VII. Base Plate Design

A. Design Iterations

The base plate design is replicated as a continuation of the tower by giving a small height and having the loads applied on top of that extrusion. Similar to real-world designs, the base plate includes bolts, flanges for the bolts to go on, and side supports for increasing the structural rigidity. Structural steel is used as the material for all iterations. In order to attain a factor of safety of 6 for the hardware and 1.5 for the structure itself, design parametrization is performed on three different designs: a single flange with 1 layer of bolts (Figure VII.1), a single flange with 2 layer of bolts (Figure VII.2), and two flanges with single layer of bolts each (Figure VII.3).

Each design is further parameterized by the number of bolts, bolt size, number of side supports, and the overall geometry. After analyzing all the designs, the base plate with 2 flanges with a single layer of bolts each is chosen as the final design. Table VIII shows the changes made across all the designs. The analysis conducted before rejecting the first two designs is shown in the Figure C-B

	Number of Bolts	**Bolt Diameter**	**Number of side supports**
Design 1	52	6 in	12
Design 2	258	2 in	12
Design 3	234	3 in	24

TABLE VIII: Major Design Changes Across Designs

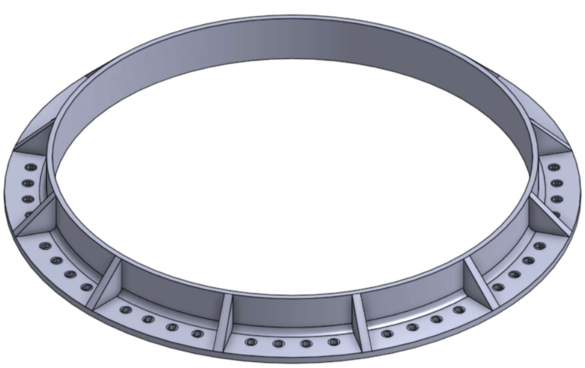


Fig. VII.1: First Base Plate Design With One Layer of Bolts

B. Deign of Bolt Hole With Respect to Thermal Expansion of the Base Plate

The bolt holes in the base are designed to allow for thermal movements. When the base heats up, the base will expand radially outwards. If the holes are designed with a circular hole then it will begin to sheer the stud bolt in the concrete. To get rid of this sheering force, the bolt hole is designed with a slot as shown in Figure VII.4

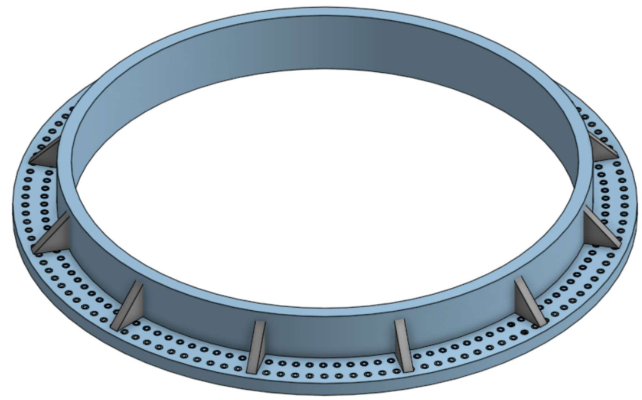


Fig. VII.2: Second Base Plate Design With One Flange and Two Layer of Bolts

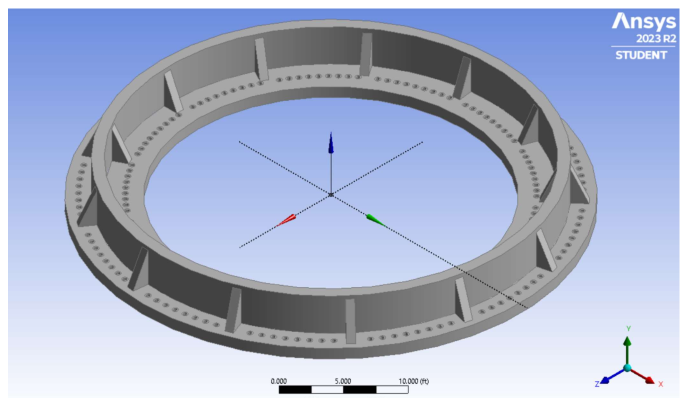


Fig. VII.3: Base Plate's Final Design: Two Flanges with Single Layer of Bolt Each

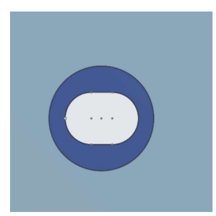


Fig. VII.4: Designing the Bolt Hole With Slot to Account for Thermal Expansion

To calculate the slot length, the thermal expansion can be calculated of the base. The base can be treated as a ring and since the thermal expansion at the bolt is of most importance it will be evaluated as a ring of a $20ft$ radius. To find the radial change of a ring of a certain radius, a similar equation to Equation 18 can be used and substituting length L for radius R.

$$\Delta R = \alpha R_0 \Delta T \tag{18}$$

ΔR	Change in Radius of Material
α	Thermal Expansion Coefficient
R_0	Original Radius
ΔT	Change in Temperature of Material

With a Radius of $20ft$, a temperature variation between -10 to $130°F$, and an α of $6.7\frac{10^{-6}}{°F}$ the equation evaluates to,

$$\Delta R = (6.710^{-6}\frac{1}{°F})(20ft)(140°F)$$
$$\Delta R = 0.019ft$$

To confirm this value in ANSYS a simplified flange model can be created without holes flanges. To simplify the model only a quarter of the model is necessary and symmetric boundary conditions can be made by constraining the movement perpendicular to the symmetry faces. The boundary conditions will be as follows. A thermal condition on the whole body with a base temperature of $-10°F$ and a current temperature of $130°F$ (This will result in the total radial change between the minimum and maximum temperatures). As shown in Figure VII.5, the maximum expansion is $0.019ft$, however where the bolts will be placed the expansion is about $0.018ft$. This value is close to the calculated value above of $0.019ft$ and the results are confirmed.

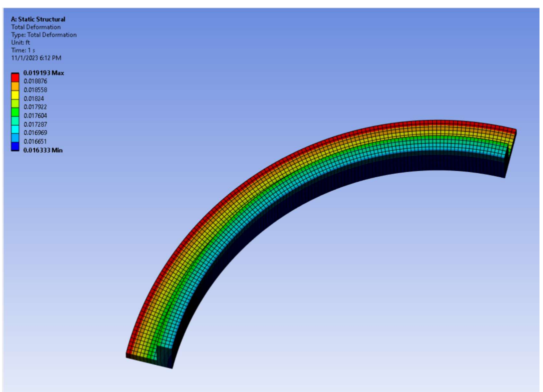


Fig. VII.5: Total Deformation of Base from Maximum Thermal Changes (-10 to 130 $°F$)

A slot length of $0.1ft$ is chosen for this design to build in a factor of safety that also accounts for installation error of the threaded studs in the ground.

C. Applied Loads and Constraints

Since the base design acts as a continuation of the tower, the reaction forces are derived from the base of the tower design (where constraint is applied) and are applied on the top of the base plate. In doing so, the signs are flipped because reaction forces are internal, and hence their direction needs to be flipped.

In order to apply the loads, "remote force" is used in order to supply the load evenly over the entire actuation and set the application point to be the middle of the extrusion since that mirrors the actual load application. The worst-case loading scenario, normal loading with extreme cold temperatures, as shown in Table IX is used for analysis. "Compression Only Support" is used to constrain the bottom of the base plate since it is in contact with the concrete, which is considered to be rigid. Accordingly, the reaction force generated from the ground would only come into play when the base plate is being compressed which models the actual scenario.

	Forces (lbf)	Moments (lbf*in)
X	-1152.3	-4541441751
Y	-12716600.0	-3009.6
Z	-980794.0	7012072.9

TABLE IX: Worst Case Forces and Moments Applied on the Base Plate (Normal Loading in Extreme Cold Weather)

To constrain the bolts, "fixed constraint" is applied to the bolt head because as the bolt is torqued into the ground, the only thing providing rigidity to the base is the bolt head. In other terms, the bolt head is fixed. A visual representation of the loads and constraints applied is shown in Figure VII.6. The team also analyzed the structure with "Compression Only Support" on the bolt head and the hole itself which yielded a result with negligible change.

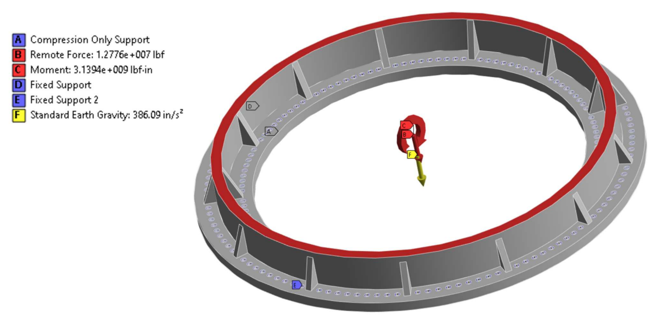


Fig. VII.6: Loads and Boundary Conditions Applied

D. Mesh Generated

"Patch Conforming Method" is used to generate a "Tetrahedron" mesh with an element size of 1.5 in. "Refinement" is added to the flanges and bolt heads because that is where the maximum stress occurs. An isometric view of the final mesh used is shown in Figure VII.7 and a close-up of the flanges and the bolt heads is shown in Figure VII.8. For conducting earlier analyses a dummy mesh with coarse elements is used to make post-processing faster. The metrics related to the final mesh quality are shown in Table X. The average element quality is around 0.75. The team tried to improve this by using "faced meshing" and playing with the element size, however, the results were similar. Finally, the skewness of the mesh is around 0.38 which also didn't change with different methods.

E. Post-processing

Since the loads applied by the wind and the nacelle bend the tower in one direction, the base plate is prone to compression and tension. While in compression, the bolts and the concrete underneath constrain the structure and provide rigidity. While in tension, however, only bolts constrain the structure because

Fig. VII.7: Final Tetrahedral Mesh Generated

Mesh Metric)	Magnitude
Total Number of Nodes	2551583
Element Size	1.5 in
Total Number of Elements	1620882
Average Aspect Ratio	2.18
Average Element Quality	0.73
Average Jacobian Ratio	0.986
Average Skewness	0.37
Average Minimum Element Edge Length	1.35
Average Maximum Element Edge Length	2.31

TABLE X: Mesh Metrics

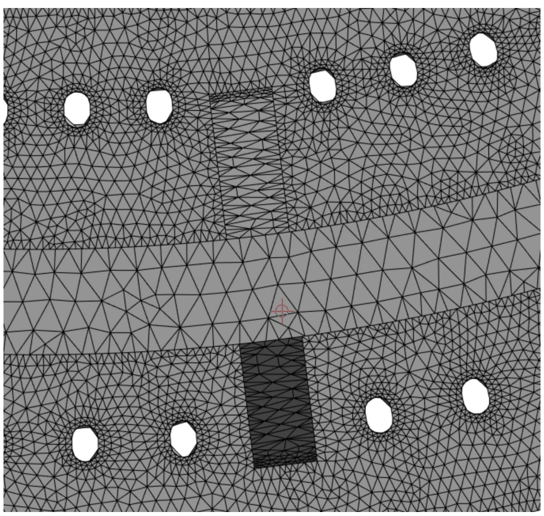


Fig. VII.8: Refinement Added Around the Bolt Holes and on the Flange

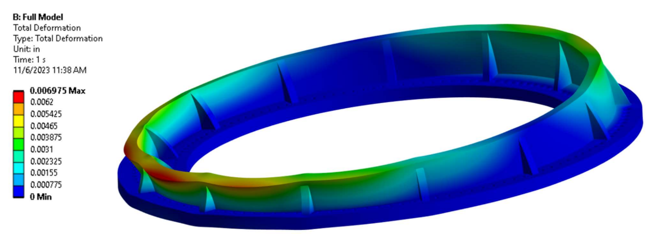


Fig. VII.9: Total Deflection (inches)

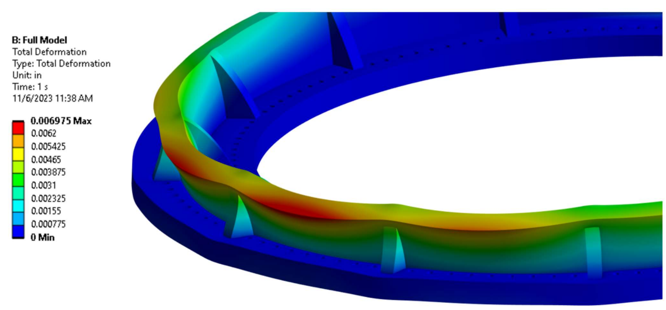


Fig. VII.10: Close up of total deflection (inches)

the ground support is modeled as ”compression-only support” which is not in contact with the plate anymore. Accordingly, the base design has a higher probability of failure under tension rather than when in compression which is also proven in the following analysis.

For all iterations made on the 3 designs, deflection is almost negligible however the structure fails in terms of stress or factor of safety for the hardware. The maximum deflection occurs at the extrusion which makes sense because that resembles the bottom part of the cantilever beam which is not constrained and the plate connection itself is constrained through bolts. The final deflection is determined to be 0.0069 inches which is less than the tower itself which also makes sense because the bottom part of the tower is closest to the rigid connection. The deflection of the base plate is shown in Figure VII.9 and the close-up of the structure where maximum deflection occurs is shown in Figure VII.10

In order to determine the stress and the corresponding factor of safety, two different analyses are done. Firstly, the structure is optimized to have a factor of safety higher than 1.65, and secondly, the factor of safety for the hardware to be higher than 6. Accordingly, the reaction forces are determined at the bolt head under maximum stress and the factor of safety is determined using hand calculations and ASTM A193 Grade B16 Standard for a 3-inch diameter bolt. More explanation regarding the same is presented under the ”Bolt Analysis”.

The von Mises stress for the base plate design is shown in Figure VII.11 and a close-up of the maximum stress is shown in Figure VII.12. As expected, the maximum stress occurs at the bolt which is under most tension. As the plate tries to flip due to the applied loads, the fixed constraints on the bolt head try to stay in place hence warping the structure around the bolt head.

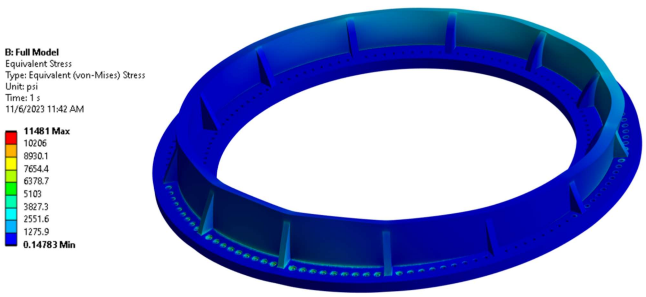


Fig. VII.11: Total Von Mises Stress (psi)

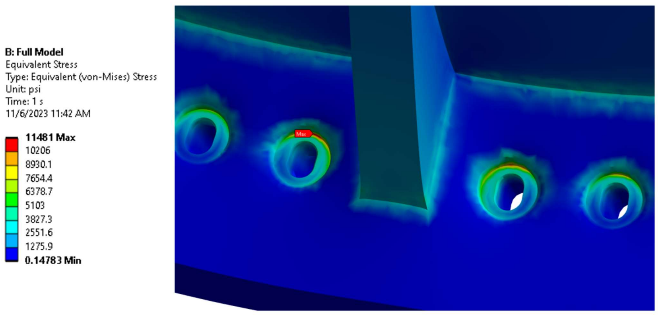


Fig. VII.12: Max Stress at the Bolt Head in Tension (psi)

A close-up of the maximum stress with a wire frame is also shown in Figure VII.13. Clearly, the maximum stress is not due to the warping of the element or singularity error however it occurs due to the warping of the structure itself as the tower tries to flip. This adds strength to the argument of having a good mesh.

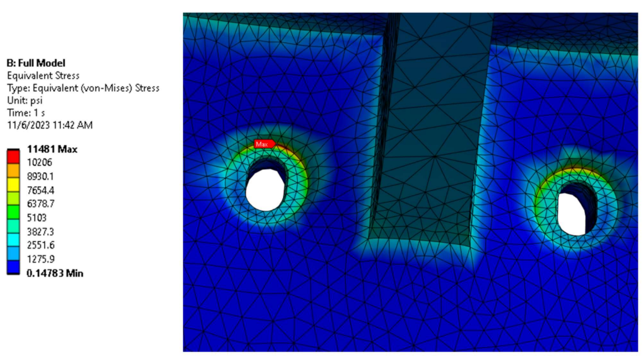


Fig. VII.13: Close up of the max stress with wireframe (psi)

Finally, the minimum factor of safety is determined to be 3.15 for the structure itself as shown in Figure VII.14. Since the maximum stress occurs at the bolt heads in tension, this minimum factor of safety also occurs around there. A close-up of this scenario is shown in Figure VII.15

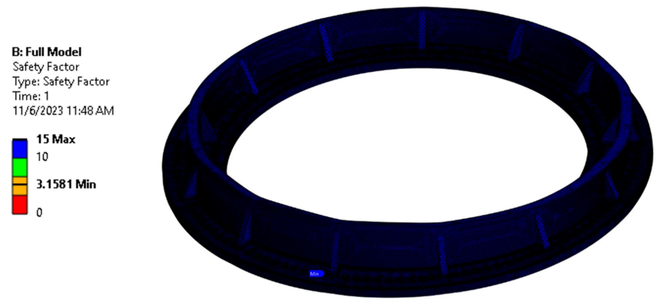


Fig. VII.14: Factor of Safety

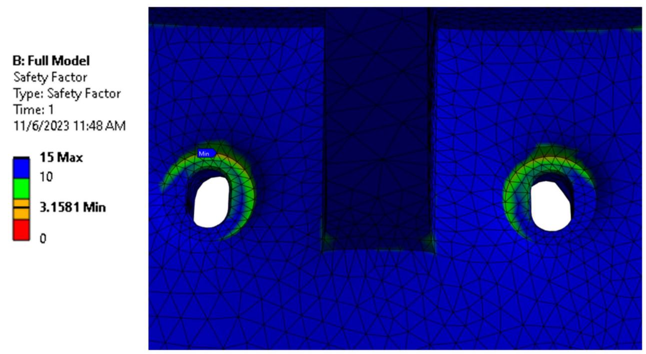


Fig. VII.15: Close up at the Lowest Factor of Safety around the Bolt Head in Tension

F. *Weld Analysis At Areas of Interest*

Since the base plate is going to be welded to the tower and the side supports are going to be welded to the base plate itself, it is important to ensure that the max shear stress around those boundaries has a considerable factor of safety for it to be welded. Accordingly, the shear stress is determined. A close-up of the max shear stress around the bolt head and two probes around the boundaries with maximum shear stress is shown in Figure VII.16 Although the design does not model the welds directly, the stress around these areas gives a good approximation of the stress in the welds. These areas will be fillet welded along all of the edges. The maximum sheer

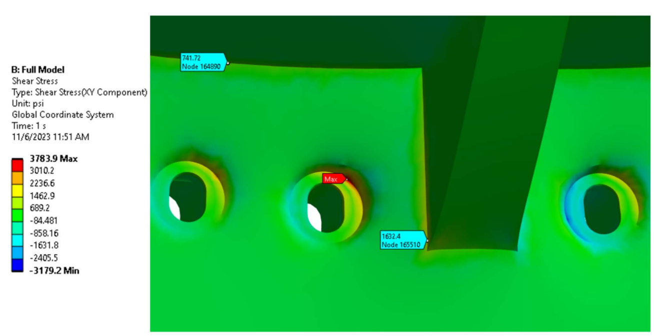


Fig. VII.16: Close up at the max shear stress (psi)

stress in the welds of the flange is 741 psi, and the maximum sheer stress in the welds of the angle brackets is 1632 psi. Using *Shigley's Mechanical Engineering Design*, the welding strength of various welds are found and compared to these maximum stresses. Figure Figure VII.17 tabulates known data for the maximum allowable shear stress in various strength fillet welds. If an electrode number of E90 is chosen, the given

Schedule A: Allowable Load for Various Sizes of Fillet Welds

	Strength Level of Weld Metal (EXX)						
	60*	70*	80	90*	100	110*	120
	Allowable shear stress on throat, ksi (1000 psi) of fillet weld or partial penetration groove weld						
$\tau =$	18.0	21.0	24.0	27.0	30.0	33.0	36.0

Fig. VII.17: Allowable Sheer Stress for Fillet Welds *Shigley's Mechanical Engineering Design*

allowable sheer stress is 27 ksi as per tests done by the AISC-AWS committee. This source also suggests a factor of safety of 1.5 to account for fatigue loading which could be present in the case of a wind turbine design. The maximum shear stress found in the design of 1632 psi should be multiplied by this value to account for fatigue. To find the resulting factor of safety for the welds in the base, the allowable stress is divided by the maximum stress.

$$FS = \frac{\tau_{allowable}}{\tau_{actual}}$$
$$FS = \frac{27ksi}{(1.632 * 1.5)ksi} = 11$$

This value exceeds the specified factor of 6 necessary for all connections. Furthermore, to check the integrity of the weld metal itself, E90 welds have a tensile strength of 90 ksi as shown in figure Figure VII.18. The maximum von-misses

AWS Electrode Number*	Tensile Strength kpsi (MPa)	Yield Strength, kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25
E70xx	70 (482)	57 (393)	22
E80xx	80 (551)	67 (462)	19
E90xx	90 (620)	77 (531)	14–17
E100xx	100 (689)	87 (600)	13–16
E120xx	120 (827)	107 (737)	14

*The American Welding Society (AWS) specification code numbering system for electrodes. This system uses an E prefixed to a four- or five-digit numbering system in which the first two or three digits designate the approximate tensile strength. The last digit includes variables in the welding technique, such as current supply. The next-to-last digit indicates the welding position, as, for example, flat, or vertical, or overhead. The complete set of specifications may be obtained from the AWS upon request.

Fig. VII.18: Electrode Strengths *Shigley's Mechanical Engineering Design*

stress found in the welded areas is found to be about 7 ksi. This yields a factor of safety well above 6. These calculations ensure that the welds in the base will be strong enough to handle the loading and resulting stress.

G. Bolt Failure Analysis

The bolts are modeled as a fixed support on an area around the bolt holes that represent a washer with a nut fixing it in place. This represents a bolt because if the bolt is working properly it will constrain any motion of the base around the area of the washer. In ANSYS, a reaction force probe is placed on the fixed constraint which is equal to the force that is transmitted to the bolt. The force in the y direction of this reaction force is used to analyze the stress in the bolt. Dividing this force by the cross-sectional area of the bolt yields the stress in the bolt and is compared to known bolt standards. An existing manufacturer, Nut, is chosen for this design because of their availability of large threaded studs for wind turbine applications and they provide specifications for their products. For the final design, a 3-inch ASTM A193 Grade B16 bolt[10] was chosen with a tensile strength of 110 Ksi. In the final design, the maximum bolt reaction force in the y direction is $1.21 * 10^5 lbf$ as shown in Table XI . Dividing this by the area of the 3 inch screw yields,

$$\sigma = \frac{1.21 * 10^5 lbf}{\pi * (1.5in)^2} = 17.1ksi$$

The factor of safety for this bolt is therefore,

$$FS = \frac{\sigma_{allowable}}{\sigma_{actual}}$$
$$FS = \frac{110ksi}{17.1ksi} = 6.4$$

This is greater than the required factor of safety for connections of 6 passing this requirement.

Direction	Reaction Forces (lbf)
X	13843
Y	-1.21e5
Z	-15945

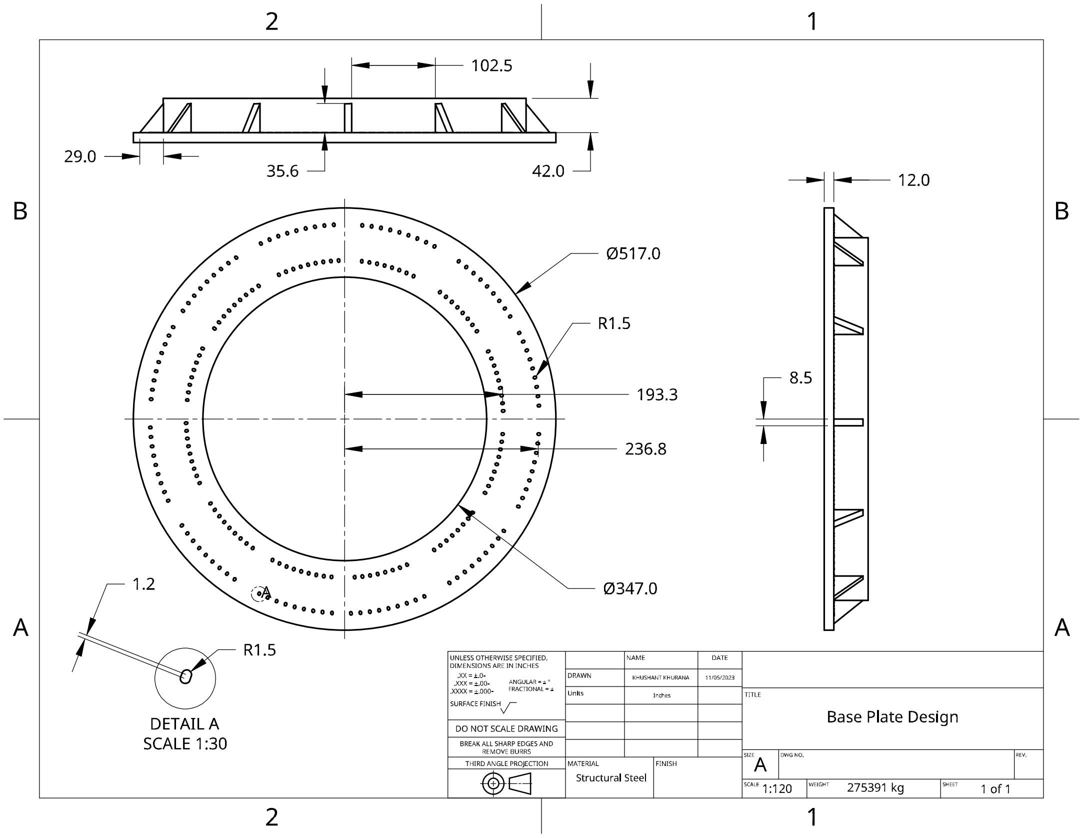
TABLE XI: Reaction Forces at the Bolt Head Under Maximum Stress

VIII. Design time estimate

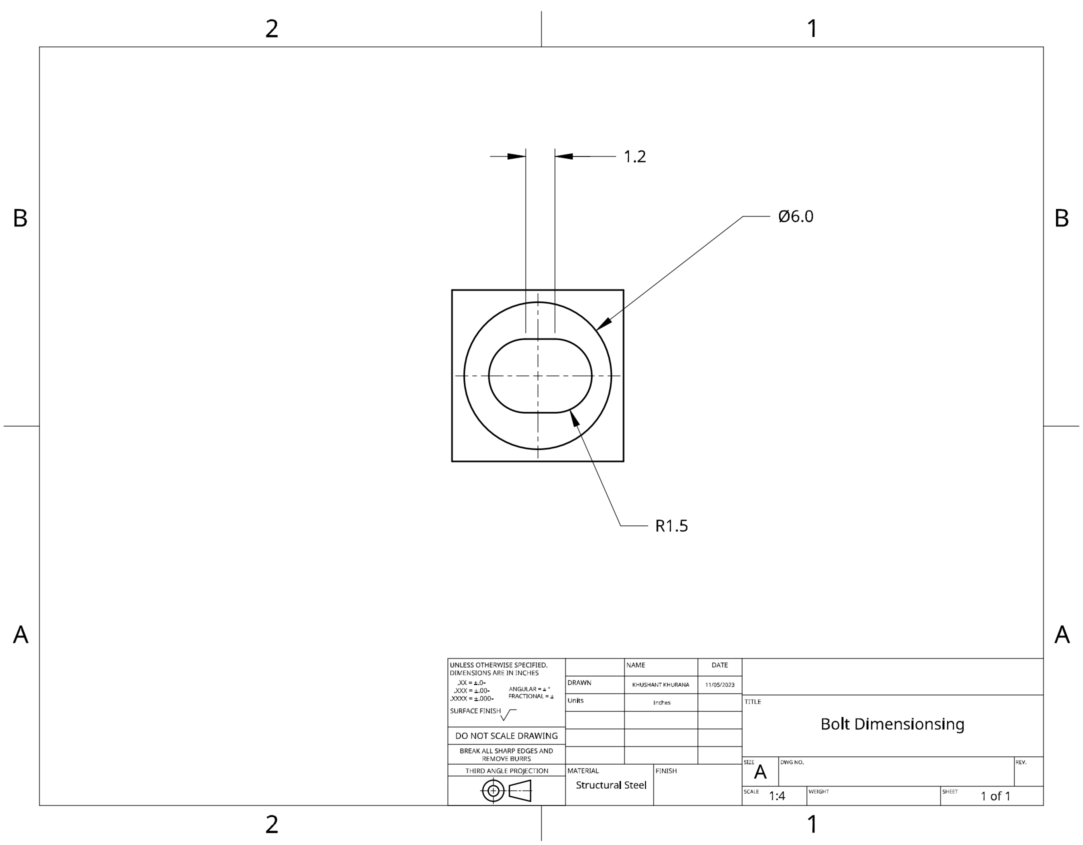
Topic	Hours Taken
Prior Research	3
Hand Calculations and Verification	10
Designing and Modelling	30
FEA Simulations	70
Post-Processing and Analysis	5
Compiling Results and Final Paper	25

TABLE XII: Rough Time Estimate for Each Aspect of the Design and Analysis.

APPENDIX B
ENGINEERING DRAWING FOR BASE



(a) Detailed Sketch of the Base Plate Design



(b) Detailed Sketch of the Bolt Design