Design and Analysis of a Street Bike Through Optimization of Joint Supports Utilizing FEA

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ME 37100 Computer Aided Design

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12 December 2024

Table of Content

Abstract
In this report, an outline of a standard street bike design will be presented to meet the needs of the customer. Optimization will be done to achieve lower cost upon manufacturing through reduction of fillets on the frame. Various plastic materials will be analyzed as a means of joint support to achieve reduction of stress concentration at sharp edges. Considerations will also be made to lower the cost (by use of lighter and cheaper materials), and the feasibility of the bike through the supporting structures as a means of a standard street bike.

Introductions
Street (road) bikes are specialized purpose bikes that must be improved for the purpose of urban commuting and navigating city environments. These bikes often encounter varying road conditions (introductions of potholes, debris, uneven pavements, etc.) and inclines terrains. The bikes are also exposed to changing weather conditions such as rain, heat, and humidity, requiring the material to factor in corrosion and wear. Weight becomes an important issue for ease of manufacturability in crowded or tight spaces while being robust enough to handle the stresses of daily use [5].

In this report, Finite Element Analysis (FEA) will be used to evaluate the structural performance of bike components under static and dynamic conditions (drop test). In static analysis, steady-state loads like rider weight, lateral forces, and braking stresses are applied to assess deformation, stress distribution, and potential failure points. Drop tests simulate dynamic impacts, such as striking a pothole, to evaluate the wheel's ability to absorb shocks without permanent damage.

Mesh control is an important factor in FEA in areas of stress concentration. Due to irregularities in the geometry, joints and part fittings introduce stress concentrations from a disturbance to the flow of stress [6]. Finer elements are used around fillets, spoke junctions, and rim edges to capture localized stress variations accurately while coarser meshes can be applied to less critical regions for computational efficiency.

When deciding materials to use for the purpose of creating the bike's frame, it is important to take into account the conditions such a bike will face. Common materials for low impact, daily use is 6061 Aluminum alloy. Materials such as carbon fiber is used for marathons and titanium can be seen to be more common lately [3]. Aluminum alloy is a common material due to its corrosion resistance, lightweight and high strength properties, in addition to the alloying elements allowing for ease for manufacturing (welding abilities) [4].

Gas Tungsten Arc Welding (TIG welding) is commonly used in manufacturing aluminum bike frames. Aluminum requires filler material during welding, and as fillet sizes increase, the amount of filler material needed also increases. This not only drives up material costs but also increases welding time, as larger fillets require more passes and more precision to achieve a strong and clean weld. The inert shielding gas is consumed more in the process, adding to the expense [7].

Larger fillets also mean additional weight in the bike frame, which could reduce performance and may require premium-grade aluminum to compensate.
High-density polyethylene (HDPE), Nylon 101, and ABS are types of thermoplastics considered in this analysis for joint supports for the bike frame. HDPE is lightweight, highly durable, and resistant to impact and moisture, making it a cost-effective choice for structural components [8]. Nylon 101, known for its good mechanical strength, toughness, and wear resistance, performs well under high-stress conditions [9]. ABS combines rigidity with good impact resistance and is easy to process [10]. Manufacturing these joint supports using molding techniques, such as injection molding, significantly reduces costs compared to traditional metal fabrication [11]. Molding processes enable high-volume production with minimal waste. Plastics also reduce the overall weight of the bike frame, potentially improving performance and energy efficiency.

Problem Statement

Welding to create fillets is a time consuming and expensive process yet necessary for the reduction of stress concentration that builds up within a bike frame. Efforts to reduce the cost of bikes include redesigning the frames, using cheaper and lighter materials and to reduce cost of materials. However, simply reducing cost by addition of cheaper materials to reduce stress concentrations at joints will be explored in this report by replacing filet cost with cheaper, manufacturable plastic supports. The design of the bike must follow standard CPSC regulations [1] and standard ISO 4210 regulations [2].

Material Selection

In the design of the frame, the first important parameter was a material choice to meet the criteria listed by the problem state. For a road bike where high stress conditions are not as prevalent, it was chosen that the material used would be Aluminum alloy 6061 [12], which is seen to be a common material choice for such applications
For the purpose of the joint support, the important parameters include the decrease in cost. Such constraint leads the main group of material to be used as plastics. Plastics can be seen to be the cheapest in terms of cost of manufacturing and processing of parts. As suggested earlier, such design can cheaply be manufactured through an injection molding process [11]. In considering the types of plastic materials that may be suitable for such application, many were limited to thermoplastics for the purpose as just mentioned. Stresses were first considered prior to the determination of the supporting strength needed. The conditions such as weathering and wear over time were considered in the choice of materials to be analyzed as well. The choices of materials considered, and some important properties of such plastic materials are tabulated in the table below.

Material	Ultimate strength (MPa)	Elastic Modulus (GPa)	Other Important Properties
ABS	30	2	Good impact strength
Nylon 101	79.29	1	Wear and high stress resistance
PE (high density)	22.1	1.07	Impact and moisture resistant

Figure 1: Properties of plastics material candidates for joint support of the frame

Design

The initial portion of the design was created by designing the skeleton of the bike. In the skeleton of the bike, the dimensions of the reach, seat tube, head tube, seat tube angle, chain stay lengths, bottom bracket drop and height, and head tube angle were set. Such dimensions were designed under the standards of CPSC [1].

I. Frame

In the design of the frame, the first choice to make was the geometry of the bike. A diamond-type frame was chosen as the base shape for its higher rigidity compared to other designs (looped-type, triangular-type) [13]. Such a conclusion was reached based on an FEA done from various initial conditions relating to body weights, braking and transverse accelerations. Configurations of the angles and tube lengths were decided based on the standards set by CPSC in 1512.14 for frame alignments and supported loading. The dimensions of the frame can be seen in the technical drawing as seen in figures 2.

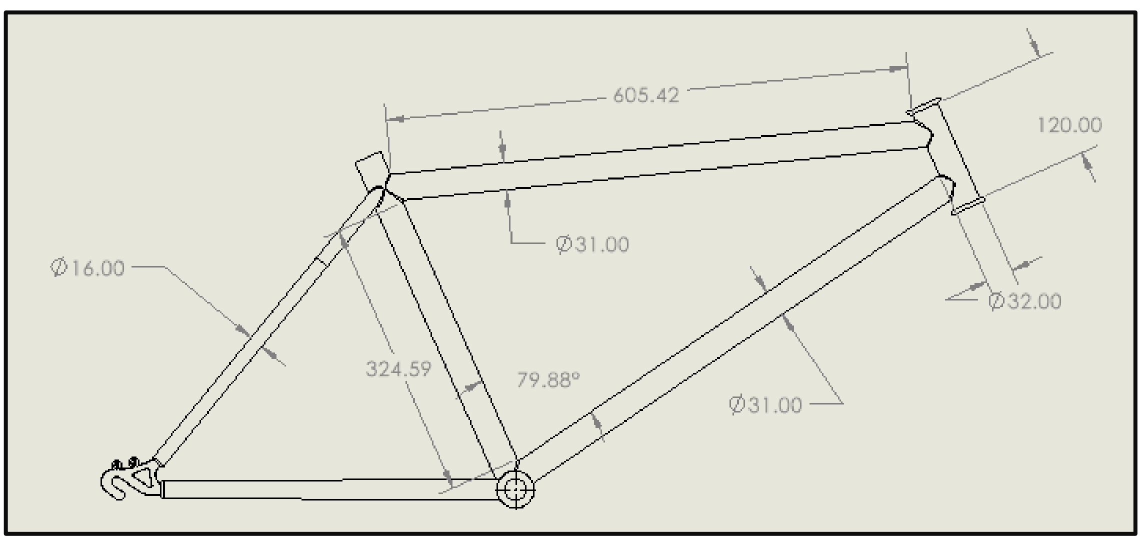

Figure 2: Frame dimensions drawing

II. Joint Support

The joint supports were designed around the frame at areas of high stress concentration. The original frame design included filets in such areas. With the joint supports, the filets are removed, and plastic joints are fitted in such areas. Each joint matches the dimensions of the frame in hovers over and are of 2 mm thickness. Such a decision was made based on the results obtained in the stress analysis portion.

III. Fork

The fork design was made fitted to the frame and matched the bottom bracket dropdown heights specified by the initial skeleton designs. Other design requirements are specified in CPSC 1512.6, and 1512.14 which includes the specifications of the steering system. Specific dimension constraints are made between connections of the fork to the handlebars. The dimension of the fork is seen in figures 3.

IV. Wheel

The wheel was designed for a typical road bike. In determination of the design, various spoke dimensions and amounts are based mainly upon its application. A classic wheel is chosen over spokeless, or minimal spokes designs to minimize cost and weight of the wheels [14]. Without its heavy applications, it is not as necessary to account for high drops as road bikes are limited to the amount of impact received by the terrain of the roads. CPSC outlines the standards of the tire, wheel and wheel hub considered in the design in 1512.10-12. The design can be seen in the drawing in figures 4.

V. Other Parts

The brake pedals were designed mainly based on fitting into the frames and follows the loose guidelines in CPSC 1512.7 and 1512.17. Handlebar designs, saddle, sprockets design was all based off of initial designs and are not the focus of such analysis done in these projects. (figures 5-7)

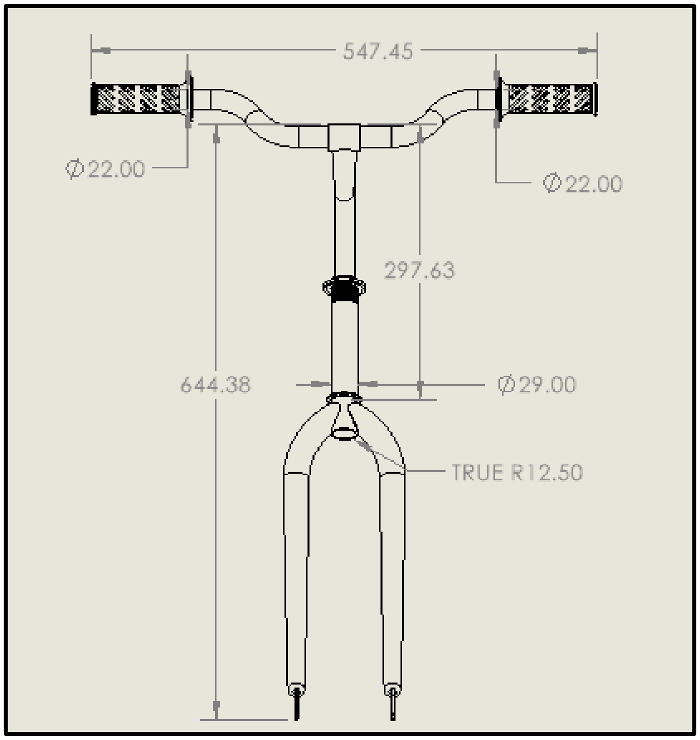

Figure 3: Fork and handle dimensions drawing. All dimensions in mm.

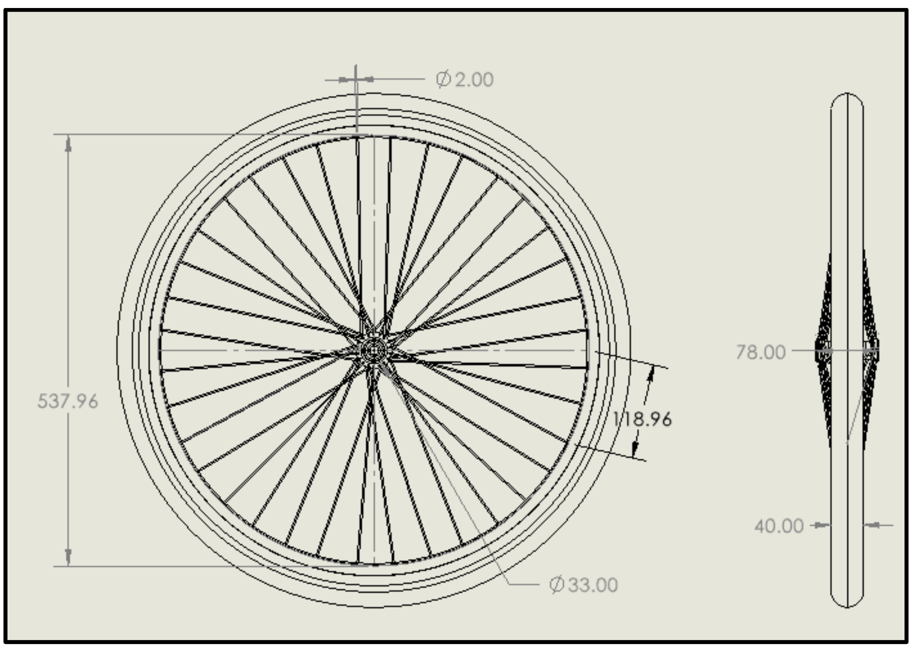

Figure 4: Wheel hub and tire technical drawing. All dimensions in mm.

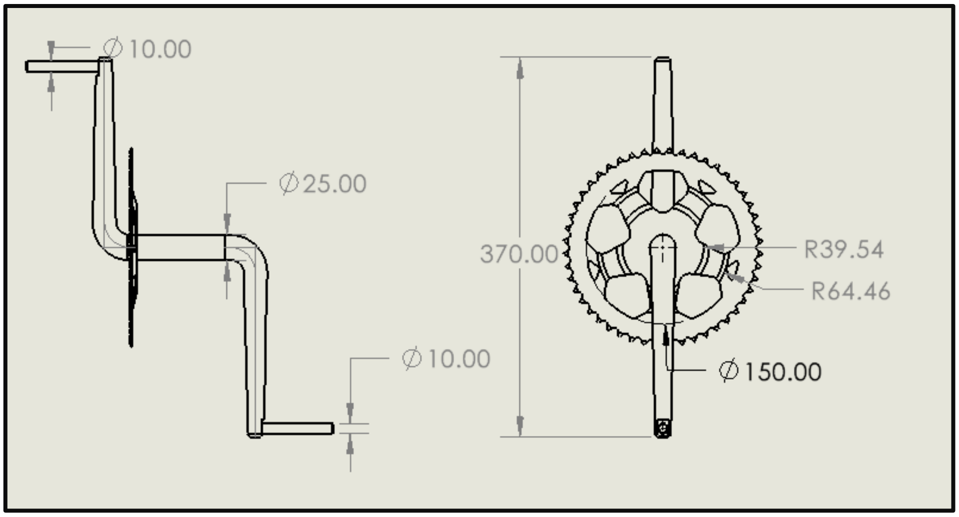

Figure 5: Technical drawing of Sprocket. All dimensions in mm.

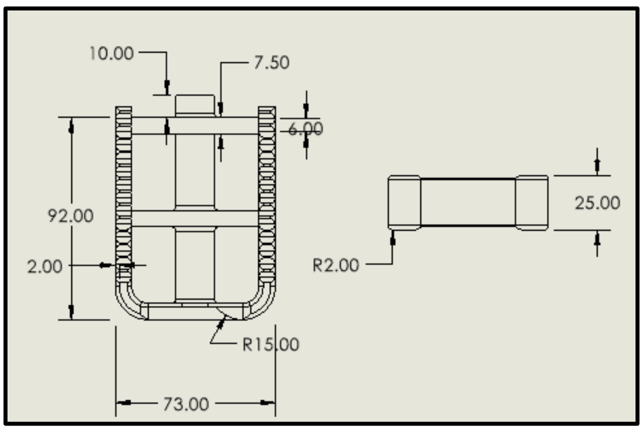

Figure 6: Pedal technical drawing. All dimensions in mm.

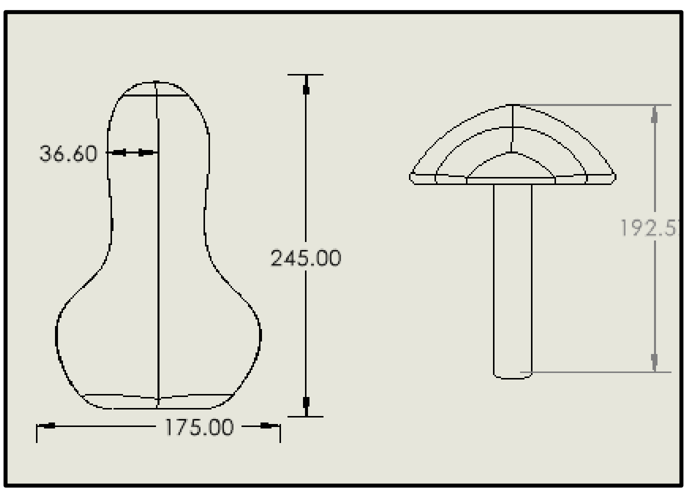

Figure 7: Saddle and seat post technical drawing. All dimensions in mm.

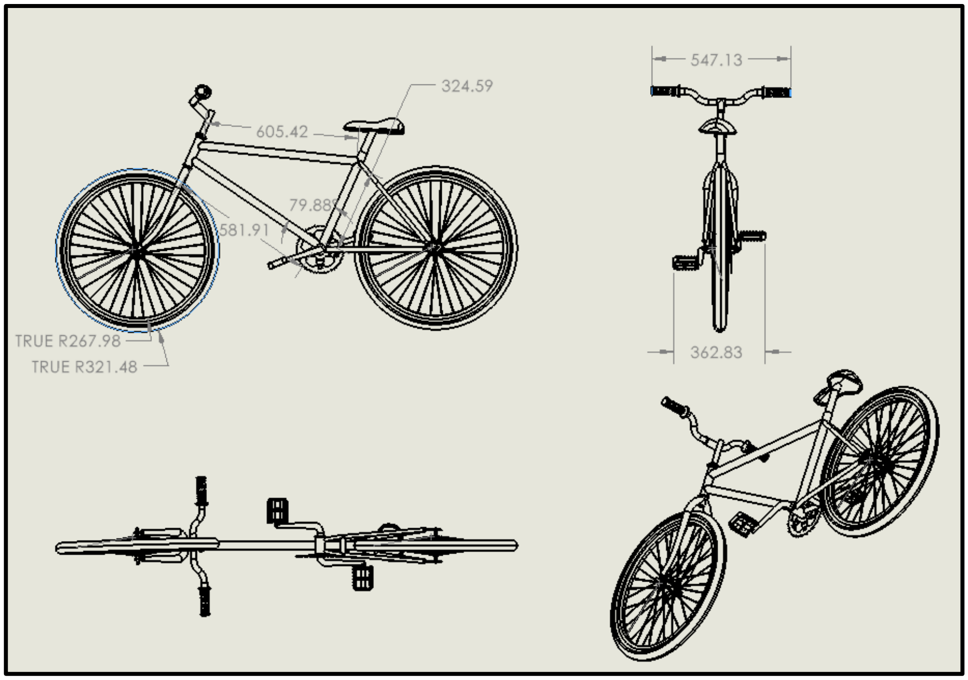

Figure 8: Final Bike Assembly Technical Drawing. All dimensions in mm.

Stress Analysis

In the FEA portion of the stress analysis, only several components of the bike will be observed. Static simulations will be done for parts that experience stresses that are deemed important based on a previously done analysis [15]. Standard meshing will be done for most parts and curvature-based model at need. Such standard meshing is done due to most stresses concentrated at joints. For this reason, mesh control is also applied to joints.

I. Frame

For the stress analysis of the frame, several designs of the frame are considered. The variations of the frame are solely at the points of the joints in order to determine the effectiveness of joint support replacements of the filets. In the analysis, a filet of 5 mm, no filet and the joint supports of the materials outlined in figure 1 will be used. In the analysis of the frame, the connection of the chain stay, and seat stay are simplified to a simple cylindrical connection from the initial design to allow for proper constraints.

Several conditions are considered for comparing the analysis of the different frame configurations. A static starts up, steady state pedaling and vertical impact case will be analyzed. The results of max stress and displacement of the different configurations are tabulated in figures 9-12. Resulting plots in appendix

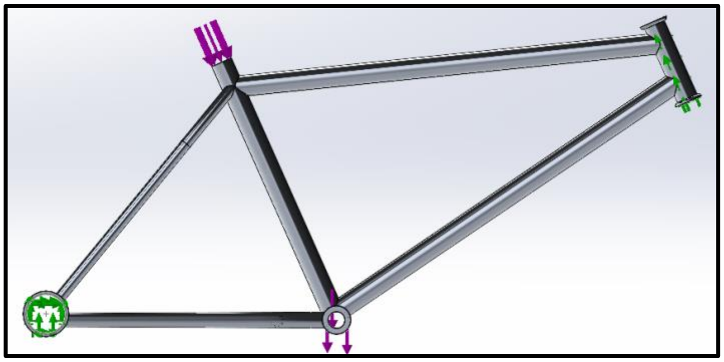

Figure 9: Constraint of the static start up. 200 N is applied at the bottom bracket and 700 N at the seat tube. Fixed support is added at the head tube and chain stay connector.

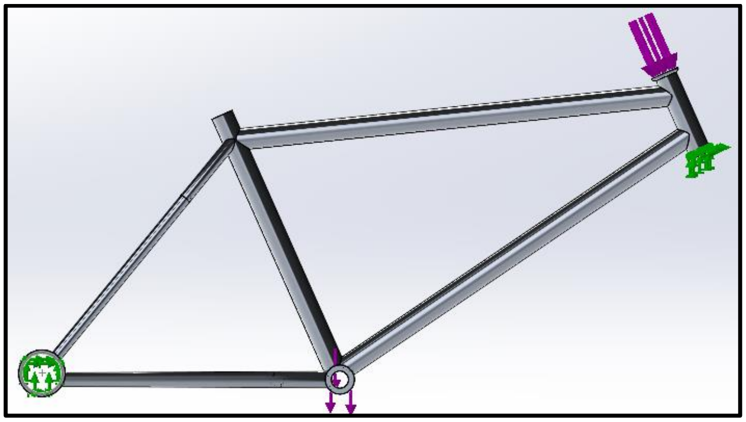

Figure 10: Constraint of the steady state pedaling case. 200 N is applied at the bottom bracket and 1000 N at the headtube. Fixed support is added at the head tube end and chain stay connector.

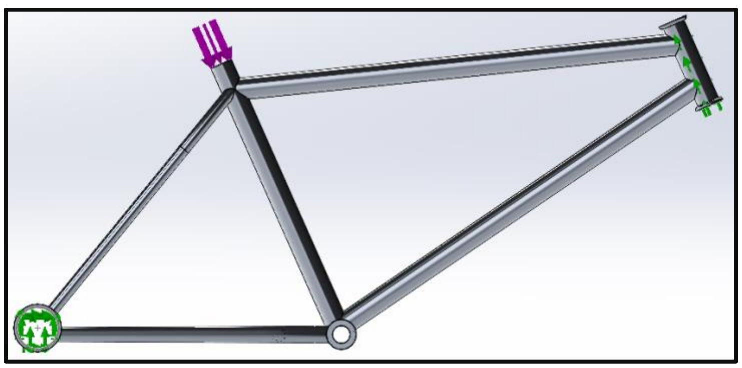

Figure 11: Constraint of the vertical impact case. 2250 N is applied to the seat tube. Fixed support is added at the head tube end and chain stay connector.

Frame Configurations	Max Stress (MPa)	Max displacement (mm)
5 mm filet	13.02	0.087
No fillet	17.59	0.09
Plastic supports - Nylon 101	15.84	0.09

Plastic supports - ABS	14.65	0.09
Plastic supports - PE (high Density)	14.75	0.09

Figure 12: Tabulated results of static startup (figure 9) of various frame configurations. Resulting plots in appendix.

Frame Configurations	Max Stress (MPa)	Max displacement (mm)
5 mm filet	7.94	0.023
No fillet	8.58	0.023
Plastic supports - Nylon 101	8.49	0.022
Plastic supports - ABS	8.42	0.022
Plastic supports - PE (high Density)	8.48	0.022

Figure 13: Tabulated results of steady state pedaling (figure 10) of various frame configurations. Resulting plots in appendix.

Frame Configurations	Max Stress (MPa)	Max displacement (mm)
5 mm filet	42.11	0.237
No fillet	45.173	0.237
Plastic supports - ABS	33.724	0.219
Plastic supports - Nylon 101	38.083	0.224

Plastic supports - PE (high Density)	37.631	0.223

Figure 14: Tabulated results of steady state pedaling (figure 9) of various frame configurations. Resulting plots in appendix.

II. Fork

For the analysis of the fork, a static analysis is done along with the handle to determine the feasibility of the design and material. Only one case will be applied for such analysis and such setup can be seen in figure 15 and 16

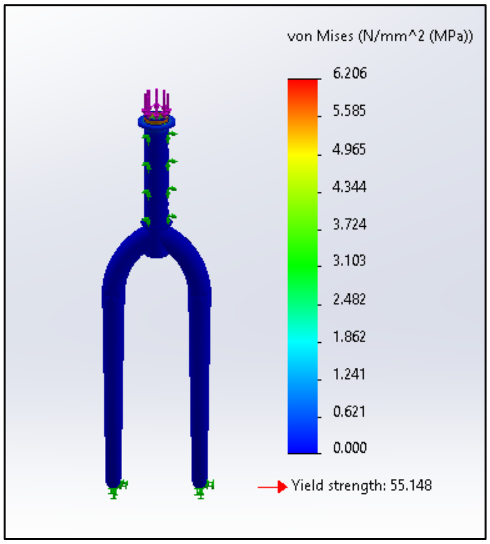

Figure 15: max von Mises Stress plots of the fork with a 1000 N force applied at stem.

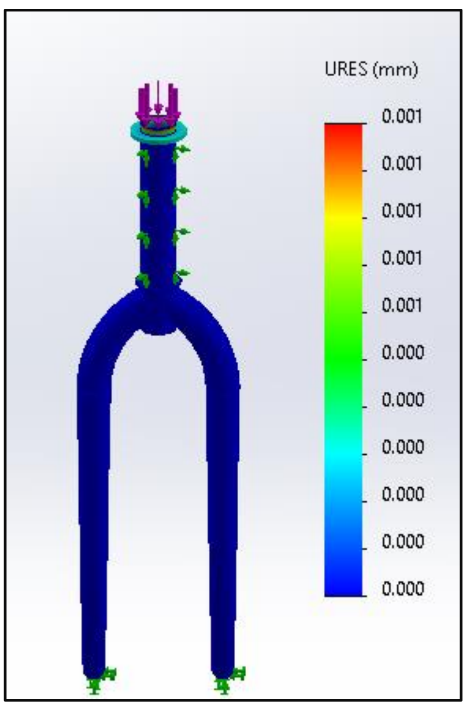

Figure 16: Max displacement plots of the fork with a 1000 N force applied at stem.

III. Wheel

To determine the feasibility of the wheel design a drop test is first performed to determine the impact strength of the wheel. Simplification of the spoke's configuration is applied prior to the analysis. A static analysis is also applied at the hub to determine hold up upon forces transferred from the frame and handle. Results are shown in figure 17.

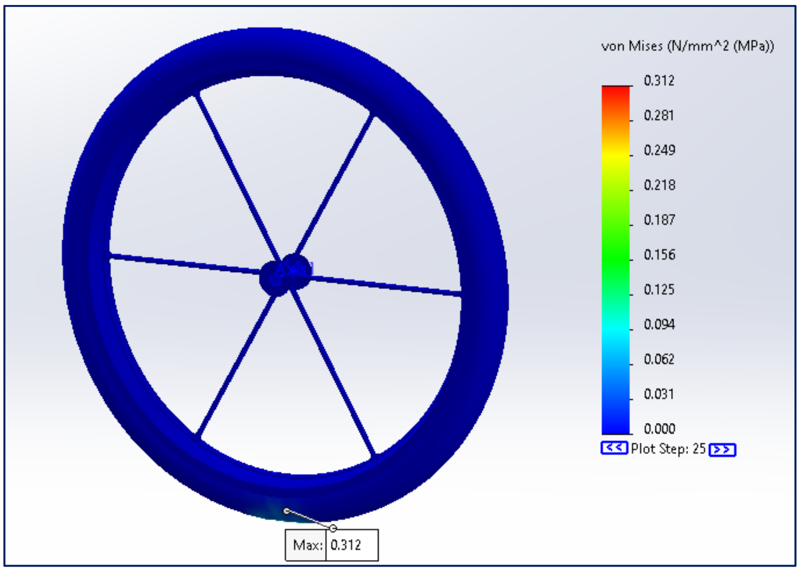

Figure 17: Drop tests resulting max von mises stress of wheel.

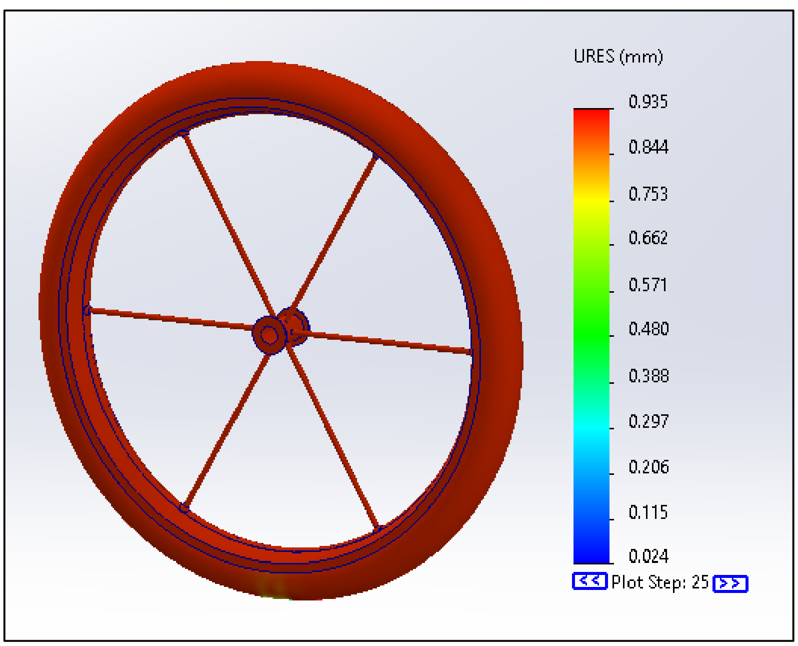

Figure 18: Drop tests resulting max displacements of wheel.

IV. Manual Comparison

To validate the results from the FEA, manual calculations are done with several simplifications. A 2D truss structure approximation is used to analyze the frame structure. Using the material properties of the Aluminum Alloy 6061 with an Elastic modulus of 69 GPa and a yield strength of 55.15 MPa, the simplified configurations and constraints for the calculations are shown in figure 17-20.

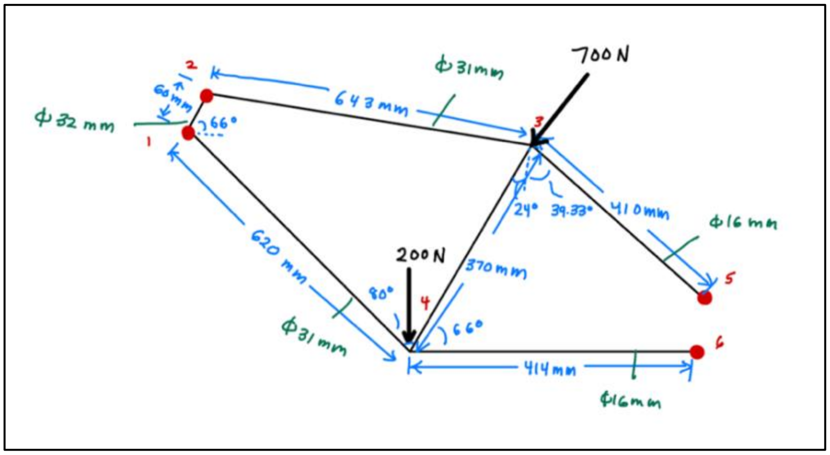

Figure 19: Dimensions and initial condition simplifications made for manual calculations of bike frame during the static start up. The '.' indicates fixed geometry

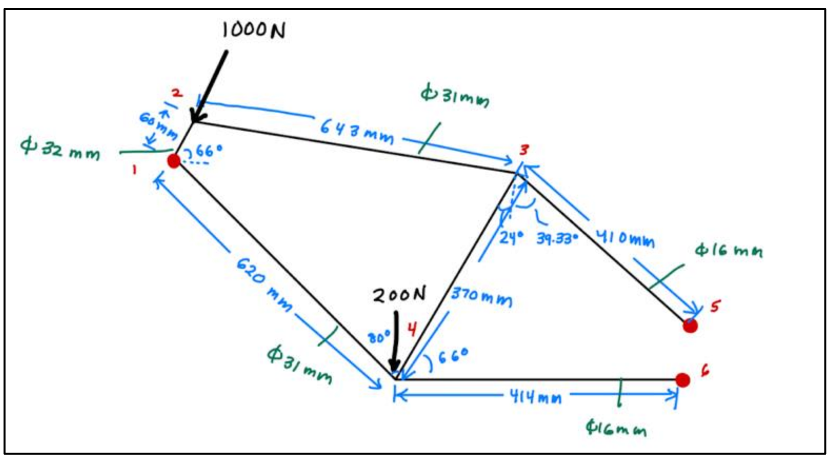

Figure 20: Dimensions and initial condition simplifications made for manual calculations of bike frame during the steady state pedaling case. The '.' Indicates fixed geometry

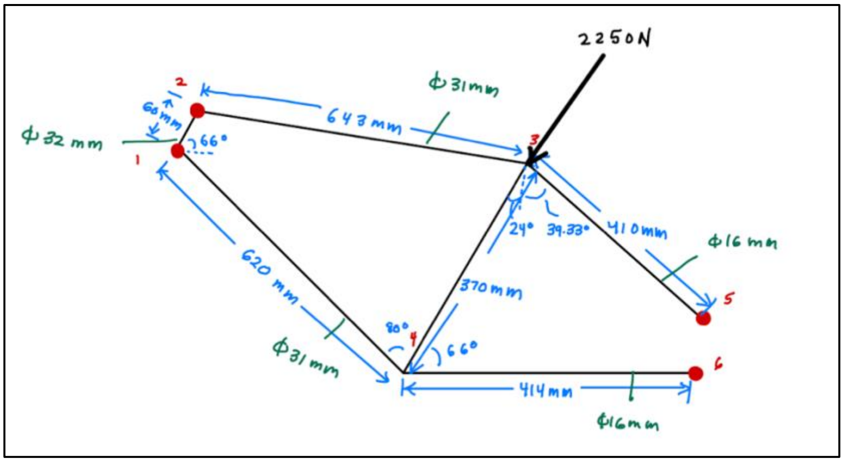

Figure 21: Dimensions and initial condition simplifications made for manual calculations of bike frame during the vertical impact case. The '.' indicates fixed geometry

The calculations are done by first determining the local stiffness matrix of each beam element [E.1].

$$k = \frac{AE}{L}\begin{bmatrix} C^2 & CS & -C^2 & -CS \\ CS & S^2 & -CS & -S^2 \\ -C^2 & -CS & C^2 & CS \\ -CS & -S^2 & CS & S^2 \end{bmatrix} \textbf{[E. 1]}$$

The displacement vector must now be solved using [E. 2], using the initial conditions of the forces from figures 17-19. Eliminations of nodes can be made based on the fixture boundary conditions

$$\{F\} = [K]\{d\} \textbf{ [E. 2]}$$

The Stress can then be solved using the equation [E. 3] from the displacements found

$$\sigma_{a-b} = \frac{E}{L}[-C \quad -S \quad C \quad S]\begin{bmatrix} u_a \\ v_a \\ u_b \\ v_b \end{bmatrix} \textbf{[E. 3]}$$

To determine that the structure will not yield, the FOS is found with [E. 4], where a value above 1 will be safe for the design.

$$n = \frac{S_y}{\sigma} \textbf{ [E. 4]}$$

Calculations for the local stiffness matrices [E. 1] are identical for all cases (static startup, steady state breaking and vertical impact) and yield the following local stiffness matrices.

$$k_{1-2} = E\begin{bmatrix} 0.0022 & 0.005 & -0.0022 & 0.005 \\ 0.005 & 0.011 & -0.005 & -0.011 \\ -0.0022 & -0.005 & 0.0022 & 0.005 \\ 0.005 & -0.0022 & 0.005 & 0.011 \end{bmatrix} N/m$$

$$k_{2-3} = E\begin{bmatrix} 0.00116 & -0.000118 & -0.00116 & -0.000118 \\ -0.000118 & 0.000199 & 0.000118 & -0.000199 \\ -0.00116 & 0.000118 & 0.00116 & -0.000118 \\ -0.000118 & -0.000199 & -0.000118 & 0.000199 \end{bmatrix} N/m$$

$$k_{1-4} = E\begin{bmatrix} 0.00087 & -0.000544 & -0.00087 & -0.000544 \\ -0.000544 & 0.000367 & 0.000544 & -0.000367 \\ -0.00087 & 0.000544 & 0.00087 & -0.000544 \\ -0.000544 & -0.000367 & -0.000544 & 0.000367 \end{bmatrix} N/m$$

$$k_{3-4} = E\begin{bmatrix} 0.000126 & -0.000153 & -0.000126 & -0.000153 \\ -0.000153 & 0.000187 & 0.000153 & -0.000367 \\ -0.000126 & 0.000153 & 0.000126 & -0.000153 \\ -0.000153 & -0.000367 & -0.000153 & 0.000187 \end{bmatrix} N/m$$

$$k_{4-6} = E\begin{bmatrix} 0.0003127 & 0 & -0.0003127 & 0 \\ 0 & 0 & 0 & 0 \\ -0.0003127 & 0 & 0.0003127 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} N/m$$

The boundary conditions for the steady pedaling case is defined as

$$\boldsymbol{u_1} = \boldsymbol{v_1} = 0\ m$$

$$\boldsymbol{u_5} = \boldsymbol{v_6} = 0\ m$$

$$\boldsymbol{u_6} = \boldsymbol{v_6} = 0\ m$$

For the static start up and vertical impact case, an additional boundary conditions is applied:

$$\boldsymbol{u_2} = \boldsymbol{v_2} = 0\ m$$

The global stiffness matrix for the static startup and vertical impact is assembled and reduced to:

$$[k] = E\begin{bmatrix} 0.001493 & 0.000194 & -0.000207 & 0.000465 \\ 0.000194 & 0.0012469 & -0.000465 & 0.00104 \\ -0.000207 & 0.000465 & 0.00133 & -7.9E-5 \\ -0.000465 & 0.00104 & -7.9E-5 & 0.001407 \end{bmatrix}$$

The global stiffness matrix for the steady pedaling is reduced to

$$[k] = E\begin{bmatrix} 0.00336 & 0.004882 & -0.00116 & -0.000118 & 0 & 0 \\ 0.004882 & 0.011 & 0.000118 & -0.0000119 & 0 & 0 \\ -0.00116 & -0.000118 & 0.001493 & 0.000194 & -0.000207 & 0.000465 \\ 0.000118 & -0.0000119 & 0.000194 & 0.0012469 & -0.000465 & 0.00104 \\ 0 & 0 & -0.000207 & 0.000465 & 0.00133 & -7.9E-5 \\ 0 & 0 & -0.000465 & 0.00104 & -7.9E-5 & 0.001407 \end{bmatrix} N/m$$

For the different conditions the force vectors are obtained as:

$$F_{Static\ Startup} = \begin{bmatrix} 284.716 \\ 639.482 \\ 0 \\ 200 \end{bmatrix} N$$

$$F_{steady\ breaking} = \begin{bmatrix} -406.74 \\ -913.545 \\ 0 \\ 0 \\ 0 \\ -200 \end{bmatrix} N$$

$$F_{vertical\ impact} = \begin{bmatrix} -915.157 \\ -2055.577 \\ 0 \\ 0 \end{bmatrix} N$$

The displacements are thus found by using [E. 2]:

$$Static\ Startup \begin{bmatrix} u_3 \\ v_3 \\ u_4 \\ v_4 \end{bmatrix} = \begin{bmatrix} -2.798E-6 \\ -1.087E-5 \\ 3.643E-6 \\ 4.935E-6 \end{bmatrix} m$$

$$Steady\ Pedaling \begin{bmatrix} u_2 \\ v_2 \\ u_3 \\ v_3 \\ u_4 \\ v_4 \end{bmatrix} = \begin{bmatrix} 2.216E-6 \\ -2.21E-6 \\ 2.074E-6 \\ 1.315E-6 \\ -2.7E-7 \\ -2.361E-6 \end{bmatrix} m$$

$$Vertical\ impact \begin{bmatrix} u_3 \\ v_3 \\ u_4 \\ v_4 \end{bmatrix} = \begin{bmatrix} -1.163E-5 \\ -4.514E-5 \\ 1.568E-6 \\ 3.036E-6 \end{bmatrix} m$$

The stresses will be obtained using [E. 3] below. The procedure for 2 elements of the static startup is set up below. A similar process is used for the rest of the elements and for the steady pedaling and vertical impact cases. The values obtained manually are tabulated in figures 21.

$$\sigma_{1-2}^{(1)} = 0\ pa$$

$$\sigma_{2-3}^{(2)} = \frac{E}{0.643}\begin{bmatrix} -0.94 & 0.101 & 0.94 & -0.101 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -2.798E-6 \\ -1.087E-5 \end{bmatrix} pa$$

Condition	σ_{1-2}(MPa)	σ_{2-3}(MPa)	σ_{1-4}(MPa)	σ_{3-4}(MPa)	σ_{3-5}(MPa)	σ_{4-6}(MPa)
Static Start up	0	-0.164	0.02	15.4	0.09	0.001
Steady State Pedaling	8.4	-0.8	-0.4	1.11	0.01	0
Vertical Impact	0	0.97	-3.4	35	0.06	0.008

Figure 21: tabulated stress of each element of the frame under different conditions.

Conclusion

To determine the effectiveness of joint support, variation to the frame is analyzed using FEA. A base frame of diamond type was first developed as seen in figures 2. Stress analysis was done for different materials as joint support without the filets to achieve similar results. The purpose of such joint support was to reduce the need of filets by reducing total materials at joints. Scribing similar levels of support while maintaining structural integrity, as seen by total displacements.

Optimization and analysis of the various other bike parts must also be done to ensure such prototype will uphold in conditions faced in urban environments. Several static cases was done for the frame based on different user experiences. A buckling study was also done on the fork and handles assembly to ensure the applied forces will not cause significant deformations. A transfer of load will happen when the user is engaging with the handles, and so static study must also be done on the wheel. Due to possible impact of the wheel from uneven grounds.

Comparing the element stresses from theory to result obtained through FEA tabulated in 12-14, values of the FEA can be seen to be higher generally than that obtained through manual calculations. Such differences can be due to simplification of geometry during manual calculations. Due to the 2D approximation not all values are captured correctly. However, such results help to validate results obtained from the FEA. From such results, the impact f the joints and filets can be seen by the deviation from the FEA.

The additions of joint support from the various materials studied can be seen to have results that can help to recover some support lost from no filets. ABS was seen to yield the best results in terms of reducing stress concentration among all the materials tested. However, joint support was not seen to recover much of the reduced stresses when it came to steady state pedaling. The least amount of stress on the frame is observed during this phase, concluding that through such joint do not reduce as much stress concentration, it can be looked passed. Although the results obtained do point to possible support from the additional plastic supports, such additions do not produce significant changes and help for the frame overall. Despite this, further studies may use this concept to use less common base frame materials to the impact experienced max von mises stress is closer to the yield strength.

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Appendix

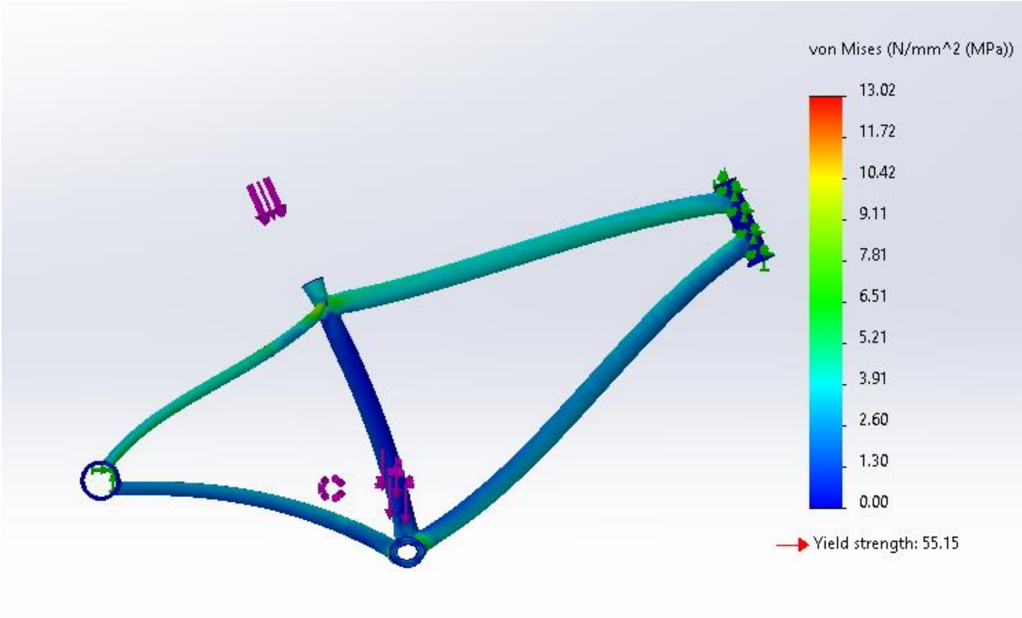

Figure A1: Max von Mises Stress experienced by frame with 5 mm filet with conditions outlined by the static startup conditions in figure 9.

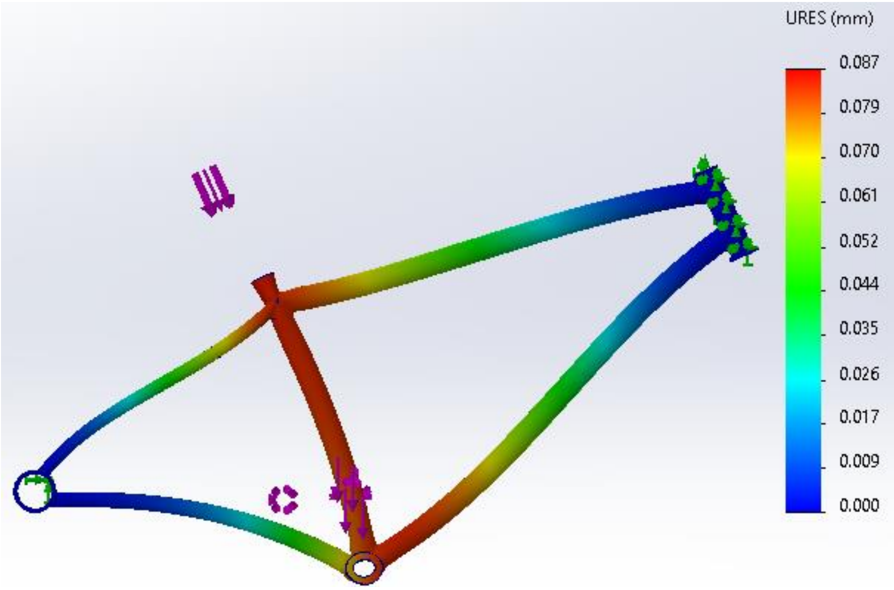

Figure A2: Max displacements experienced by frame with 5 mm filet with conditions outlined by the static startup conditions in figure 9.

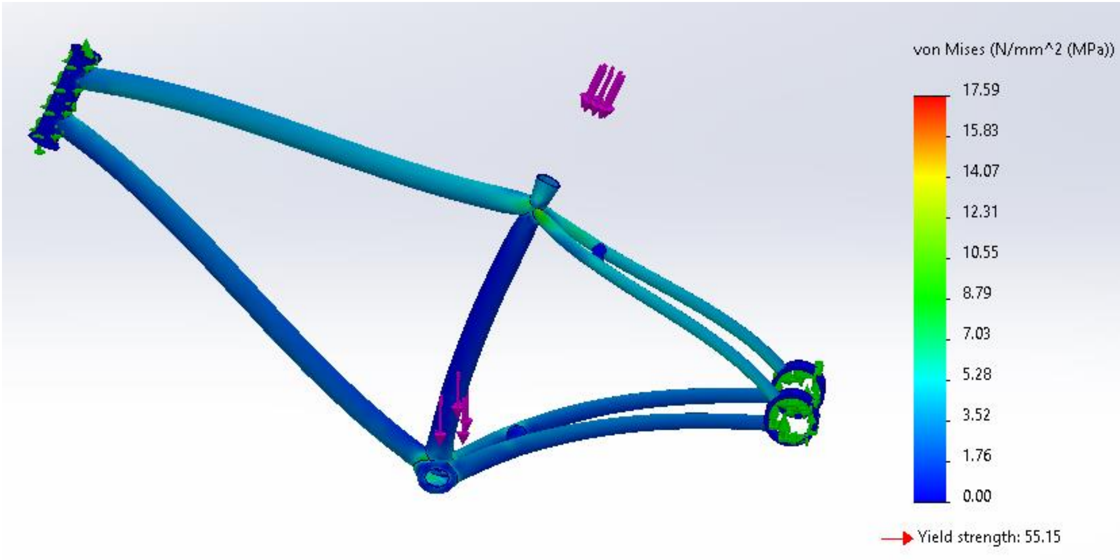

Figure A3: Max von Mises Stress experienced by frame with no filet with conditions outlined by the static startup conditions in figure 9.

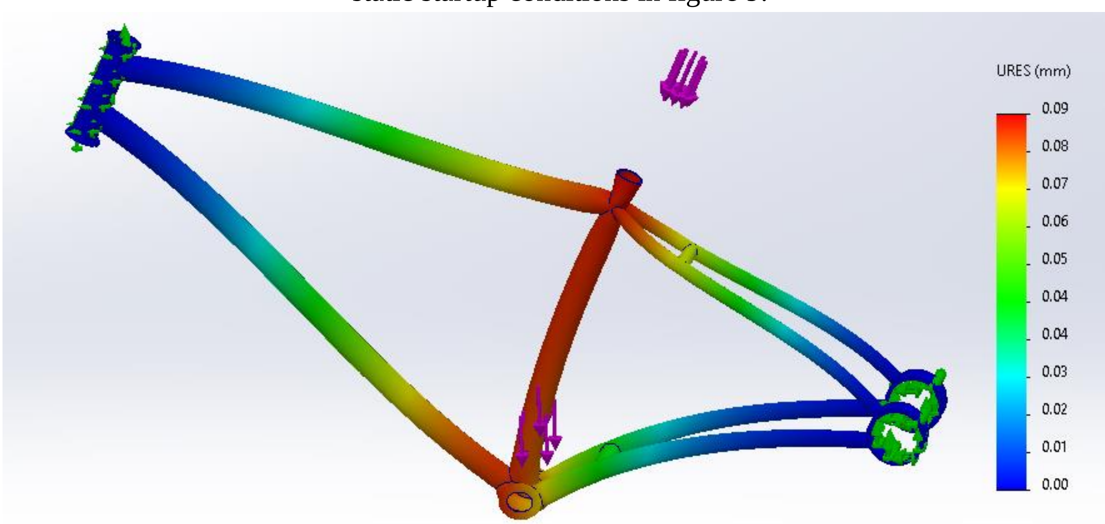

Figure A4: Max displacement experienced by frame with no filet with conditions outlined by the static startup conditions in figure 9.

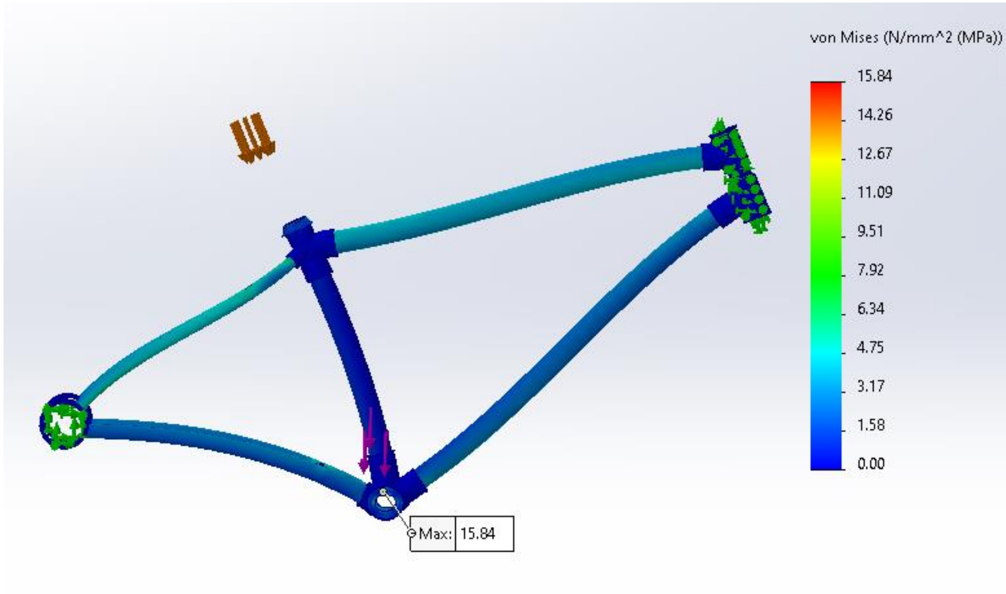

Figure A5: Max von Mises Stress experienced by frame with joint support made with Nylon 101 conditions outlined by the static startup conditions in figure 9.

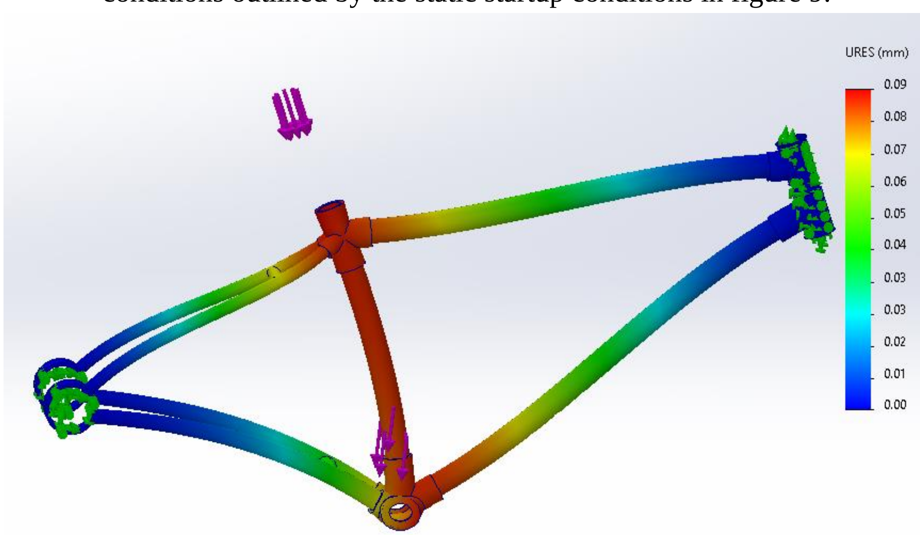

Figure A6: Max displacement experienced by frame with joint support made with Nylon 101 conditions outlined by the static startup conditions in figure 9.

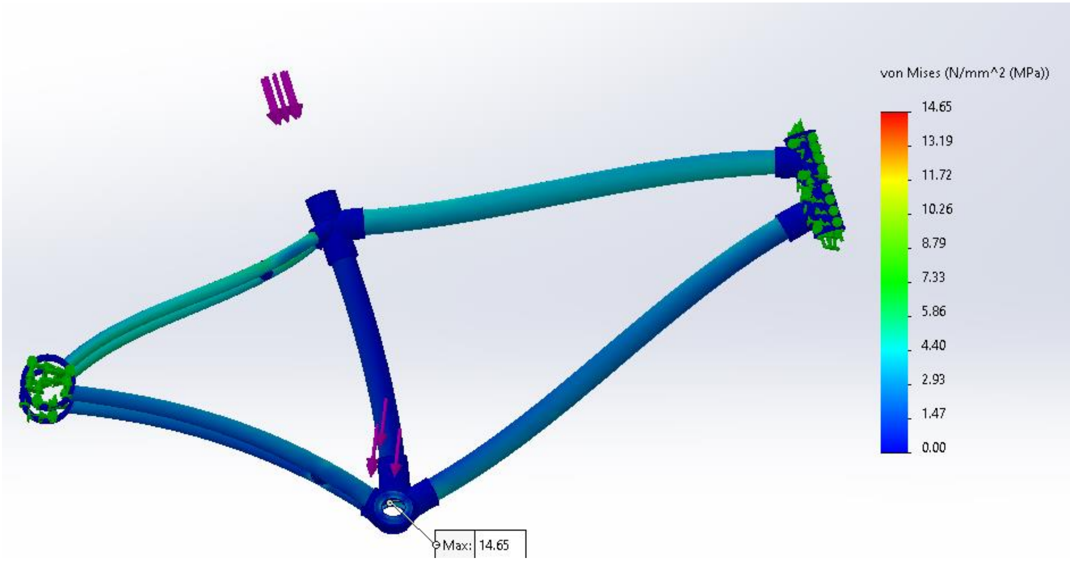

Figure A7: Max von Mises Stress experienced by frame with joint support made with ABS conditions outlined by the static startup conditions in figure 9.

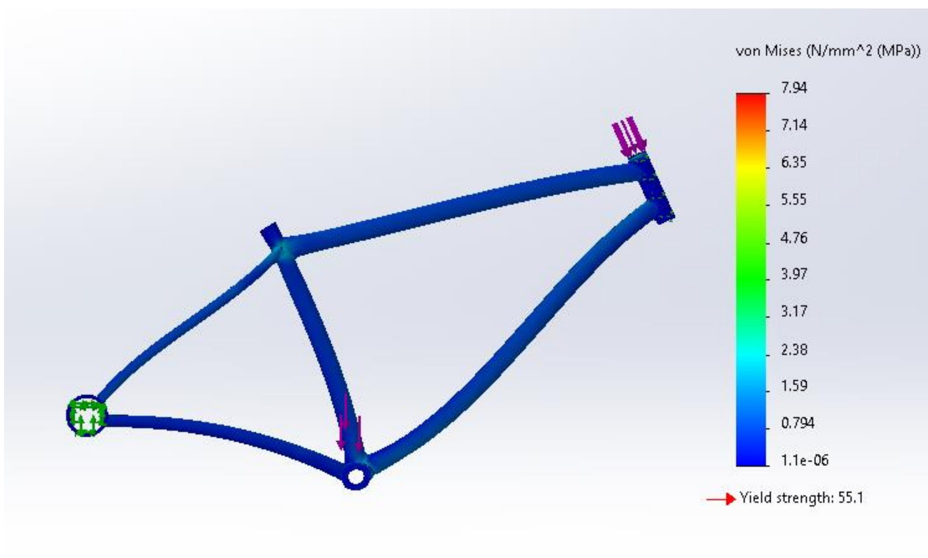

Figure A8: Max von Mises Stress experienced by frame with 5 mm filet conditions outlined by the steady state pedaling outlined by conditions in figure 10.

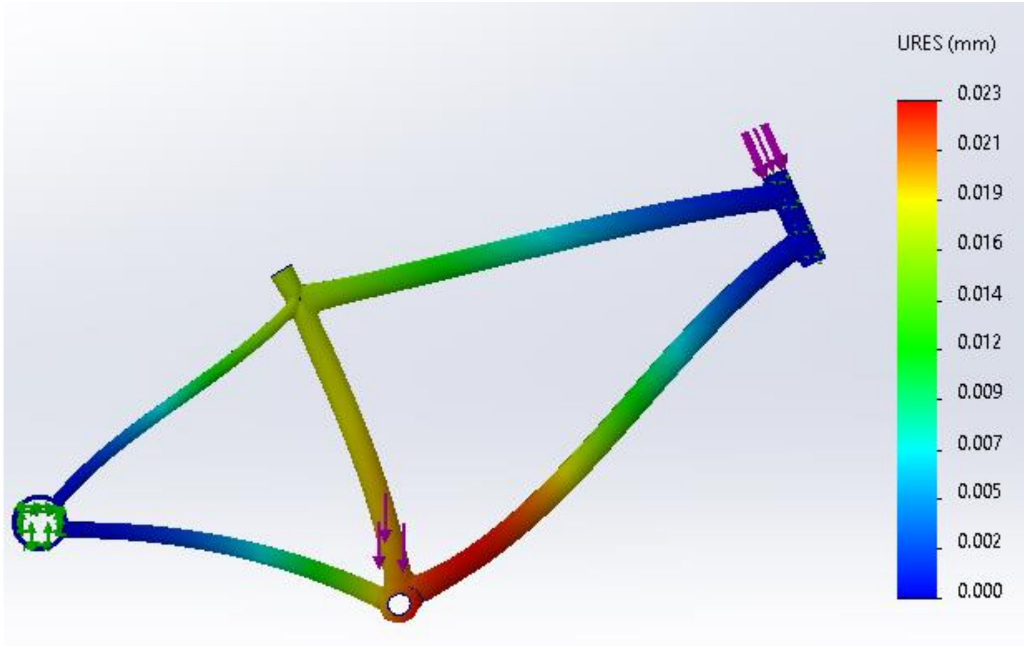

Figure A9: Max displacement experienced by frame with 5 mm filet conditions outlined by the steady state pedaling outlined by conditions in figure 10.

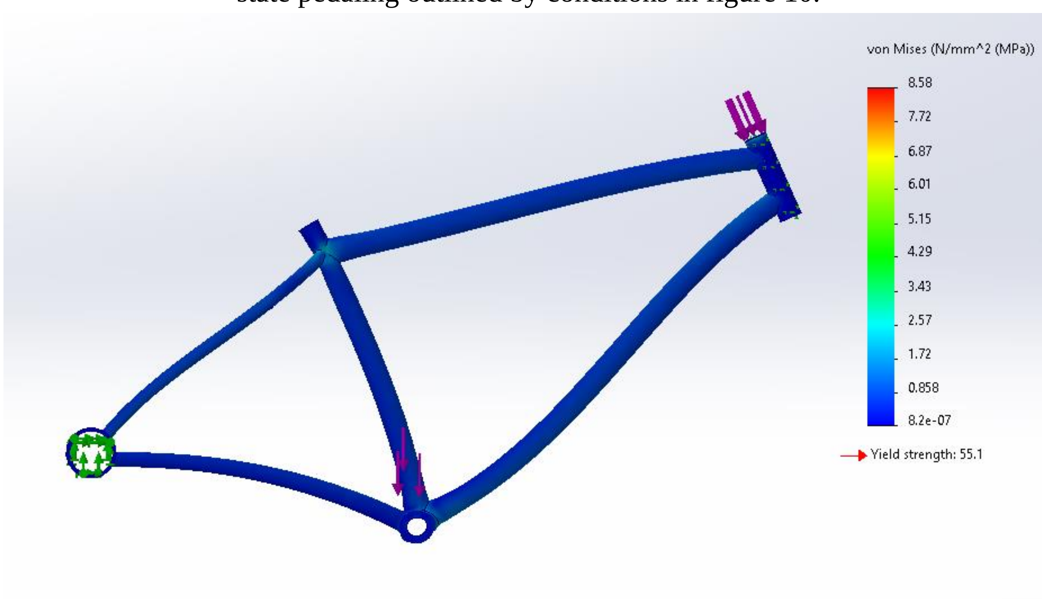

Figure A10: Max von Mises Stress experienced by frame with no filet conditions outlined by the steady state pedaling outlined by conditions in figure 10.

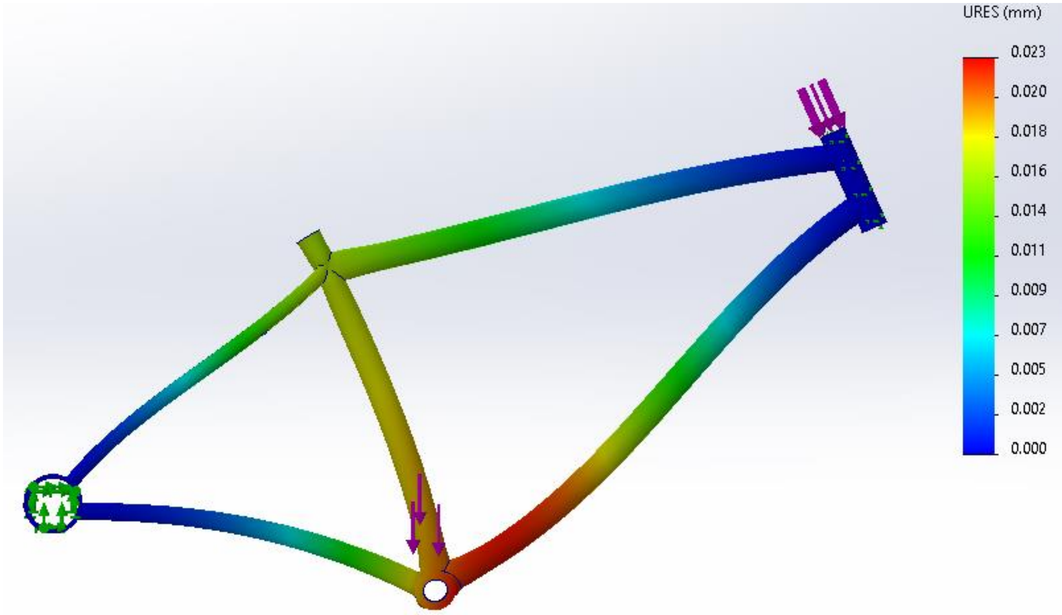

Figure A11: Max displacements experienced by frame with no filet conditions outlined by the steady state pedaling outlined by conditions in figure 10.

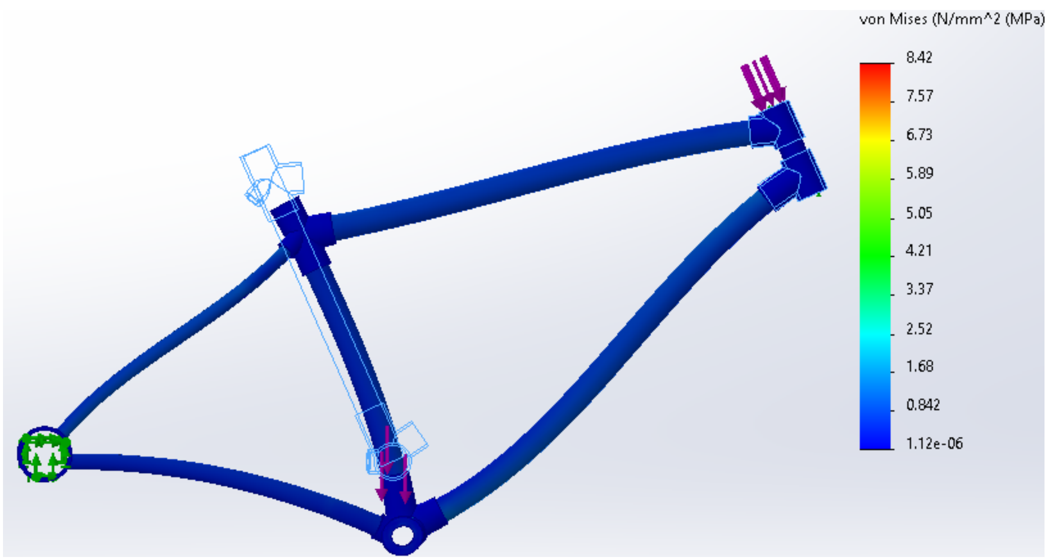

Figure A12: Max von Mises Stress experienced by frame with joint support made with ABS conditions outlined by the steady state pedaling in figure 10.

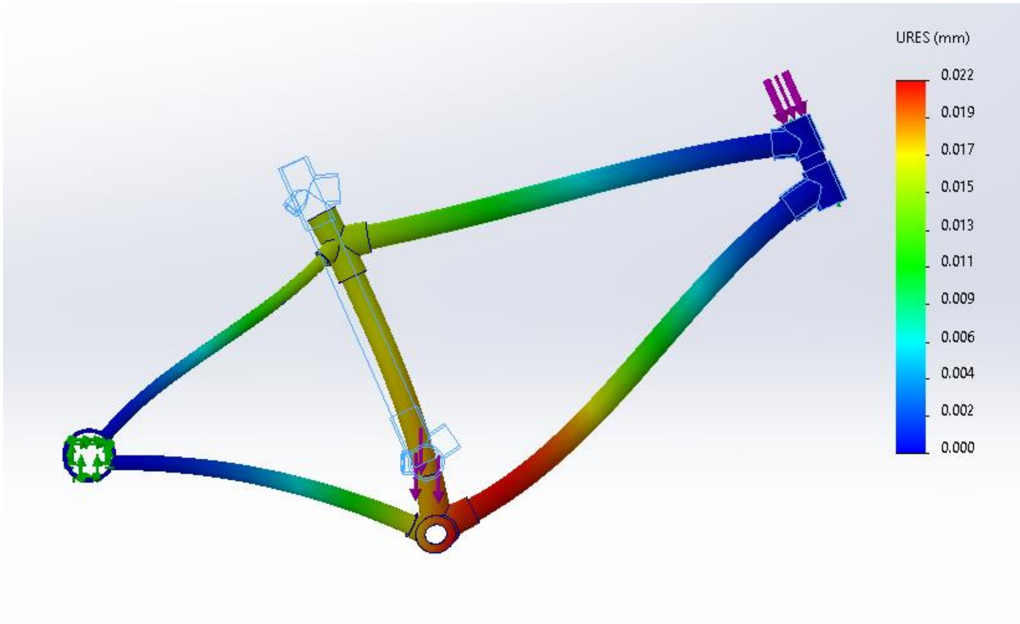

Figure A13: Max displacement experienced by frame with joint support made with ABS conditions outlined by the steady state pedaling in figure 10.

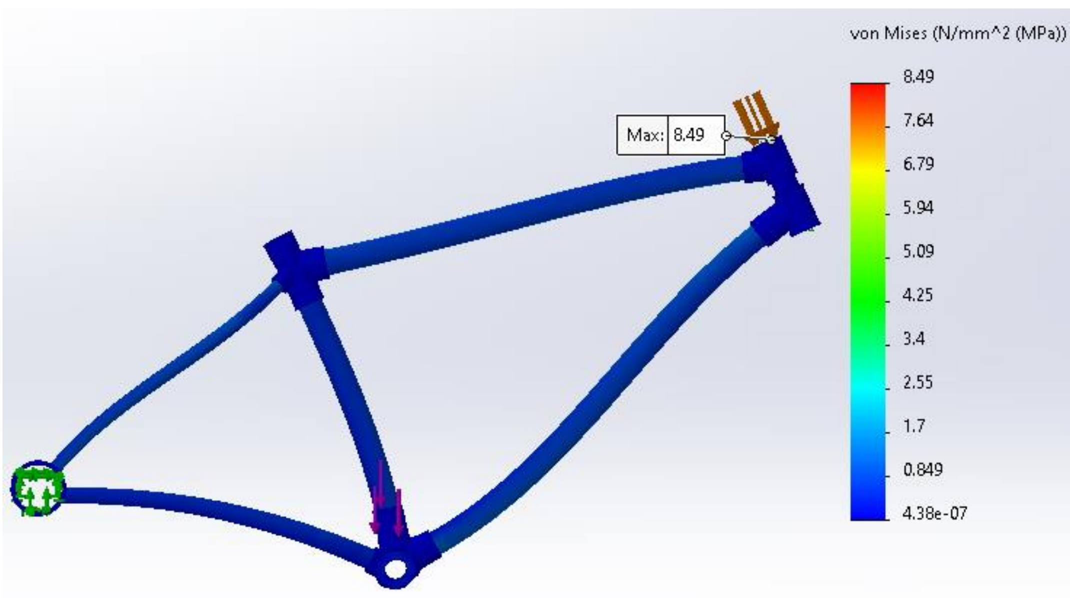

Figure A14: Max von Mises Stress experienced by frame with joint support made with Nylon 101 conditions outlined by the steady state pedaling in figure 10.

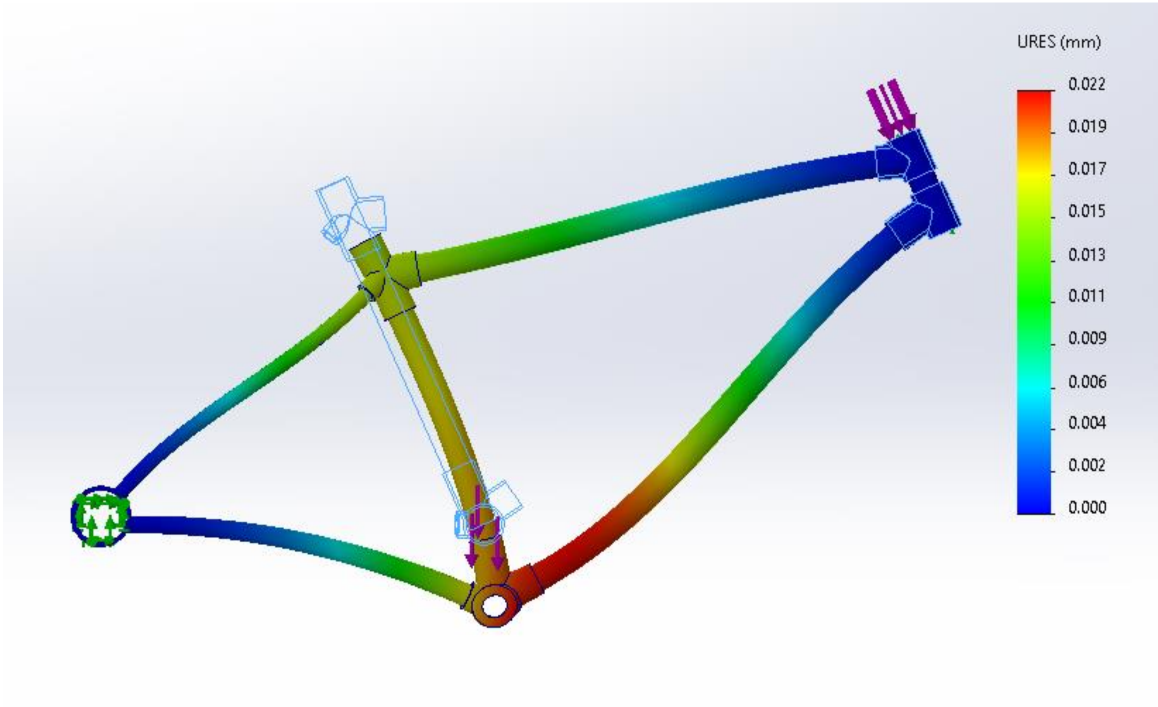

Figure A15: Max displacement experienced by frame with joint support made with Nylon 101 conditions outlined by the steady state pedaling in figure 10.

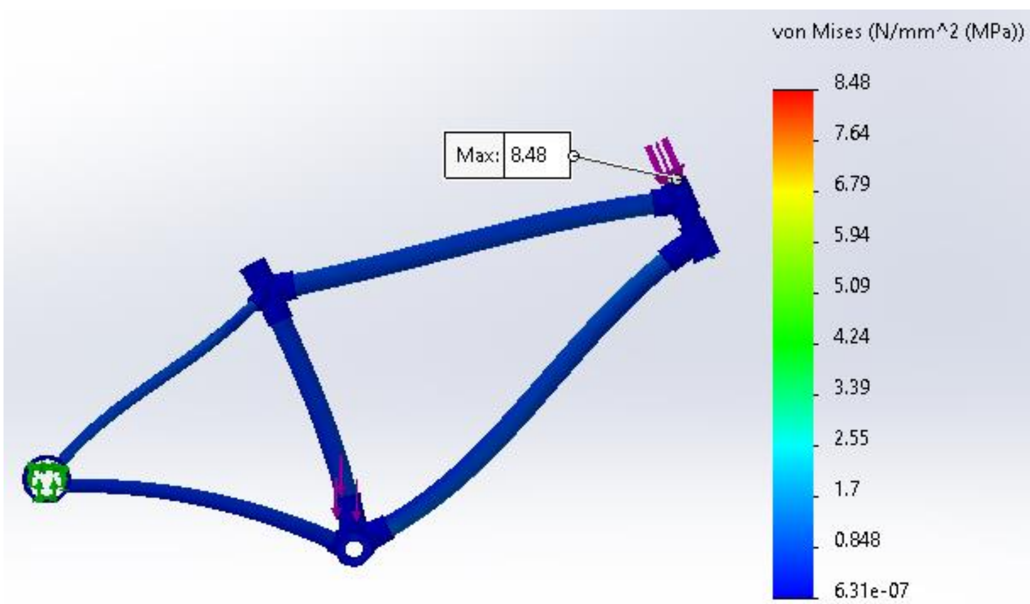

Figure A16: Max von Mises Stress experienced by frame with joint support made with HDPE conditions outlined by the steady state pedaling in figure 10.

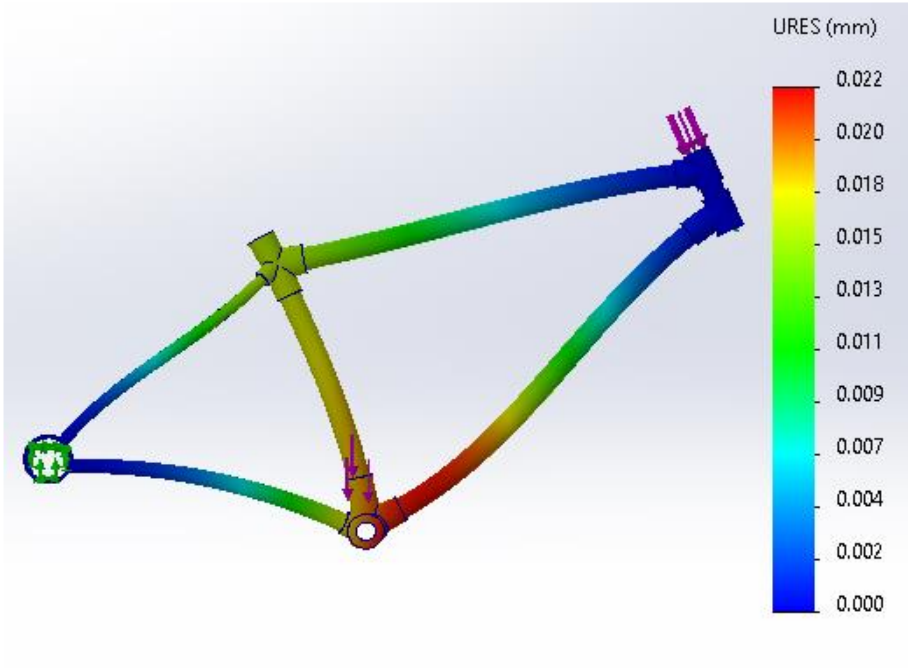

Figure A17: Max displacement experienced by frame with joint support made with ABS conditions outlined by the steady state pedaling in figure 10.

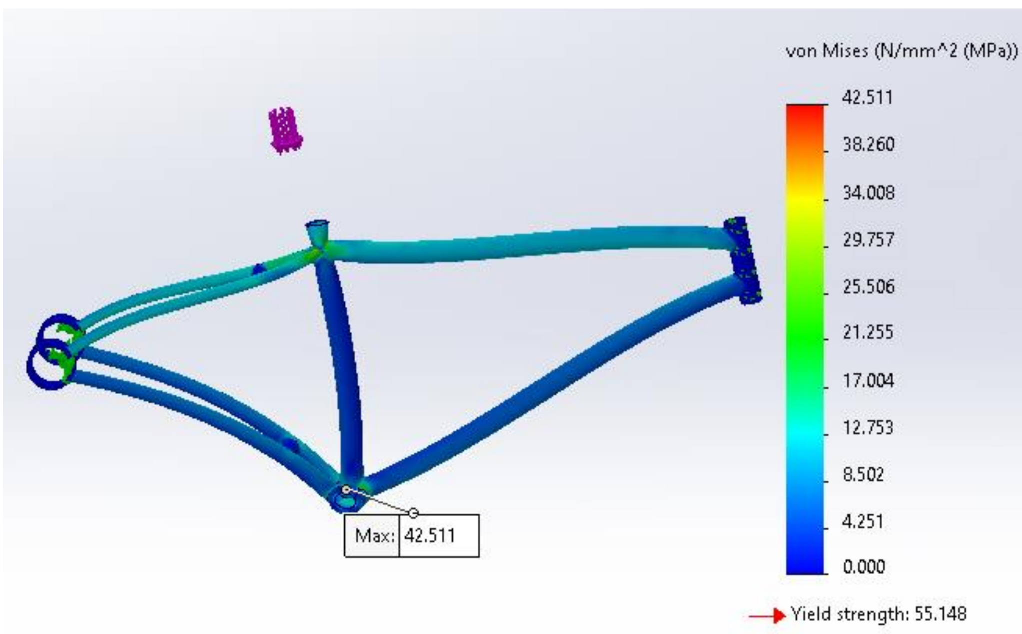

Figure A18: Max von Mises stress experienced by frame with 5 mm filet with conditions outlined by the vertical impact conditions in figure 11.

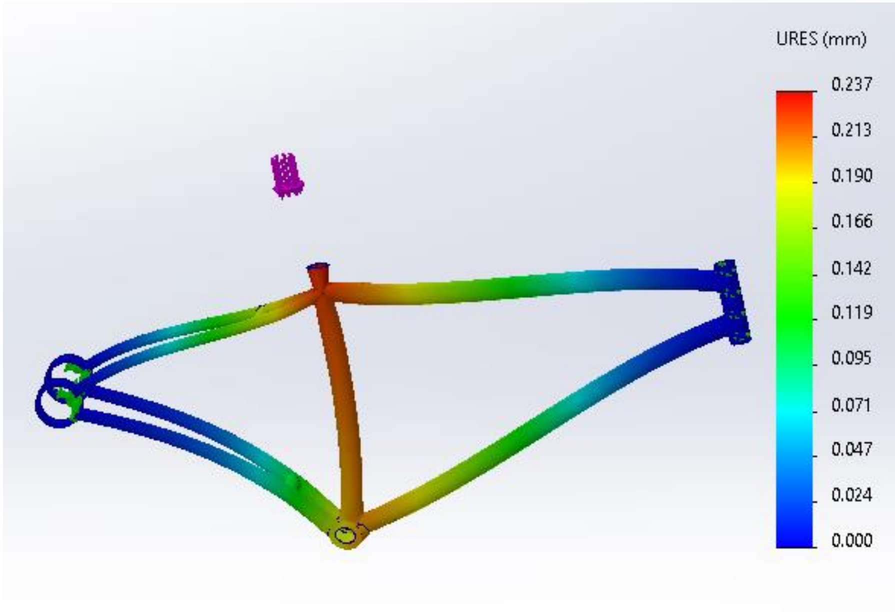

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Figure A19: Max displacement experienced by frame with 5 mm filet with conditions outlined by the vertical impact conditions in figure 11.

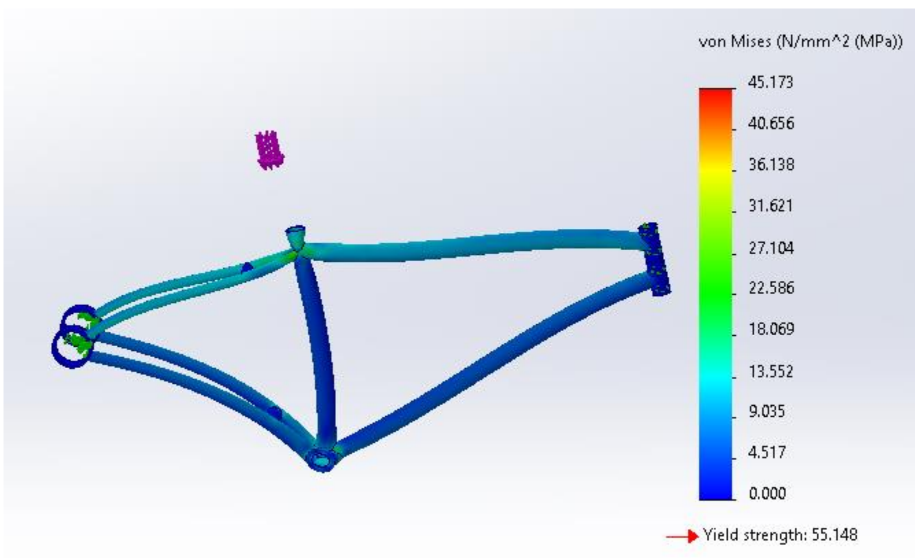

Figure A20: Max von Mises stress experienced by frame with no filet with conditions outlined by the vertical impact conditions in figure 11.

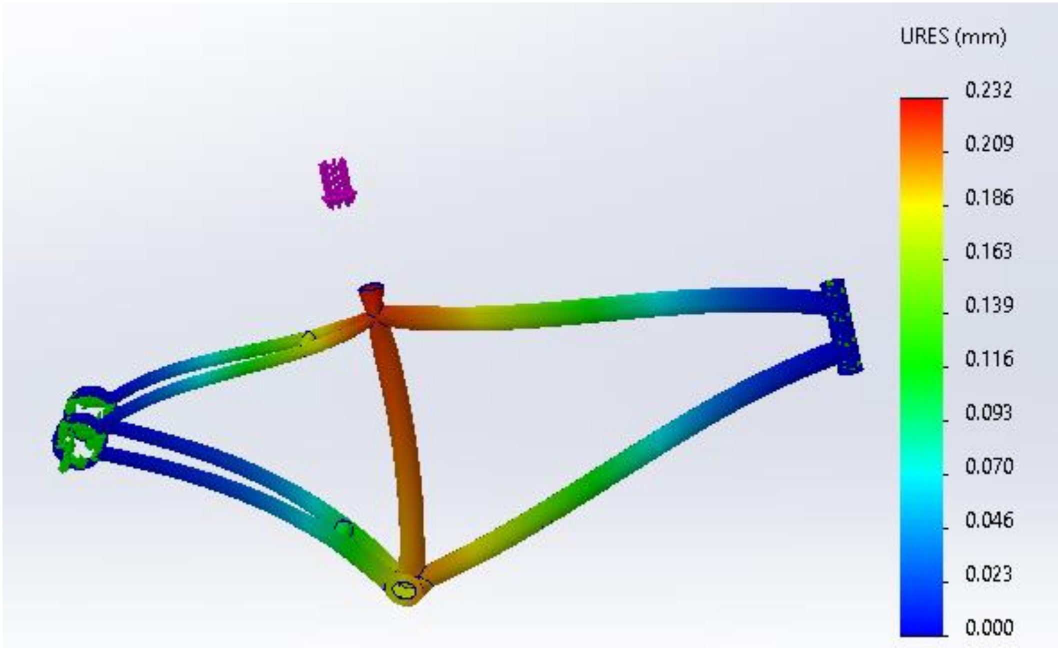

Figure A21: Max displacement experienced by frame with no filet with conditions outlined by the vertical impact conditions in figure 11.

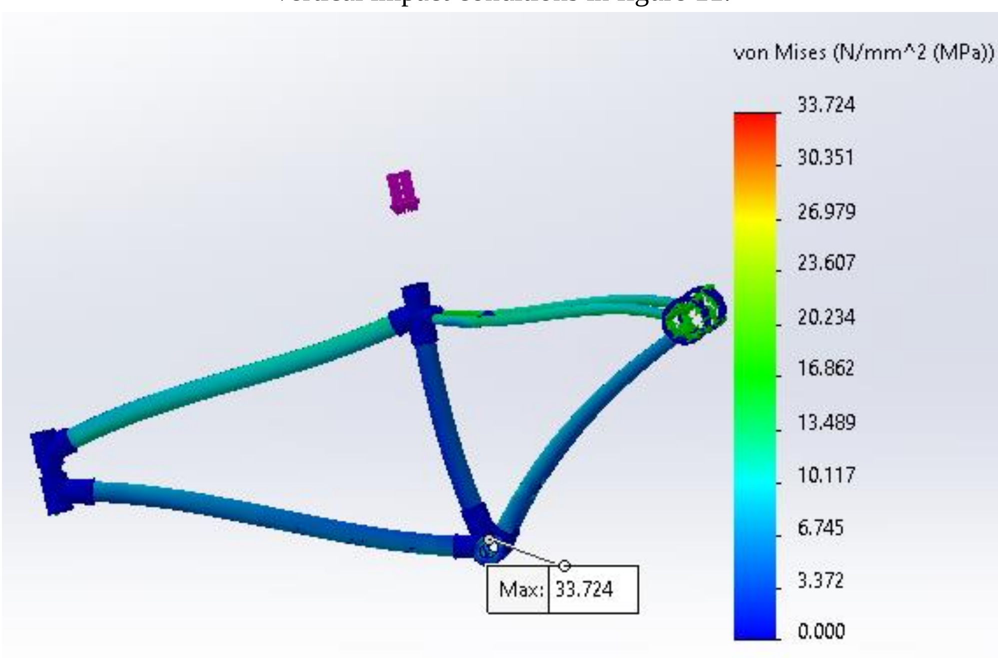

Figure A22: Max von Mises stress experienced by frame with ABS joint Support with conditions outlined by the vertical impact conditions in figure 11.

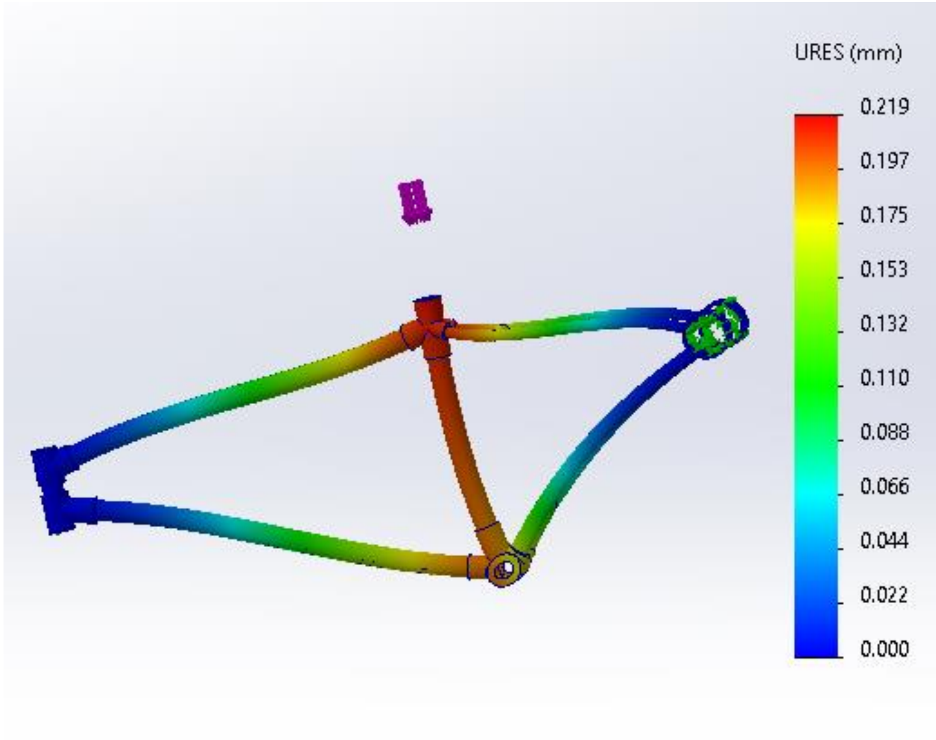

Figure A23: Max displacement experienced by frame with ABS joint Support with conditions outlined by the vertical impact conditions in figure 11.

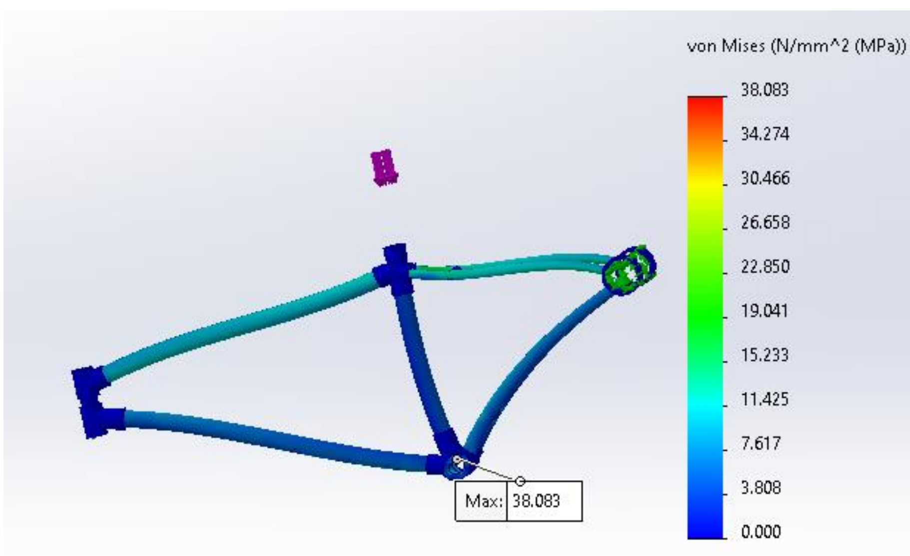

Figure A24: Max von Mises stress experienced by frame with Nylon 101 joint Support with conditions outlined by the vertical impact conditions in figure 11.

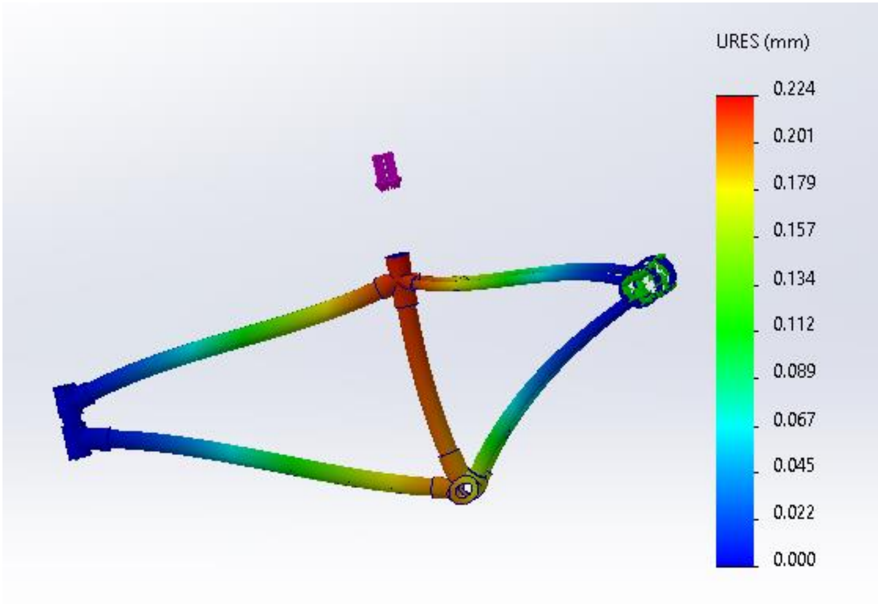

Figure A25: Max displacement experienced by frame with Nylon 101 joint Support with conditions outlined by the vertical impact conditions in figure 11.

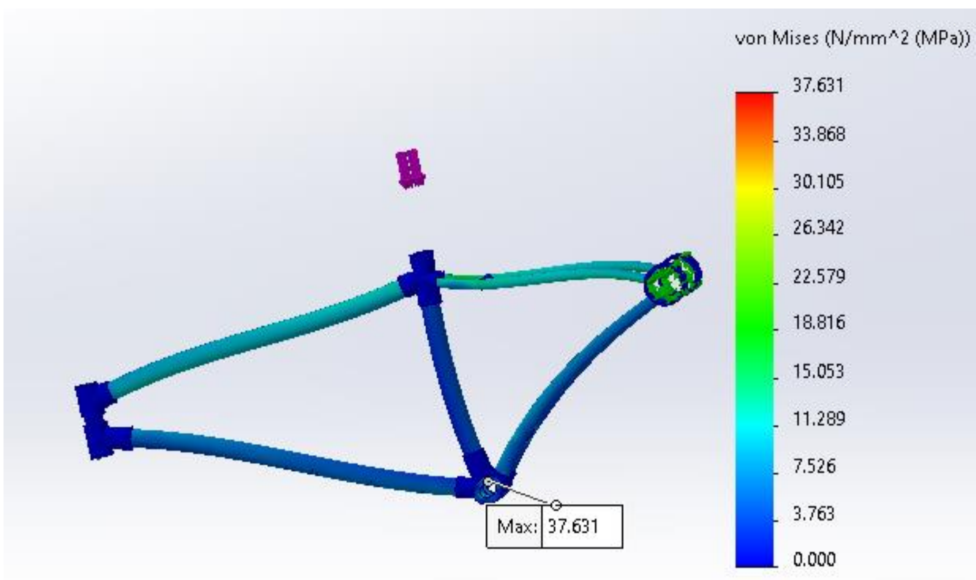

Figure A26: Max von Mises experienced by frame with HDPE joint Support with conditions outlined by the vertical impact conditions in figure 11.

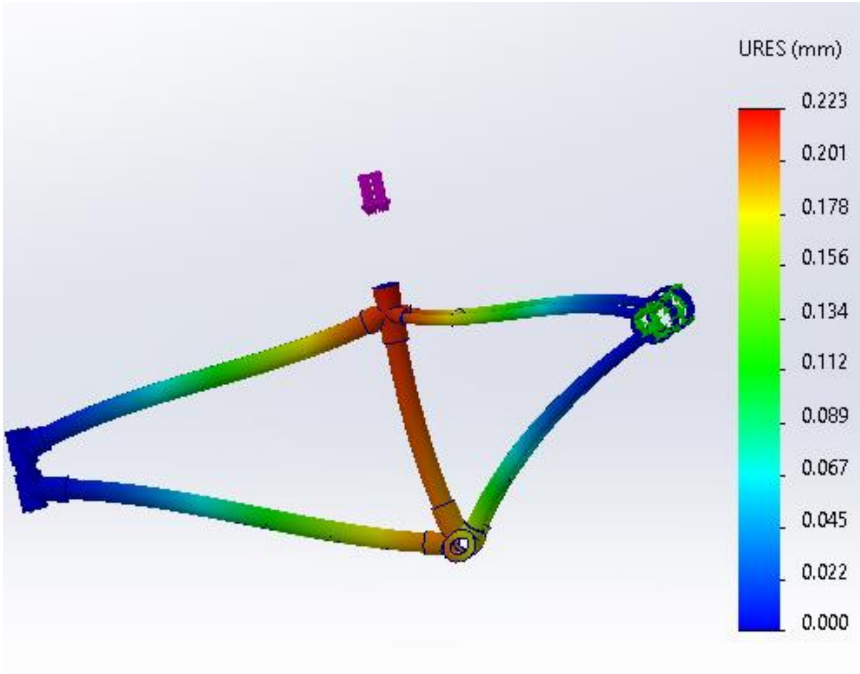

Figure A27: Max displacement experienced by frame with HDPE joint Support with conditions outlined by the vertical impact conditions in figure 11.