0.0528	0.3733	0.4770	0.5133	30
23	300	0.0521	0.4000	0.5111	0.5500	30
24	320	0.0518	0.4267	0.5452	0.5867	30
25	330	0.0518	0.4400	0.5622	0.6050	30
26	340	0.0518	0.4533	0.5793	0.6233	30
27	350	0.0518	0.4667	0.5963	0.6417	30
28	360	0.0518	0.4800	0.6133	0.6600	30
29	380	0.0518	0.5067	0.6474	0.6967	30
30	390	0.0518	0.5200	0.6644	0.7150	30
31	400(2)	0.0549	0.5333	0.6815	0.7333	30
32	400(9)	0.0537	0.5333	0.6815	0.7333	30

Table 9: Frame displacements – two criteria

4.3.3 Results

Results of this thesis show that:

a. The frame fulfills criterion 1 for Class B – E2309 until a load of 30 kN
b. Both criteria 1 and 2 are fulfilled for Class B – E2309 until 30 kN from 50-mm support length and thickness is at most $\frac{1}{16}$ of support length.
   The corresponding frame displacement for 50-mm span is 0.0531 mm.
c. To fulfill both criteria – Class B for 20 mm and 30 mm support span, the load is limited to 14.38 kN and 22.01 kN, respectively.
d. The frame fulfills criterion 1 for Class A – E2309 until a load of 13.7 kN.
   Since 13.7 kN is lower than 14.38 kN, if the frame fulfills Class A, it fulfills both criteria 1 and 2.

In summary,

<table>
<tr><th colspan="2">Two criteria
from ASTM D790 and E2309</th><th>Frame capacity
[kN]</th></tr>
<tr><td colspan="2">Two criteria - Class A</td><td>13.7</td></tr>
<tr><td rowspan="3">Two criteria
Class B</td><td>L = 20 mm</td><td>14.38</td></tr>
<tr><td>L = 30 mm</td><td>22.01</td></tr>
<tr><td>L = [50; 400] mm</td><td>30</td></tr>
</table>

Table 10: Frame capacity

5 DISCUSSION

5.1 Actuator recommendation

Actuator is a device converting energy into mechanical motion. Based on the power source, there are two types of actuators commonly used in the material testing machine: electromechanical and hydraulic, both have their strengths and weaknesses.

- Electromechanical actuators are leading in speed and position accuracy, but they are expensive and can overheat, which reduces their lifespan. [30]

- Hydraulic actuators have the advantage of load capability and can maintain constant force regardless of the change in speed [30]. High load capability means that they can offer much larger force than mechanical actuators of the same size. They are also reasonably priced and more suitable for this bending frame. It is worth noting that the system can leak hydraulic fluid, commonly oil to the environment, but this can be prevented with proper maintenance.

5.2 Limitation

- The new bending frame has a limit on the option of support distance, it is only appliable to 31 span distances as shown in Table 3, Chapter 3.1.2. However, value of span and number of holes can be customized according to the regular test and the design can be continuously developed to match the university requirement.
- Figure 36 and 38 are the original front plate and frame assembly of the author, they can be used for future reference. In this frame, a horizontal slot marked in centimeters is used in place of 64 holes, the support rod is attached to the slot through a pair of adapter and its distance from center of the slot is indicated through the position line (Figure 37).
- For the purpose of simplifying bending simulation in Finite Element Analysis, the model in Figure 28 was a more appropriate candidate and was chosen throughout this thesis.

Figure 36: Front and back plate of the original frame

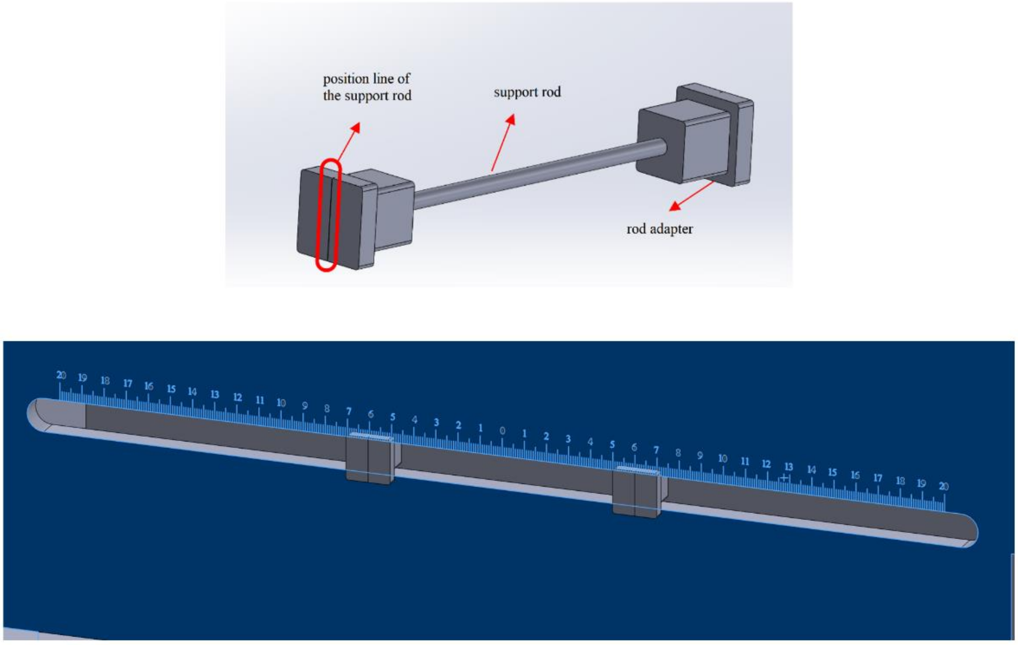


Figure 37: Support rod and adapter

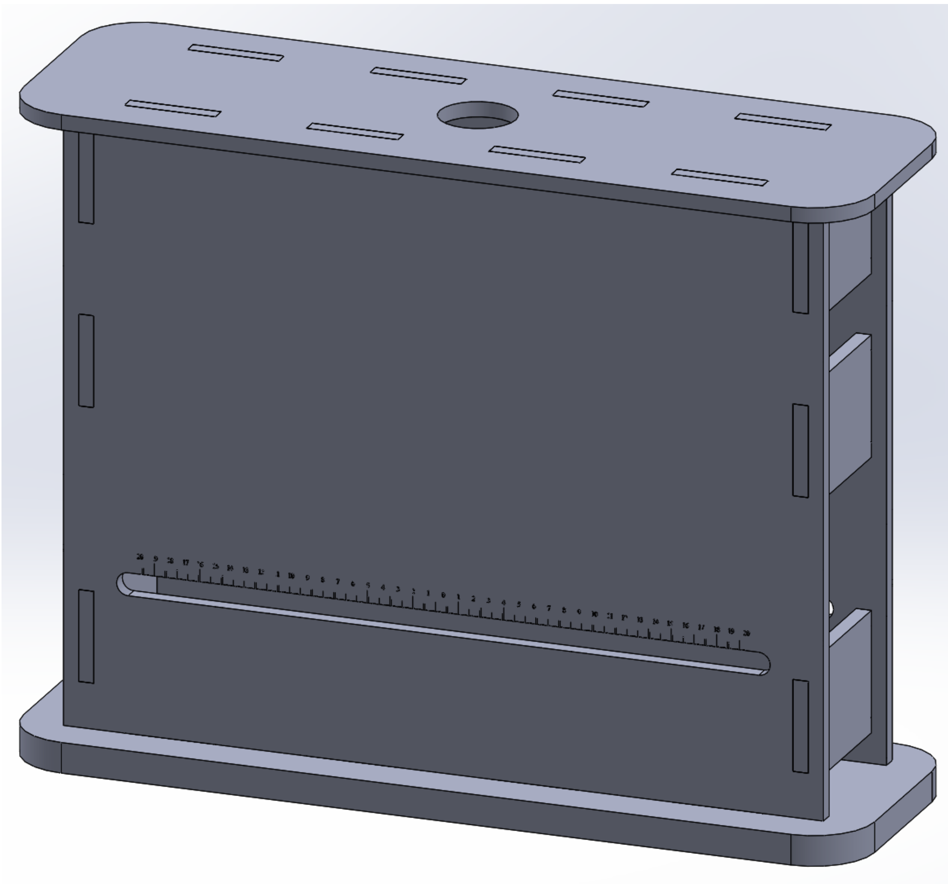


Figure 38: Assembly of the original frame

5.3 Frame deformation of supervisor's model

Similar to chapter 3.3, bending tests were also simulated in the frame model of supervisor Rene Herrmann, as depicted in Table 10 and Figure 39.

No.	Span L [mm]	Applied Load [N]	σ_{max} [Pa]	ε_{max}	F_{max} [N]	Frame Displacement at 1N [10^{-7} mm]
1	60	1	2264.7	1.132E-08	44156.0	8.272
2	120	1	2059.7	1.030E-08	48550.8	7.961
3	180	1	2485.6	1.243E-08	40231.7	7.879
4	240	1	1985.1	9.926E-09	50375.3	7.943
5	300	1	2250.9	1.125E-08	44426.7	8.145
6	360	1	2202.8	1.101E-08	45396.8	8.473
7	420	1	2139.3	1.070E-08	46744.3	8.968

Table 11: Frame deformation of Rene's model

In this case, maximum load that fulfills both of two criteria is also 40.2 kN

No.	Span L [mm]	Frame displacement [mm]				F_{max} that satisfies two criteria [kN]
		Criterion 1 Class B – 40.2 kN A	Criterion 2			
			3-point bending $B = \frac{L}{750}$	4-point bending		
				One third $C = \frac{23L}{13500}$	One half $D = \frac{11L}{6000}$	
1	60	0.03325	0.0800	0.1022	0.1100	40.2
2	120	0.03200	0.1600	0.2044	0.2200	40.2
3	180	0.03167	0.2400	0.3067	0.3300	40.2
4	240	0.03193	0.3200	0.4089	0.4400	40.2
5	300	0.03274	0.4000	0.5111	0.5500	40.2
6	360	0.03406	0.4800	0.6133	0.6600	40.2
7	420	0.03605	0.5600	0.7156	0.7700	40.2

Table 12: Supervisor frame - two criteria

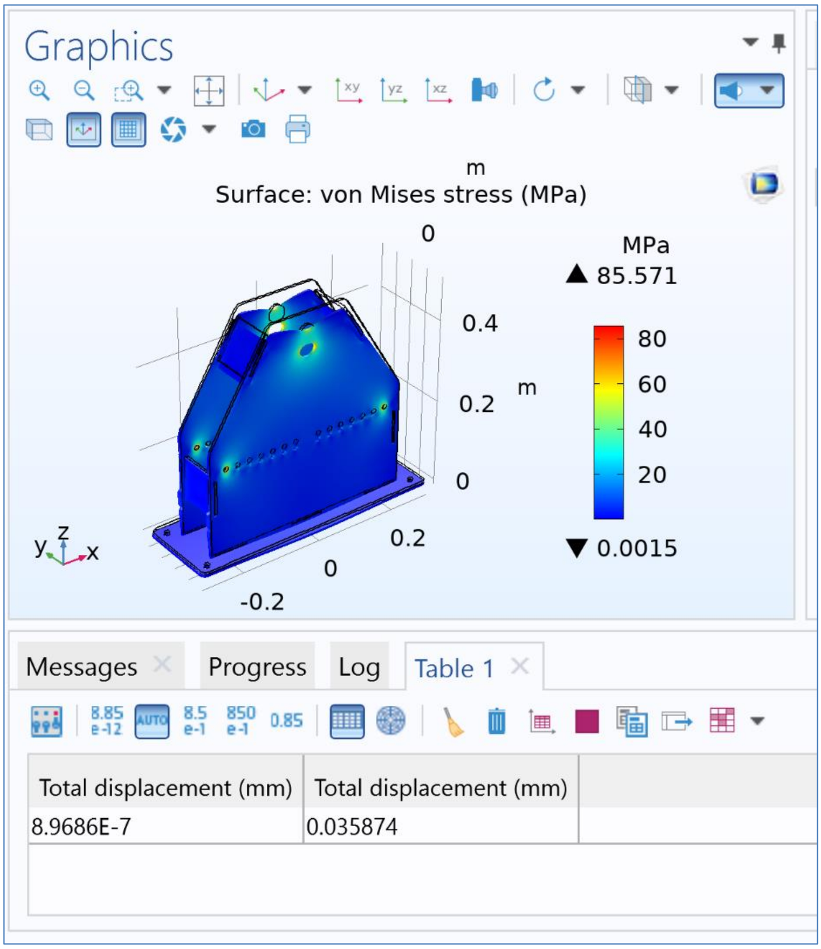


Figure 39: COMSOL bending simulation – 420-mm span

The result showed that this frame can handle a maximum load of 40.2 kN and a maximum displacement of $8.968 \times 10^{-7} \times 40200 = 0.03605$ mm, fulfilling both criterion 1 – Class B and criterion 2.

Meanwhile, the author's frame fulfills criterion 1 – Class B and criterion 2 from 50-mm span L until 30 kN. (based on Chapter 3.3.3)

When the actuator holes are created on the front and back plates instead of on the top plate, the applied load is evenly distributed to the front and back plates, which accordingly enhances the frame capacity and reduces its displacement.

For this reason, in the future development of the frame design, one should take into consideration where to install the actuator, in order to minimize the frame displacement and maximize its capacity.

5.4 180-degree rotation

Depending on the dimension of the specimen and support distance of regular tests, operators can choose to rotate the frame 180 degrees to save some travel distance of the actuator.

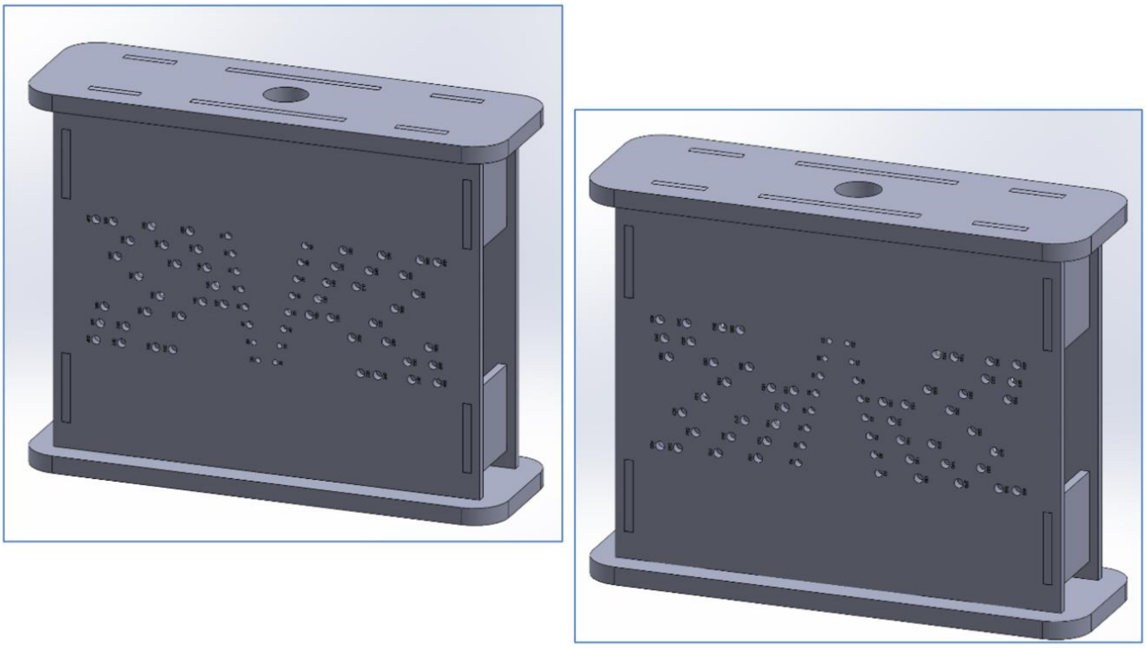


Figure 40: Normal frame (left) and 180^o frame (right)

The loading limits to fulfill two criteria for 180^o frame are:

Criteria		**Maximum load [kN]**
Criterion 1 – Class B		26.7 maximum frame displacement of 0.04859 mm
Criterion 2	**from 50-mm span**	26.7
	20-mm span	16.42
	30-mm span	24.15

Table 13: 180^o frame – maximum load

Particular results from Finite Element Analysis:

No.	Span L [mm]	Applied force [N]	σ_{max} [Pa]	F_{max} [N]	Frame displacement [10^{-6} mm]
1	20	1	3516	28441.4	1.624
2	30	1	3740.3	26735.8	1.656
3	40	1	3340.8	29933.0	1.674
4	50	1	3354.6	29809.8	1.702
5	60	1	3365.4	29714.1	1.729
6	70	1	3373.6	29641.9	1.754
7	80	1	3380.1	29584.9	1.776
8	90	1	3385.3	29539.5	1.793
9	100	1	3350.4	29847.2	1.670
10	120	1	3362.6	29738.9	1.707
11	140	1	3371	29664.8	1.733
12	150	1	3350.6	29845.4	1.671
13	160	1	3378	29603.3	1.754
14	180	1	3387.3	29522.0	1.772
15	200	1	3339.9	29941.0	1.661
16	210	1	3371.4	29661.3	1.732
17	220	1	3310.2	30209.7	1.625
18	240	1	3378.5	29598.9	1.758
19	250	1	3357.3	29785.8	1.708
20	260	1	3323.6	30087.9	1.662
21	270	1	3383.8	29552.6	1.778
22	280	1	3350.9	29842.7	1.709
23	300	1	3369	29682.4	1.748
24	320	1	3380.8	29578.8	1.780
25	330	1	3350.5	29846.3	1.735
26	340	1	3344.2	29902.5	1.737
27	350	1	3377.1	29611.2	1.783
28	360	1	3385.2	29540.4	1.806
29	380	1	3364	29726.5	1.779
30	390	1	3359.3	29768.1	1.787
31	400 (2)	1	3354.3	29812.5	1.792
32	400 (9)	1	3385.9	29534.2	1.820

Table 14: 180-degree frame deformation

Similar to Chapter 3.3, comparing frame deflection values from FEA, 3-point and 4-point bending to find the maximum load.

No.	Span L [mm]	Frame displacement [mm]				Maximum load that satisfies two criteria [kN]
		Criterion 1	Criterion 2			
			3-point bending	4-point bending		
		Class B – 26.7 kN A	$B = \frac{L}{750}$	One third $C = \frac{23L}{13500}$	One half $D = \frac{11L}{6000}$	
1	20	0.04336	0.0267	0.0341	0.0367	16.42
2	30	0.04422	0.0400	0.0511	0.0550	24.15
3	40	0.04470	0.0533	0.0681	0.0733	26.7
4	50	0.04544	0.0667	0.0852	0.0917	26.7
5	60	0.04616	0.0800	0.1022	0.1100	26.7
6	70	0.04683	0.0933	0.1193	0.1283	26.7
7	80	0.04742	0.1067	0.1363	0.1467	26.7
8	90	0.04787	0.1200	0.1533	0.1650	26.7
9	100	0.04459	0.1333	0.1704	0.1833	26.7
10	120	0.04558	0.1600	0.2044	0.2200	26.7
11	140	0.04627	0.1867	0.2385	0.2567	26.7
12	150	0.04462	0.2000	0.2556	0.2750	26.7
13	160	0.04683	0.2133	0.2726	0.2933	26.7
14	180	0.04731	0.2400	0.3067	0.3300	26.7
15	200	0.04435	0.2667	0.3407	0.3667	26.7
16	210	0.04624	0.2800	0.3578	0.3850	26.7
17	220	0.04339	0.2933	0.3748	0.4033	26.7
18	240	0.04694	0.3200	0.4089	0.4400	26.7
19	250	0.04560	0.3333	0.4259	0.4583	26.7
20	260	0.04438	0.3467	0.4430	0.4767	26.7
21	270	0.04747	0.3600	0.4600	0.4950	26.7
22	280	0.04563	0.3733	0.4770	0.5133	26.7
23	300	0.04667	0.4000	0.5111	0.5500	26.7
24	320	0.04753	0.4267	0.5452	0.5867	26.7
25	330	0.04632	0.4400	0.5622	0.6050	26.7
26	340	0.04638	0.4533	0.5793	0.6233	26.7
27	350	0.04761	0.4667	0.5963	0.6417	26.7
28	360	0.04822	0.4800	0.6133	0.6600	26.7
29	380	0.04750	0.5067	0.6474	0.6967	26.7
30	390	0.04771	0.5200	0.6644	0.7150	26.7
31	400(2)	0.04785	0.5333	0.6815	0.7333	26.7
32	400(9)	0.04859	0.5333	0.6815	0.7333	26.7

Table 15: 180º frame – two criteria

6 CONCLUSION

This thesis developed a bending frame design that comprises 8 parts: one base, one top, one front, one back, and 4 support side plates. Steel AISI 4340 were chosen as the material for all parts of the frame thanks to its high strength and toughness, ideal resistance to stress and atmospheric corrosion. As the frame is built using sheet metal, laser cutting gives great advantage over mechanical cutting of precision, speed, cost-effectiveness, fewer waste and smooth finishes. Laser cutting is followed by welding to permanently join parts of the frame into one single entity, it is an affordable method and requires a skilled welder to safely perform and ensure the quality of the welded assembly.

To ensure the accuracy of the bending tests, ASTM and ISO standards were applied for the reference of specimen dimensions, support distances and frame deformation assessment. ASTM D790 and ASTM 2309 limit strain of the frame to 0.0005, while its largest displacement was limited to 1% of the specimen deflection by ASTM D790. Finite Element Method and Euler – Bernoulli theory were used to simulate bending tests, compute maximum stresses and total displacements of the frame under loading. Hooke's law indicates the relationship between deflection, force, stress and strain, and was used to calculate the frame maximum strain and load capacity.

With a combination of above resources and experience learning, this study results in a new bending frame that fulfills ASTM D790 and E2309 - Class A of E2309 until 13.7 kN. It fulfills D790 and Class B – E2309 to 14.38 kN for 20-mm span, to 22.01 kN for 30-mm span, and to 30 kN for the range from 50 – 400 mm span.

The author recommends using hydraulic actuators for this frame because they have high load capability, can maintain constant force regardless of the change in speed, and are reasonably priced. Although the frame is only applicable to 31 support distances, span values and support-hole quantity can be customized based on regular testing requirements. For the future development of the frame design, support holes can be replaced by a support slot for a wider selection of spans; and the actuator can be attached from the front and back plates instead of from the top plate to reduce the frame displacement and increase its load capacity.

Most importantly, the idea of the alternative frame was proved to be feasible and effective. In comparison with the traditional frame, this bending frame is lighter, safer, more affordable, while at the same time has a high load capacity and fulfills ASTM D790 and ASTM E2309.

It is worth noting that frame is not limited by the design of the supervisor or the author, it can be continuously developed and customized to satisfy university demands and flexural test standards.

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APPENDICES

Testometric™ **M350-5 CT**

QControl quality solutions

info@qcontrol.gr www.qcontrol.gr
ΤΗΛ. 210 9416 200 FAX. 210 9415 211

Range kN	5	Data sampling rate	Maximum 12kHz with up to 200Hz data frames.
Accuracy	+/- 0.5% of reading down to 1/1000th of load cell capacity.	Overall dimensions W x D x H	590 x 450 x 1575
Vertical space mm	1275	Weight kg	146
Crosshead travel/resolution mm	1100 by 0.001	Electrical supply	Dual input selectable 115 or 230V 1ph 50/60Hz.
Throat mm	295	Operating temp degree C	-10 to +40
Frame stiffness kN/mm	50	Operating humidity	+10 to +90% non-condensing
Speed range mm/min	0.001 to 2000	Machine Configuration	Table top, base cabinet available
Speed accuracy	+/- 0.1% under stable conditions.	Number of Columns	2
Crosshead guidance	Linear slides integral within column	Available load cells	5N, 10N, 20N, 100N, 250N, 500N. 1kN, 2.5kN, 3kN, 5kN Maximum of four load cells up to capacity of machine.
Max force at full speed kN	5	Spigot Ø mm	20
Max speed at full load mm/min	2000	Power kW	0.45

Figure 41: Testometric M350 – 5CT [28]