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CR-STEM and Its Application to the Design and Analysis of an Automobile Engine

A Group Project

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by

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Abstract

Internal combustion engines are one of the most popular means of powering vehicles today. The major qualifying project (MQP) draws theories, principles and computational techniques from computers, science, technology, engineering and mathematics to design and optimize a crank-slider mechanism for automotive engine applications. The theories, principles and computational techniques guide the design iterations and selection of the appropriate approaches for studying the kinematics and dynamics of automobile engines. The designs created in this project can be used in a learning environment which teaches kinematics and dynamics of automobile engines. The team focused on the crankshaft assembly, designing most of the parts, assembling them, and optimizing the performance. By studying the motion of the piston and the crankshaft the team determined the optimal ratio of crank radius and connecting rod. The deliverables and findings in the MQP are additional guides for design parameter selection in automobiles and efficiency evaluation of engine performance.

Acknowledgements

The team would like to acknowledge Elm Park Auto for their contribution in sourcing and donating a used motor for the team to use during the design process and presentation.

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Chapter 1: The Role of the Internal Combustion Engine

The internal combustion engine, or ICE, is a form of heat engine that is used to convert chemical energy into mechanical energy of motion. This is usually done by way of gasoline combustion, and its subsequent pressure increases actuate a set of mechanisms to transfer the mechanical energy to various components of vehicle, electrical generators and power transducers. One of the power transmitting mechanisms of mechanical energy is the variation of the basic slider-crank mechanism, which we studied in this major qualifying project. Throughout the development of the MQP, we were exposed to the theoretical concepts of kinematics and dynamics of automobile engines. The kinematics and dynamics provided the foundation for the design iterations, simulations and stress-strain analysis of the automobile engine. Through simulation, we showed how the variation of the ratio of the crank radius and connecting rod influences the kinematics of the piston, the total energy in the engine and engine performance. We learned about Hamiltonian mechanics and experienced how the total mechanical energy can be expressed in terms of the position of the piston, linear momentum, angular position of the crank angle and angular momentum. We extensively made use of engineering tools to establish correlations among the operational parameters of the engine as the ratio of the crank radius and connecting rod was varied. The changes in the kinematics and dynamics of the automobile engine are depicted in two dimensional graphs. The position, velocity and acceleration of the crank-shaft piston were expressed as functions of time and the crank angle. For values of the crank angle ranging from 0 to 360 degrees, we plotted the graphs of these kinematic quantities. The engineering design of an automobile engine or other machines is an iterated process. The iterations are carried out until the components and operational parameters of the engine are selected to meet the predetermined performance specifications. Selecting suitable design parameters, appropriate physical laws and constitutive relations for designing an engine or a machine is not straightforward. The kinematics and dynamics drawn from the theoretical foundation of computer, reading, science, technology, engineering and mathematics will reduce the burden of doing several design iterations. In this MQP, our literacy skills, computational competency and a discovery mind were strengthened.

The purpose of this project is to design and optimize a crank-slider mechanism for automotive engine applications. The crank-slider mechanism in a motor is the crankshaft and piston assembly. This assembly is the starting point for power transfer from component to component and through the rest of the motor. It is imperative that the ratio of the crank radius and length of the connecting rod supports the power transmitting activities. The objective of the MQP is to create a working solidworks model of a crankshaft assembly that is optimized based on the ratio of the crank radius and the connecting rod length, as well as performance and safety under load. The deliverable at the end of the MQP will be a comprehensive design breakdown, featuring multiple iterations and demonstrating the optimization process. Simulations of the kinematics, dynamics and stress-strain of the automobile engine were conducted. The results from these simulations guided the selection of the ratio of the crank radius and length of the connecting rod.

The remaining part of the report contains the literature background, the work accomplished using the concepts drawn from CR-STEM theories, engineering working drawings, conclusion, references and appendices. In Chapter 2, selected applications of engines are presented.

Chapter 2: Applications of the Internal Combustion Engine

Different types of engines can be found everywhere in day to day life. Engine types vary heavily based on the application for which they are being utilized. Jet engines power the airplane which transport thousands of people every day as well as power many of our military's fighter jets. Electric engines have become much more prevalent in vehicles within the last decade. The most popular engine found in vehicles is the ICE. These engines power ships, passenger vehicles and heavy machinery. ICEs have subcategories based on the fuel that they use. Diesel engines are typically found in large machinery, trucks, and large ships while gasoline engines are found in passenger vehicles and small craft.

While the ICE generally is known today for its everyday application in vehicles such as cars and trucks, it dates back much further and has a much wider array of applications. From the early to mid 1700s, many iterations of the modern ICE were invented, ranging from basic gas turbines to easily recognizable four-stroke gasoline engines. Today, the most common type of ICE is a reciprocating piston engine, a category that includes most automotive and marine applications, while some railroad locomotives will still utilize this technology. With the exception of diesel locomotives and automobiles, most of these applications utilize basic gasoline as fuel and feature a standard four-stroke engine cycle. Very similar ICEs can be found in the power generation application. Many buildings or building complexes feature very large diesel powered backup generators to ensure constant power to the building in the event of a blackout. This is especially important in certain applications, such as hospitals.

The slider-crank mechanism is a variation of a basic four-bar linkage that features both rotational and linear motion at the same time. While the most common application for this mechanism is the internal combustion engine, it can be seen in others as well, such as certain pumps, compressors, and hydraulic actuators.

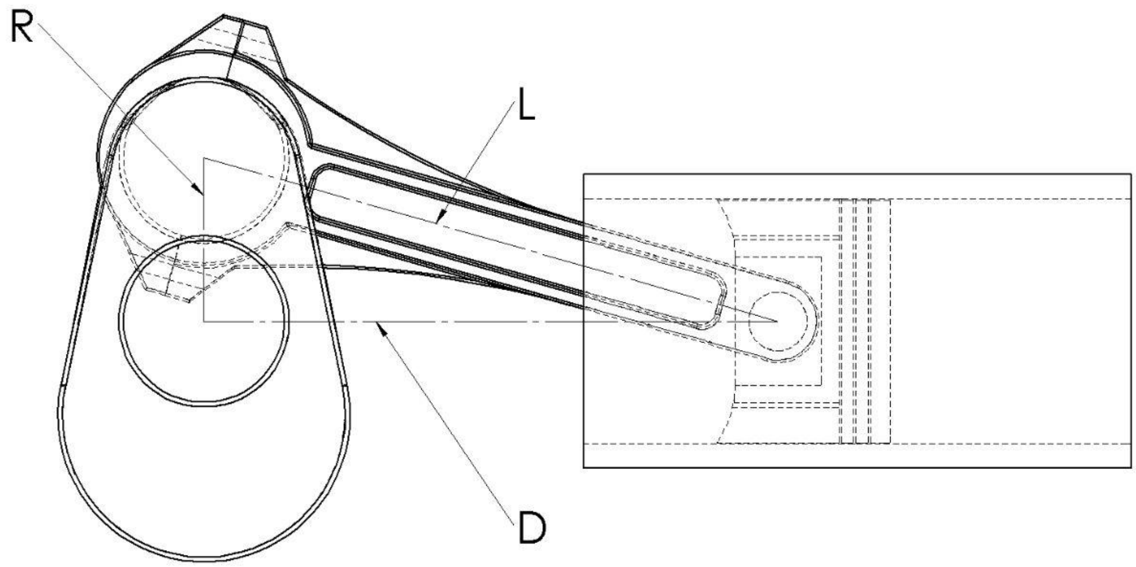

Figure 1: Slider crank mechanism diagram

Seen above is a representation of a basic slider-crank mechanism. Most are composed of similar components; a rotating link (R), an intermediary connecting link (L), and a horizontally oscillating slider (in this application, this slider is the piston). This linkage is a method of converting linear motion to rotational motion, or vice versa. For example, a hand pump would use an external rotational force to actuate a cylinder, in order to move fluid, whereas an internal combustion engine's linkage would convert linear motion in a piston to rotational motion in a crankshaft.

As previously stated, the four-stroke reciprocating piston ICE is the most commonplace permutation found today, being in almost every automobile on the roads across the world. Their purpose is to generate kinetic energy, or motion, through the burning of fuel. Gasoline, the more common fuel used in automobile applications, burns in an explosive manner, releasing large amounts of heat upon combustion. The ensuing increase in pressure due to this explosion is what generates motion in the engine. Pistons, contained within a specified number of cylinders, are actuated back and forth in a timed series of fuel ignitions. A specially designed crankshaft is positioned between/under the cylinders and attached to the pistons, and is given rotational motion by their movement. The cylinders in a reciprocating piston engine can have a variety of different configurations, including but not limited to “V”, inline, or flat configurations. The pattern and order in which the cylinders fire are integral to the motion of the crankshaft, as this is what allows for smooth transmission of power and constant rotational motion. This timing is mechanically carried out by a series of belts and camshafts, which control the timing of intake and exhaust from each cylinder, actuated by valves. One valve is dedicated to allowing the air-fuel mixture to enter the cylinder prior to combustion, while the other opens to allow residual exhaust gasses to be pushed out of the cylinder by the returning piston. As the operator/driver opens the throttle, the rate that all of these operations are carried out increases. These operations are all timed together to result in smooth transmission of power throughout the engine, from the camshaft rotation to the speed of the crankshaft.

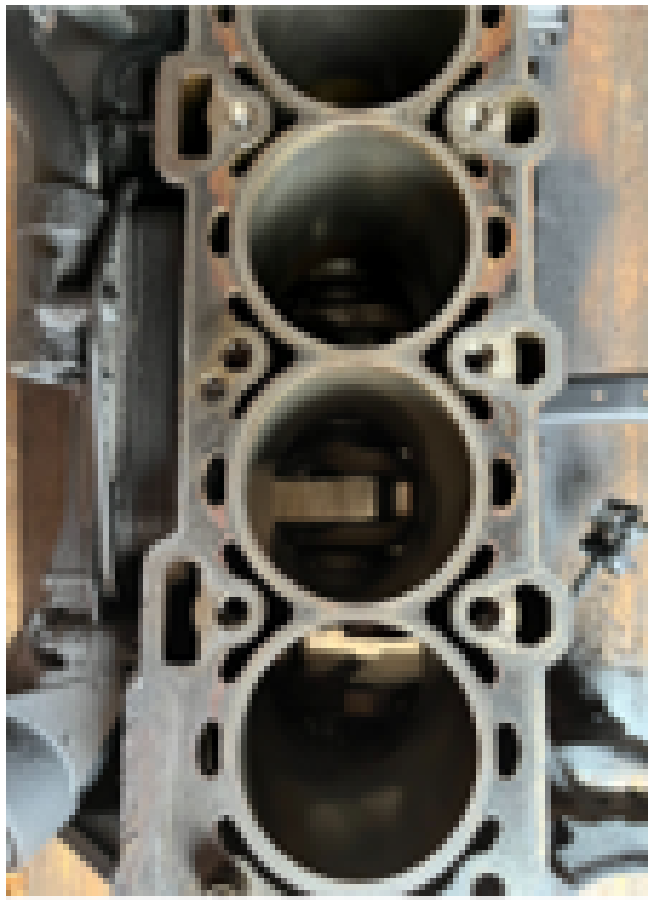

Figure 2: This photo shows the topside of an engine block, with the cylinders exposed.

Each individual component of a standard reciprocating ICE is designed and manufactured in a specific way, to best serve their purpose in the engine. Many components are made of different materials, as well as using various manufacturing methods that best suit the needs of the part in question. For example, large parts such as the block are generally cast, while smaller, more intricate parts such as a valve or pushrod might be forged or machined, for greater detail. A balance must be struck between quality and cost, especially when it comes to components that need to be manufactured on a large scale. Material choice, manufacturing method, and cost will all affect performance of the part in question.

In an internal combustion engine, the piston is the first component under load in the power cycle. It is where the combustion event in the cylinder produces kinetic energy in the system. Most automotive pistons are made of aluminum alloys, due to its high level of corrosion and wear resistance as well as low density and coefficient of thermal expansion, and most are cast, with follow up machining/finishing done after. However, some manufacturers predict that the future of piston design is in forged steel. Steel is denser than aluminum but three times stronger, leading to a piston that is more resilient to higher pressures and temperatures with no increase in weight. Being one of the primary moving parts in an internal combustion engine, this material choice and manufacturing consideration is critical. The piston design affects many different parameters, such as power output and fuel efficiency. The pistons account for nearly 60% of all friction within an engine, and this goes to take away from both of the aforementioned parameters. When designing a piston, it is paramount to consider friction between the piston and the cylinder, as well as the mass and durability of the piston itself. All of these factors will help dictate both power output and fuel efficiency of the engine.

Figure 3: Shown above is the piston-connecting rod assembly, taken from the physical inline four cylinder engine provided by Elm Park Auto. Two configurations are shown; one featuring the two segments joined, and the other with them separated, and the hardware removed.

Being the interface between the piston and the crankshaft, the connecting rod is equally as critical as other components, albeit in its own way. Generally, consumer automotive connecting rods are made of cast carbon steel. The carbon steel is often chosen due to its high strength and durability, which is critical in a component such as this, which is under high pressures and loading during engine operation. When mass producing parts such as this, casting is an obvious choice, and modern techniques result in high quality parts featuring tight tolerances and high resistance to wear and fatigue. When cast, the rod is one single component, whereas during assembly it is broken into two halves; an upper and a lower that are fastened together around the crankshaft. Prior to assembly, this single cast part is broken in two places, creating two separate parts that fit together perfectly in a certain way along the crack. This ensures the most effective union between the parts as possible.

Figure 4: This image shows a detailed view of the break between the upper and lower connecting rod segments. Note the uneven break, which results in a one-way fit around the crankshaft.

The crankshaft is just as critical, as it is the main axis of rotation in the engine and delivers power directly to the transmission. It is subject to very high loads, temperatures, and rotational speeds. Similar to the connecting rod, the crankshaft is usually cast, and made of carbon steel to withstand the extreme conditions it is subjected to, with machining done after to provide good finish on segments that interact with other parts. These segments are where the connecting rods and crankshaft bearing is located.

Figure 5: This photo shows the underside of an engine block, with the crankshaft exposed. The machined down segments are where the connecting rods bolt on, and bearings hold the shaft in place between them.

While the ICE is one of the most viable options for power generation in the transportation/automotive industry, there are drawbacks to their operation, namely the environmental footprint associated with gasoline or diesel powered engines. While modern engines boast fuel efficiency and low carbon emissions, this has not always been true. In their most basic state, standard automobile engines can emit environmentally harmful waste into the atmosphere, contributing to global warming and other climate change symptoms. The adaptation of various regulations requiring smaller engine size and emission limits, as well as the adoption of hybrid vehicle systems have slowed this rate of pollution, but not completely. And now, with the looming innovation surrounding all electric vehicles, the future for the ICE powered automobile is uncertain, as these offer greater economic, performance, and environmental incentives. However, for the foreseeable future, innovation will continue to drive the ICE to more efficient and clean variations.

Chapter 3: The Design Process of a Crankshaft Assembly

This section describes the development and design of the system created in this project, going into depth on the breakdown of all the components found in the crankshaft assembly as well as the design process to achieve a realistic model.

3.1 Breakdown of Components

As previously stated, the goal of this project was to design and optimize an automotive piston-crankshaft, a variation of a simple slider-crank mechanism. While most ICEs feature an array of cylinders, this design features only one that can be replicated for a fully designed engine. This mechanism consists of 5 basic parts; two sections of a connecting rod, a crankshaft section, a connecting pin, and a piston. While all manufactured differently and feature different materials, they form an effective mechanism to deliver power in an ICE.

Table 1: Assembly parts list/BOM

Part #	Part Name/ Description	Material	Young's Modulus (E) (N/m^2)	Stiffness (k) (N/m)	Effective Mass (m) (kg)
1	Piston	4032 Alloy	7.9E10	8.57E9	1.0966
2	Upper Connecting Rod	Cast Carbon Steel	2E11	7.34E7	1.7597
3	Lower Connecting Rod	Cast Carbon Steel	2E11	—	0.2661
4	Piston Connecting Pin	Carbon Steel	2.1E11	1.13E9	0.2964
5	Crankshaft Section	Cast Carbon Steel	2E11	3.8E9	2.6089

As previously stated, the piston is one of the more critical components in an automotive internal combustion engine. Because it is constantly under extreme conditions (i.e. high temperatures and pressures), design, material choice, and manufacturing need to be precise. While not suitable for application in a physical engine, the design featured in this project was able to simulate conditions physical parts are under in everyday applications. Material choice and manufacturing were also taken into account. This piston design was intended to be able to be manufactured using the aforementioned combination of die-casting and machining, for better fit and finish. 4032 Aluminum alloy, a common material used for this application, was also selected for this part. This accurate material choice gives realism to the design, which comes heavily into play during many of the analyses performed.

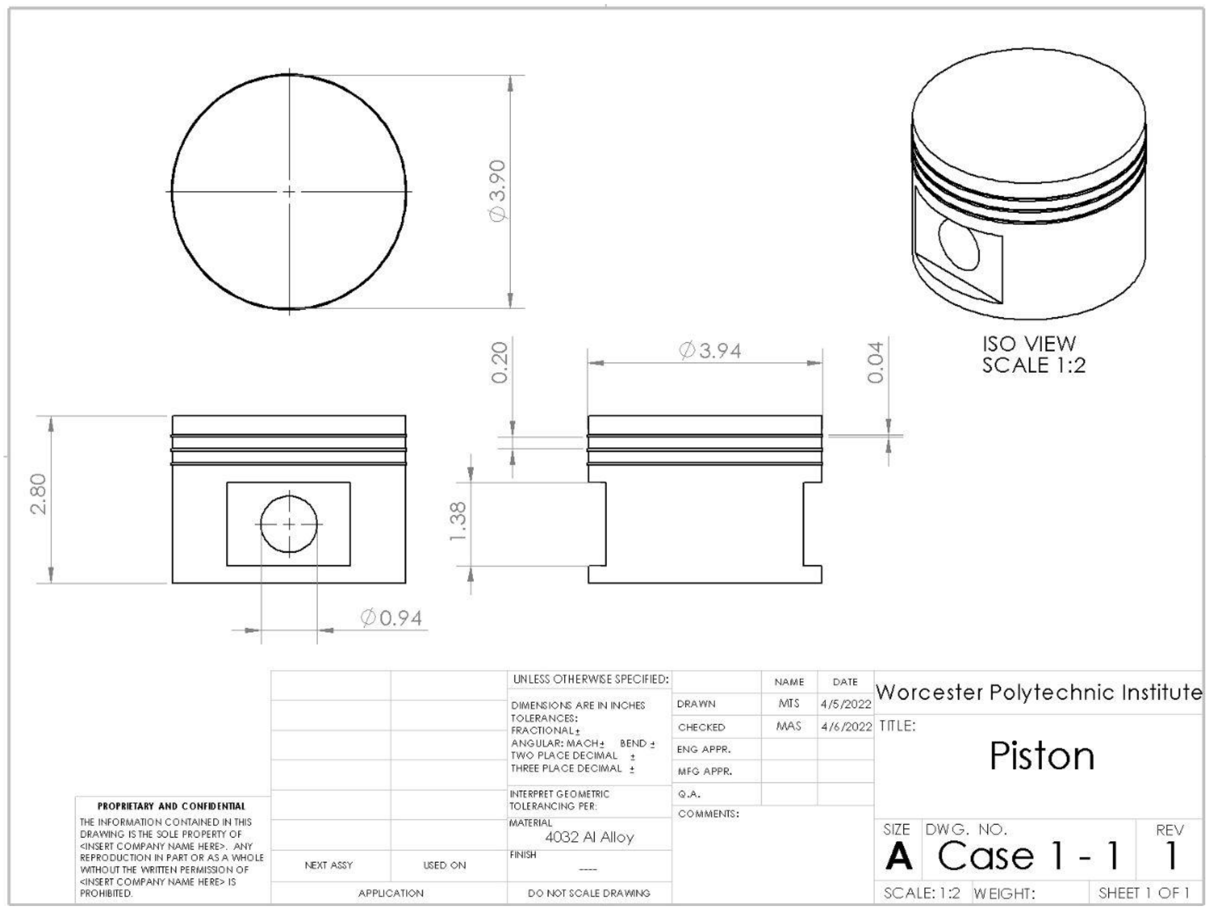

Figure 6: This schematic shows technical information pertaining to the original piston design

Similar considerations were taken for the two sections of the connecting rod. For the simplicity of this design, the upper and lower sections were created individually, reflecting the final nature of the physical part. However, it was taken into account the fact that a part like this would need to be cast for high volume production. The simplistic yet effective design of each, coupled with the material choice of cast carbon steel (an industry standard for everyday applications), make them realistic representations of physical automotive connecting rods. The crankshaft is a similar component to the connecting rod, given that it is under similar conditions as well as being manufactured in a similar way. This design features the same material choice of cast carbon steel, as well as a design that is compatible with the same casting process used for the connecting rod components. While not perfectly transferable to a physical engine, the way these components were designed allow them to effectively simulate their physical counterparts.

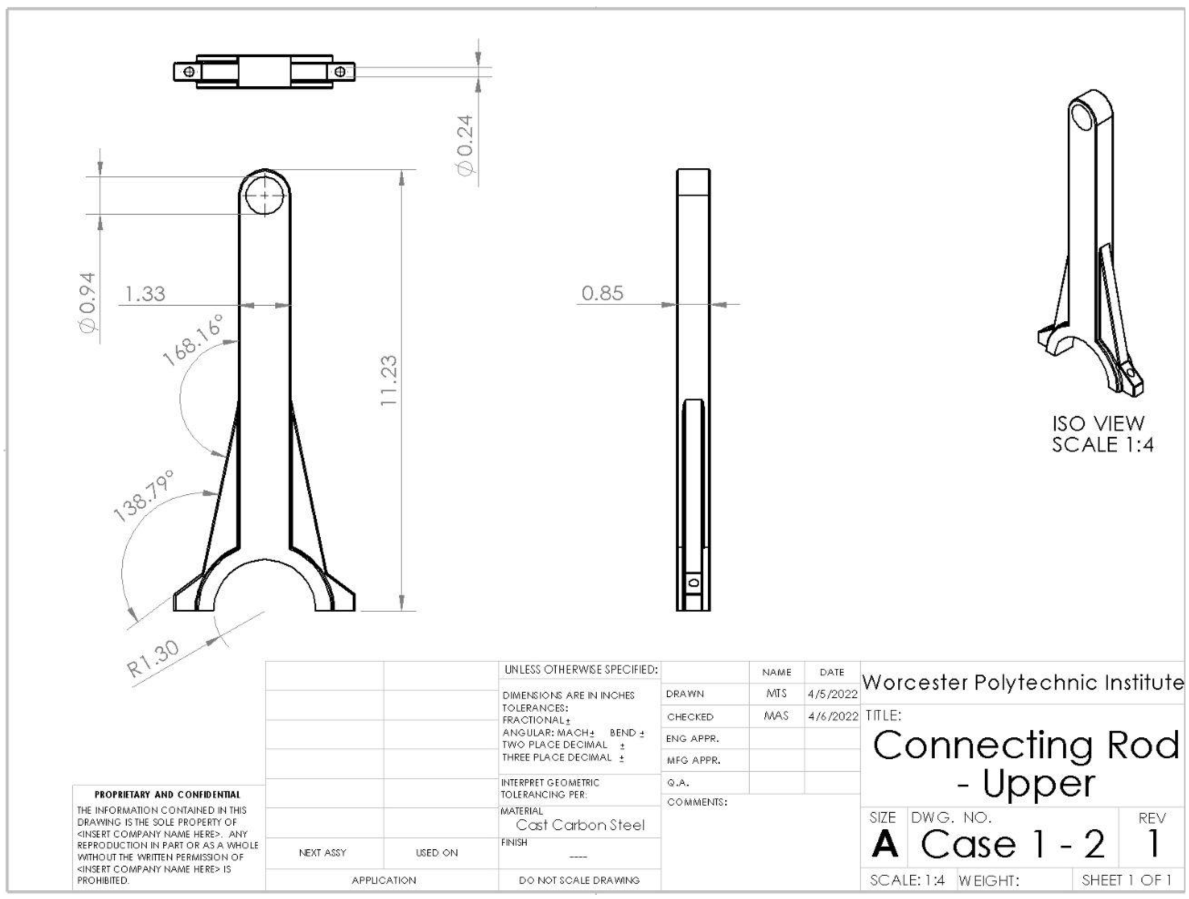

Figure 7: This schematic shows technical information pertaining to the original connecting rod design

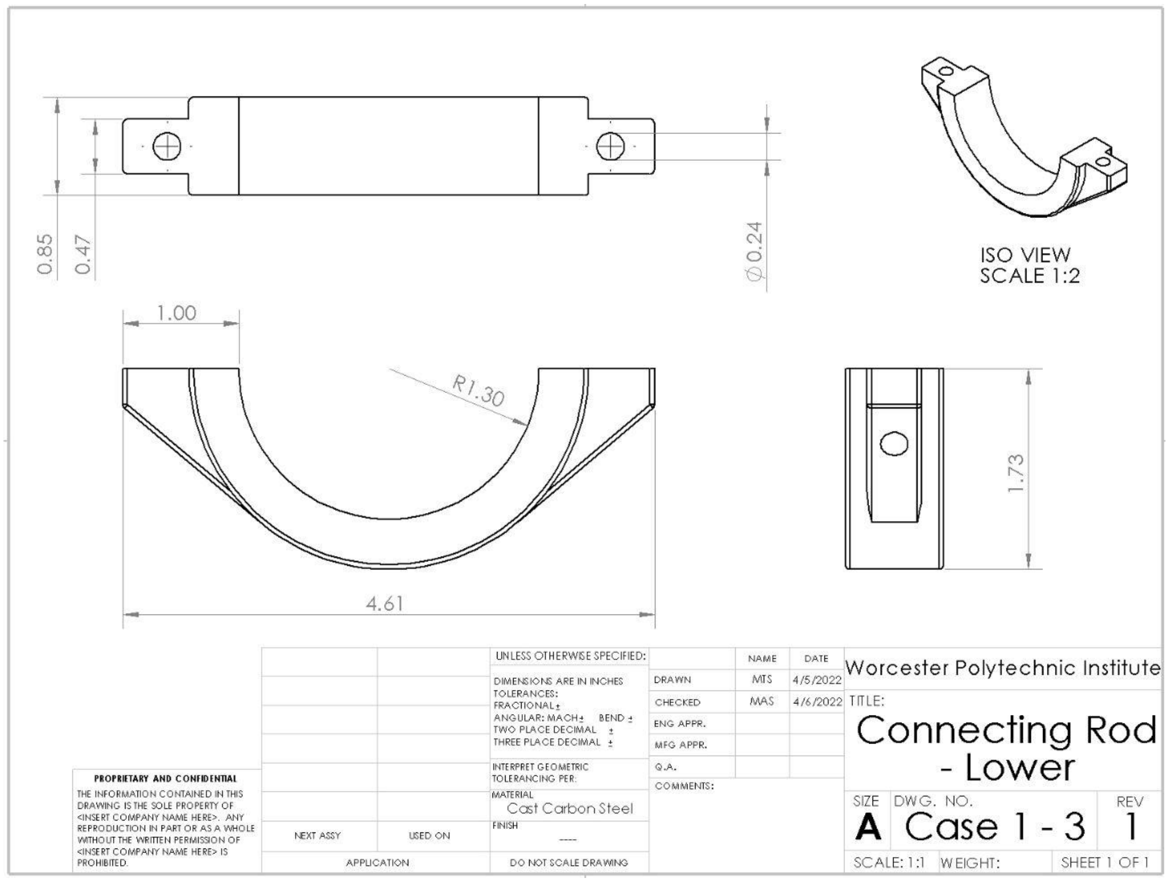

Figure 8: This schematic shows technical information pertaining to the original connecting rod design.

While a very simple design, the piston connecting pin is an important component, and was designed to simulate the very critical role it fills. Made of forged carbon steel, it connects the piston to the connecting rod, enabling smooth rotation as the piston oscillates. While these can take on many shapes and often feature a number of components, this design is a simple cylinder, with the intention of enabling smooth motion for a better analysis of the other parts, such as the geometry of the connecting rod and crankshaft.

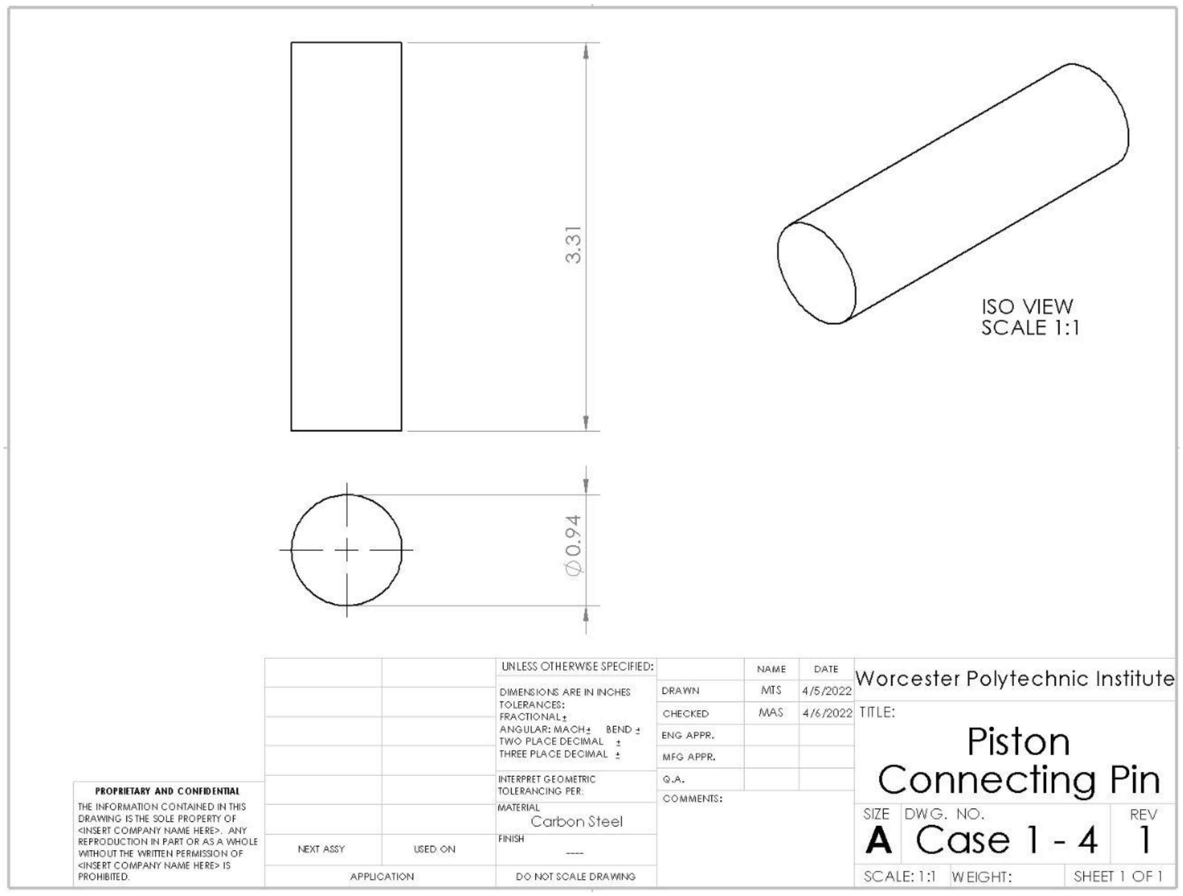

Figure 9: This schematic shows technical information pertaining to the original pin design.

3.2 Development Process

The objective of this design was to provide optimal performance, while also being economical, realistic, and safe/effective under load. This resulted in design research, iteration, and analysis to yield the most effective result. First, the team conducted research on each part of the assembly to better understand common materials and sizes used in the industry today. By doing so, each part would be designed using materials that are realistic to their applications in terms of their strength, manufacturability and cost. Using the range of measurements discovered in the research, each part was then designed using Solidworks. Each part was designed to be easily edited and fitted with the other parts of the assembly. This allowed for easy manipulation of the parts to create multiple revisions of the assembly. Once the assembly was together and functional, each part was modified to remove any sharp edges which would be unrealistic.

To reach final working design concepts, the initial idea went through a number of iterations. These iterations focused on maximizing the kinematic performance of the assembly, while static analysis could be done once optimal motion was achieved. These design iterations were centered around the effect that the ratio of the connecting rod length (L) to the crank radius (R) had on the motion of the system. This ratio of r/L affects the torque that the piston can put on the crankshaft, as well as the motion of the piston itself, both under load and being driven by the crankshaft in its non-combustion strokes. The initial design iteration, highlighted in the drawings shown in the above section (Figures 8-10), features a r/L ratio of 0.4. Analysis was done on this design, in addition to four others, featuring ratios of 0.2, 0.3, 0.5, and 0.6. In this analysis, the crankshaft was spun at a constant 60 rotations per minute, and the position, velocity, and acceleration of the piston itself was recorded, in addition to the angles that the connecting rod would meet the crank at different intervals throughout the stroke. The r/L ratio analyzed here is 0.4.

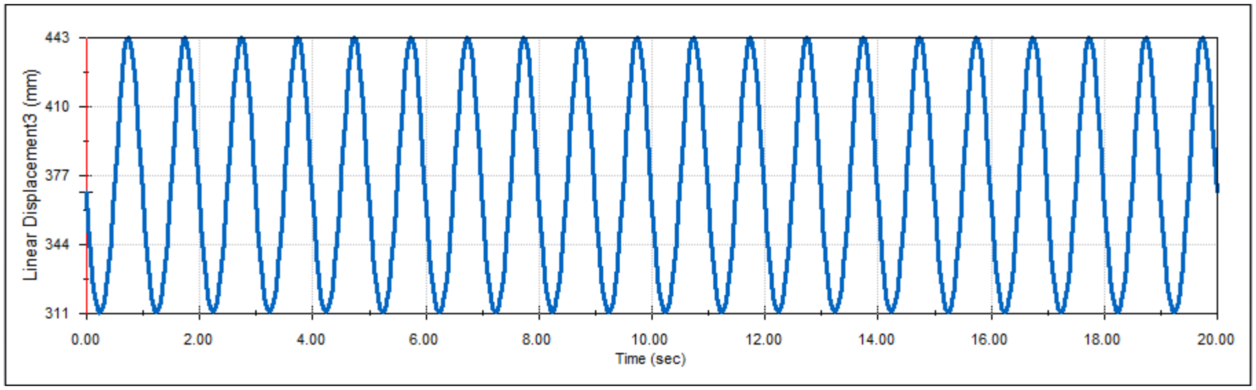

Figure 10: This graph shows the position/displacement of the piston over a 20 second period, with the crankshaft rotating at 60 RPM.

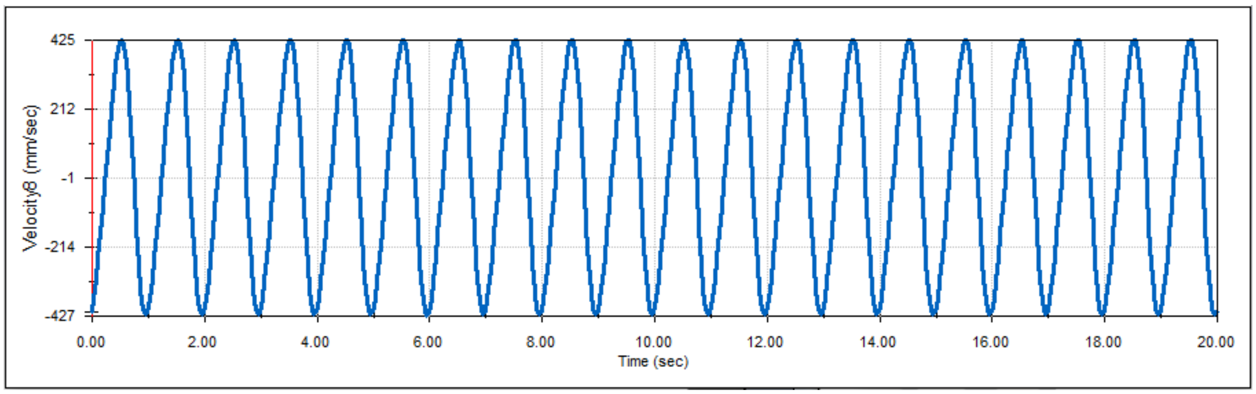

Figure 11: This graph shows the velocity of the piston over a 20 second period, with the crankshaft rotating at 60 RPM.

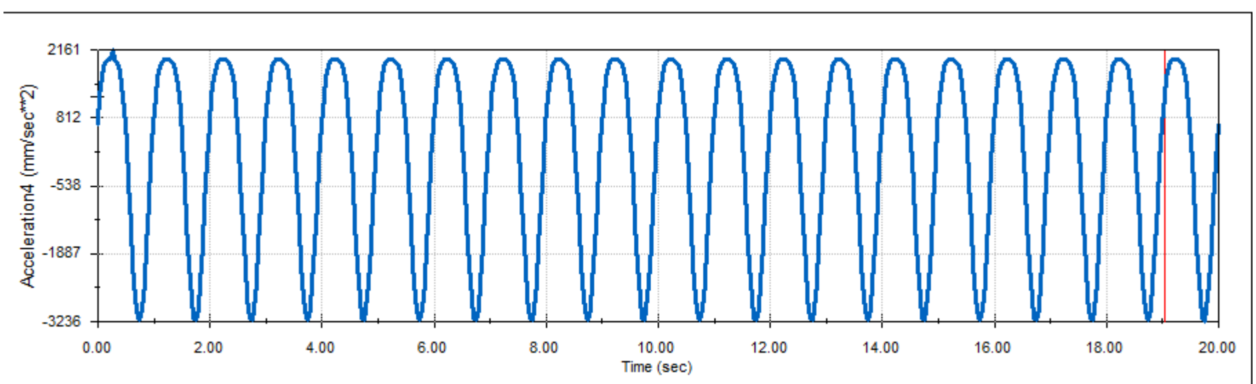

Figure 12: This graph shows the linear acceleration of the piston over a 20 second period, with the crankshaft rotating at 60 RPM.

Chapter 4: The Analysis of a Crankshaft Assembly

This section goes into detail on the analysis performed on both preliminary designs as well as the final iteration, as well as highlighting specific developments between preliminary iterations and the one presented here.

4.1 Final Design Iteration

Below (Figures 13-15), updated parts for the final design iteration can be seen. Three parts were reworked; the crankshaft, the piston, and the connecting rod. This was done to reflect design realism, as well as reduce weight (in the case of the connecting rod and piston) and balance rotation (for the crankshaft). In addition to these cosmetic and functional changes, the r/L ratio reflected in this design iteration is 0.5. Up by 0.1 from the original ratio of 0.4. While not featuring as high piston velocity and energy as a ratio of 0.6, the larger connecting rod of this design performs better under the high stresses found in the cylinder during combustion. In addition to this, the different geometry of the connecting rod provides a better transfer of power from the combustion chamber to the engine.

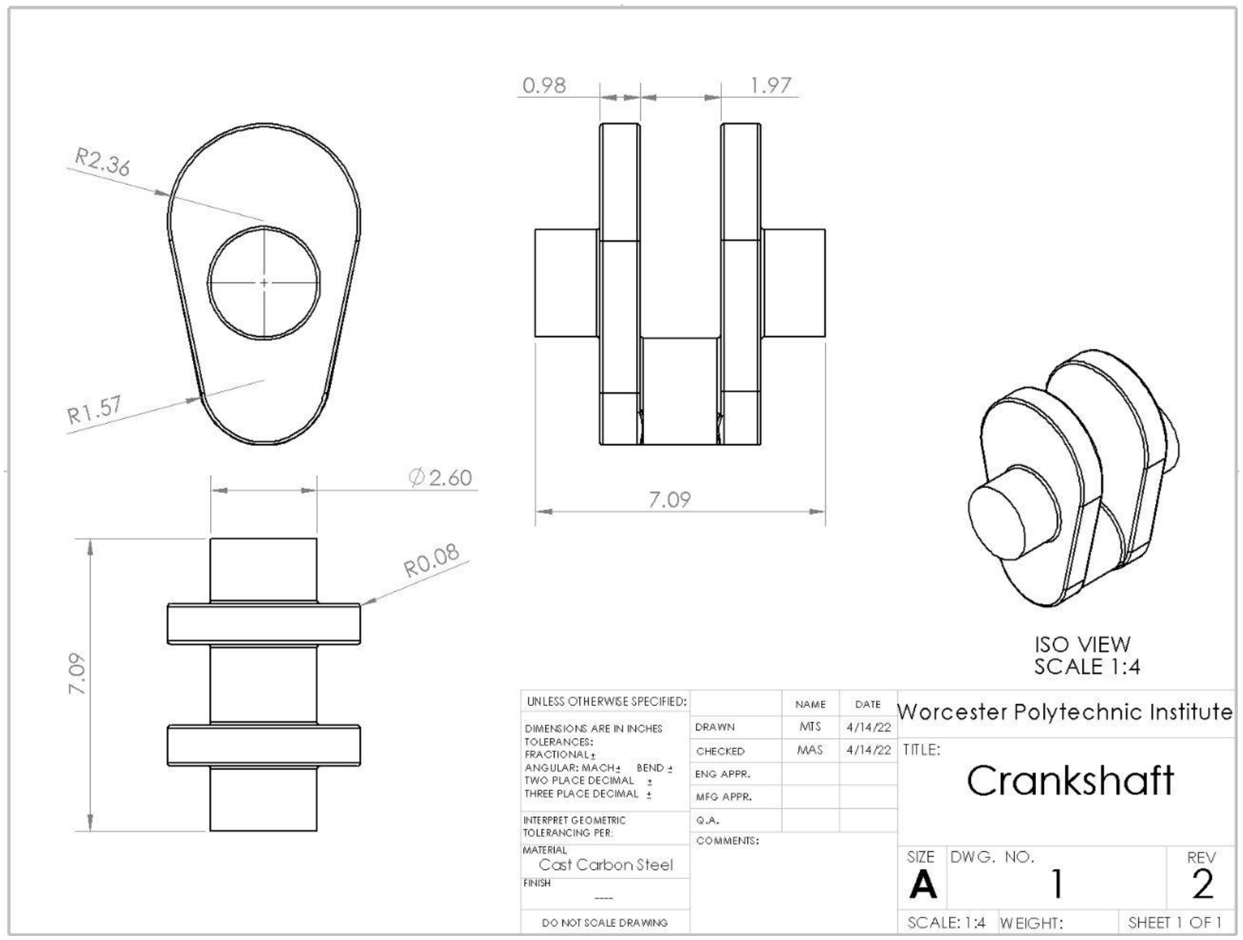

Figure 13: This schematic shows technical information pertaining to the final crankshaft design iteration

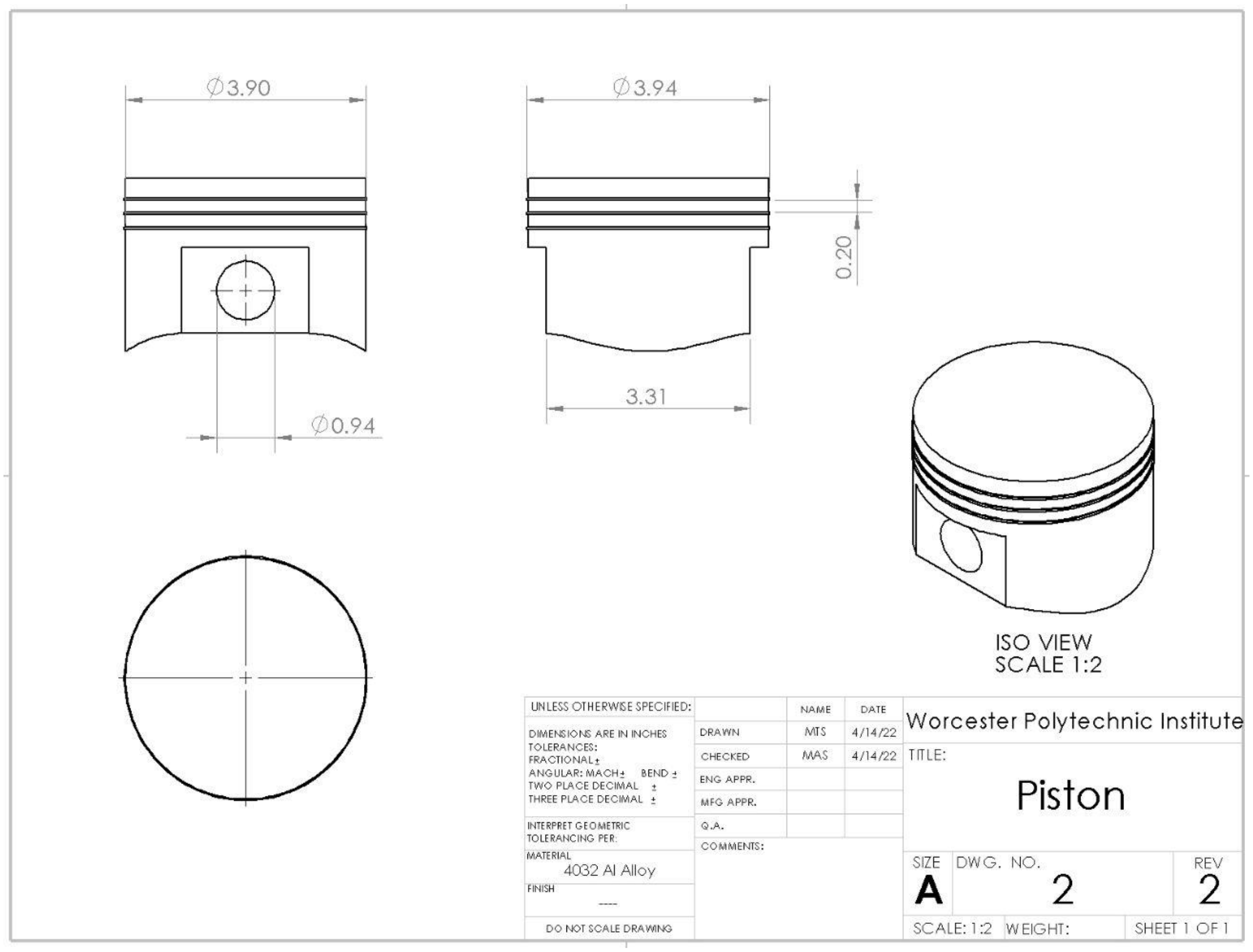

Figure 14: This schematic shows technical information pertaining to the final piston design iteration

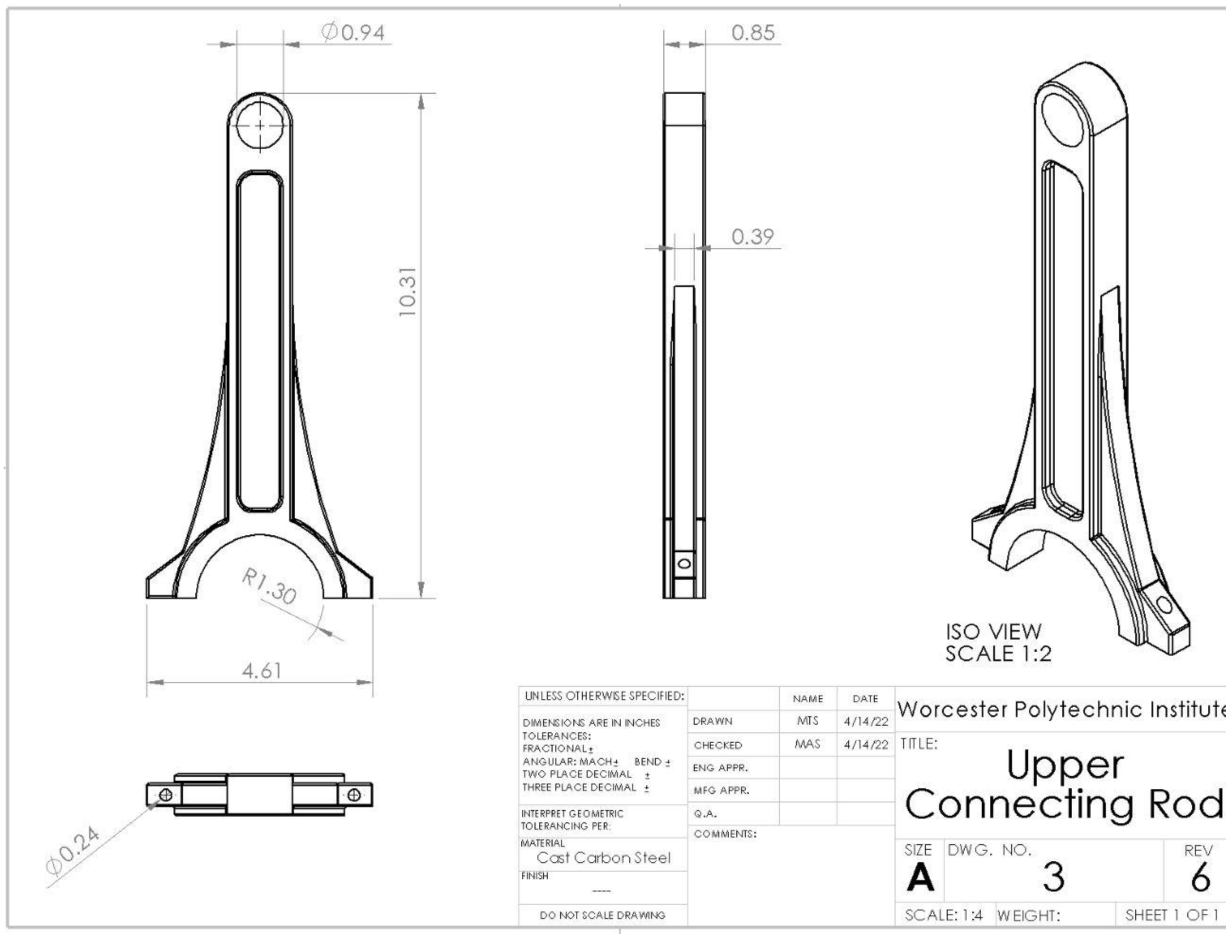

Figure 15: This schematic shows technical information pertaining to the final connecting rod design iteration

4.2 Static Analysis

Because one of the design objectives of this project was to be safe and effective under realistic loading conditions, static analysis of the assembly was required. Employing the use of finite element analysis (FEA) tools in Solidworks, the team was able to effectively simulate the loading conditions that the design would realistically be under, and observe how the parts behaved.

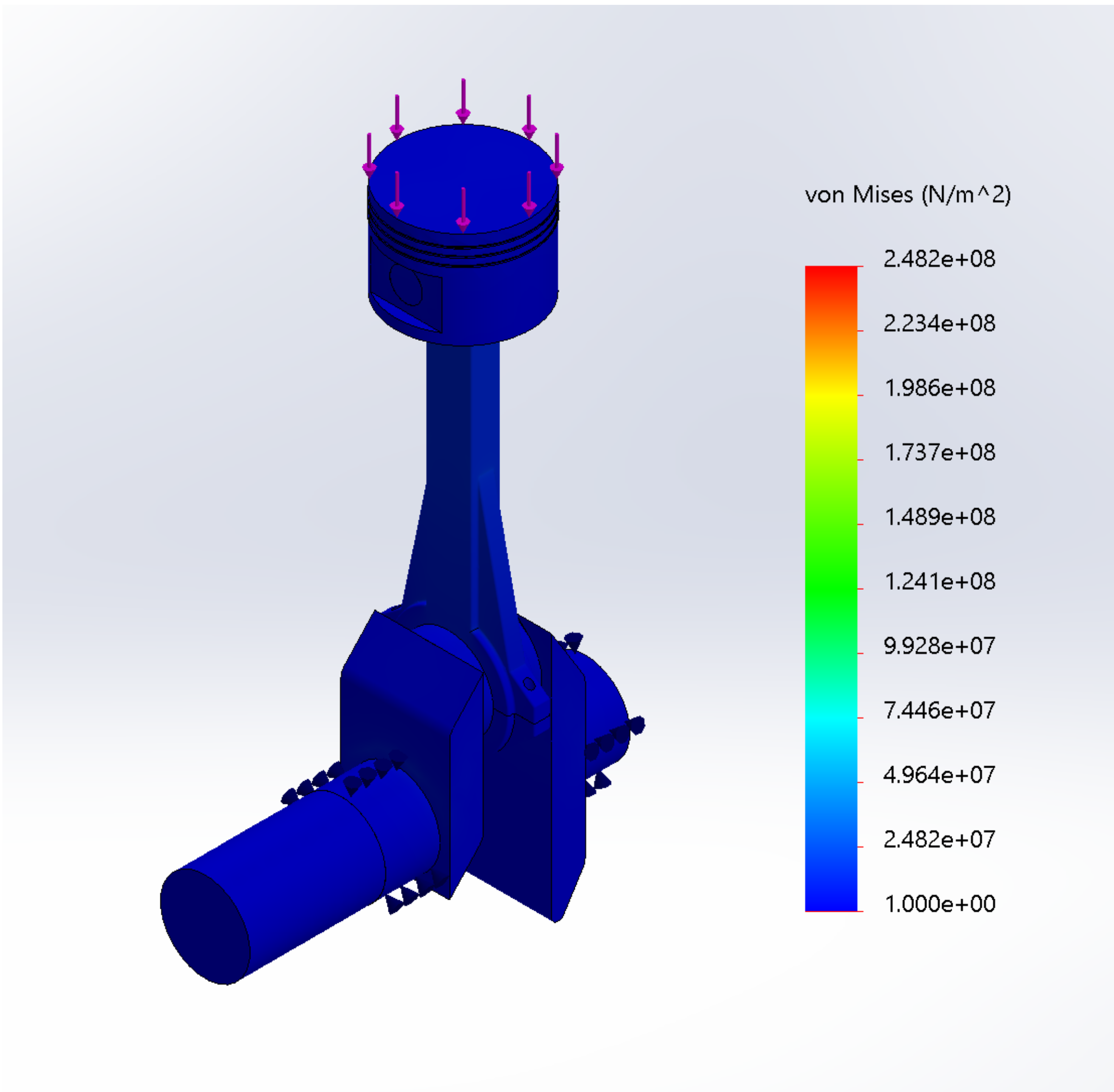

Figure 16: This chart shows stress in N/m^2 throughout the initial piston-crankshaft assembly at the point of combustion. The highest value on the legend is the yield strength of the connecting rod.

The static analysis seen in figure 16 shows the stress in the assembly when under realistic loading conditions. In many commercial cars, the pistons can experience up to a metric ton of force when combustion occurs. This was simulated by applying roughly 2200 pounds of force on the piston in the upright position, where it would be located when combustion occurs. As seen in the simulation, there is very little in the way of stress concentration in the assembly when compared to the yield strength of the material. In addition, this load was applied when the assembly was in the vertical position, whereas in reality, this system would be rotating, not static as it is displayed in Figure 16.

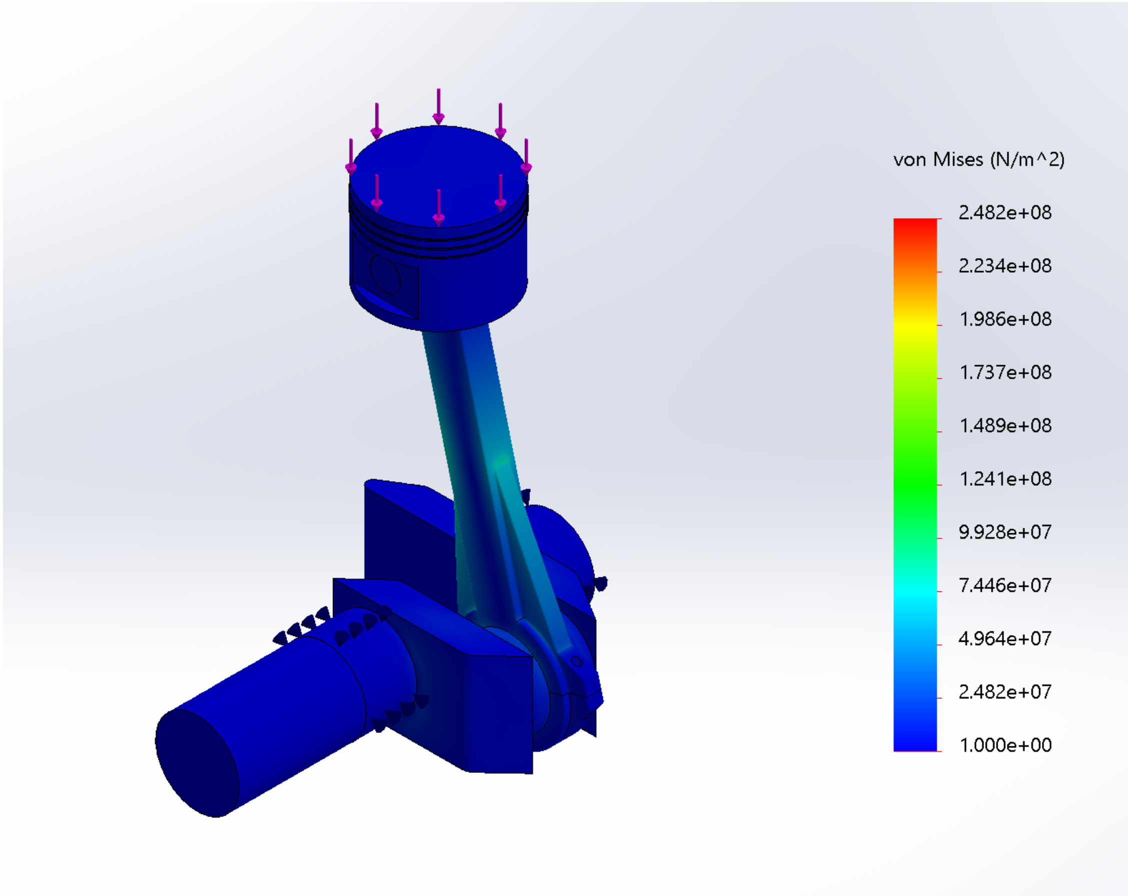

Figure 17: This chart shows stress in N/m² throughout the initial piston-crankshaft assembly halfway through the combustion stroke. The highest value on the legend is the yield strength of the connecting rod.

A second analysis was performed when the system is halfway through its combustion stroke, with the crankshaft in a horizontal orientation. The same 2200 pounds of force are applied, and the system is assumed to be locked. At that point in the rotation, the stress in the connecting rod is still one order of magnitude off from the yield strength of the material. In addition, and as previously stated, this system would be in motion under the conditions assumed for the simulation. Because of this, it can be stipulated that this system is safe under normal loading conditions in an average consumer internal combustion engine.

However, it was important that a similar analysis be run of the final design iteration, as a check to make sure that modifications and changes made to the design did not have a detrimental effect on the system's performance and safety under load. This analysis was conducted in the same way as the previous, with the assembly under the same loading conditions, to ensure that the developments made to the design were not to the detriment of its safety and performance.

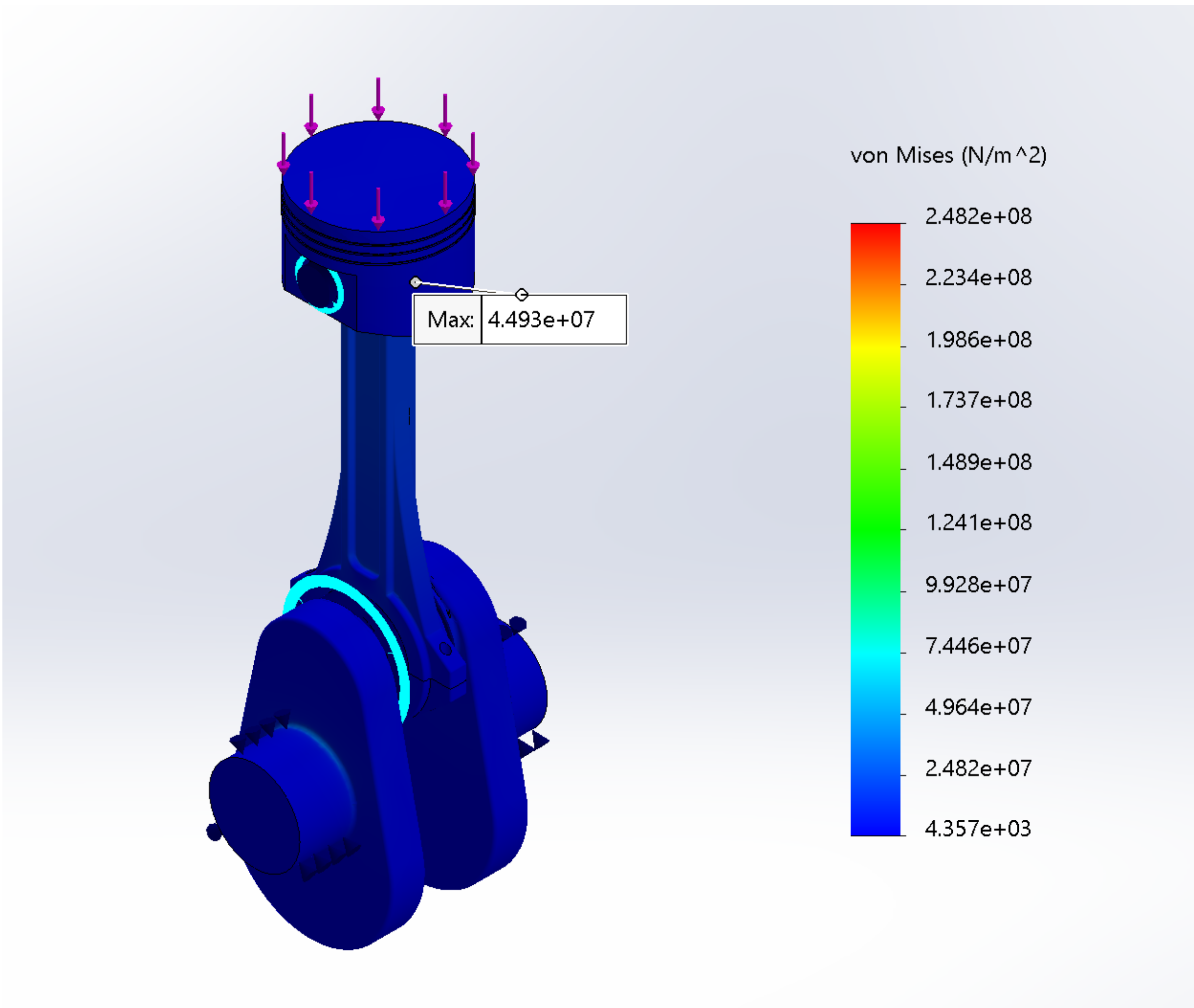

Figure 18: This chart shows stress in N/m^2 throughout the final design iteration at the point of combustion. The highest value on the legend is the yield strength of the connecting rod.

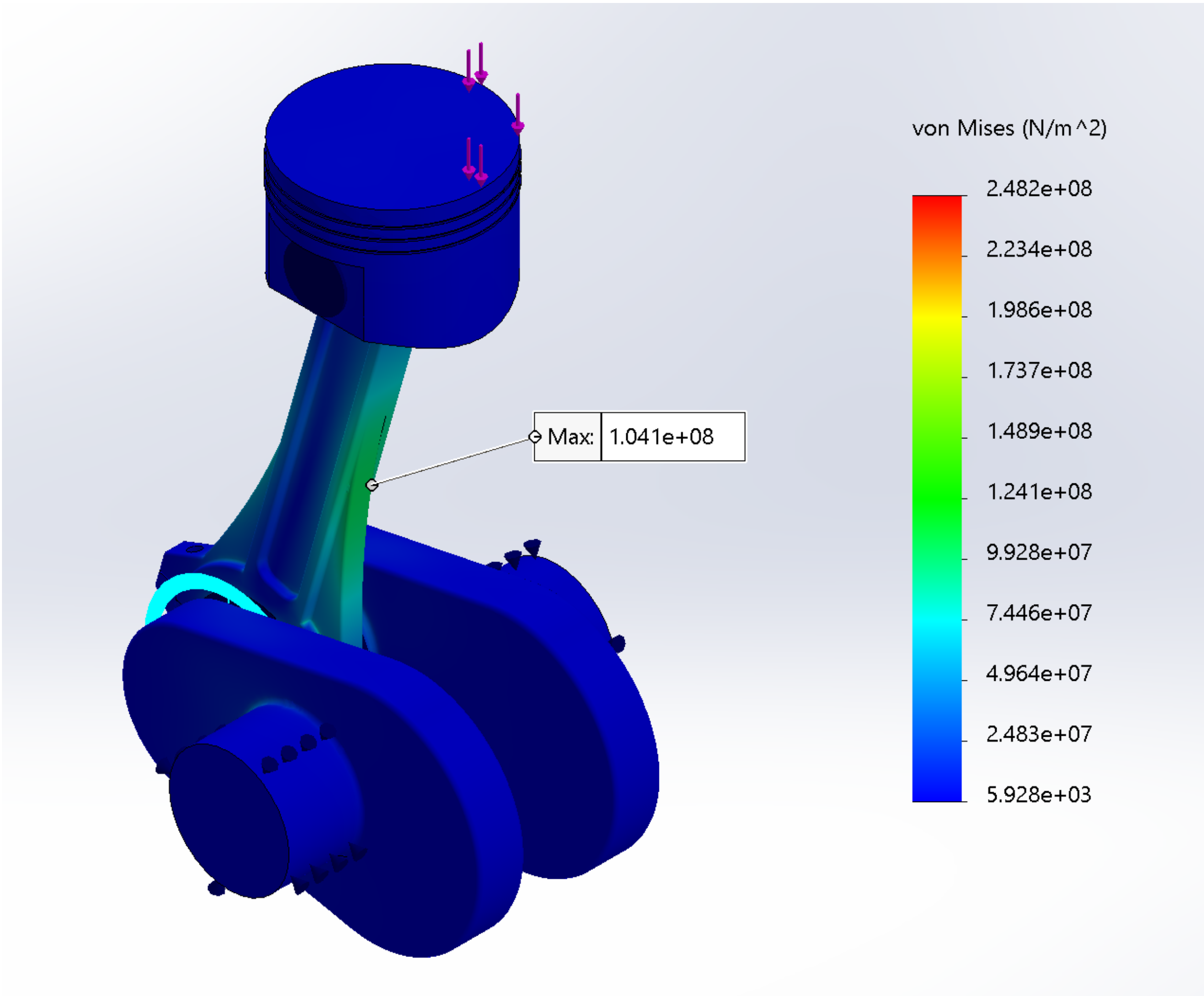

Figure 19: This chart shows stress in N/m² throughout the final design iteration at the point of combustion. The highest value on the legend is the yield strength of the connecting rod.

Seen in the two charts above is the final design iteration under the same loading conditions that each of the previous designs was tested with. It is clear to see that the design changes made from earlier versions were not to the detriment of design integrity. At the top of the stroke, or the point of combustion, the 2200 pounds of force exerted on the piston results in negligible stress in the system. On the contrary, at the halfway point of the stroke, the 2200 pounds result in higher stress levels, as highlighted by the green coloring of the inside faces of the connecting rod. While higher than at the beginning of the stroke, this stress should not be concerning. At this point in the stroke, the forces experienced by the system are less than at the start of the stroke. The estimated 2200 pounds are the maximum that the system will experience. However, testing the system for the maximum value throughout the stroke is an effective strategy for ensuring the safety and performance of the system, per the objective.

While important to highlight how the system will perform under one loading condition, it is also paramount to consider how this will perform over time, with this loading condition being repeated countless times. When considering the design of a system such as this, fatigue needs to be taken into account to see the chances of failure and reduction of life that it will undergo.

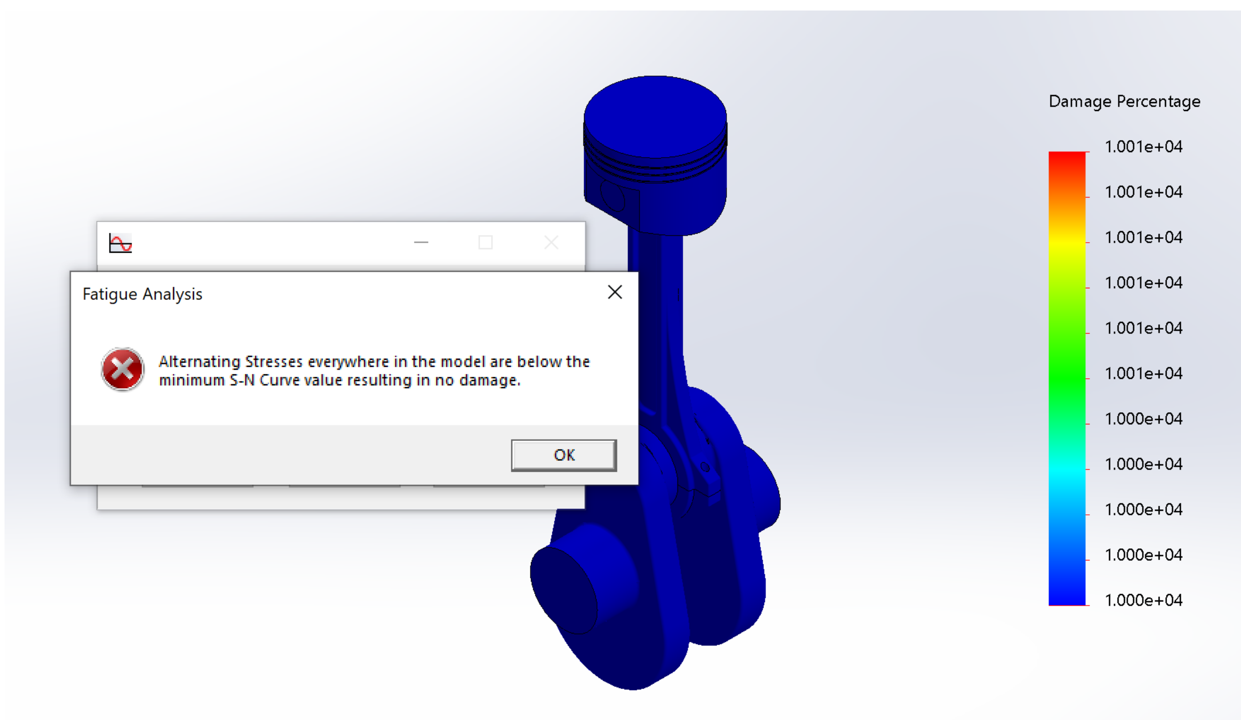

Figure 20: This simulation shows the fatigue analysis run on the optimized assembly. The

Solidworks error message can be interpreted as stating that the design is safe and will not fail under the loading conditions specified.

This system was tested for fatigue failure by subjecting the assembly to the same loading conditions presented in figures 17 and 18, but repeatedly. In all, the assembly experienced the 2200 pounds of force allocated previously, 1,000,000,000 times. This is the same as a car idling at around 1000 RPM constantly for 4 years straight. It is safe to say, and backed up by results in Solidworks, that this design is safe under the loading conditions specified in the objectives, and will continue to perform well with prolonged use in an automotive application.

4.3 Motion Analysis

In addition to studying the performance of this system under static and cyclic loading, it was important to understand how it performs in motion, and, as previously stated, how this performance varied with the geometry of the assembly. Below the analyses of position, velocity, and acceleration of the piston under a constant rotational speed of 60 RPM, as carried out for each iteration.

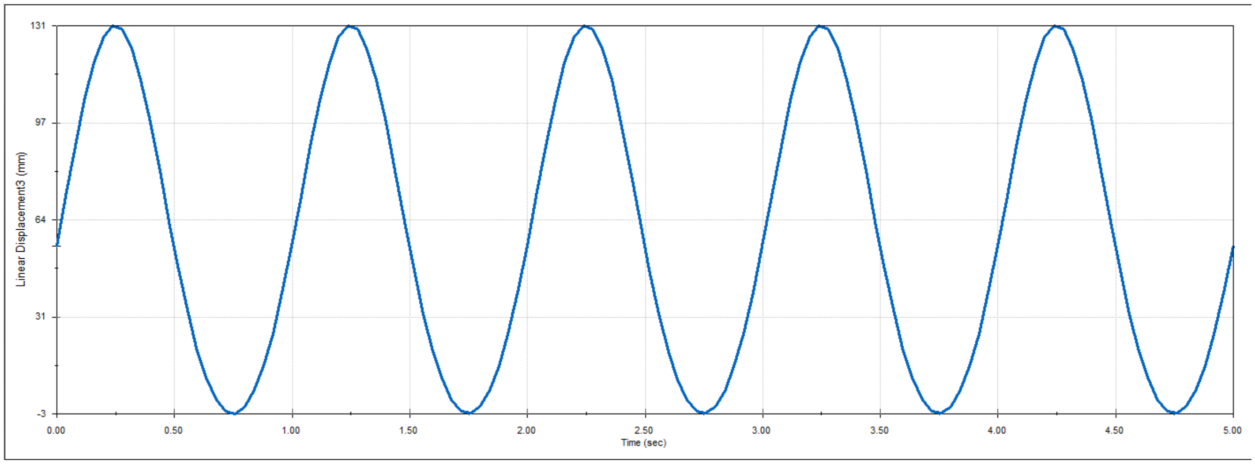

Figure 21: This graph shows the position/displacement of the reworked piston over a 5 second period, with the crankshaft rotating at 60 RPM.

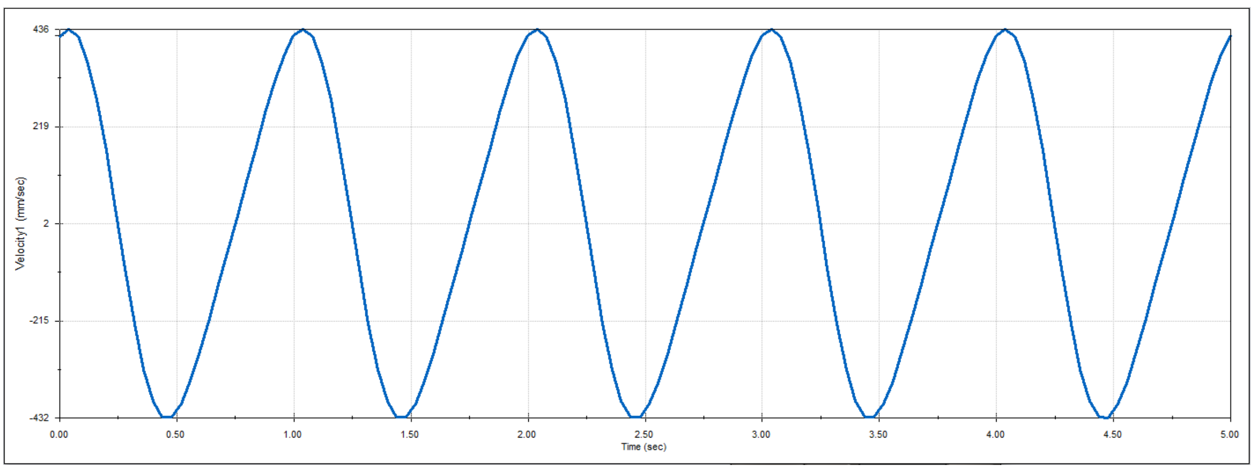

Figure 22: This graph shows the linear velocity of the reworked piston over a 5 second period, with the crankshaft rotating at 60 RPM.

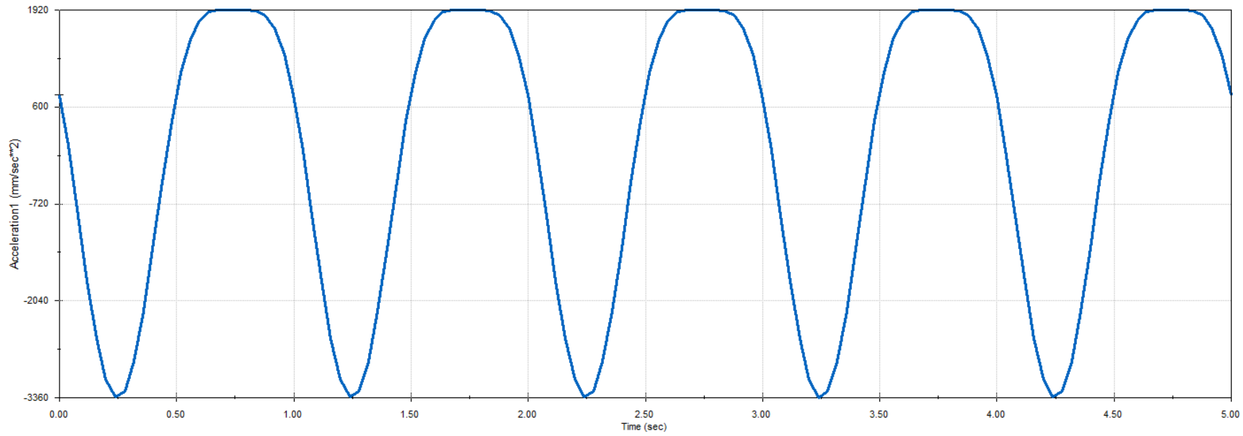

Figure 23: This graph shows the linear acceleration of the piston over a 5 second period, with the crankshaft rotating at 60 RPM.

While similar in appearance to the graphs corresponding to other previous iterations, these give important information to support the decision to employ the r/L ratio of 0.5 in this design. As previously stated, this design was chosen due to it being a balance between high kinematic performance, as well as strong under static and cyclic loading conditions. While clear that this system is strong, it is important to compare its motion to previous iterations. Notably, the design iteration featuring the ratio of 0.6 showed the best kinematic performance, with the piston reaching a velocity of 440 mm/s (see Figure 41, Appendix C), whereas this design only reaches a maximum velocity of 436 mm/s. It was decided that although ensuing energy and momentum calculations would result in values reflecting poorer engine performance, a smaller ratio would be utilized. This provides an optimal amount of both facets described in this chapter; performance in motion and under load.

Chapter 5: Conclusions and Recommendations

The purpose of this project was to design and optimize a crank-slider mechanism with an automotive application. The results discussed above also provide hands-on content to teach kinematics and dynamics in a hands-on classroom setting. The team was successful in designing a crankshaft assembly which is safe in both dynamic and static conditions. By modifying the crank radius to connecting rod length ratio, the team was able to determine the optimal geometry of the parts. The final iteration demonstrated a 0.5 ratio as it performed the strongest under both static and dynamic environments simultaneously. Other ratios such as the 0.6 proved to be stronger statically but lacked success in smooth, efficient motion. Contrarily, a ratio of 0.2 demonstrated smooth motion but lacked the strength under load which was seen in the higher ratios. The total mechanical energy was determined through simulation of the Hamiltonian functions.

The assembly presented in this project was designed with the idea of manufacturability from the start. One way to further this project's work would be to collect a team of manufacturing engineers to create a working prototype of the model designed by the team. A similar project form could also be used to run a multitude of other projects based on other vital engine assemblies such as the camshafts and the rack and pinion assemblies. To further build on the findings of this project, a future team could look into the bearings and lubrication requirements to improve the efficiency of the design.

Beyond delivering the team's findings to the classroom, the results of this lab aim to improve efficiency and durability of the crankshaft assembly. By doing so, the individual parts of the assembly will see a longer service life, limiting the need for new motors and new parts. This will therefore create less waste, as there will be fewer replacement parts as well as fewer junk motors. Overall, the designs put forth in this project aim to mitigate engine part waste by manufacturing stronger, more durable parts for the crankshaft assembly and aiding in the education of future students in the area of dynamics with a hands-on, real world application.

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Appendices

Appendix A - Preliminary Part/Assembly Drawings

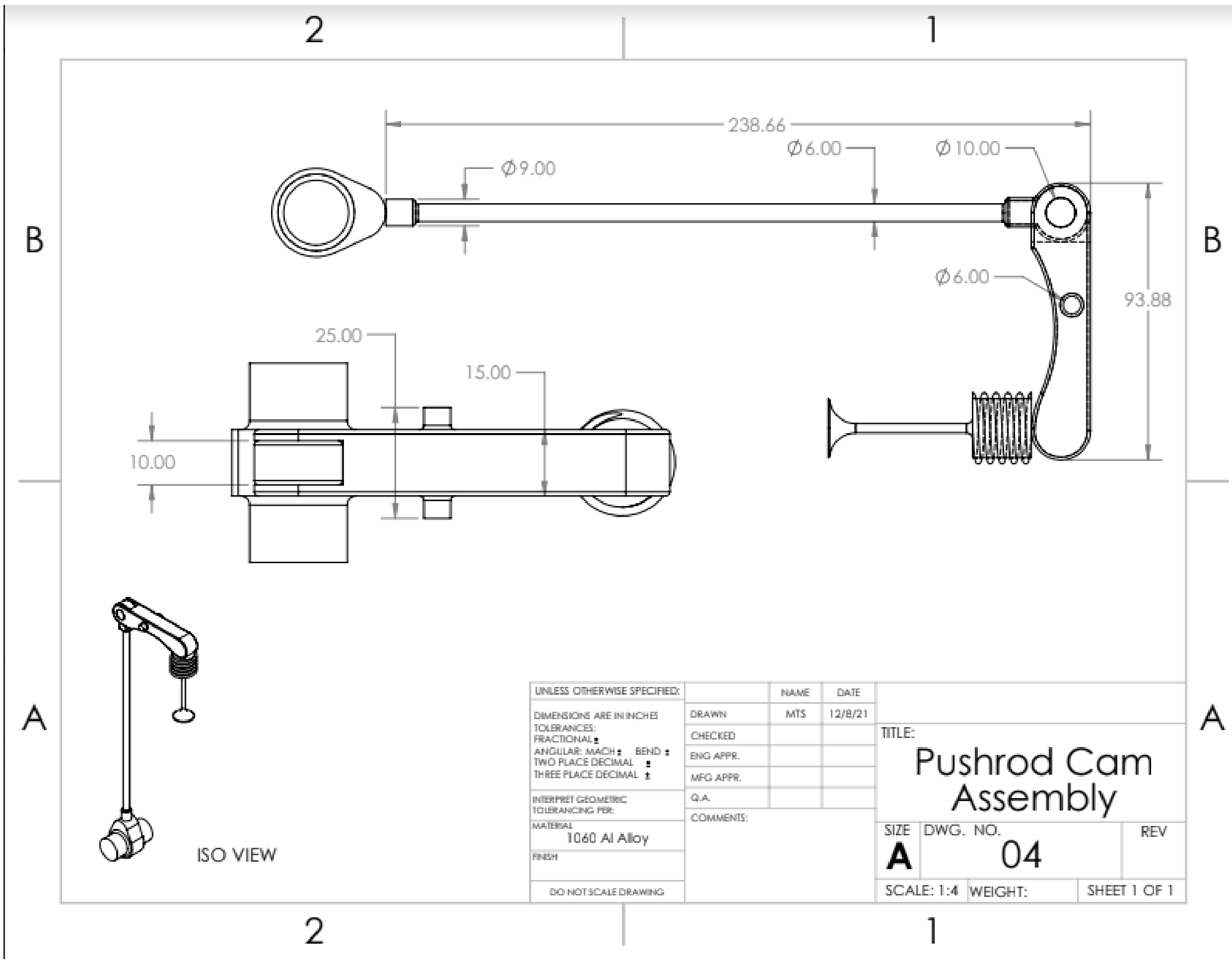

Figure 24: This schematic shows a preliminary pushrod-cam-valve assembly that the team designed and briefly pursued for analysis.

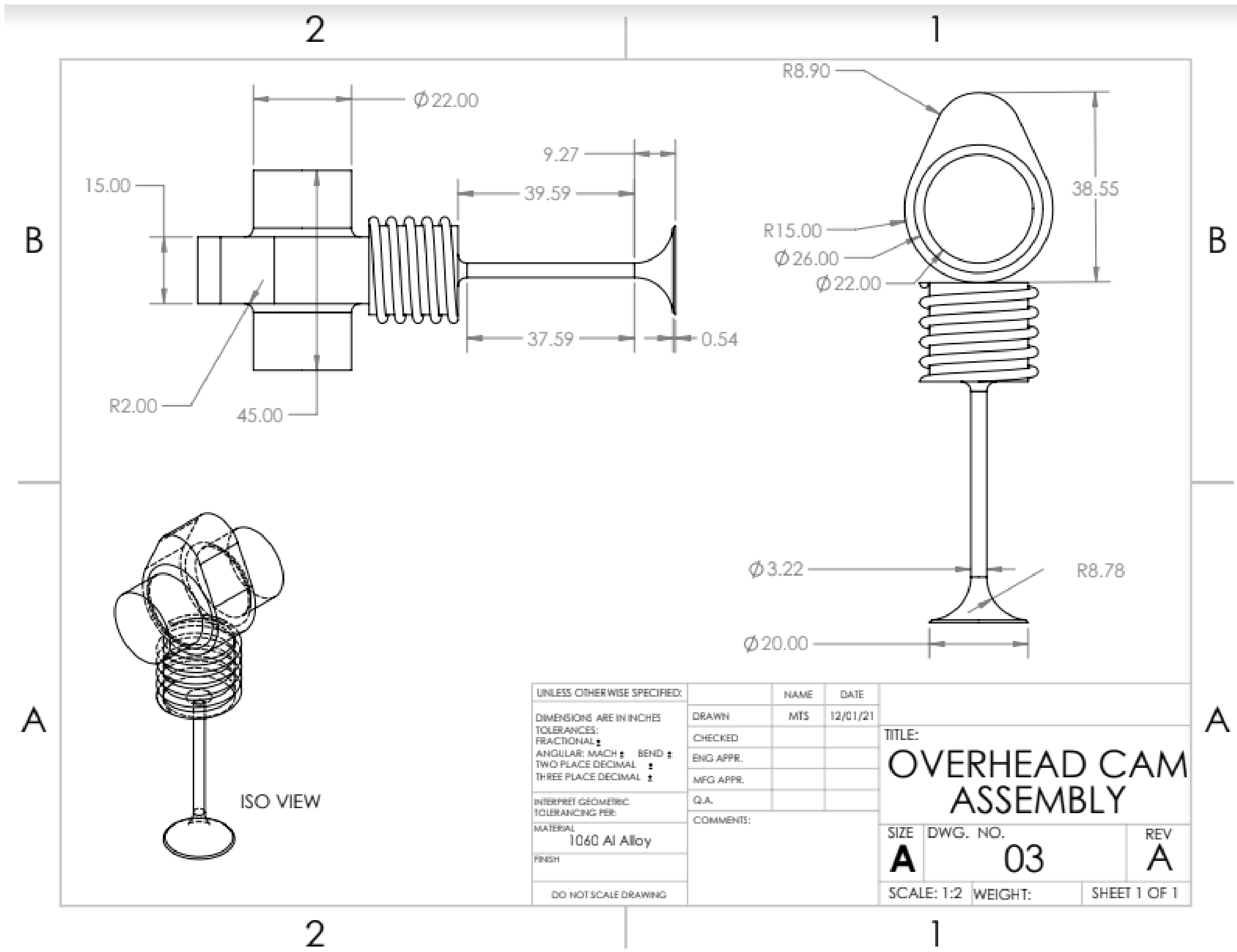

Figure 25: This schematic shows a preliminary direct overhead cam-valve assembly that the team designed and briefly pursued for analysis.

Appendix B - Static FEA Results

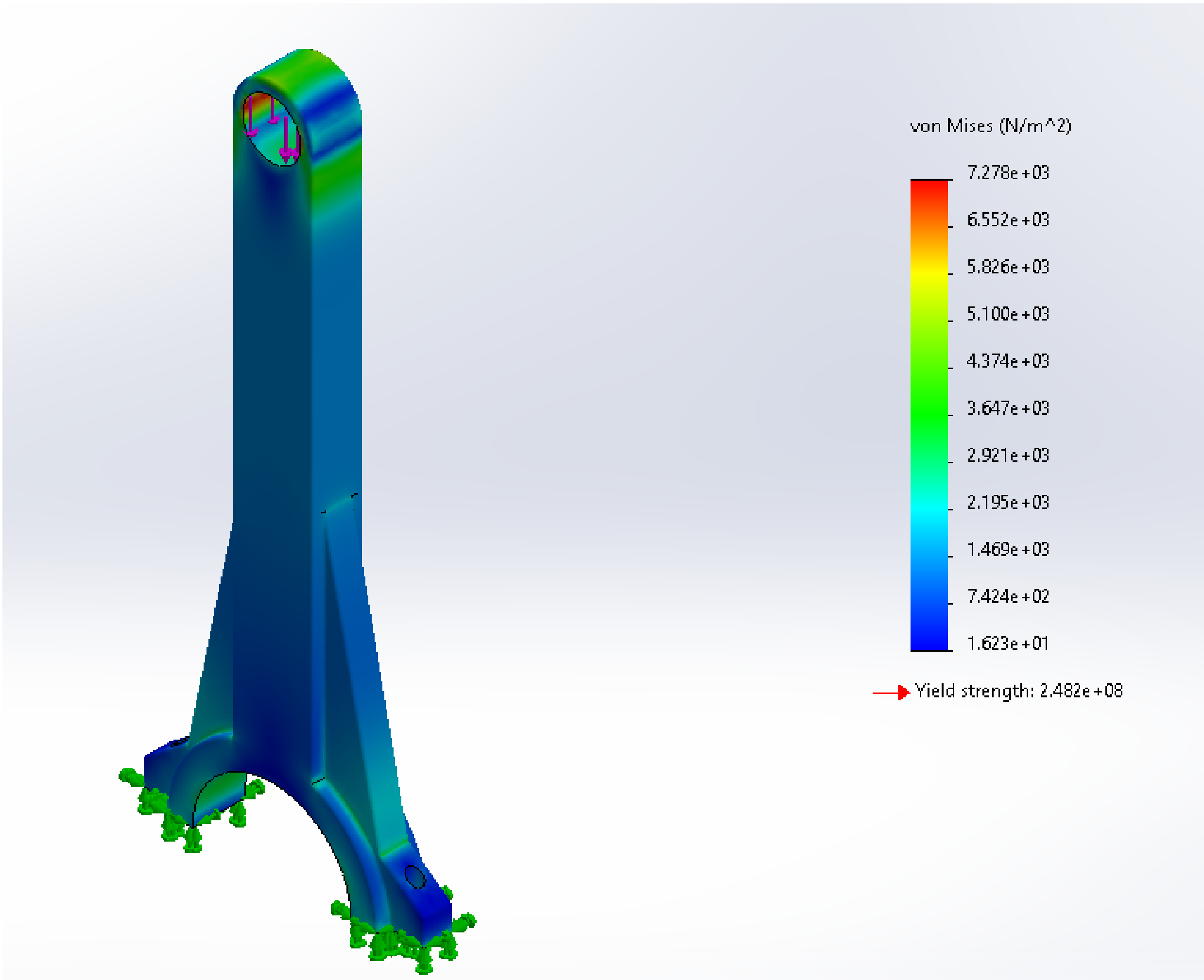

Figure 26: Preliminary stress analysis of upper connecting rod, done on the initial design highlighted in chapter 3.

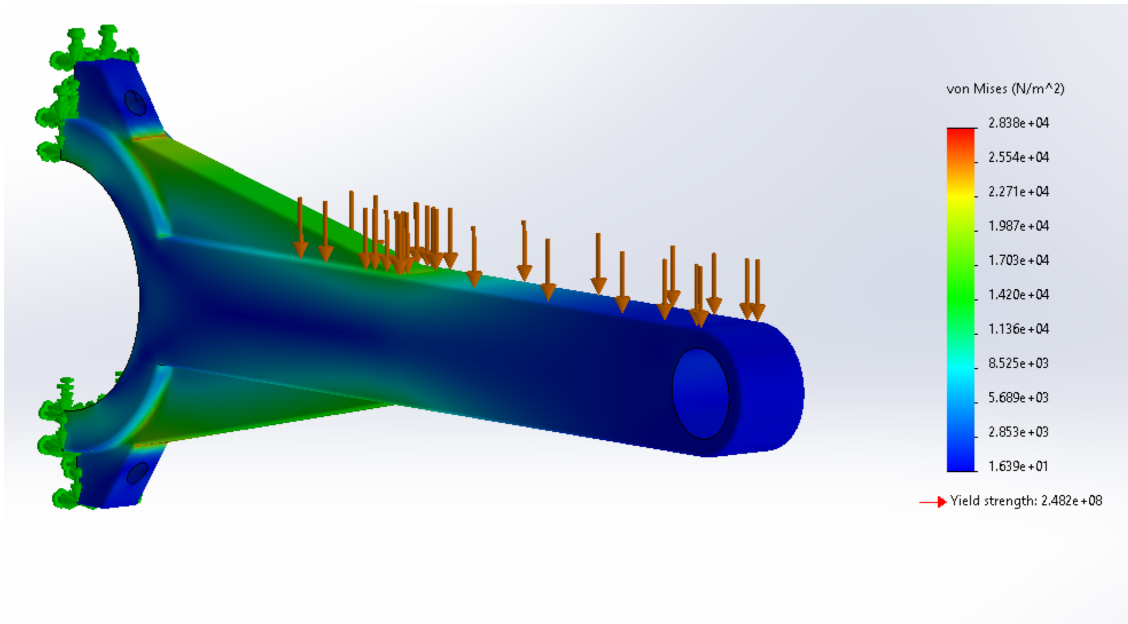

Figure 27: Preliminary stress analysis of upper connecting rod, done on the initial design highlighted in chapter 3.

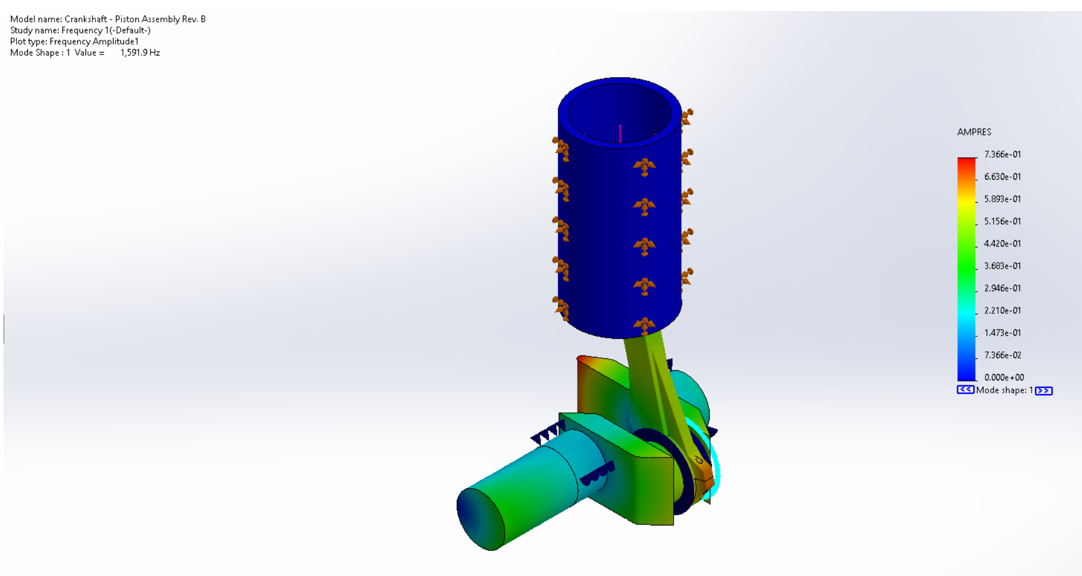

Figure 28: Preliminary frequency on the initial design, looking for resonance in the system.

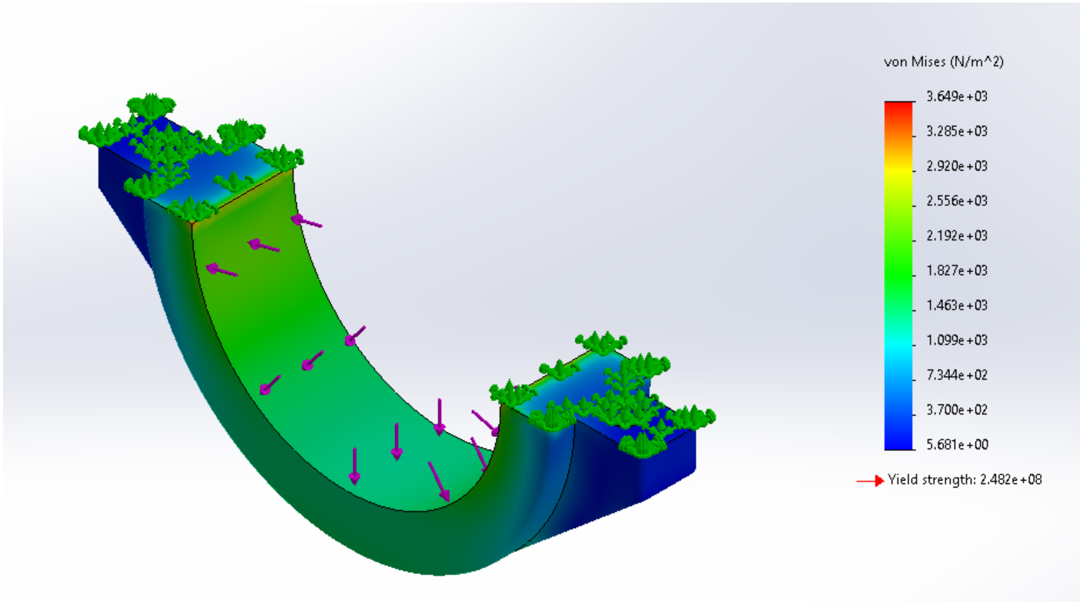

Figure 29: Preliminary stress analysis on the lower connecting rod, highlighting the pressure exerted on it by the crankshaft.

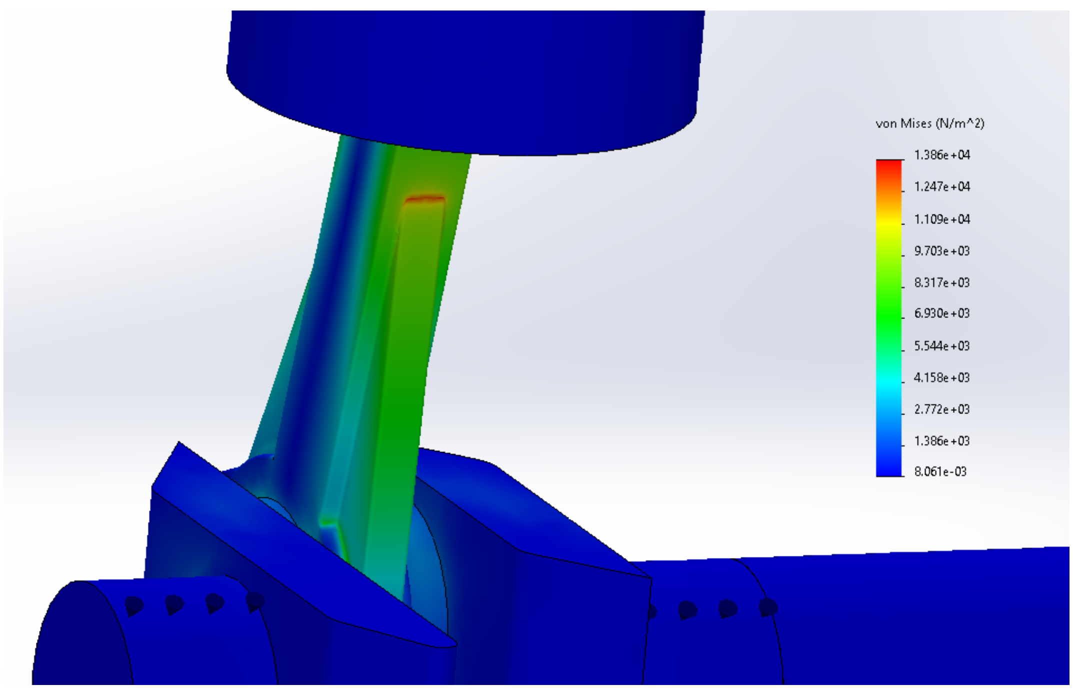

Figure 30: Preliminary stress analysis on the full system at the halfway point of the stroke. This highlights a notable stress concentration removed in the final design.

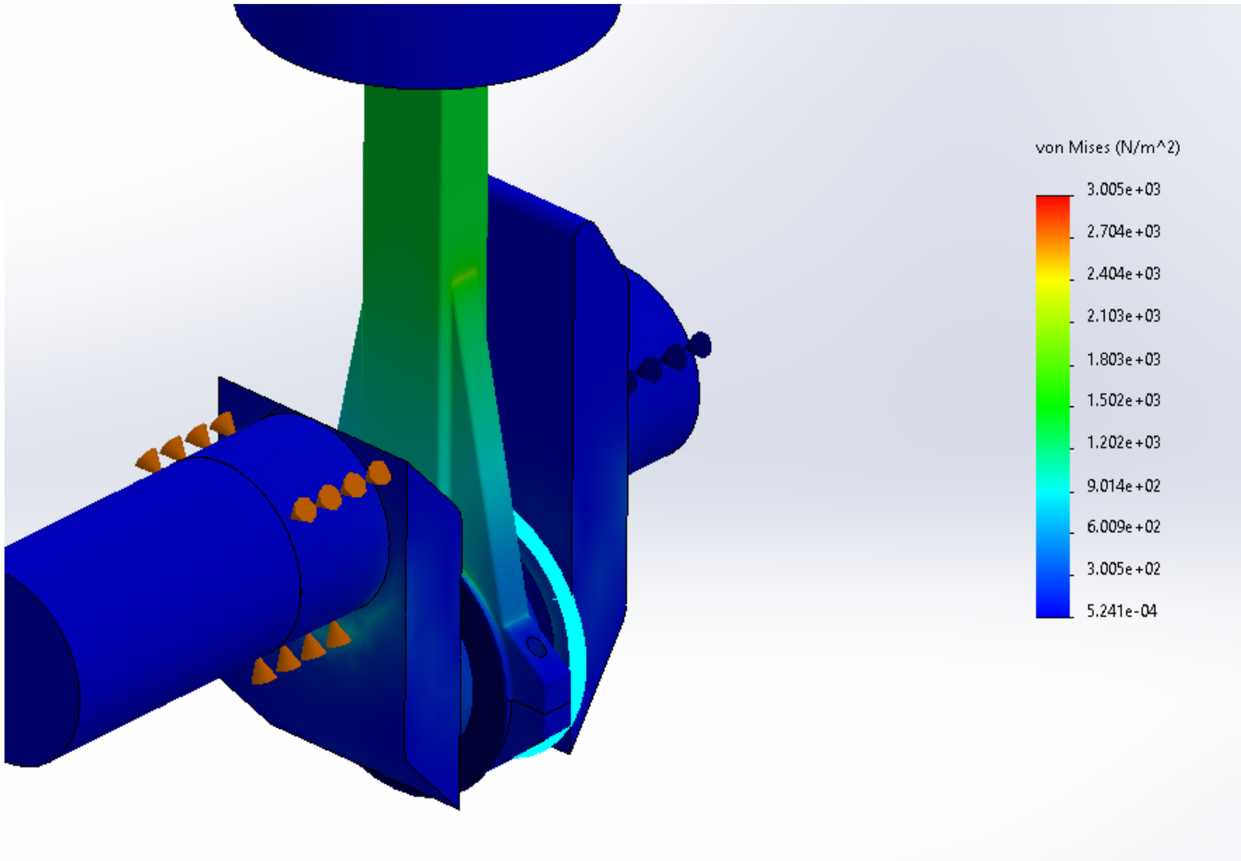

Figure 31: Preliminary stress analysis on the full system at the bottom of the stroke.

Appendix C - Motion Analysis Graphs

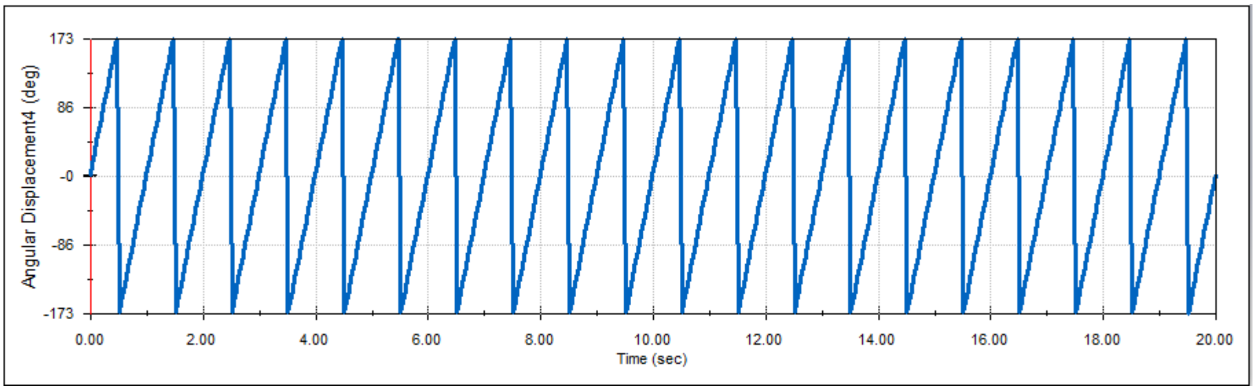

Figure 32: Angular position graph for ratio of 0.4

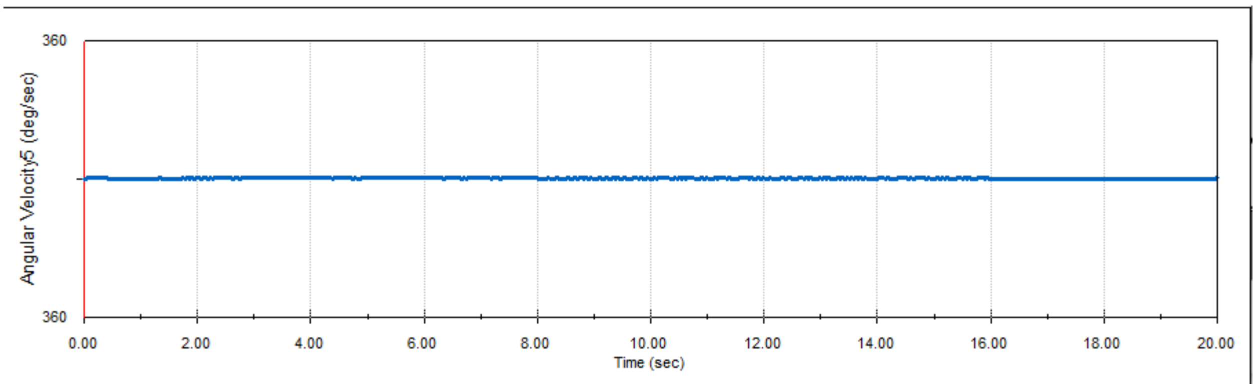

Figure 33: Angular velocity graph for ratio of 0.4

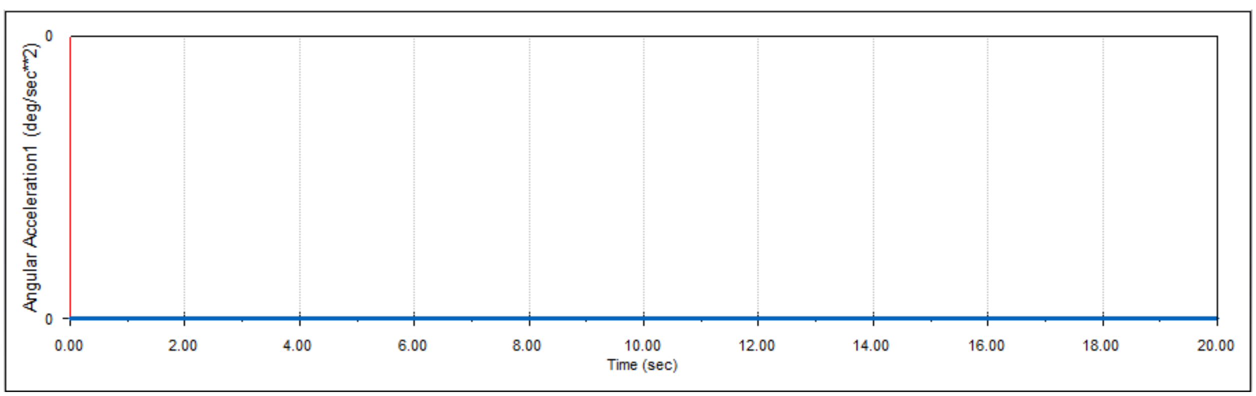

Figure 34: Angular acceleration graph for ratio of 0.4

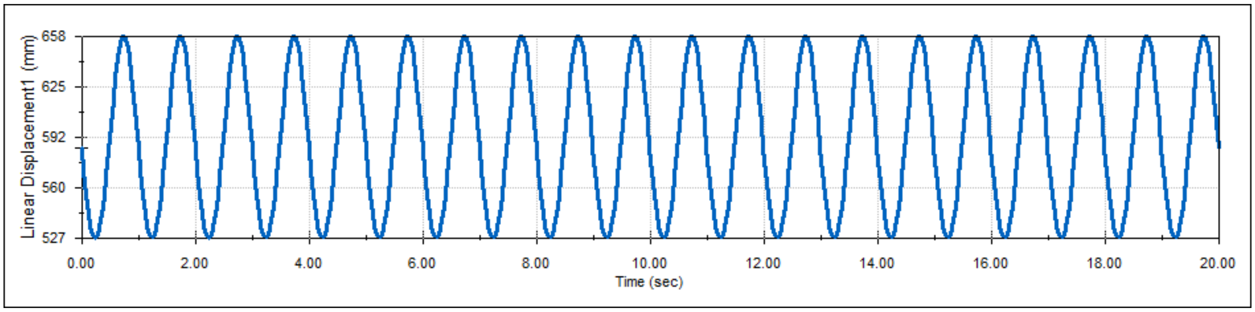

Figure 35: Linear position graph for ratio of 0.2

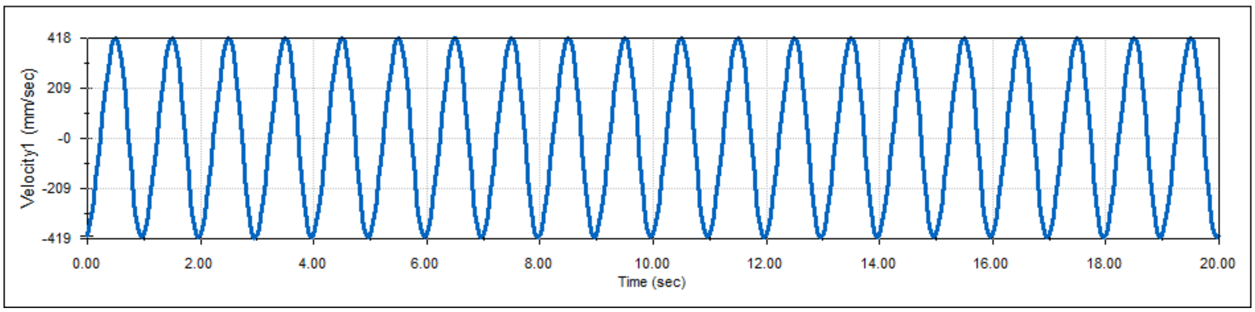

Figure 36: Linear velocity graph for ratio of 0.2

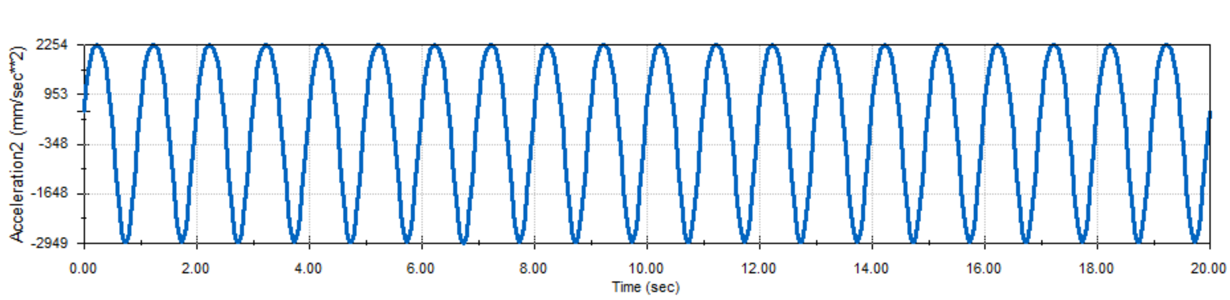

Figure 37: Linear Acceleration graph for ratio of 0.2

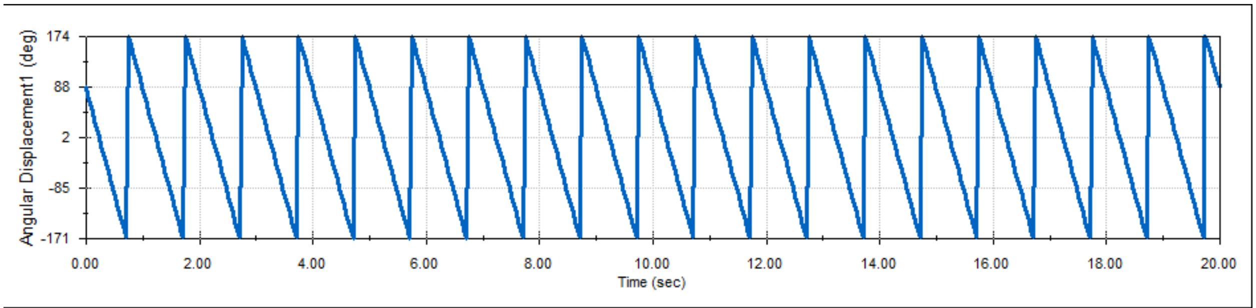

Figure 38: Angular position graph for ratio of 0.2

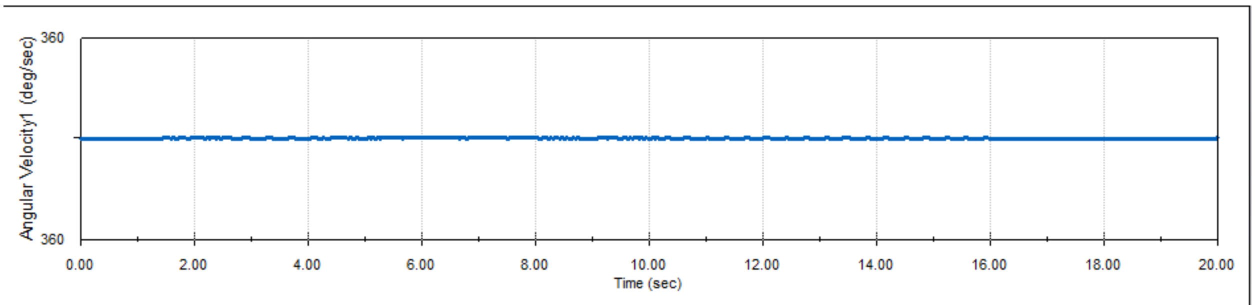

Figure 39: Angular velocity graph for ratio of 0.2

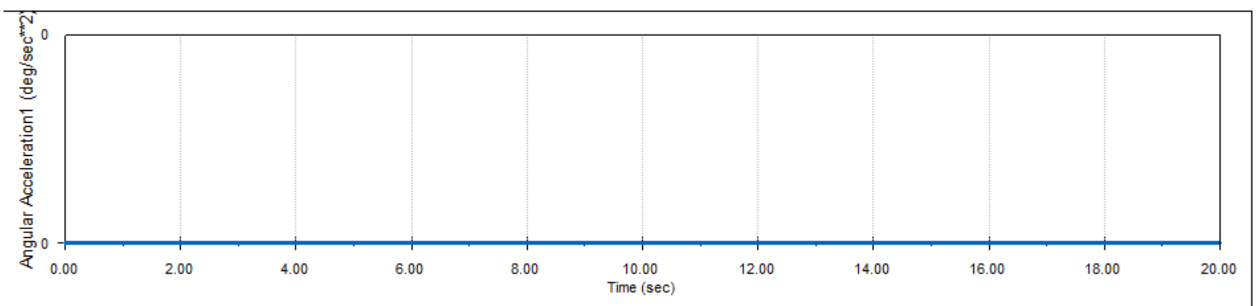

Figure 40: Angular acceleration graph for ratio of 0.2

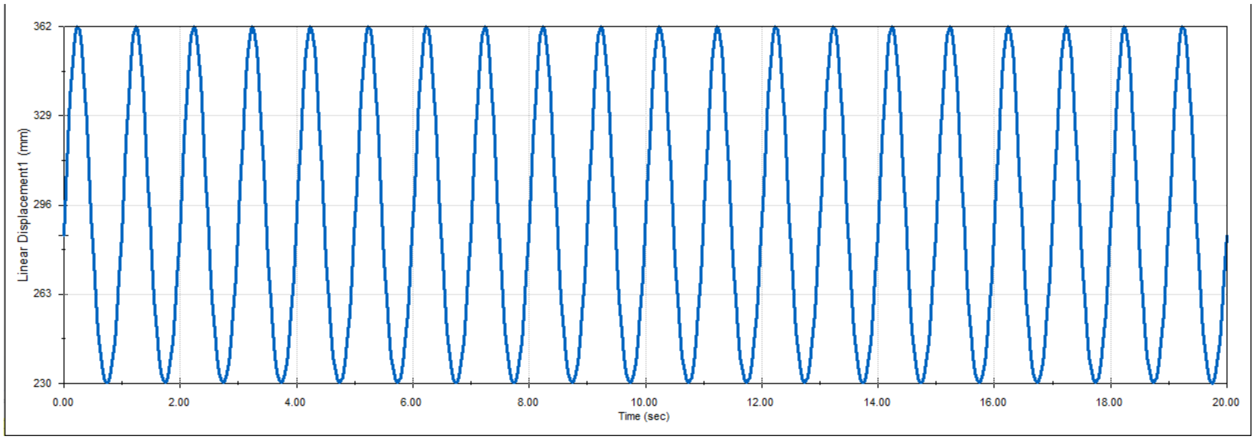

Figure 41: Linear position graph for ratio of 0.6

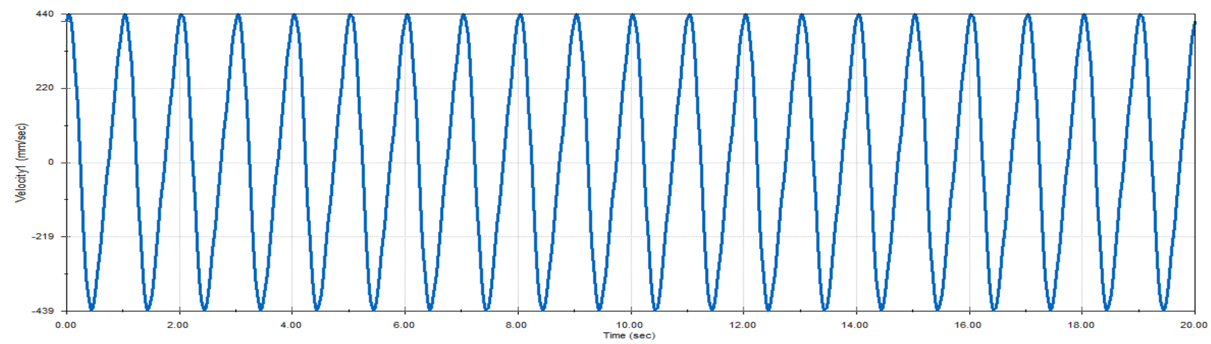

Figure 42: Linear velocity graph for ratio of 0.6

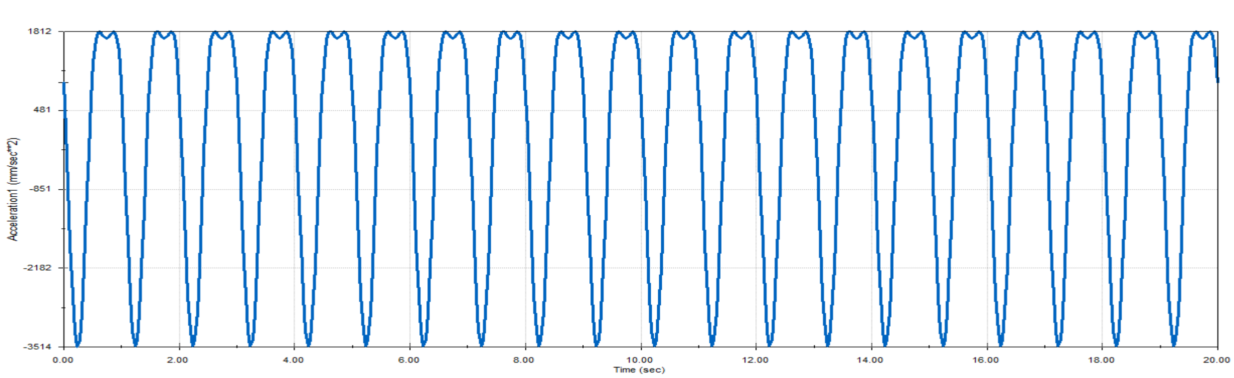

Figure 43: Linear acceleration graph for ratio of 0.6

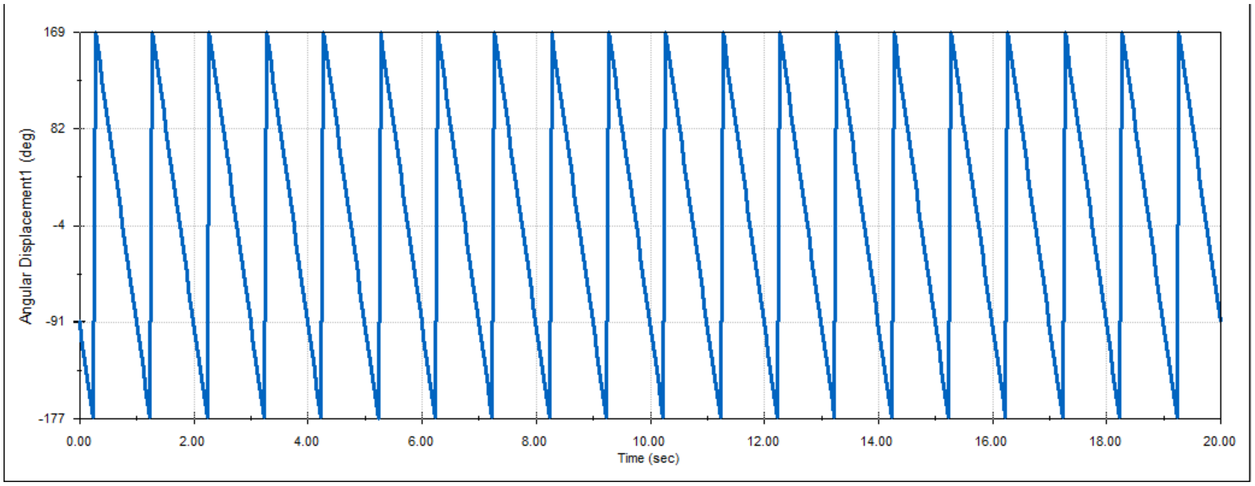

Figure 44: Angular position graph for ratio of 0.6

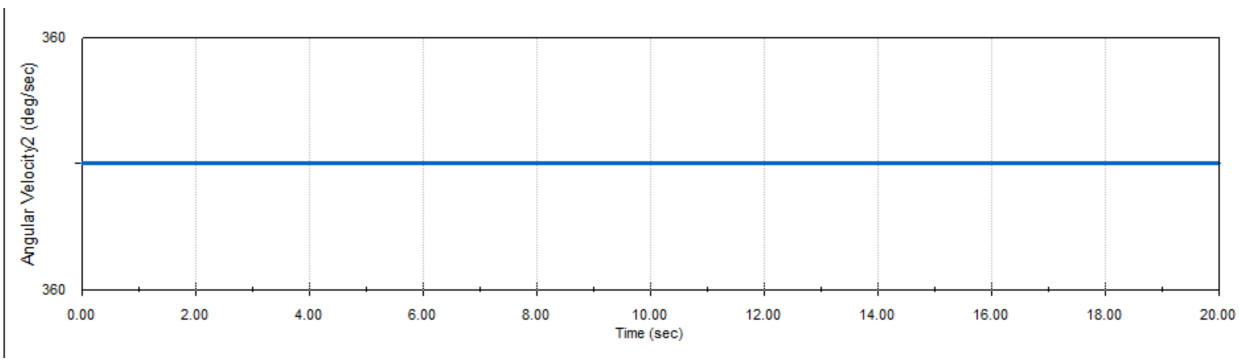

Figure 45: Angular velocity graph for ratio of 0.6

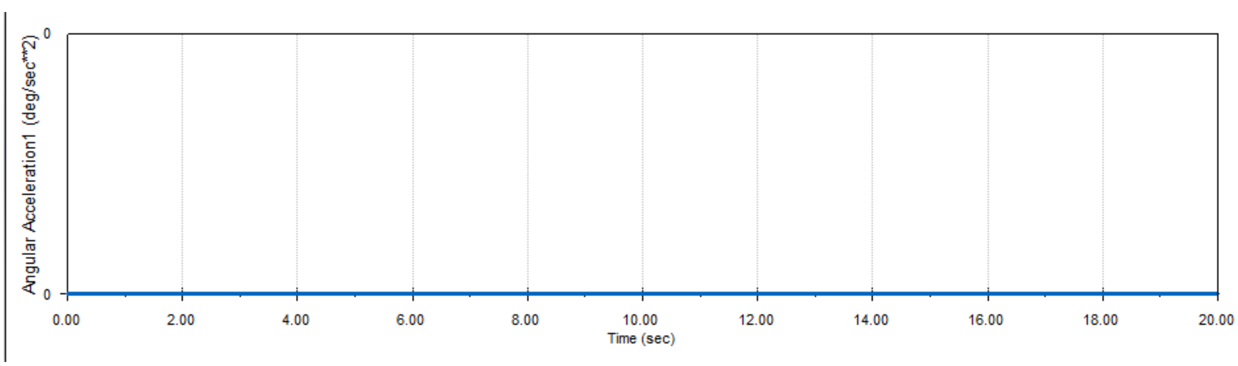

Figure 46: Angular acceleration graph for ratio of 0.6

Appendix D - Project Presentation Poster

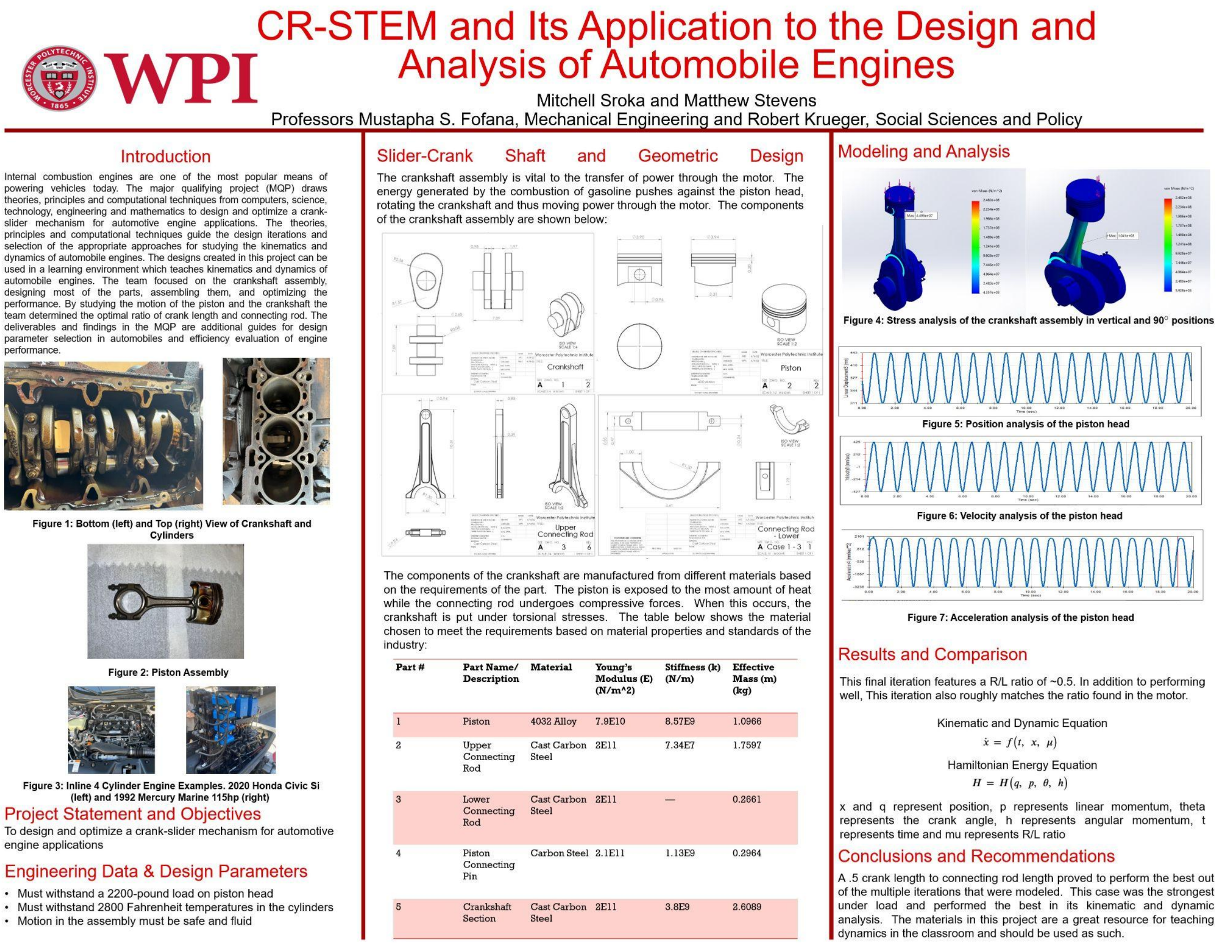

Figure 47: This is the poster the team used to present the results of this project to the WPI Mechanical and Materials Engineering Department.