



MAJOR PROJECT

2020

TITLE:

Applying
contemporary design
and manufacturing
processes to the
Mountain bike
industry.

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1 ABSTRACT

This project is a feasibility study of the application of generative design and additive manufacturing in the development and manufacture of a mountain bike. This was done by developing the swingarm and link arm of the rear suspension linkage system using generative design and constrained by additive manufacturing. A continuous carbon fibre 3D printer and required material were chosen due to it having similar properties to the prepreg carbon fibre, which is used in the manufacturing of these components. The outcome of the generative design was chosen based upon the lowest mass of the component. Finite element analysis was carried out on the generative design components and compared to the results of their original counterparts. The link arm outperformed the original component in almost all measured value with a fifty-six per cent mass reduction. The swingarm was substandard on almost all values with additional mass. Due to this being the first development stage, there is room for improvement once the geometry changes for brake mount and bearing inserts are accounted in the next phase. The print time and cost of the generative design components if manufactured, were found to be reasonable when compared to a similar additive manufacturing processes for a bike company. However, after the understanding the load paths and stress concentrations, it was found that a hybrid approach of additive manufacturing lugs and premade carbon fibre tubes would be the most feasible option if additive manufacturing was to be used across the bike industry. Generative designs is a game-changer in the world of design; it levels the playing field, and now small companies can compete with the big bike companies.

2 TABLE OF CONTENTS

1	Abstract.....	0
3	Acknowledgements.....	3
4	Table of Abbreviations	4
5	Figures	5
6	List of Tables	7
7	List of Graphs	8
8	List of Appendices	8
9	Introduction	10
10	Aim of Project	11
11	Methodology.....	12
11.1	First Phase	12
11.2	Second Phase	12
11.3	Phase Three.....	13
11.4	Phase Four.....	13
11.5	Phase Five	13
12	Theory	14
12.1	Mountain Biking.....	14
12.2	The Modern-Day Mountain Bike.....	16
12.3	Mechanical Linkages	16
12.4	Mountain Bike Linkage.....	17
12.4.1	Suspension Progression	18
12.4.2	Average Leverage Ratio	18
12.4.3	Anti-Squat & Pedal-Bob	19
12.4.4	Pedal Kick Back.....	19
12.4.5	Anti-rise.....	19
12.5	Enduro Mountain Bike	20
12.6	Material Selection	21
12.6.1	Carbon Fiber	22
12.6.2	Quality Issues	23
12.6.3	Environmental Impact.....	24
12.7	Additive Manufacturing (3D Printing).....	25
12.7.1	Additive Manufacturing in Mountain Bike Industry	26
12.7.2	Continuous Carbon Fibre Additive Manufacturing	29
12.7.3	Fused Deposition Modeling using Continuous Carbon Fiber.....	30
12.7.4	Cost Estimation	31

13	Computational Theory	31
13.1.1	Linear Static Analysis.....	32
13.1.2	Stress Theories	32
13.1.3	Element & Mesh.....	34
13.1.4	Shape Optimisation.....	35
13.1.5	Generative Design.....	36
13.2	Computational Methods.....	37
13.2.1	Fusion 360	37
14	Assumptions.....	37
14.1	Calculations.....	38
14.1.1	Equations & Calculations	38
14.2	Loading & Constraints.....	40
14.3	Meshing.....	40
14.4	Material.....	42
14.5	Manufacturing	43
15	Design Phase	44
15.1	Generative Design.....	45
15.1.1	Single Direction Load Swing Arm	47
15.1.2	Single Direction Load Link Arm	47
15.1.3	Multi-Directional Load Swingarm	48
15.1.4	Multi-Directional Load Link Arm	49
15.2	Shape Optimisation.....	49
15.2.1	Swingarm Shape Optimisation.....	50
15.2.2	Link Arm Shape Optimisation.....	53
16	FEA Results.....	56
16.1	Original Swingarm FEA.....	59
16.2	Generative Design Swingarm FEA.....	63
16.3	Original Link Arm FEA.....	67
16.4	Generative Design Link Arm FEA.....	71
16.5	FEA Evaluation	75
16.5.1	Swingarm Comparison	75
16.5.2	Link Arm Comparison.....	76
16.5.3	Von Mises & Maximum Principal	76
17	Next Development Stage	77
18	Cost Estimation	78
19	Conclusion.....	79
20	References	82
21	Appendix	92

3 ACKNOWLEDGEMENTS

The author would like to thank the following for their help and support throughout this project.

Kelvin Lake – Thank you for sharing your vast amount of knowledge and experience in this project.

Your passion for extreme sports has helped this project no end.

Ford Motor Company – For the opportunity and support through this project

4 TABLE OF ABBREVIATIONS

HL – Horst linkage

LDSP – Linkage driven single pivot

LR – Linkage ratio

IC – Instant centre

BB – Bottom bracket

CC – Centre of curvature

AS – Anti-squat

PD – Pedal bob

PK – Pedal kickback

AR- Anti-rise

CAE – Computer-aided engineering

CAD – Computer-aided design

FEA – Finite element analysis

AM – Additive Manufacturing

OEM – Original equipment manufacturer

FDM – Fused deposition modelling

CCF – Continous carbon fibre

GD – Generative design

SO – Shape optimisation

TO – Topology optimisation

AI – Artificial intelligence

5 FIGURES

Figure 1 Orbea Rallon Linkage System Explained	17
Figure 2 Anisoprint Composite Fiber Coextrusion Diagram	30
Figure 3 Example of Anisoprint CCF layup	30
Figure 4 First Order Tetrahedral Element.....	34
Figure 5 Second Order Tetrahedral Element	34
Figure 6 Load Path Colour Scale of Chain Stay.....	35
Figure 7 Axle Loading Condition CAD Model	40
Figure 8 Original Swing Arm CAD Model	44
Figure 9 Orginal Link Arm CAD Model	44
Figure 10 Original Complete Bike CAD Model	45
Figure 11 Preserved Geometry Swingarm	45
Figure 12 Starting Shape Swingarm	46
Figure 13 Starting Shape	46
Figure 14 Preserved Geometry	46
Figure 15 Generative Design Swingarm Single Load.....	47
Figure 16 Generative Design Link Arm.....	47
Figure 17 Area of Concern Link Arm	47
Figure 18 Preserved Geometry Swingarm	48
Figure 19 Generative Design Swingarm	48
Figure 20 Preserved Geometry Link Arm	49
Figure 21 Generative Design Link Arm.....	49
Figure 22 Preserved Geometry Swingarm Shape Optimisation	50
Figure 23 Shape Optimisation Results Swingarm	50
Figure 24 Comparison of Shape Optimisation and Generative Design Swingarm.....	51

Figure 25 Side View of Comparison of Shape Optimisation and Generative Design Swingarm.....	52
Figure 26 Front View of Comparison of Shape Optimisation and Generative Design Swingarm.....	52
Figure 27 Preserved Geometry Link Arm	53
Figure 28 Link Arm Shape Optimisation Model	53
Figure 29 Rear View of Comparison of Shape Optimisation and Generative Design Link Arm	54
Figure 30 Comparison of Shape Optimisation and Generative Design Link	54
Figure 31 Side View of Comparison of Shape Optimisation and Generative Design Link Arm	55
Figure 32 Side View Comparison of Shape Optimisation and Generative Design Link Arm.....	55
Figure 33 Surface Probs at Max Stress and Strain with Equivalent Strain as Measurable on Swingarm	57
Figure 34 Surface Probs at Max Stress and Strain Location with VonMises Strain as Measurable on Swingarm	57
Figure 35 Max 1st Principal Stress Original Swingarm.....	60
Figure 36 Max VonMises Stress Original Swingarm.....	60
Figure 37 Max Equivalent Strain Original Swingarm.....	61
Figure 38 Max 3rd Principal Stress Original Swingarm	61
Figure 39 Max Displacement Original Swingarm	62
Figure 40 Max VonMises Stress Generative Design Swingarm.....	64
Figure 41 Max 1st Principal Stress Generative Design Swingarm.....	64
Figure 42 Max 1st Principal Strain Generative Design Swingarm	65
Figure 43 Max Equivalent Strain Generative Design Swingarm.....	65
Figure 44 Max 3rd Principal Stress Generative Design Swingarm	66
Figure 45 Max Displacement Generative Design Swingarm	66
Figure 46 Max 1st Principal Stress Link Arm	68
Figure 47 Max VonMises Stress Link Arm	68
Figure 48 Max 1st Principal Strain Link Arm	69

Figure 49 Max Equivalent Strain Link Arm	69
Figure 50 Max 3rd Principal Stress Link Arm	69
Figure 51 Displacement Side View Link Arm.....	70
Figure 52 Max Displacement Link Arm	70
Figure 53 Max Von Mises Stress Generative Design Link Arm	72
Figure 54 Max 1st Principal Stress Generative Design Link Arm	72
Figure 55 Max 3rd Principle Stress Generative Design Link Arm.....	73
Figure 56 Max Equivalent Strain Generative Design Link Arm	73
Figure 57 Max Displacement Generative Design Link Arm.....	74
Figure 58 1st Principal Strain Generative Design Link Arm.....	74

6 LIST OF TABLES

Table 1 Easy Composites Carbon Fiber Data Sheet	22
Table 2 1st Order Meshing Experiment Results.....	41
Table 3 2nd Order Meshing Experiment Results	42
Table 4 MarkForged CFF Properties.....	58
Table 5 Original Swingarm FEA Results.....	59
Table 6 Generative Design Swingarm FEA Results.....	63
Table 7 Original Link Arm FEA Results	67
Table 8 Generative Design Link Arm FEA Results	71
Table 9 Swingarm Comparison Matrix.....	75
Table 10 Link Arm Comparison Matrix.....	76
Table 11 Cost of Components.....	78

7 LIST OF GRAPHS

Graph 1 Growth of 3D Printer Manufactures from 1985-2019	25
Graph 2 3D Printing vs Traditional Manufacturing.....	26
Graph 3 3D Printing Growth & Cost Projection.....	26

8 LIST OF APPENDICES

Appendix 1 MarkForged Carbon Filament Data Sheet.....	91
Appendix 2 Anisoprint Composite Carbon Fibre Properties.....	92
Appendix 3 Easy Composite Carbon Fibre Sheet Data Sheet.....	93
Appendix 4 Performance Composite Carbon Fibre Data Sheet.....	94
Appendix 5 Max von Mises Stress FEA Results Swingarm.....	95
Appendix 6 Max Equivalent Strain FEA Results Swingarm	96
Appendix 7 Max Displacement FEA Results Swingarm	97
Appendix 8 Max von Mises Stress FEA Results Generative Design Swingarm	98
Appendix 9 Max Equivalent Strain FEA Results Generative Design Swingarm	99
Appendix 10 Max Displacement FEA Results Generative Design Swingarm	100
Appendix 11 Max von Mises Stress FEA Results Link Arm	101
Appendix 12 Max Equivalent Strain FEA Results Link Arm.....	102
Appendix 13 Max Displacement FEA Results Link Arm.....	103
Appendix 14 Max von Mises Stress FEA Results Generative Design Link Arm.....	104
Appendix 15 Max Equivalent Strain FEA Results Generative Design Link Arm.....	105
Appendix 16 Max Displacement FEA Results Generative Design Link Arm.....	106
Appendix 17 Link Arm Print Time.....	107

Appendix 18 Swingarm Print Time.....	108
Appendix 19 Link Arm Generative Design Report.....	109
Appendix 20 Swingarm Generative Design Report.....	112

9 INTRODUCTION

Now mountain biking is becoming more of a mainstream sport due to the recent explosion of social media. Marketing companies such as Redbull are investing heavily in TV and internet streaming of mountain bike competitions as UCI, Rampage and Crankworx (Redbull, 2020). Mountain biking has expanded all over the world now. The vast expansions have brought intense competition between companies. Generally, bikes are bought and kept for several years by a customer. This is why bike companies always bring a new feature out every year to entice new customers to upgrade there bike. Companies like to be seen to be innovating if that is to increase sales or have the edge over the competition. In the ever-changing mountain bike industry, there is always a need for improvement; even if the improvement may not be necessary. With the advancements of computer-aided engineering and advance manufacturing techniques, these changes can now be made as a purposeful improvement rather than a new feature to increase sales. In this project, the adoption of generative design as the design methodology with the use of additive manufacturing to manufacture the outcome. These such tools are being widely adopted into industries where strength and mass have enormous implications. The adoption of these tools in aerospace and formula one are examples of some. Airbus and Autodesk revealed there bionic partition 2.0, a wall and jumpseat support structure that was forty-five per cent lighter than the original with equal strength, which would save half a million metric tones of CO2 emissions a year (Autodesk, 2019). While Mercedes AMG Patronas Motorsport is using generative design and additive manufacturing to reduce the weight of suspension components (Ruto, 2020). With industry such as these investing heavily in these tools, it is fair to say that they are the future.

With the accessibility of generative design now being incorporated in many CAD packages and the ability to constrain designs based on manufacturing processes, it is now an achievable prospect that the bikes of the future may be designed using generative design. An early adoption of this in the

mountain biking industry is Starling Cycles who have started using generative design on their swingarm, while still in prototype stage this may be the start of a change in the industry for the better (Pearce, 2020). This project will explore if generative design can improve the design of linkage components using these advance design and manufacturing tools. The outcomes of the designs will be verified by using finite element analysis with the assumed value of their environment.

10 AIM OF PROJECT

This project aims to challenge the status quo of the mountain bike industry. Mountain bikes since the beginning have been designed with tube-like structures as the way to construct frame and linkages; this project sets out to change such established designs. Company's such as Starling Cycles and Pole Bicycles have done just that by changing how bikes are made and what they are made from. Now with the social media giving far more exposure to smaller companies who are not as established as Giant, Trek or Specialized (Market Research Future, 2020) which are already heavily invested in the traditional manufacturing techniques. It allows a chance for smaller companies the ability to innovate and become the new standard. While the aim is to improve the current components using generative design, the aim is also to see if generative design and additive manufacturing can be a direct replacement for the current well-established process.

With the use of Autodesk generative design and additive manufacturing constraints, components of a full suspension enduro bike will be redesigned. The GD components will be evaluated against there original components with the FEA results being the measurable values.

11 METHODOLOGY

This section gives the method of how the aims will be achieved. The development is broken into phases which will allow for better evaluation. Furthermore, if a problem did arise, it can be easily identified.

11.1 FIRST PHASE

The first phase of the development will be to design the bike using Autodesk Fusion 360. Each component is designed as the original equipment manufacturer intended. Due to the dimensions of components not being available, measurements from a bike will be used. Once each component is created, critical geometries will be identified for the use in GD. Each component will have standardised material so a comparison can be made from FEA results.

11.2 SECOND PHASE

The second phase will be a researched base phase. Assumptions of the mass of the rider and potential energy of the bike from a given height will be calculated. The calculations made will give an estimated load and direction to allow for simulation to be carried out. Research into AM manufacturing processes and materials will be carried out. This will allow for assumptions of materials and manufacturing cost estimations to be made.

Once the load has been assumed, the mesh size and quality of the mesh will be determined. This will be done by creating a static load simulation of the swing arm which has the most complicated geometry of all the components of the linkage system. A standard simulation is used, but the mesh size will be reduced incrementally, and the max stress, strain and solve time will be recorded until either the computational time is excessive or the difference in max stress is minimal. This will be carried out with parabolic and linear element orders to see which one will give the most accurate

results. Using the optimised mesh size and order FEA can be carried out on each component. This will give baseline data for which the new designs to be compared and evaluated.

11.3 PHASE THREE

A single directional load GD simulation will be done first to understand the outcomes and what factors affect the outcome. The single load will be done to reduce the solve time, thus speed up the development process. A multi-directional loaded GD and SO simulation will be carried out. The GD and SO outcomes will be compared visually to see how the manufacturing constraints of GD have differed the outcomes.

11.4 PHASE FOUR

FEA simulations of the GD outcome and the original components will be carried out. The results will be compared using values of the FEA such as stress, strain, mass and displacement.

11.5 PHASE FIVE

Further development stages will be stated of the components if the designs were to be pursued. Also, a justification argument of the use of GD and AM for the design and manufacture of mountain bike components will be given against the traditional techniques.

12 THEORY

This section will give a better understanding of the mountain biking industry and how advanced design and manufacturing techniques can be used to innovate the current well-established process. Furthermore, background information on computational development, material selection and manufacturing methods will be given.

12.1 MOUNTAIN BIKING

The mountain bike industry is now a global industry, with the most prominent regions in America, Europe and the Asia Pacific (Market Research Future, 2020). With the US market worth 6.2Bn USD (Statista, 2019) and the UK industry worth nearly 1Bn GBP (Cycling Industry, 2019) in 2019. With a projected worldwide growth of a further 2.52bn USD by 2024 (Report Linker, 2020), it is only going to larger. Companies such as Giant who are said to be one of the biggest in the industry made record revenue in 2019 of 2.1bn USD (Bicycle Retailer, 2020). The increase in value is down to many factors; social media, marketing and e-bikes.

One company who has been prevalent in the industry is Redbull who have since 1988 have been sponsoring mountain bike competitions (Redbull, 2020). Now they have an internet streaming service, sponsor athletes, make extreme sports films and have their own competitions. With this amount of exposure, it is no wonder the mountain bike industry is growing exponentially. This exposure is even aiding smaller companies with sales. Starling Cycles a garaged based firm at the time had a review in Dirt Magazine regarding a bike (Dirt Mountainbike, 2017). While Dirt magazine is a UK based magazine due to the social media presence and available worldwide, Starling Cycles had thirty orders in the first week of the review from across the world (NSMB, 2018). The excellent review did not come without its merit; the Starling Cycles bike was ahead of its time with regards to geometry and material

selection. Now smaller firms such as Starling Cycles and Pole Bicycles who push the boundaries with regards to design and manufacturing of bikes have exposure and a worldwide market.

With the increased sales volume year on year and with very little in radical innovation, why does the price of mountain bike still rise year on year? With new components commonly being a slight deviation from an existing model but the price always seems to increase from the previous years model. An interview with Nick Murdick, the product manager of Shimano said: *"We set a target price for a product first, and then figure out how to get there"* (Murdick, 2018). With this ethos, the price of mountain bikes will only increase over time if a company like Shimano who generally set the price of components are doing such thing. An example of this price increase was shown by Seb Scott from Bikeradar, who looked at the price of a Specialized Enduro from 2013 and 2019. The 2013 base model was £2,600, and in 2020 the same model is £4,500 (Scott, 2020). Accounting for inflation, the 2013 model would cost £3,000 in 2019 (Bank of England, 2020). The most significant change of these models is with the geometry, which is an indirect fixed cost which is not proportional to manufacturing volumes. Generally, in manufacturing, once a product is matured such as the Specialised enduro the price per unit will decrease with economies of scale and by adopting lean manufacturing principals. However, as seen, the price has increased over time. This increased cost could be due to the increased tariffs, labour and transport costs. With ninety-five percent of all bike bought in the US being made in Asia (Bicycle Universe, 2020), it is clear that this may not be the best practice. Giant have started to move their bike manufacturing to the US and Europe to save on such cost implications (Bloomberg, 2019). With the shift from Asian manufactured bikes to US and European, it is an opportunity for bike companies to start fresh and to change the manufacturing process altogether. This could see the adoption of industry 4.0 methodologies in manufacturing methods. Automotive manufactures such as Ford Motor Company, General Motors and Volkswagen Group have adopted industry 4.0 due to their high volume (Dutt, et al., 2020). With the bike industry have that expected growth over the next four years, the investment in industry 4.0 can be warranted.

12.2 THE MODERN-DAY MOUNTAIN BIKE

Today's all-mountain bikes are commonly full suspension. In the early 2000s, having a full-suspension mountain bike would be a trade-off between control and comfort of going downhill and pedal efficiency of going up (UCI, 2019). Now with advancements in mountain bike design, a modern-day full suspension bike can pedal uphill as good as hard-tail and descend like a downhill bike (MBR, 2020). This advancements in bike geometry design have been the most significant innovation in recent times. However, these advancements are reaching their limits

The modern-day full suspension mountain bike is comprised of a frame, rear suspension linkage, front suspension, wheels, brakes and drivetrain. These fundamentals components have not changed for decades; however, the design and compliance of these have.

The rear suspension design of the bike has been a primary contributing factor in the increased pedal efficiency and bike control of the modern bike. To understand this further, the suspension needs to be detailed as its simplest form.

12.3 MECHANICAL LINKAGES

Firstly an understanding of what a mechanical linkage is and what relation it has with a mountain bike. A mechanical linkage can be defined as an assembly of rigid bodies connected by joints that provide constrained motion in a mechanical system (Reuleaux, 1963). The purpose of the linkage is to provide output motion in response to an input motion (Slocum, 2008). A linkage must contain at least two nodes which are the attachment points to other links via joints. The order of a link can be determined by the number of nodes that the link is connected to which can be named as followed: binary two nodes, ternary three nodes, and quaternary four nodes (Richards, 2014). A mechanical system is a kinematic chain when one link is grounded, such as a frame; therefore, a point of reference (McCarthy & Soh, 2011). The point of reference will be the point of motion of the other links.

12.4 MOUNTAIN BIKE LINKAGE

To give more clarity of the mechanical linkage of a mountain bike, as seen in Figure 1, it indicates the components of the linkage system. All blue arrows indicate the pivot points (nodes) while the orange arrows indicate the components bars (links).



Figure 1 Orbea Rallon Linkage System Explained

In the environment of mountain biking when defined to the mechanical linkage definition, as seen in Figure 1. The input motion is the impact of the bike while absorbing terrain or shocks while the output motion is the axle path of which the rear axle follows to keep the wheel in contact with the terrain. The primary function is to keep the wheel of the mountain bike in contact with the terrain as much as possible while absorbing shocks thus giving the rider far more control of the bike (Bu, et al., 2010').

The interpretation of the primary function of the suspension system can be seen in interviews with some of the leading minds in the mountain biking world such as Jose Gonzalez, the director of suspension at Trek Cycles which states *"The most important element of suspension in a sports application is to add or enhance control for the rider. This is more important than comfort, and it is why performance suspension, balances comfort, and control with the emphasis on enhanced control. It's more important to have predictability, stability, traction/ grip, good terrain tracking and feel along*

with a high level of bump absorption capability; but comfort doesn't trump those things" (Gonzalez, 2011).

Also, Dave Weagle the inventor of the Split Pivot suspension design and is regarded as one of the most influential people in suspension design said in an interview with MBR magazine: "The primary function of suspension on a mountain bike (or any vehicle for that matter) is supposed to be increased rider comfort and control through the mitigation of impacts at the wheels" (Weagle, 2011). Looking at what was said by Gonzalez and Weagle, it is clear to see that the most crucial function of suspension is bike control. However, just absorbing impacts does not directly give more control over the bike; it is far more complicated than that.

The suspension linkage system, coupled with other components such as chain tension, crank angle, shock actuation, and shock setup has a massive effect on the control of the bike (i-track suspension, 2020). These are defined throughout development in this report, the impact of the proposed design on these attributes is discussed. Here are some of the characteristics that have a direct link to control of a bike:

12.4.1 Suspension Progression

Suspension progression is the force required to compress the suspension through its travel. The force required will increase when the bikes goes further through its travel. A progressive suspension gives bottom-out resistance and thus allows the bike to use the full travel more efficiently but not excessively (Enduro-MTB, 2019).

12.4.2 Average Leverage Ratio

The leverage ratio of a mountain bike is the ratio between rear-wheel travel and shock stroke (Bikeradar, 2018). Having a shock stroke of 50mm does not equate to having 50mm of travel. The leverage ratio is heavily based upon the design of the linkage, and the curve of which it changes defines how a bike will feel absorbing impacts.

12.4.3 Anti-Squat & Pedal-Bob

Pedal bob is the force exerted on the bike by pedalling. The pedal stroke accelerates the bike in a forward motion which will shift the rider's weight back and forth. The pedal stroke will also force the suspension into compression, thus forcing further into its compression; however, the chain tension will counteract this force (Pole, 2015). Furthermore, due to the force only being exerted partially through the stroke, it's not a consistent movement thus, making the bike oscillate in rhythm with the pedal stroke.

Anti-squat is the amount of resistance that the linkage system contains to reduce pedal bob. This comes in two main forms: driving force from the rear wheel and chain pull force (Bikeradar, 2018).

12.4.4 Pedal Kick Back

Pedal kickback has a direct relationship to anti-squat in terms of the chain tension force. As stated chain pull force previously relies on the movement of the cassette when the suspension is in compression; the term of this occurrence is chain growth. The cassette will rotate clockwise allowing the suspension to compress due to slack in the chain (Pole, 2015).

If the cassette is unable to move due to it being locked up or the cassette is in slower rotation than the chain needs, it to be then crank will be forced to more counter-clockwise thus throwing the pedals back.

Based upon the relationship of chain pull force and anti-squat a relationship between the amount of pedal kickback and anti-squat can be calculated. If a bike has high anti-squat due to chain force tension, then the more pedal kickback is generated.

12.4.5 Anti-rise

Anti-rise is like anti-squat but in reverse. When the bike is in forwarding motion, and the rear brakes are applied to the rider's, weight is shifted forward. If theoretically, this motion is isolated with no other factor involved, the bike will rise out of the travel of the bike and braking traction will be reduced

(Pinkbike, 2020). When the braking force is applied, the brake calliper will move around the brake rotor counter-clockwise. Now if the brake calliper is brought into the motion and the braking force applied to the rotor, it will reduce the amount that the calliper moves around the disk rotor and will keep the suspension in compression (i-track suspension, 2020). The amount the suspension compress under braking is proportional to this movement around the disk. High levels of AR tend to make the suspension feel firmer and less reactive over smaller bumps; however, AR allows the bike to sit deeper into its travel more often. Anti-rise is a trade-off between the suspension being in travel that will give better braking traction or keeping the geometry of the bike while under braking.

While these characteristics of a bike are not directly used in this project, it is vitally important that they are thought of when considering the function of the bike and components which will have a direct connection to the strength, toughness, and weight of a bike.

12.5 ENDURO MOUNTAIN BIKE

To understand the loads that the bike will be under the function of the bike needs to be defined, thus allowing assumptions to be made for the development. The type of suspension linkage system that will be developed will be an enduro mountain bike system. To define an Enduro bike is still a subjective matter. Enduro is a form of mountain bike racing that entails riding from the bottom of a mountain to the top and back down again. This means the bike needs to be a hybrid of a gravity orientated long-travel downhill mountain bike but also needs the ability to climb mountains like a cross country bike. There is no set definition of what is classed as an enduro bike but RedBull a partner in the enduro world series defines it as a mountain bike that has *"140-170mm suspension travel, 27.5 or 29-inch wheels, a dropper seat post, strong brakes and big discs for long descents, and they are as light as possible while still able to survive long days of punishing terrain. If a bike can make it through an Enduro World Series event, that means it is tough as nails"* (RedBull, 2018). Based on Redbull's definition, it is clear to see the importance of strength, toughness, and weight of the bike. Enduro bikes cover some of the toughest terrains going up and down. However, when the bike is riding down

the mountain is when the bike is under the most stress and where the strength, toughness, and design of the mountain bike will be tested.

To put some perspective on the amount of strength testing is carried out on enduro mountain bikes. Santa Cruz Cycles one of the leading mountain bikes manufacturers, carried out destructive testing on its carbon fibre Normad bike frame, which goes far beyond the ISO 4210 industry standards (ISO, 2020). The compressive load of which the two-year-old used frame broke on its testbed is 2050lbs which is 9118.85 newtons, which Santa Cruz claim is 2.56 times the forces that the would be seen in a worst-case scenario (Levy, 2012).

However, that test was based upon strength, but mountain bikes need to be able to absorb fast impacts that are down to the toughness of the bike (Santa Cruz Cycles, 2012). Toughness is the amount of energy that the bike can withstand without fracture (Barthelat, 2014). Another test that Santa Cruz carried out on their carbon fibre nomad bikes was an impact test. This entailed dropping a mass from a height and seeing if the bike was able to absorb the load or fracture. The point of which the bike fractured was at 0.9m a weight of 110lbs or 50kg was dropped (Levy, 2012).

Based on the testing that Santa Cruz carry out on their mountain bikes, it is clear the importance that the bikes design and material can withstand these kinds of forces.

12.6 MATERIAL SELECTION

As seen in section 12.5, there are some key attributes that an enduro mountain bike must be strong, tough, and light. Material selection plays a pivotal role in satisfying these attributes. The common materials which are used in enduro bikes are Carbon fibre and Aluminium (Giant Bicycles, 2018). Both have adequate properties for an enduro bike with regards to Young's modulus, Poisson's ratio, and shear modulus however carbon fibre has a far lower density thus making it the choice for high-end enduro mountain bikes (Collotta, et al., 2017). Where Carbon fibre becomes the more favourable option is the ability to add more carbon strands in places of high stress. It is vital that the material

chosen to replace the current carbon fibre in bike manufacturing is equal to or exceeds the properties or can be designed to exceed such properties with the use of additive manufacturing.

12.6.1 Carbon Fiber

Carbon fibre is one of the most popular materials in the bike industry due to its high stiffness, high tensile strength, and low weight to strength ratio. With all these properties, it is clear why it is the most used material in high-end bike frames (RedBull, 2017). It is used in all disciplines of riding from road cycling to downhill. However it is not just the properties that make it popular, it is the ability to layer the carbon fibre so the bike components can have desired properties in different directions (Elkington, et al., 2015). Elkington et al. study of the approach of laying composite sheets was the first known study of the method of the layup of carbon fibre. It was the initial step toward the use of design for manufacture knowledge base surrounding hand layup.

12.6.1.1 Carbon Fiber Properties

Carbon fibre as a material is anisotropic material which means the properties of the material are directionally dependant (Jiang & Smith, 2017). Traditional carbon fibre is commonly impregnated into resin and formed into sheets. The carbon fibre can be either laid parallel giving unidirectional properties or woven in multiple directions giving quasi-isotropic properties. Quasi-isotropic is where a material shows isotropic properties but in-plane (Mizutani, et al., 2003). Example of the

Property	1mm Thick	2mm Thick	3mm Thick
Tensile Modulus at 0°/90°	37200MPa (74400 psi)	43900MPa (87800 psi)	47400MPa (94800 psi)
Tensile Modulus at 45°	32300MPa (64600 psi)	34500MPa (69000 psi)	27100MPa (54200 psi)
Tensile Strength at 0°/90°	503MPa (1006 psi)	558MPa (1116 psi)	644MPa (1288 psi)
Tensile Strength at 45°	557MPa (1114 psi)	622MPa (1244 psi)	443MPa (886 psi)
Percentage Elongation at 0°/90°	2.27%	0.0291	0.0388
Percentage Elongation at 45°	3.13%	0.0411	0.041
Youngs Modulus at 0°/90° Gloss Side in Compression	32.4 GPa (4699223 psi)	35.1 GPa (5090825 psi)	10.3 GPa (1493889 psi)
Youngs Modulus at 0°/90° Gloss Side in Tension	31.6 GPa (4583193 psi)	35.3 GPa (5119832 psi)	10.5 GPa (1522896 psi)
Density	1152 kg/m ³	1020 kg/m ³	1269 kg/m ³

Table 1 Easy Composites Carbon Fiber Data Sheet

directional strength can be seen in Table 1. The fabric layers of which the sheet is composed of can be seen in Appendix 3.

12.6.1.2 Carbon Fiber in Bike Components

When a bike is manufactured using layered carbon fibre, the orientation of the carbon fibre sheets is commonly determined in the FEA simulation in the development phase. The load conditions which the bike will be under will be simulated, allowing the load paths to be calculated. In high load areas, more unidirectional sheets can be used to distribute the load (Hope Tech, 2019). This allows the bike to have less redundant material where it is not needed, thus reducing the weight of the bike.

However, the manufacturing process of layered carbon fibre is very time consuming as said by Ashton Payne a design engineer at Hope Tech "*the length of man-hours to lay the prepreg in the mould tool, is a number of days rather than hours*" (Payne, 2017). Each sheet of carbon fibre must be laid by hand by a composite engineer in the correct orientation. The Hope Tech's HB160 enduro bike frame has five different types of carbon fibre which are cut into one hundred and seventy-seven different sheets and hand laid by carbon specialists (Clarke, 2017). Once the carbon fibre sheets are laid in the mould, a bladder is inserted to the cavity of the frame which is then put into a vacuum and heated until the frame is formed. While the process spoke about for manufacturing the frame of Hope's HB160, it is a similar process for all carbon fibre bike components in some form. It is clear to see that this is a very labour intensive manufacturing process that will be at the cost of the customer. As seen in the study by Elkington et al. to automate the process of laying carbon fibre, an automated system must be able to establish eight laying techniques to eliminate human interaction in this process (Elkington, et al., 2015). While this may be possible, theoretically, robots lack of level of delicacy, thus not making them suitable for such a process yet (Vinoski, 2018).

12.6.2 Quality Issues

As with all manufacturing quality issues is a big concern, and carbon fibre is no exception. Due to laying carbon fibre being such a labour-intensive process, human errors happen. Carbon fibres strength is

based upon the layers being bonded correctly; this is where the quality issues arise (Inagaki, 2000). Once the prepreg is laid and the forming process is completed, it is difficult to measure the bonding levels and layup. This is becoming a severe issue with the increasing demand for carbon fibre components, and satisfying this demand; unskilled labour is being used in places such as China (CISION, 2018). Joe McEwen quoted *"The quality is nowhere near the aerospace industry, I've seen wrinkling when I have chopped up carbon parts. While it may be fit for purpose, it is not good for a bike to have such undetectable internal flaws."* (McEwen, 2019). Joe is the founder of Starling Cycles who spent his career as the head of composite research at Airbus but makes Starling Cycles bikes from steel due to the low quality of carbon fibre frames. If carbon fibre bikes are designed and manufactured correctly, then no other material can compare.

12.6.3 Environmental Impact

The environmental impact of carbon fibre bike is a controversial subject in the mountain biking industry. While no materials or manufacturing processes can be said to be green, materials such as aluminium and steel are far more widely recyclable (Alupro, 2020) compared to carbon fibre. Furthermore In the manufacturing process, of carbon fibre shapes are cut from large sheets then laid in a mould; this is where the most significant amount of waste is made. Pole Bicycles highlighted this in an interview when visiting a leading carbon fibre factory in China which he quoted *"I asked an engineer, where are you putting the cutting waste of the carbon? He said: ocean fill."* (Kokkonen, 2019). Further research has shown the government guidelines in China is to dispose of the carbon waste in the ocean (Keyuan, 2015), (Pole Bicycles, 2019). The epoxy used is toxic and cannot be recycled, so if it exceeds its expiry date, it is dumped in the ocean (Sutton, 2017).

One of the most significant constraints of the recyclability of carbon fibre is the epoxy used in the prepreg. The current process is heat the carbon fibre with solvents until the epoxy melts, and then the carbon strands are ground and used in reinforcing plastics (Materials Today, 2017). This process still needs a vast amount of energy to melt the epoxy and still produces toxic fumes (The Guardian, 2017).

However, this process is not widely adopted in China currently, but bike manufactures such as Trek, and Specialized is taken it upon themselves to recycle old bike components to stop them going to landfill (Cycling Industry, 2017). However, they are yet to develop a demand for recycled fibres, and they are still trying to utilise them in reinforced plastics (Specialized, 2020).

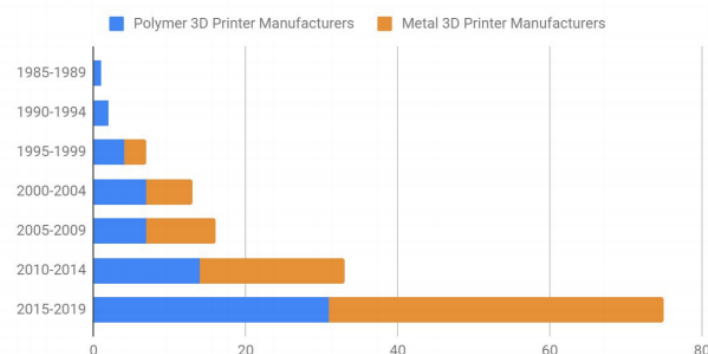
With the environmental aspect of carbon fibre prepreg considered it is clear that a revision in the process or an alternative process which produced small to none waste is needed.

12.7 ADDITIVE MANUFACTURING (3D PRINTING)

Additive manufacturing is giving the ability to manufacture geometry which could not have been imagined of before. With the AM market estimated to be worth 9.3bn USD in 2019 (AMFG, 2019) and the growth of companies offering industrial AM solutions has grown exponentially, this can be seen in

Graph 1. With big companies such as

GE heavily investing in AM not just as a product, but a method of manufacturing. GE Aviation is using AM to reduce assemblies on their GE9X jet engine. By using AM, GE has

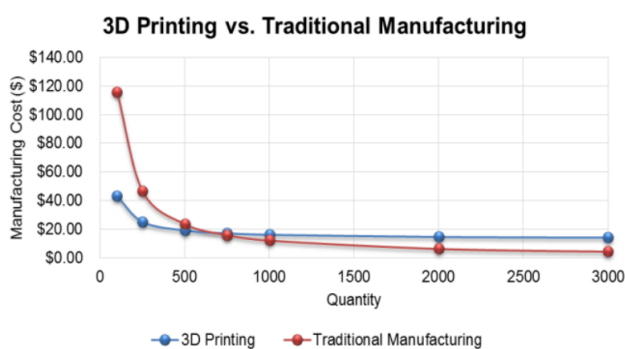


Graph 1 Growth of 3D Printer Manufactures from 1985-2019 (AMFG, 2019)

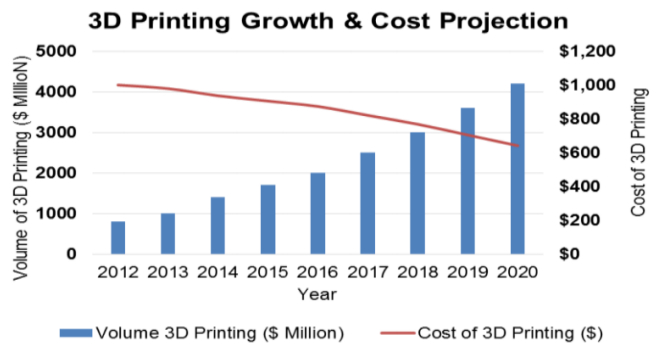
reduced a twenty part assembly to

one (GE, 2020). Boeing has estimated that using AM to produce parts for planes; it would have a cost saving of up to 2-3 million USD (Vincent, 2017). GE has also started to print the turbine blades of the GE9X engine (GE, 2018). Turbine blades operate in the most extreme conditions, with temperatures exceeding 1600 degree celsius and spinning at 25,000 rpm (NASA, 2010) it is a true reflection of the capabilities of AM. However, AM does come with cost and production limitations if not correctly implemented. Traditional manufacturing techniques such as mould based manufacturing become cost-effective in mass production when the volume outweighs the cost of tooling and productions overheads (Pereira, et al., 2019). Traditional methods have been optimised to manufacture one

product with maximum efficiency. However, once the product becomes end of life or a revision is needed, then the process will need to be revised, which incurs more cost. This could render parts of that process redundant and become scrap. The time taken to get the new product to the customer will further increase Carbon3d estimate this time to be 6-23 weeks (Carbon3d, 2020). AM changes that, while mass production is currently a constraint, any part can be printed without any time implication such as tooling change in the moulding method. This dynamic and agile approach allows the rapid, design to market time when compared to traditional manufacturing. Research carried out by Bashin and Bodla seen in Graph 2 and Graph (Bhasin & Bodla, 2018). Shows how AM printing is a far more cost-effective method if in lower volumes, once the volume becomes mass production that moulding method does become cost-effective.



Graph 2 3D Printing vs Traditional Manufacturing



Graph 3 3D Printing Growth & Cost Projection

(Bhasin & Bodla, 2018)

The cost of AM printing is also falling over eight years; the cost AM printer has fallen by thirty-six per cent. With the significant investment in AM and the need for a more dynamic and agile manufacturing method, it is clear that AM is the future once the constraint of mass production is exploited.

12.7.1 Additive Manufacturing in Mountain Bike Industry

After the research of AM in section 12.7, it is clear that AM is an ideal method for manufacturing mountain bikes components. With the low volumes in some cases and persistent development of new products, it can be warranted that it would be a favourable alternative compared to traditional methods. One bike manufacturer has adopted a hybrid of AM as their primary method of

manufacturing bike frames. Atherton bikes, owned by downhill riders the Atherton's have teamed up with Renishaw to produce a range of mountain bikes using AM and advance design technology (Atherton Bikes, 2019). The Atherton bikes have 3D printed titanium lugs, which are then bonded with carbon fibre tubes to produce their bikes. The print time for the lugs is currently sixteen hours, and a complete bike will be done from order to shipping in two weeks (Farmer, 2019). While this is approximately the same as the normal process (Allied Cycle Works, 2018), the Atherton is a small operation, and this is far less labour intensive. Due to the low labour costs, the bikes RRP is competitive against other similar level bikes such as Specialized, Santa Cruz and Trek; without the economies of scales, they have from mass production. What makes this method so different from other products is the ability to make custom bikes to riders preference. If a rider requests a reach of X and a standover height of Y, an algorithm will calculate the geometry changes of the set preference and adjust other geometry values accordingly. This ensures the bike does not change its characteristics due to slight geometry changes. With this customisation, the Athertons claim they have four times more sizes than other bike manufacturers, or they have a full custom option where the bike can be fully customisable to the riders preference (Atherton Bikes, 2020). This method is working not only selling bikes but at competition as well. Rachel Atherton currently has six UCI downhill world cup titles and five world championships; this rapid part production allows the Atherton race team to make bikes changes between races. If a course is a high-speed course, then they can increase the swingarm length to give a longer wheelbase which gives more high-speed stability. If a part geometry needed to be changed In the traditional method, FEA would need to be carried out on the new design, a mould would need to be fabricated, the part would need to be made, and the new design would need to be tested. The time scale of this would be months not days and certainly could not be done in between races.

Another company who are prototyping AM in bike manufacturing is Arevo in Silicon Valley. They currently are using robotic arms and CCF printing to print bike frames and forks. While this is a road-based bike, Arevo claims that it reduced the typical time of a new bike design from eighteen months to eighteen days (Arevo, 2018). Engineering manager of Ibis Cycles Colin Hughes can see the potential

in this technology and states: *"Arevo's process could offer companies, especially small or midsize brands like Ibis, the chance to prove a design works with less effort."* (Hughes , 2018).

The rapid design to prototype that Arevo can offer, and the reduced cost of labour as the Atherton's have shown are just some of the advantages that AM can bring to the mountain bike world compared to the traditional prepreg method. Another is the amount of physical waste of traditional prepreg method uses compared to AM. Pole Bicycles Kokkonen claim that: *"thirty per cent of carbon prepreg cutting is waste, as well as: EPS inner mould waste, air pressure bag waste, sticker base waste from prepreg, resin waste, sandblasting waste and the waste of labour"* (Kokkonen, 2018) That amount of waste per bike adds up substantially when considered the scale of which the bikes are produced. AM almost eliminates all of this waste, due to the nature of AM the only material used is what is needed except some support structures, which can be easily ground down and recycled into the new filament (ALL3DP, 2020).

To further the argument for AM vs traditional prepreg it must be looked at as a lean manufacturing method, and then the advantages come far more apparent. One principle of lean manufacturing is the reduction of waste, this is not just a waste as a physical entity but waste that the customer is not willing to pay for, essentially it is a cost that does not add value to the product (Monden, 2012). The seven waste is defined as over-production, inventory, motion, defects, over-processing, waiting, and transport (Kanbanize, 2020).

While all these wastes are as important as each other, one affects all the other. Over-production is the key waste; the output must be equal to the demand. Activating a resource to increase the efficiency of production will drive the cost up substantially (Goldratt, 2009). Over-production incurs waste in all the other six wastes. As seen by Atherton Bikes and Arevo, a bike can be produced in a timely manner to demand. This allows the companies to have less money tied up in inventory such as raw materials and completed bikes which if sales are not as forecasted will be sold at a reduced price. It reduces the chance of defects; there are no excessive transport costs; and no wasted labour hours.

The AM manufacturing model can be a just in time manufacturing model, which is used in mass manufacturing, such as the automotive industry (Ford Motor Company, 2019). The management of inventory to machine output allows the raw material to be delivered when needed, processed and shipped. This model has shown by Toyota and Ford to increase the flow of production and in turn, will aid in matching output to demand (Toyota, 2020) (Ford Motor Company, 2020).

With the substantial investment in AM and advantages being so apparent in the manufacturing of medium to low volumes of high-quality products, it wonders the question why AM is not being used in the manufacturing of mountain bikes. To try and give a better understanding of the technology that could be a replacement for traditional prepreg, the CCF AM process which is used by Arevo and other companies will be detailed.

12.7.2 Continuous Carbon Fibre Additive Manufacturing

While carbon fibre 3D printing is still in its early stages of development, Continuous carbon fibre (CCF) prepreg filament seems an ideal substitute for prepreg carbon fibre. A study carried out by Qingxi et al. found that the flexural stress of an anisotropic CCF specimen was 541.65MPa (Qingxi, et al., 2018)

Markforged and Anisoprint are AM companies which specialise in industrial continuous carbon fibre prepreg filament which is available for purchase. Markforged claims that their reinforced continuous carbon fibre filament when compared to Aluminium 6061, it has a 50% higher flexural strength to weight ratio and 300% in tension (Markforged, 2020). The data can be seen in Appendix 1; all of the claimed figures have been tested and verified by ASTM international. While Anisoprint claims there, CCF has five times the strength to weight and stiffness to weight ratio of 2024-T351 Aluminium (Anisoprint, 2020). Based on the findings of Qingxi et al. and the claims of Anisoprint seen in Appendix 2 Anisoprint Composite Carbon Fiber Properties, the data of Anisoprint and Markforged can be deemed credible. Furthermore, both materials based on their claims are more than ample for the use in mountain bike component manufacturing.

However, material properties need to be defined and explained further. Anisoprint only gives data on the ultimate tensile and compressive strength. This could be due to brittle materials such as carbon do not have a well defined tensile yield strength. As found by Mouritz that a surface crack as small as 0.3-0.4 μm can reduce the break limit by up to 50% (Mouritz, 2012). Anisoprint CFF is bound with a polymer, thus will have a yield strength and elastic limit before the ultimate strength is reached; however, this is not given in the material datasheet.

12.7.3 Fused Deposition Modeling using Continuous Carbon Fiber

CCF FDM printing is said to be an exciting technology in printing carbon fibre strands; however, it is yet to be able to do it in a pressurised environment which would be the next step for high-quality components (Zhang, et al., 2020). Currently, it is in the early stages of its life span, thus build size and costs is still at a premium. However,

current manufactures, such as Markforged and Anisoprint, have two different types of CCF but mostly share the same fundamentals seen in Figure 3. CCF is bonded to a polymer then fed through an extruder where the filament is added and printed just

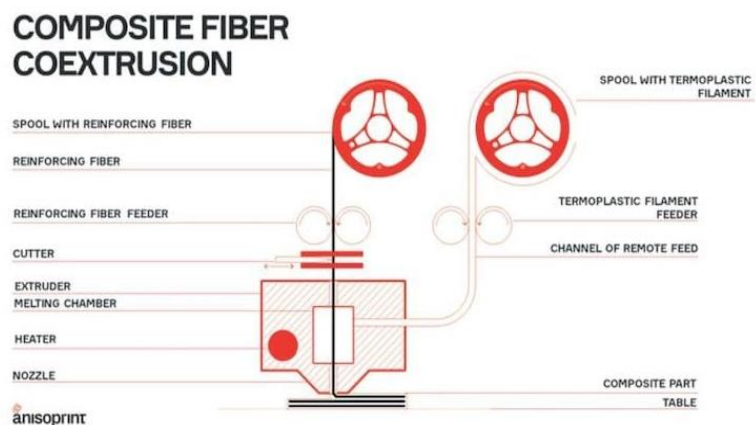


Figure 3 Anisoprint Composite Fiber Coextrusion Diagram

the same as most FDM printers. When the filament is passed through a heated extruder, it melts the thermoset filament just beyond its glass transition temperature and then is deposited on the bed. An example of this is Anisoprint Seen in Figure 2. Where Anisoprint differs from Markforged is the technology that is used

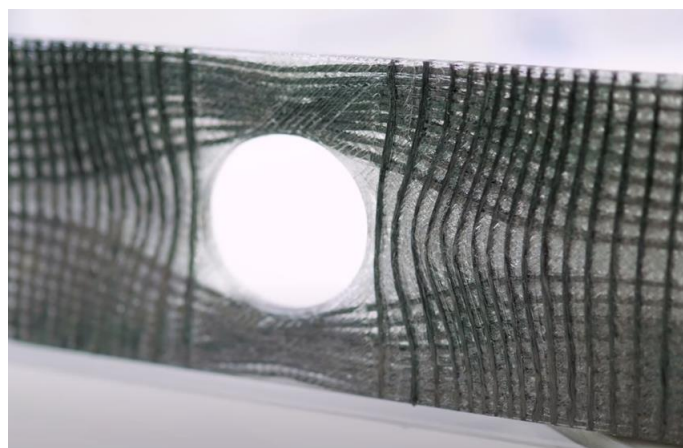


Figure 2 Example of Anisoprint CCF layup

to Prepare the model for CCF printing. Aura is a 3D model slicer and quoted from Anisoprint "*generates reinforcing fibres trajectories in each layer and allows to adjust reinforcement scheme to obtain strong and lightweight parts*" (Anisoprint, 2020). This allows fibres to be laid to disperse the load of high-stress points; this can be seen in Figure 2. Holes commonly have high-stress concentration (Dieter, 1991); thus, with the CCF layup, it will disperse the stress around the hole and through the material. Being able to design the fibre trajectory will allow for directional strength to be set. Having this ability of directional strength of the layup will make it a direct replacement for prepreg layup in the future. Which will make it an ideal manufacturing method for bike components when the technology advances further, and print size and cost is reduced. Furthermore, to address the environmental issue due to the carbon fibre stands being set in a thermoplastic, it can be melted down and recycled far easier and with less energy used than traditional epoxy or thermoset.

12.7.4 Cost Estimation

The Anisoprint PROM IS 500 printer is deemed to be a viable option due to the print capacity of 600 x 420 x 300mm (Anisoprint, 2020). The cost of such a printer is 250,00 USD (Aniwaa, 2020), the 750m filament spool of the CCF fibre is 320GBP USD (iMakr, 2020). A PTEG spool of 750g is 20GBP (3D GBIRE, 2020). While the power consumption of this printer is unavailable, a study of the power consumption of a 3D printer producing a five-hour print, in the UK would cost £0.04 (King, 2017).

While within this project parts will not be printed, the manufacturing process must be outlined so constraints can be factored into the design.

13 COMPUTATIONAL THEORY

To gain a better insight into how CAE can be used in the development of mechanical parts or systems, some key fundamentals must be explained. FEA is an analysis carried out using software where calculations about failures, deformation, and stress are given under a specific loading condition (Hughes, 1987). This analysis is a useful tool in the development and allows engineers to reduce the

number of prototypes due to many loading conditions already being satisfied before a physical prototype being made. In this section, some essential factors of FEA need to be highlighted to ensure that the simulation is deemed credible and is carried out within its limitations

13.1.1 Linear Static Analysis

Linear static analysis is an analysis used in FEA where load and displacement have a linear relationship (FEA for all, 2017). This type of analysis is common practice in most FE simulators. Therefore it is essential to know its limits and where it can be used. If a material abides Hooke's law, then force and displacement have a linear relationship and can be said that force is proportional to displacement (Britannica, 2020). The linear relationship of a material is what is used in the linear static analysis. However, once a material goes beyond the point of force is proportional to the displacement (limit of proportionality), the material will behave in a non-linear manner where force has no relationship with displacement. The linear static analysis will assume the relationship still to be linear even if the force surpasses the limit of proportionality. FEA with force beyond that limit of proportionality will not be deemed credible (Midas, 2019). Linear static analysis is commonly used due to the little computational power needed when compared to non-linear analysis. Furthermore, for projects with new materials such as this where new materials are being used in early development, and data of the non-linear behaviour is not yet available.

13.1.2 Stress Theories

When dealing with designs of components, the physical properties of the materials are commonly found using physical experiments where subjects are exerted to simple stress conditions (Roylance, 2008). The most commonly used experiment is a uniaxial tensile test which the subject will be stressed until yield or fracture whichever comes first. However, simple stress conditions do not give a good representation of the strength of a material under a complex stress condition. A number of theories are used to determine the point of failure; in this project, only two will be used due to Autodesk only accounting for such stress theories.

13.1.2.1 *Von Mises (Maximum Distortion Energy Criterion)*

The von Mises criterion is a scalar quantity is a calculation of the maximum value of distortion energy per unit volume of material (von Mises, 1913). A material structure will change shape and yield if the distortion energy exerted upon it is greater than the distortion energy per unit volume of the material (Kurowski, 2012). Von Mises stress (equivalent stress) computes when the material will yield when under complex loading from uniaxial tensile stress. Furthermore, von Mises stress satisfies where two stress states have equal distortion energy they will have equal von Mises stress (Jones , 2009). While von Mises is commonly used for materials such as metals and ductile materials, it will be used in this report due to the MarkForged having ductile properties due to it being a reinforced polymer. Furthermore, many carbon fibre composite studies have used von Mises scale as a measure of stress such as Stanciu et al., and Bougherara et al. thus the von Mises scale will be used as a measure of equivalent stress (Stanciu, et al., 2017) (Bougherara, et al., 2018).

13.1.2.2 *Maximum Principal Stress*

Maximum principal stress is the theory that material will fail when the maximum principal stress reaches the value of maximum stress at the elastic limit in simple tension (Roylance, 2008). The principal stress is the value that is normal to the plane where shear stress is zero (Chadwick, 2012).

1st principal stress is the value of tensile stress that is normal to the plane where shear stress is zero (Chadwick, 2012). This value will indicate the tensile stress that the material subject is under.

3rd principal compressive stress is the value of compression stress normal to where shear stress is zero. Failures of materials can occur before the tensile yield if the compression yield of the material is exceeded (Roylance, 2008).

The maximum principal stress theory is commonly used for brittle materials and will be used in this report due to the carbon fibre reinforcing of MarkForged material. By using both theories of elastic failure, it will give a better understanding of the stress of the components is under. While both are

used for different material types, without physical experimental results of the material, it will be challenging to identify which theory is best suited for the material.

13.1.3 Element & Mesh

Element type and mesh sizing are one of the most critical parts of the FEA study. It determines the credibility and accuracy that can be achieved. To better understand how element type and mesh sizing influence the credibility and accuracy, it needs to be explained in-depth. However, due to there being several different element types, only tetrahedral first and second-order elements that Autodesk offer will be explained.

13.1.3.1 Linear (First Order)

A first-order tetrahedral element can be seen in Figure 4 is comprised of four corner nodes highlighted in red and six straight edges in black. Each node has three degrees of freedom, but due to the number of nodes, the edges must always be straight this can be led to an inaccurate representation of the curved boundaries (Liu & Quek, 2014). However, first-order elements have there place in FEA and can be used in simple FEA studies and draft quality studies (Solidworks, 2019). The low number of nodes compared to other orders allows for quicker computational time (Rao, 2018).

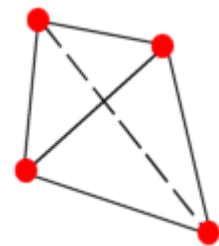


Figure 4 First Order Tetrahedral Element

13.1.4 Parabolic (Second Order)

A second-order element can be seen in Figure 5 it has the same configuration as the first-order element. However, it has six additional mid-side nodes. The additional six nodes allow the element has far more degrees of freedom compared to a first-order element, thus allowing for better representation of curved boundaries (Kroutromanos, 2018). The increased number of nodes allows for far better accuracy and is stated by Solidworks as a high-quality mesh (Solidworks, 2019).

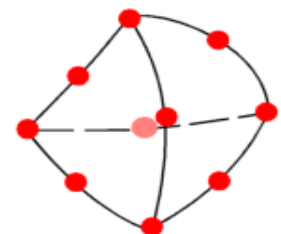


Figure 5 Second Order Tetrahedral Element

13.1.4.1 Mesh Density

Mesh density is the number of elements used to divide a model up based upon the dimension of the element. The higher the density of the mesh, the more accurate the results will be; however, with the increased number of elements, the computational time increases exponentially (Hutton, 2003). This can be seen in a study carried out with Liu and Glass (Liu & Glass, 2013) which saw a mesh density of a model increase by sixteen times, computing time increase by 41 times but the percentage of error of stress only decreasing by 0.18 per cent. After considering the findings in that study, it shows the importance of correct mesh size with regards to computational time.

13.1.5 Shape Optimisation

Shape optimisation is a design method of which to reduce the mass of a design by removing material to satisfy the load path (Chang, 2015). As with all FEA based studies, the fundamentals of constraints, loads, element type, mesh density, and the optimising target must be known. SO software gives the stiffness and density of the material a range of which it can be from its actual value and zero. An element can be within this range; however, it is encouraged to be the actual value and zero (Abbey, 2018). The elements in between actual and zero are still present but are represented on a colour scale which can be seen in Figure 6. The red elements indicate the critical load path and yellow, green, and blue being non-critical. If the software can find a defined load path with values set the actual values, then the rest of the elements will become redundant (Woon, et al., 2001).

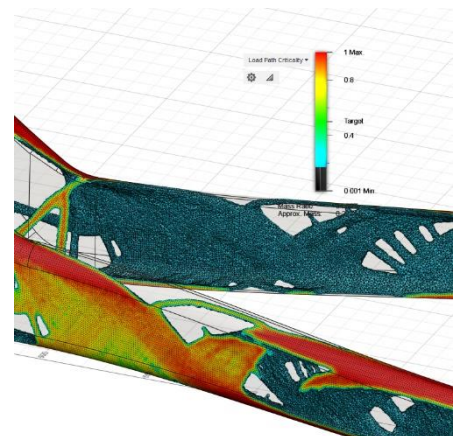


Figure 6 Load Path Colour Scale of Chain Stay

SO is a useful tool in the development phase of design, it allows a better understanding of the load paths of design. The removal of redundant material will have an apparent reduction in mass which will reduce material cost (Mostafa, 2019). However, SO does not factor in manufacturing constraints

with common outcomes having organic-like structures which can have significant implications on manufacturing feasibility and cost.

13.1.6 Generative Design

Generative design is an algorithm based computational method of development of almost anything from mechanical parts to neural networks (Perez, 2016), (Tonelli & Mouret, 2013). Four fundamentals are required; starting conditions and parameters, a generative mechanism (rules and algorithms), the act of generating variants, and the selection process of most favoured outcome (Dino, 2012). With regards to this project, parameters such as loading and constraints such as fixing points are inputted, and then artificial intelligence algorithms find solutions and display all variants (Akella, 2018). In relation to mechanical design, GD creates new design solutions instead of other optimisation techniques such as SO where it is an improvement of a preexisting design. Traditional optimisation techniques are based on the engineer's imagination or previous experience to dictate the form of a product. This may satisfy the parameters and constraints but may not be the most optimised design with regards to material, size, weight, strength, manufacturing methods, and cost constraints (Autodesk, 2020). An advantage of using GD over traditional optimisation techniques is that it considers manufacturing constraints in the design. This reduces the number of iterations and feedback cycles needed to have a product that satisfies all parameters. However, GD does have its constraints and limitations; therefore, it is vitally important that they are understood. The most vital constraint is the correct identification of function and environment that the will be design will be exposed to. GD designs are not designed for unexpected treatment. Most designs are far less resilient, which could lead to unexpected failures (Leitao, et al., 2013). The other main limitation is the computing power required to carry out GD. Computing software must calculate every possible outcome; this could mean several hours, possibly days for a standard computer to find such solutions. This is overcome by using cloud-based computing, Autodesk Fusion 360 uploads the GD study to their cloud and where Autodesk has engineering workstation-grade hardware which would allow for far quicker solve time (Smell, 2017).

GD is an exciting new design technology that will be implemented far more in the development of products as the software improves, and the price reduces. This is the reason why this design methodology has been chosen for this project. Mountain bike design has changed very little in its life; this could be the factor in which the most significant change could happen. However, for this design method to be adopted the environment that the bike will be under needs to be fully understood, which potentially could be the hardest step to overcome.

13.2 COMPUTATIONAL METHODS

13.2.1 Fusion 360

Autodesk Fusion 360 is a cloud-based package from Autodesk. It has been chosen as the software package due to its having all the desired tools, which are design, FEA, shape optimisation, and generative design. One feature which will be used extensively in this project is the cloud-based solver which allows the simulation environment to be set up locally then sent to the cloud to be solved. This will allow for far smaller meshing and is how Autodesk use their generative design tool.

14 ASSUMPTIONS

For this project to obtain its objectives, several assumptions must be made. As mountain biking is a dynamic sport every terrain is different, every rider is different and every bike set up is different, it is difficult to simulate for all these environments. The assumptions will be made to give some static load conditions that can be used to see if the improvements can be made. The rider's weight will be assumed to be 100 kg with all cycling gear. The weight of the bike will be 14.5 kg (Orbea, 2019) a height of 10 meters will be the drop assumed which will be to flat however the rear wheel will be the first point of contact.

14.1 CALCULATIONS

The force calculated will be deemed to be a conservative force from the point of start to finish point (Britannica, 2020) thus mechanical forces will be dissipated into other forces such as friction and air resistance. The force is calculated from the relationship of the potential energy capacity of work being done.

14.1.1 Equations & Calculations

Potential Energy

$$U = mgx$$

Work

$$W = Fd$$

Therefore:

$$U = W$$

Due to force being a function of the position, it can be said that the potential energy is the integral of force depending on its position.

Therefore:

$$U(x) = - \int_{x_0}^x F(x) \cdot dx$$

The potential energy is known; therefore, the derivative of potential energy will be equal to the force.

$$F(x) = - \frac{dU(x)}{dx} = - \frac{d}{dx} \cdot mgx$$

Therefore:

$$F = -mg$$

$$F = -114.5 * 9.81 = -1123.245N$$

The force of impact will be assumed to be 1123.245N at the point of initial impact, which will be the rear wheel. A factor of safety will be considered of 3; thus, it will be assumed to be 3500N. Due to the bike being a linkage thus components will rotate around the axis of fixture. The force is calculated as a moment around the fixed point.

Moment:

$$M = Fd$$

$$M = 1123.245 * 0.44 = 494.228Nm$$

*Note 0.44m is the length of the swing arm axle to the pivot point.

A factor of safety will be considered of 4 at this point to ensure the integrity of the component at such a vital point of the bike.

The calculations of forces based upon the potential energy of the bike from the hypothetical situation is a similar outcome to the Santa Cruz's destructive testing as stated in section 12.5 Santa Cruz of the breaking load of their bike was 9118.85 newtons which were approximately 2.5 times more than the bike will ever be exposed to. Based upon the calculations and the results from Santa Cruz it will be assumed that the loading will be 3500 newtons at the rear axle and 2000 newtons at the pivot point can be deemed plausible

14.2 LOADING & CONSTRAINTS

To have a standardised loading condition, a rear axle and fixing bolt will be used in each simulation. These will be a standard thickness and will be inserted as separate bodies; an example of this can be seen in Figure 7.

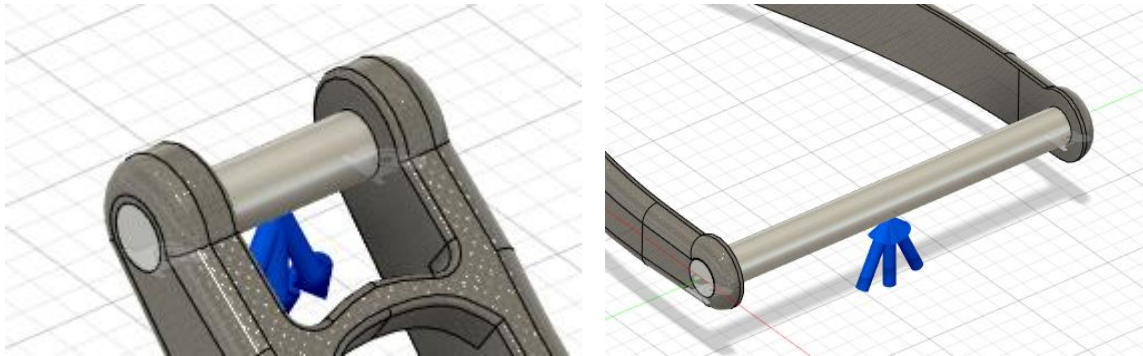


Figure 7 Axle Loading Condition CAD Model

As calculated in section 14.1.1, the impact force of 3500N will be applied to the rear axle pivot of the bike, and the 2000N moment force will be applied to the main pivot of each component. However, the impact and moment forces are assumed to be in one direction which will be classed as a perfect landing thus does not take into consideration nonperfect landings which are common occurrences in mountain biking. A nonperfect landing can be considered to be a landing of which the bike lands at an angle from straight down but the rider, bike, and/or momentum may allow for a ride away. This nonperfect landing will be considered in the study by applying additional forces at positive and negative 25-degree angles from the Z direction; this will be the case for loads either end of the component. Each fixing point is constrained to a pin constraint, thus allowing the component to rotate around the axis.

14.3 MESHING

The meshing size of the simulation is based on experimental results based upon a similar method to the Liu and Glass study (Liu & Glass, 2013). The mesh started at a range of 5mm and is reduced at increments of which max stress, strain and solve time were recorded; it was carried out for linear and

parabolic. The swingarm will be used as the component for the experiment due to it being the most complex of the geometry.

The results of the meshing experiment are seen in Table 2 and Table 3. The starting mesh size was 5mm and then at increments until 0.75mm. 0.75mm mesh would be the value of which the percentage difference will be taken. Due to Autodesk Fusion 360 having a cloud-based solver, the computational power is far higher than any standard computer thus having far quicker solve times.

The difference between linear and parabolic is evident when comparing the results of 0.75mm mesh size. With the max stress of 75.99MPa and 92.64 respectively, the difference between the two indicates the accuracy of the parabolic elements, thus based on the assumption of higher stress being more accurate parabolic will be the element of choice.

The mesh size of the parabolic was decided based upon the balance of accuracy and solve time. The 0.75mm parabolic mesh solve time was 1352.3 seconds due to the excessive time it was not deemed a viable option based upon those results and the number of models to be simulated. Therefore, the 1mm mesh has the lowest percentage difference of stress and strain compared to the 0.75mm mesh and a solve time of 56% quicker. The 1mm mesh will be used as the standard mesh size throughout the project. A sixty-degree max angle curve will be used on all meshes throughout the project.

Linear

Mesh Size in (mm)	Max Stress (MPa)	% Difference	Nodes	Elements	Max Strain	% Difference	Time Taken (Seconds)
5	48.27	36.48	8229	32053	0.000572	31.18	2.1
4	50.27	33.85	13166	55197	0.000581	30.04	3.1
3	53.93	29.03	26069	117977	0.000629	24.30	6.6
2	58.58	22.91	73009	359046	0.000695	16.37	18.5
1	69.13	9.03	470866	2520972	0.000841	-1.23	138.7
0.9	72.43	4.68	618028	3337147	0.000836	-0.60	194.8
0.75	75.99		993227	5429675	0.000831		316.4

Table 2 1st Order Meshing Experiment Results

Parabolic

Mesh Size in (mm)	Max Stress (MPa)	% Difference	Nodes	Elements	Max Strain	% Difference	Time Taken (Seconds)
5	74.05	20.07	54437	32595	0.000907	21.13	7.7
4	72.17	22.10	89119	55385	0.000949	17.51	13.0
3	77.81	16.01	183297	118622	0.001055	8.26	25.0
2	82.54	10.90	530524	358795	0.001149	0.09	80.9
1	88.39	4.59	3566852	2520972	0.001124	2.26	604.9
0.9	86.95	6.14	4700506	3337147	0.001163	-1.13	801.1
0.75	92.64		7600288	5429675	0.001150		1352.3

Table 3 2nd Order Meshing Experiment Results

14.4 MATERIAL

As stated in section 12.6.1.1, carbon fibre components are anisotropic thus have different properties in a different direction. Autodesk Fusion 360 is unable to simulate such properties thus will assume the properties of the material to be isotropic. However, this would be a further consideration in future development by using Autodesk Simulation mechanical to simulate the directional loading of carbon fibre layup (Autodesk, 2020).

The original components of the bike will have different thicknesses of carbon fibre at high-stress points, also carbon fibre being laid to disperse the load better. Again this will not be considered in the design of the components due to the information not being available. In consideration of this, the original components will have a uniform wall thickness of 3mm.

The material used in the simulation will be MarkForged carbon fibre; this will be used for all components to have a standardisation of material so the results can be compared. However, due to the data of yield stress not being available, it will be assumed to be 540MPa approximately two-thirds of the ultimate tensile strength which is 800MPa and a young's modulus of 60GPa. The assumption of yield tensile strength will be based upon a factor of safety, while a carbon composite will commonly have a yield strength far closer the ultimate strength due to its high level of stiffness. In this project, having a far lower yield strength will reduce the chance of failures and highlight design flaws. The actual values of the MarkForged CCF can be seen in Appendix 1

14.5 MANUFACTURING

The manufacturing constraints that will be used for the generative design will be additive manufacturing. The overhang angle will be no higher than 45 degrees and have a minimum wall thickness of 3mm.

15 DESIGN PHASE

The components that will be redesigned using the GD and SO can be seen in Figure 8 and Figure 9. Each component has a uniform wall thickness of 3mm and is made from the Markforged carbon fibre they have a dimensional accuracy of $\pm 1\text{mm}$. These components will be the base of which the designs of GD and SO will be evaluated.

Both these components are linked by the rear axle. This can be seen in Figure 10 to gain a better understanding of the kinematics of the linkage.

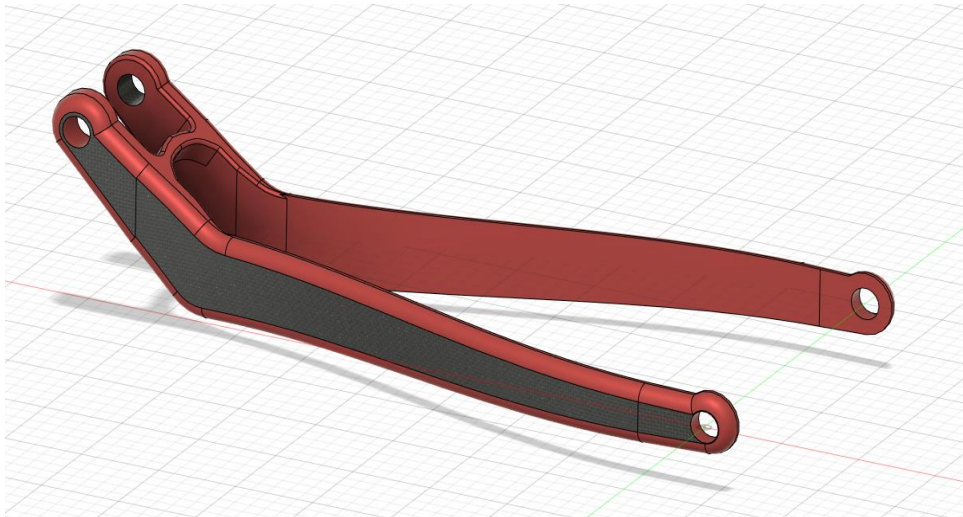


Figure 8 Original Swing Arm CAD Model

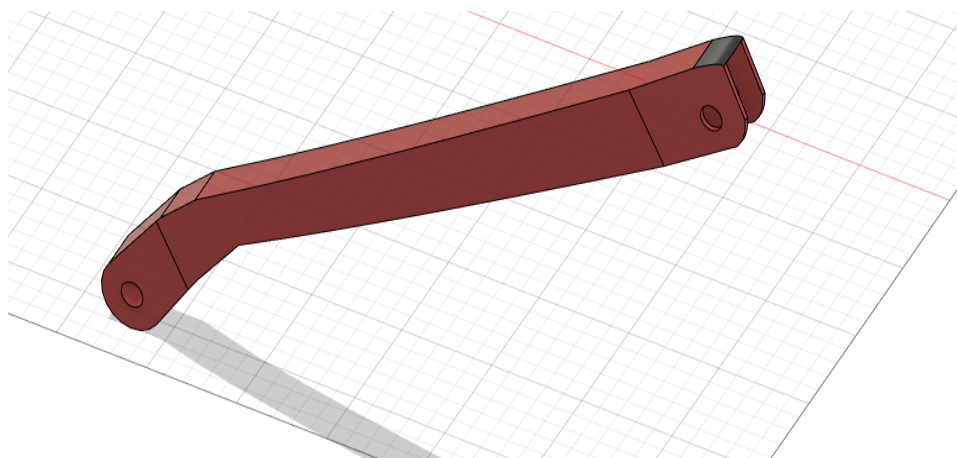


Figure 9 Original Link Arm CAD Model

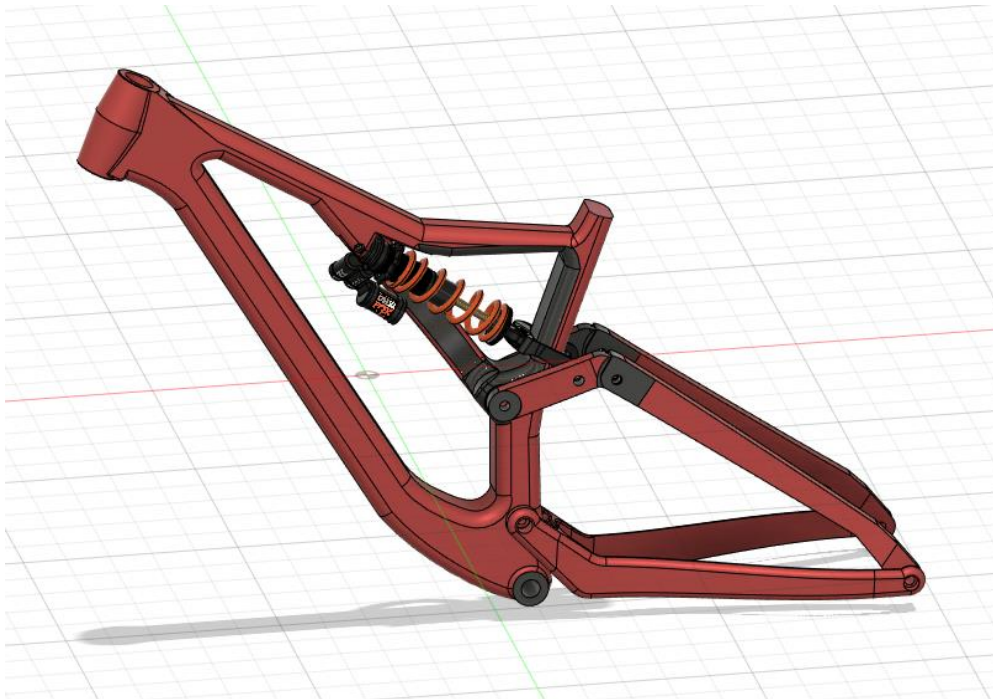


Figure 10 Original Complete Bike CAD Model

15.1 GENERATIVE DESIGN

As spoken previously in section 13.1.6 fundamentals must be set. The new designs must not deviate much from the form of the original shape due to it being designed that way to interact and contain other components such as wheels, brake mount, and chain. The critical geometry must be preserved so that the components can be mounted and move with minimal interference with other components. This was achieved by using constraints within GD preserve and obstacle geometry and starting shape. All fixing points are constrained by the pin constraint.

Preserve geometry function allows to select bodies or faces within the design space to which GD keeps precisely as designed. An example of this is Figure 11. The green bodies are identified as the critical geometries and will be kept as designed.

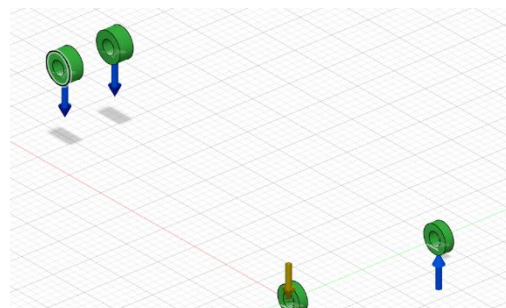


Figure 11 Preserved Geometry Swingarm

Starting Shape allows for the original part to be used as a guide of the form that the software is to follow. In Figure 12, the yellow body is the original swingarm. In this example, GD could have split one body into two to make the most efficient design. However, that possible design would have made each end of the axle move independently and would not be the same as the original function thus making the design not fit for purpose.

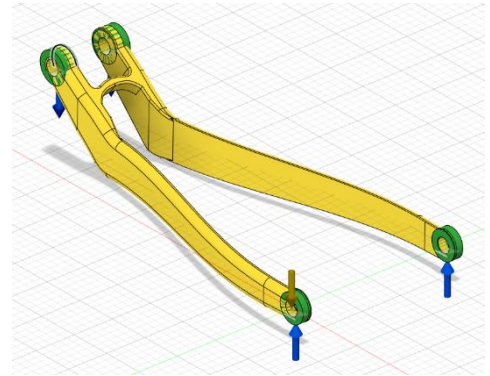


Figure 12 Starting Shape Swingarm

Obstacle geometry is a function that allows a design envelope for GD to work within. A body is designed that the preserved geometry will be joined to. The GD software will design outcomes within that envelope, limiting the size of the design. In this project, a negative of the component will be the obstacle geometry to ensure the new design does not interfere with other components.

The manufacturing constraints will be additive manufacturing which was set at no more than a 45-degree overhang and a minimum wall thickness of 3mm to ensure that the part will not get damaged from impacts from foreign bodies. The objectives of the GD were set to minimise mass and a minimum factor of safety of two. The outcome design will be selected based upon the lowest weight.

Figure 14 is the link arm preserved geometry, and Figure 13 is the form of which the GD software will follow. The Blue arrows are an indication of the direction of loading.

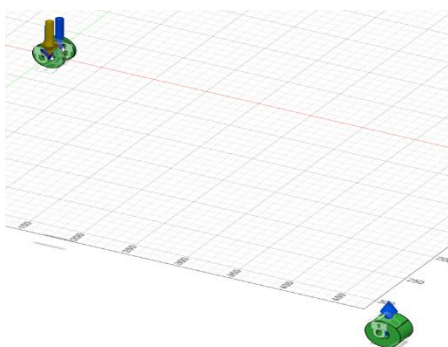


Figure 14 Preserved Geometry

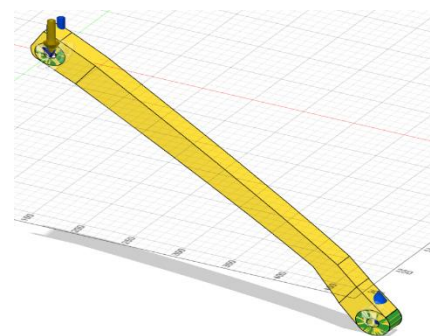


Figure 13 Starting Shape

15.1.1 Single Direction Load Swing Arm

The first GD outcome of the swingarm with single directional loading had a mass of 207g and a max von mises stress of 13.3MPa. The design satisfies the conditions set however seen in Figure 15 visually the design does not look robust and due to it being single direction loading, if an unexpected impact from any other direction could cause failure to the component.

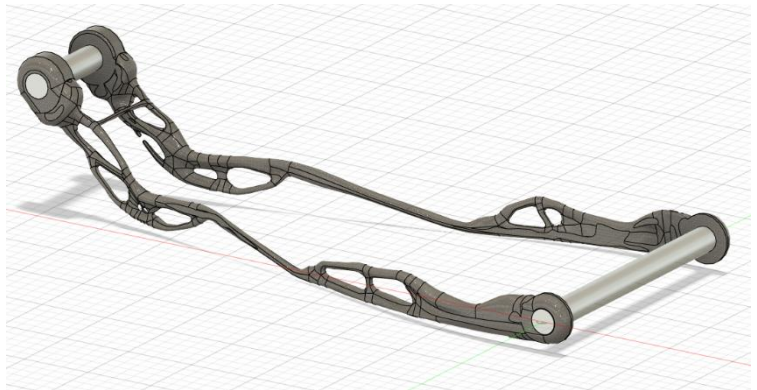


Figure 15 Generative Design Swingarm Single Load

15.1.2 Single Direction Load Link Arm

The first outcome of the link arm with a single directional load had a mass of 147g and a max von mises stress of 13.1MPa. The outcome that is seen in Figure 16 does look robust and has thick sections to disperse the load energy through the component. However, a closer look Figure 17 this could be an area that could lead to failure. Due to small material thickness and complexity of geometry could lead to manufacturing quality issues.

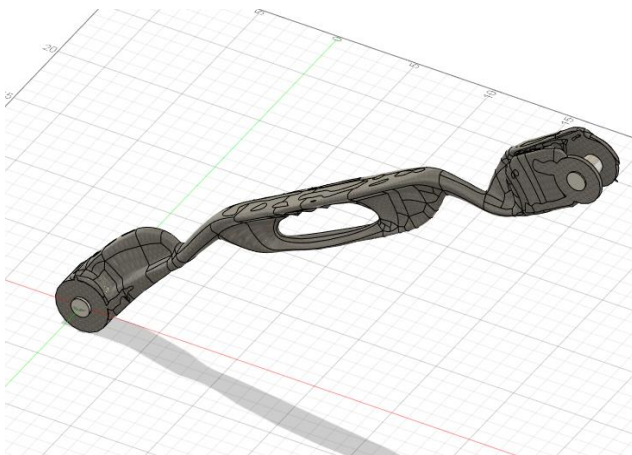


Figure 16 Generative Design Link Arm

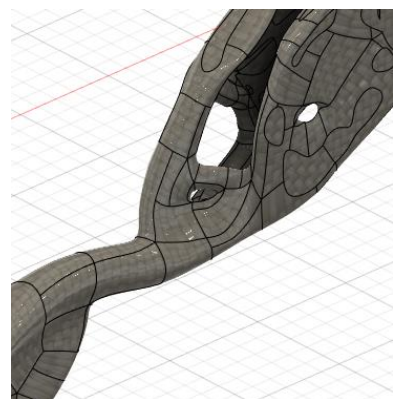


Figure 17 Area of Concern Link Arm

15.1.3 Multi-Directional Load Swingarm

As previously stated in 14.2, there is a need for multiple directional loading to ensure that the bike can absorb a non-perfect landing. The multi-directional loading while may not be a real-world situation due to the multi-directional loads being all applied at the same time in different directions. It will give a far more realistic design with regards to strength, robustness, and resilience with the

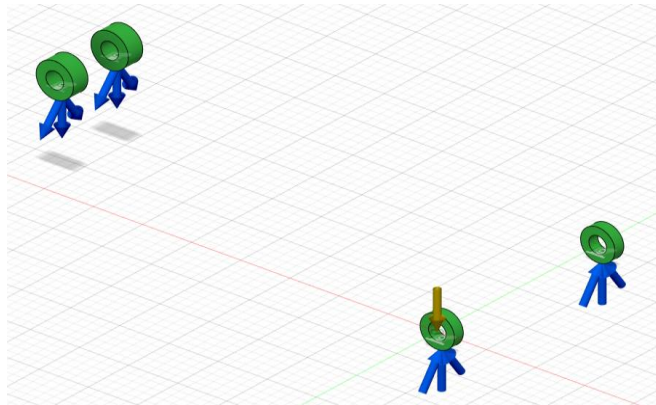


Figure 18 Preserved Geometry Swingarm

possibility of being able to absorb unexpected impacts. This loading conditions can be seen in Figure 18. All other constraints remained the same from single to multi-directional loads.

The outcome of the multi-directional load swing arm is seen in Figure 19. It has a mass of 280g, and a max von mises stress of 35.9MPa. An increase of 73g in mass and increased max stress of 22.6MPa. Visually the design outcome looks far more robust than the single directional load outcome. While the load path is the same, there is far more material where the body meets the preserved geometry, which will aid in dispersing energy.

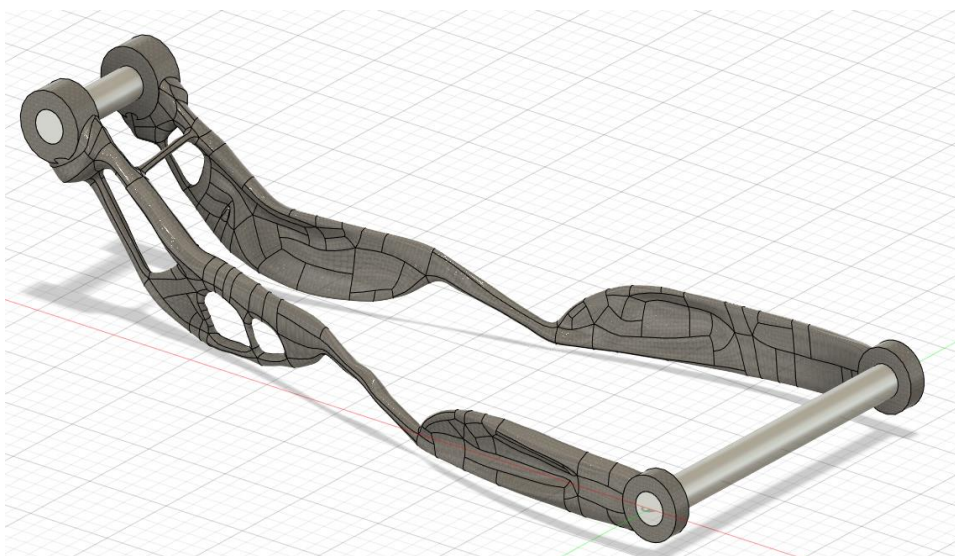


Figure 19 Generative Design Swingarm

15.1.4 Multi-Directional Load Link Arm

The outcome of the link arm of the multi-directional load seen in Figure 21 is very similar to the single direction loaded link arm. The loading condition is seen in Figure 20. The mass is 149g with a max von misses stress of 35.4MPa. With the increased load, there has been an increase in the mass of 2g and increased max stress of 22.3MPa. Looking at the design visually where the body meets the preserved geometry, the material has been increased. The holes, such as in Figure 17, this is now a solid body that should increase the strength and reduce the likelihood of failures.

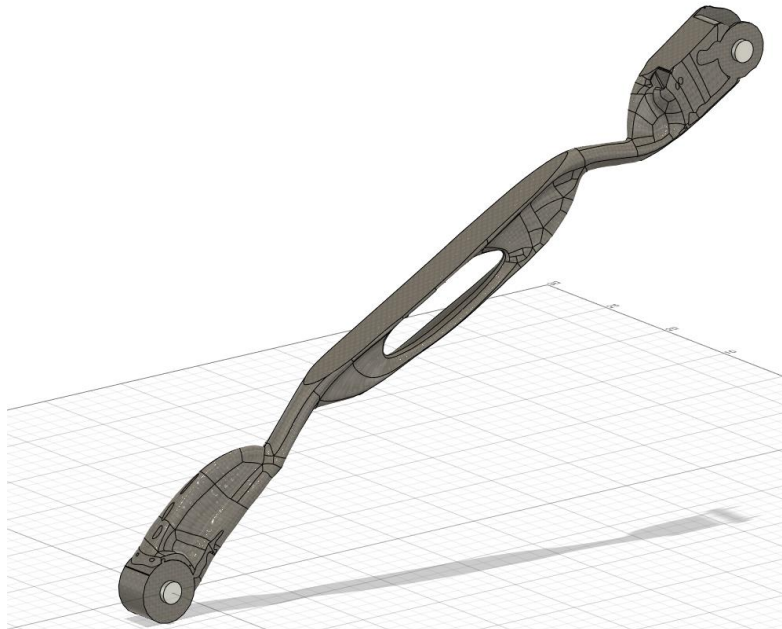


Figure 21 Generative Design Link Arm

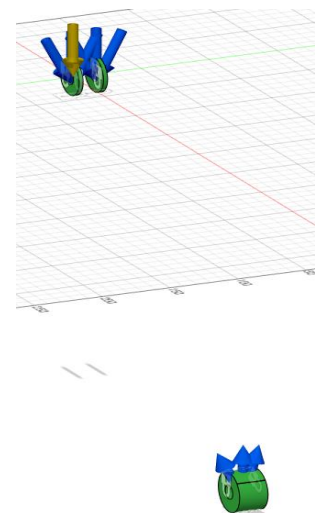


Figure 20 Preserved Geometry Link Arm

15.2 SHAPE OPTIMISATION

To utilise shape optimisation software changes had to be made to the components. While the form did not change the usual hollow-bodied components had to be made solid. This would allow the software to maximise the number of elements to optimise. Each component was loaded using the standard axle with the same multi-directional loads. The 1mm parabolic mesh was used on all components, as discussed in section 14.3.

15.2.1 Swingarm Shape Optimisation

The SO of the swingarm, three areas were identified as a geometry that needed to be preserved. Each pivot eyelet point where the axles were inserted and the bridge between each arm. These areas are highlighted seen in Figure 22. The optimisation target for the swingarm was to maximise stiffness with a target mass of thirty per cent of the original mass.

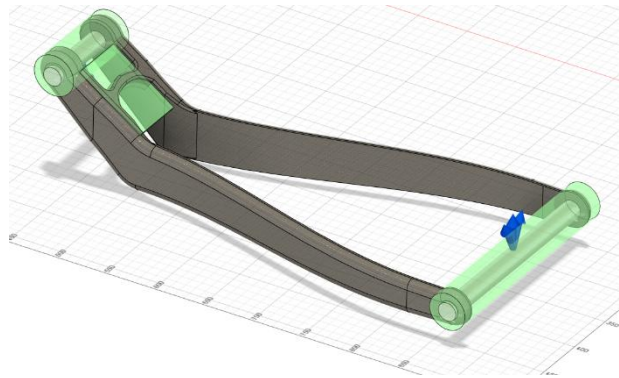


Figure 22 Preserved Geometry Swingarm Shape Optimisation

The outcome from the shape optimisation is seen in Figure 23. The final mass is 181g with a mass ratio of 29.9% of the original mass. However, it is essential to note that the initial mass was of a solid body. Visually the swingarm has taken an organic form; there is a substantial amount of material around the rear axle eyelets to disperse the 3500N load. The load can be seen to disperse through the part where the material is reduced and becomes strand-like.

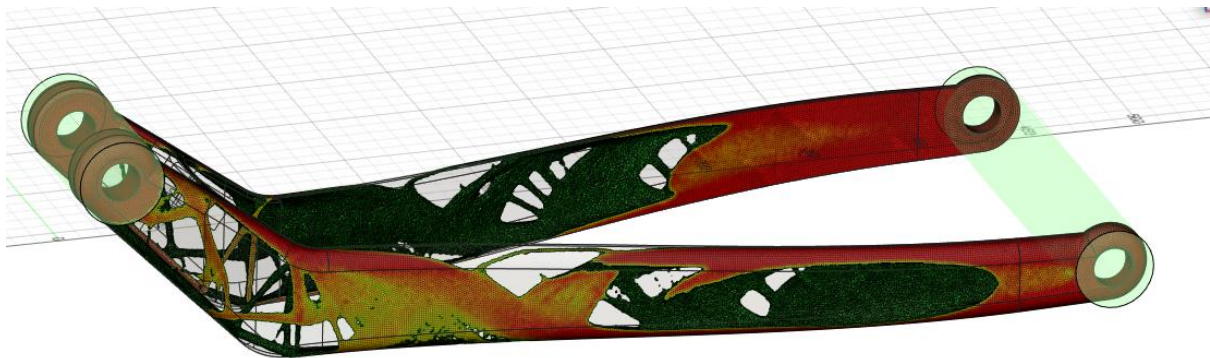


Figure 23 Shape Optimisation Results Swingarm

While the SO swingarm is almost 100g lighter than the GD swingarm, it must be considered that the SO does not consider manufacturing constraints; thus, this design may not be able to be manufactured. An example of this would be the intricate webbing and support material around the main pivot eyelets. While additive manufacturing would be able to manufacture such design, the

properties of the material may not be to the desired specification due to the process of printing (Chua, et al., 2003).

However, when the results of SO are compared to GD, several similarities have occurred the areas highlighted in pink are the areas of similarities and the areas highlighted in yellow are the ones where it differs. In Figure 24, the load path of each component is shown as a line. Both components have similar load paths until the point highlighted by the arrows. This could be due to the manufacturing constraint of the GD. It is possible that due to the way GD has overcome the support of the main pivot eyelet within the constraints of manufacturing that it has changed the load path.

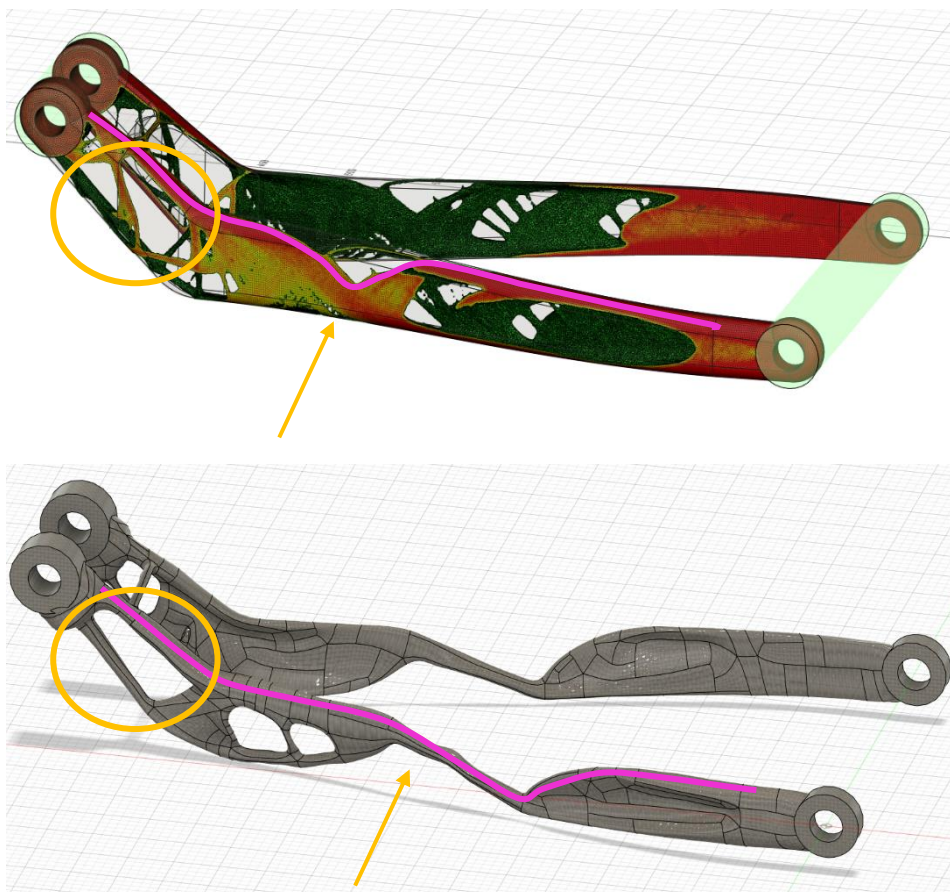


Figure 24 Comparison of Shape Optimisation and Generative Design Swingarm

Figure 25 and Figure 26 show similarities between SO and GD. The main pivot eyelet has two sweeping supports, and both have a cavity before the rear axle pivot. Overall the shape optimisation could be said to be the most optimised version of the swingarm due to its lower mass and sharing several

similarities to the GD model. However, it may not be the best possible solution without the consideration of manufacturing.

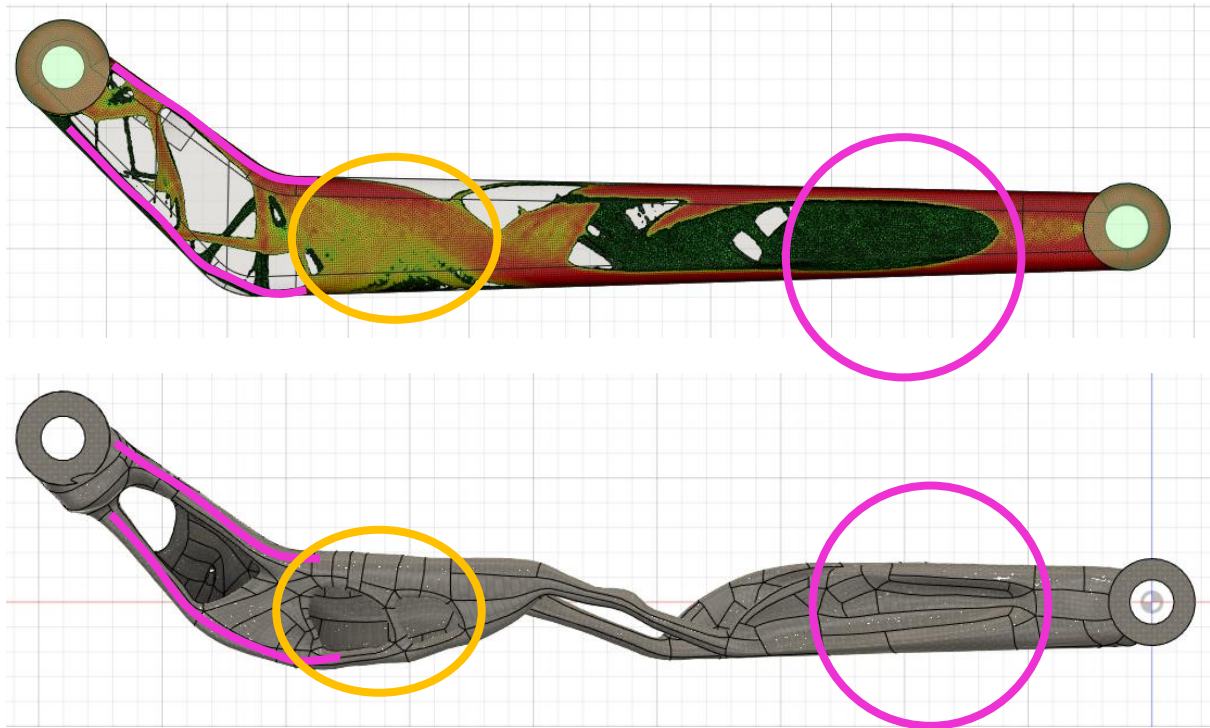


Figure 25 Side View of Comparison of Shape Optimisation and Generative Design Swingarm

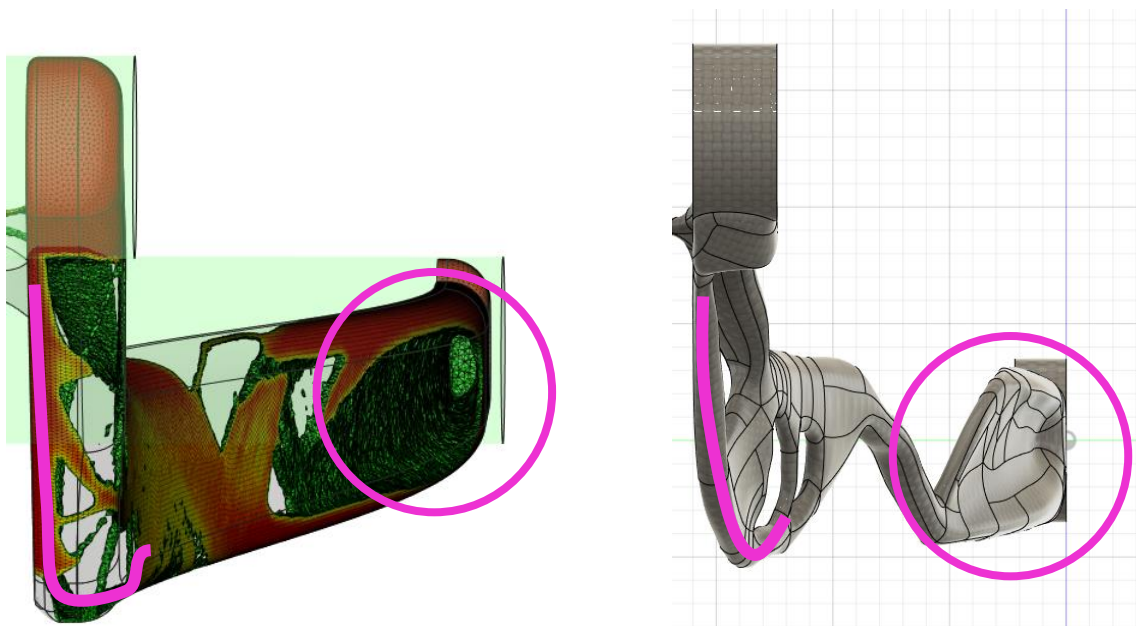


Figure 26 Front View of Comparison of Shape Optimisation and Generative Design Swingarm

15.2.2 Link Arm Shape Optimisation

The SO of the link arm is shown in Figure 27. The highlighted areas are the pivot eyelets at each end.

An axle is placed through each pivot eyelet and loaded. The optimisation target was to maximise stiffness and a target weight of thirty per cent of the original mass.

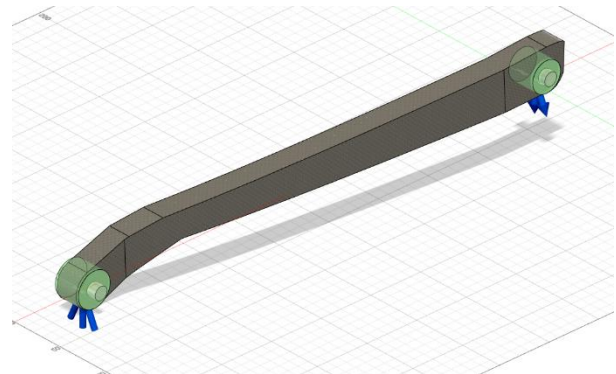


Figure 27 Preserved Geometry Link Arm

The outcome of the link arm is seen in Figure 28, and it has a mass of 104g and a mass ration of

27.6%. Visually the link arm does not look it would be able to handle such loading. At each pivot point, there is a large amount of material that disperses most of the load. However, the main concern is the lack of material connecting each pivot point. The wall thickness would indicate that the mass target reduction has been met but at the cost of stiffness and strength.

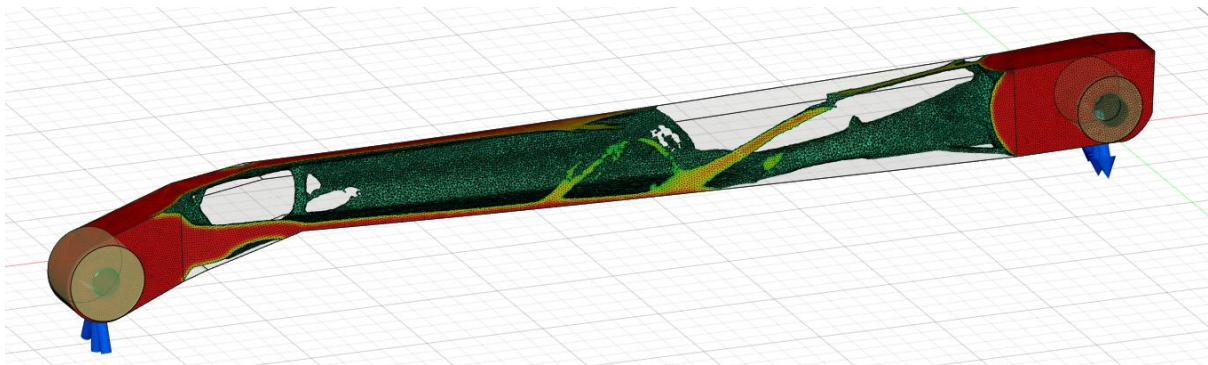


Figure 28 Link Arm Shape Optimisation Model

With the assumed lack of stiffness around the link pivot, this could lead to higher deflection and strain in these areas. This higher level of deflection in these areas could lead to the linkage of the bike not working to its optimised level and fatigue failure.

The comparison of the SO and GD can be seen in Figure 29, Figure 30, Figure 31, and Figure 32. If the preserved geometry is disregarded in the comparison, there are little similarities with both designs.

The SO outcome seems to disperse the load in a hollow manner while the GD has a centralised body this is illustrated Figure 29.

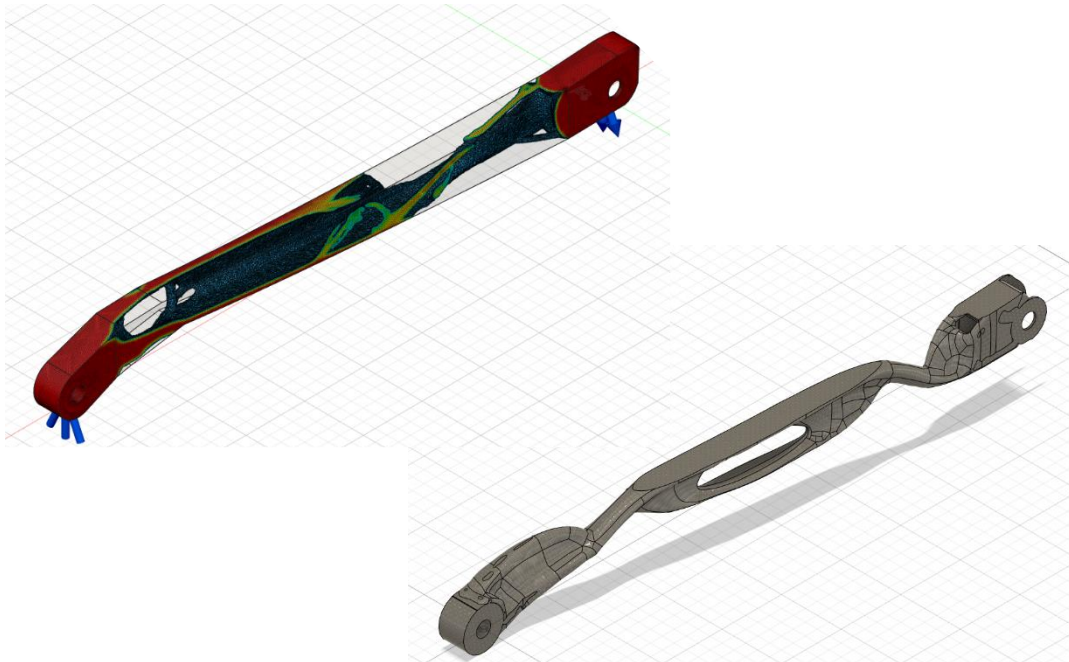


Figure 30 Comparison of Shape Optimisation and Generative Design Link

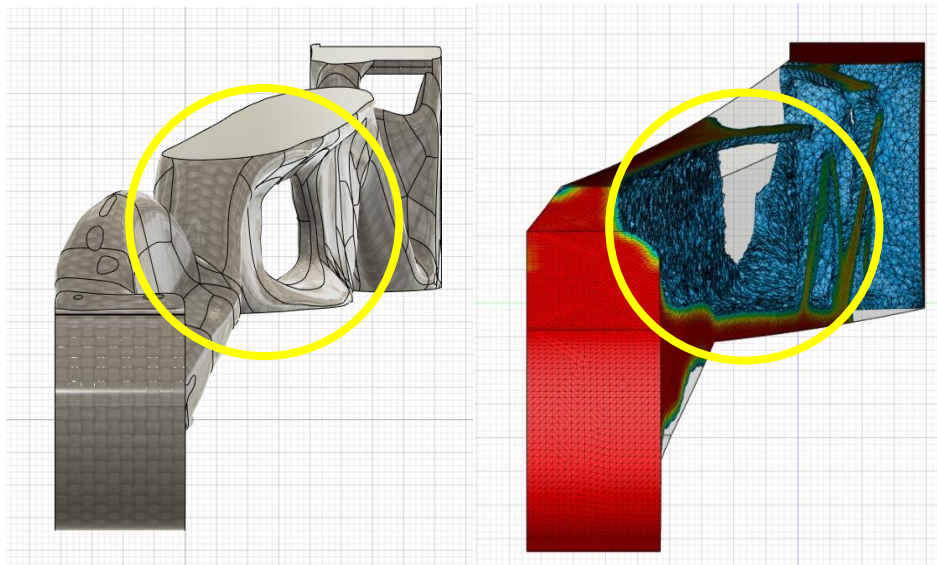


Figure 29 Rear View of Comparison of Shape Optimisation and Generative Design Link Arm

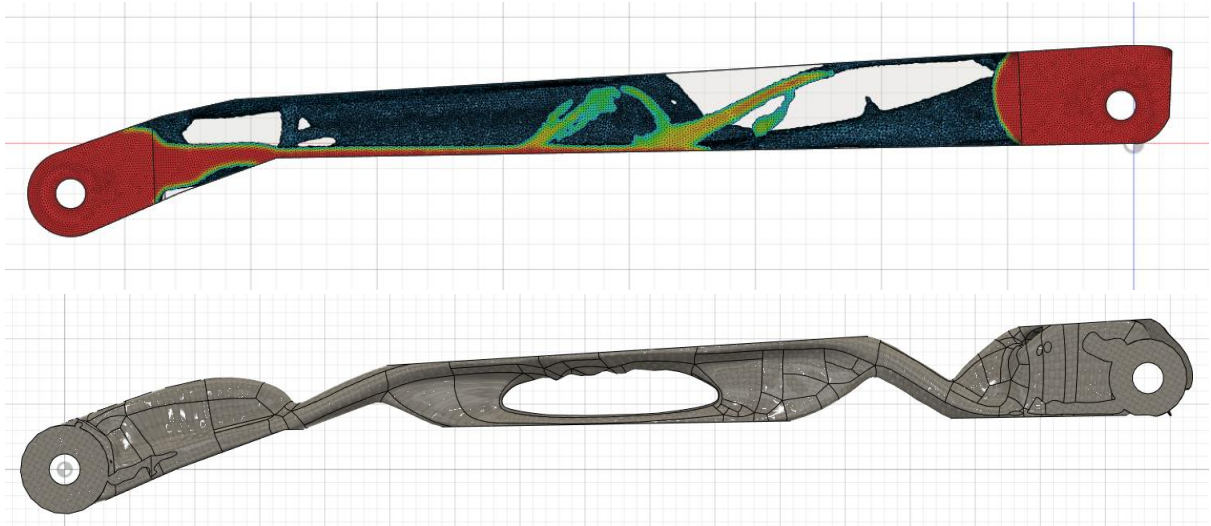


Figure 32 Side View Comparison of Shape Optimisation and Generative Design Link Arm

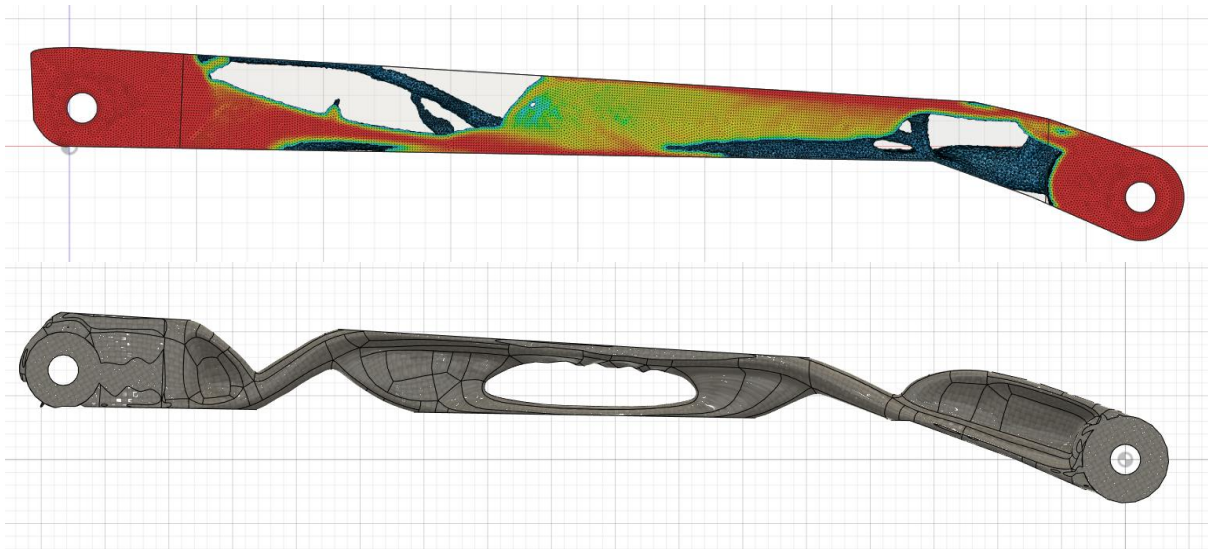


Figure 31 Side View of Comparison of Shape Optimisation and Generative Design Link Arm

The reason for the difference in the two outcomes could be assumed to be the manufacturing constraints that are used in the GD outcome. With a difference of 45g between each outcome, it could be said that the GD is not the most optimised outcome with regards to mass, but the most optimised outcome for real-world application of the component.

Based on the outcomes of SO compared to GD, it can be assumed that GD may not be the most optimised with regards to mass. However, Autodesk Fusion 360 does not have a feature to converge the SO model to become a design model; thus, an FEA analysis cannot be carried out on the specific optimised part. SO in Autodesk Fusion 360 is used as a guide of the most optimised shape and will

have to be designed as a new part. This would be excessively time consuming, and each optimised component would have to be verified that it is fit for purpose by simulating using FEA. All the interactions would come at the cost of time and money.

16 FEA RESULTS

To make the results comparable, all FEA study's were loaded with the standard load on the axles with a 1mm mesh parabolic mesh from experimental results from 14.3. However, after the investigation of the locations of max VonMises stress and equivalent strain, it was found that the original link arm and GD swing arm had different locations for both which was not expected. This can be seen in Figure 33 and Figure 34.

Due to the proportional relationship of stress and strain, and both values were below the limit of proportionality of the material; it was identified that there was a discrepancy in the results. This was assumed to be down to the accuracy of the mesh, to rectify this discrepancy the mesh size was further reduced on each component. The mesh was reduced to 0.75mm on each component; however, the link arm still had the same location discrepancy. A mesh size of 0.6mm was applied to the link arm, and the swingarm was set at 0.75mm.

After the adjustment of mesh size, the location of all max VonMises stress and the equivalent strain was found at the same location. The experiment carried out in 14.3 while it served a purpose of giving a baseline data of stress and strain; it was found that one mesh size is not adequate for all components and if a future experiment were to be done, it would be on a component by component basis.

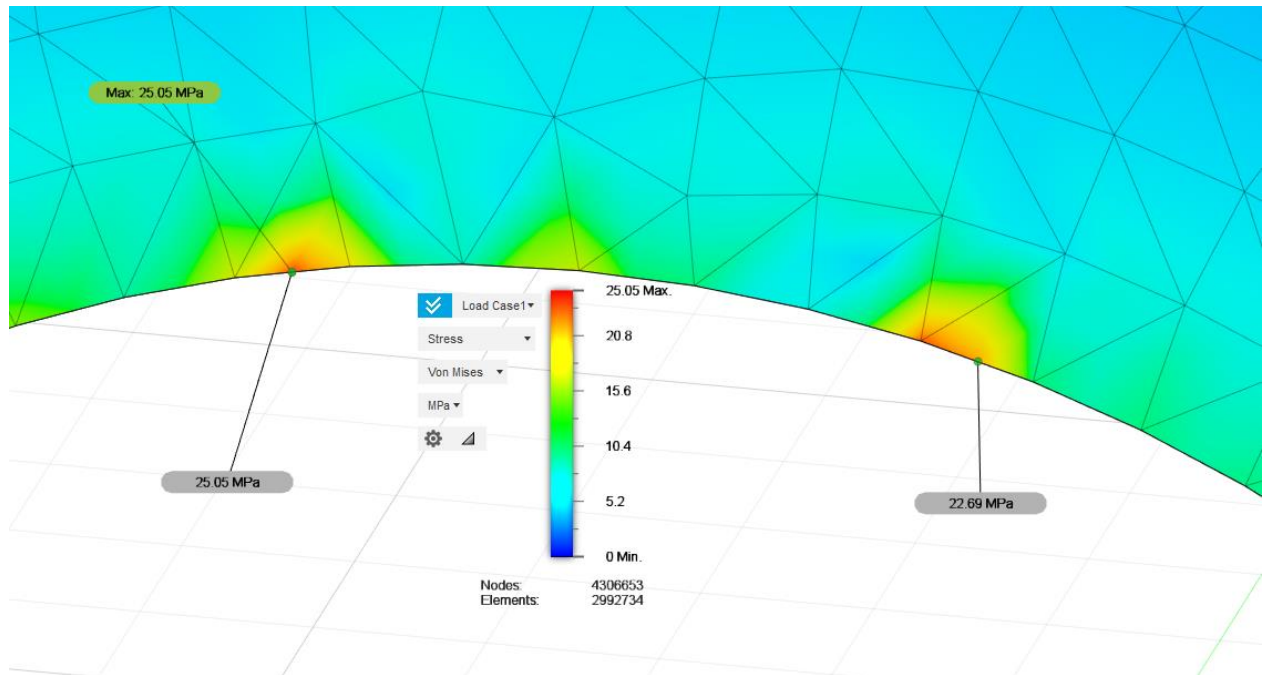


Figure 34 Surface Probs at Max Stress and Strain Location with VonMises Strain as Measurable on Swingarm

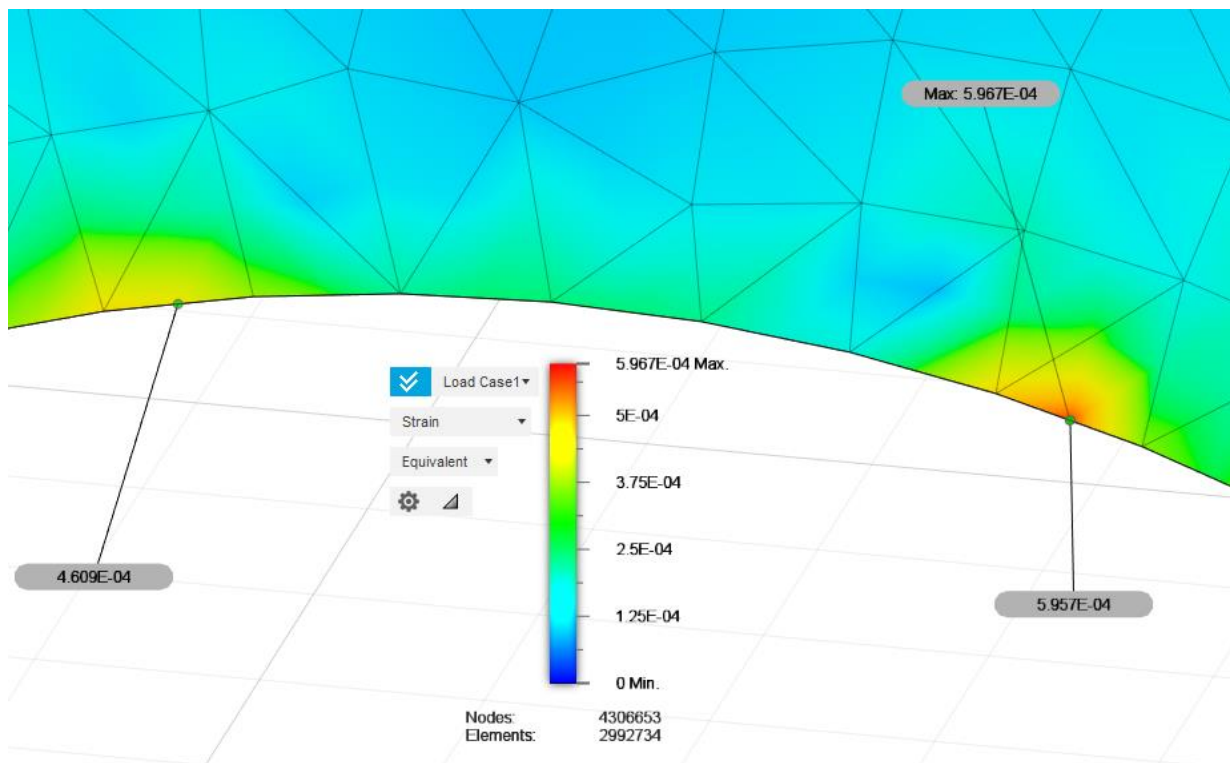


Figure 33 Surface Probs at Max Stress and Strain with Equivalent Strain as Measurable on Swingarm

To better understand the results, it must be noted that the values from MarkForged are ultimate strength and do not consider promotional limit and yield strength as previously spoken in section 14.4 and will only be assumed. The material data can be seen in Table 4.

The ideal max stress of the components would be well below the yield strength of the material. If the max stress of the components were within ten per cent of the yield strength, then the component or material would have been revised.

Markforged CFF Properties

Parameter	Value
Tensile Modulus (GPa)	60
Tensile Ultimate (MPa)	800
Yield Tensile Strength	540
Compressive Ultimate (MPa)	320
Flexural Strength (MPa)	500

***Note all parameters in fibre direction**

Table 4 MarkForged CFF Properties

While every property of the material is equally important, the ultimate compressive strength is the lowest and the load that the bike will be exerted to the most, due to the nature of mountain biking. As the bike goes through its travel from a drop, the bike compresses; thus, the material must have the compressive strength to endure such load and return to its original form. The 3rd principal stress is the value of compression stress.

16.1 ORIGINAL SWINGARM FEA

The FEA results of the swing can be seen in Table 5 also result from models can be found in Appendix 5, Appendix 6, and Appendix 7. The maximum VonMises stress was 22.9MPa, and 1st principal stress was 26.27MPa which was located at the rear axle pivot point seen in Figure 35 and Figure 36. Based on the findings, it can be said that the maximum tensile stress (1st principal) is at the location of the max VonMises stress this is due to von Mises stress accounting for the principal stress. Therefore, It is no surprise that both stresses were found at the same location. The equivalent max strain of 6.88E-04 was also located at the same position as 1st principal strain of 6.9818E-04 seen in Figure 37 this is due to stress is directly proportional to the strain if within the proportional limit of the material (Askeland, 1993). This is verification that the material is within its elastic limit and abiding Hooke's law. The 3rd principal stress value of 24.95MPa is at 180 degrees from the 1st principal on the opposite rear axle pivot face and is far below the compressive strength and is deemed acceptable seen in Figure 38.

The max displacement of the component is 0.001676mm and is located within the rear axle eyelet seen in Figure 39.

Original Swing Arm FEA Results

	1mm Mesh	0.75mm Mesh
Measurable	Value	Value
VM Stress (Mpa)	28.14	22.9
1st Principal Stress	24.48	26.27
3rd Principal Stress	-37.39	-24.95
Equivalent Strain	7.110E-04	6.880E-04
1st Principal Strain	6.190E-04	6.918E-04
3rd Principal Strain	-7.370E-04	-6.380E-04
Displacement (mm)	1.676E-03	1.740E-03
Nodes	3241045	6361519
Elements	2045719	4178238
Mass (g)	239.116	239.116

Table 5 Original Swingarm FEA Results

The results of the FEA are seen to be acceptable due to them being a fraction of the materials ultimate properties. However, the location of the results may be an area of concern. It was expected that the area around the rear axle pivot would have a high-stress and strain concentration. The locations of stress, strain and displacement are at the internal faces of the swingarm, where the real component has the inserts for bearings which reduced the material and could further increase the values.

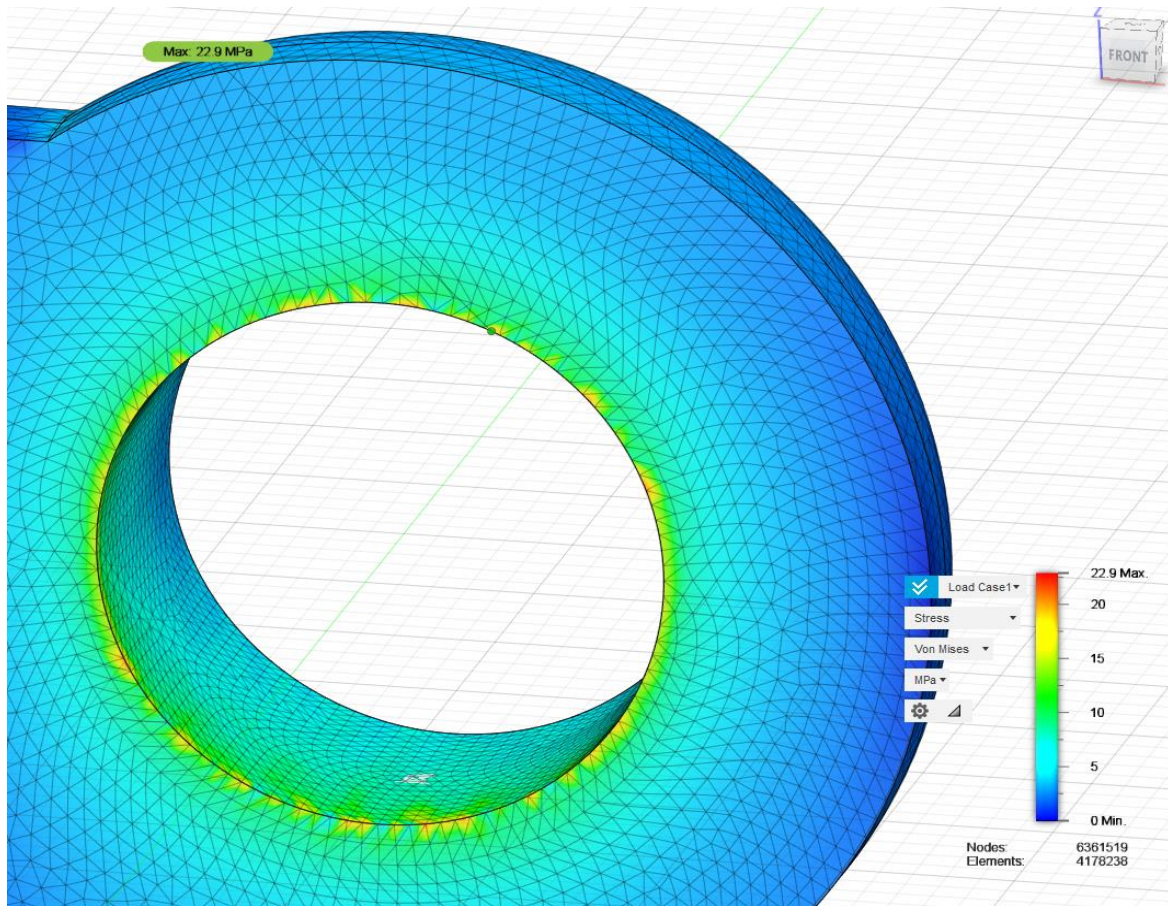


Figure 36 Max VonMises Stress Original Swingarm

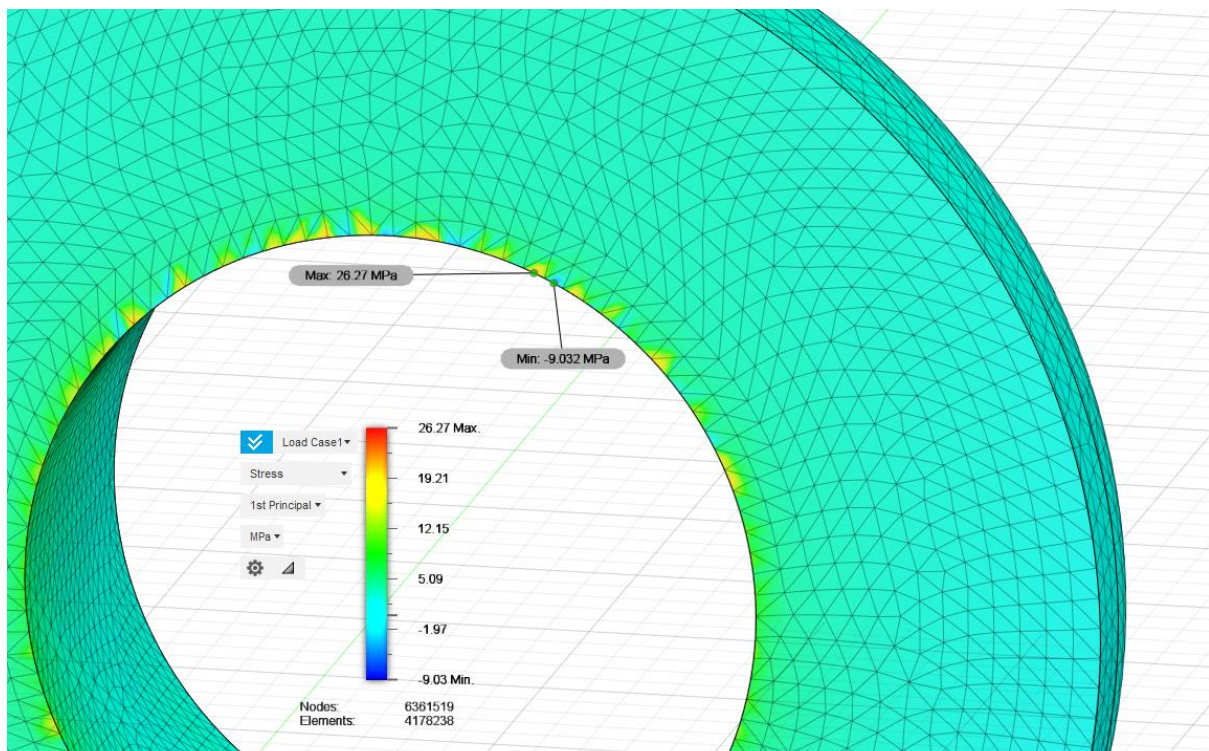


Figure 35 Max 1st Principal Stress Original Swingarm

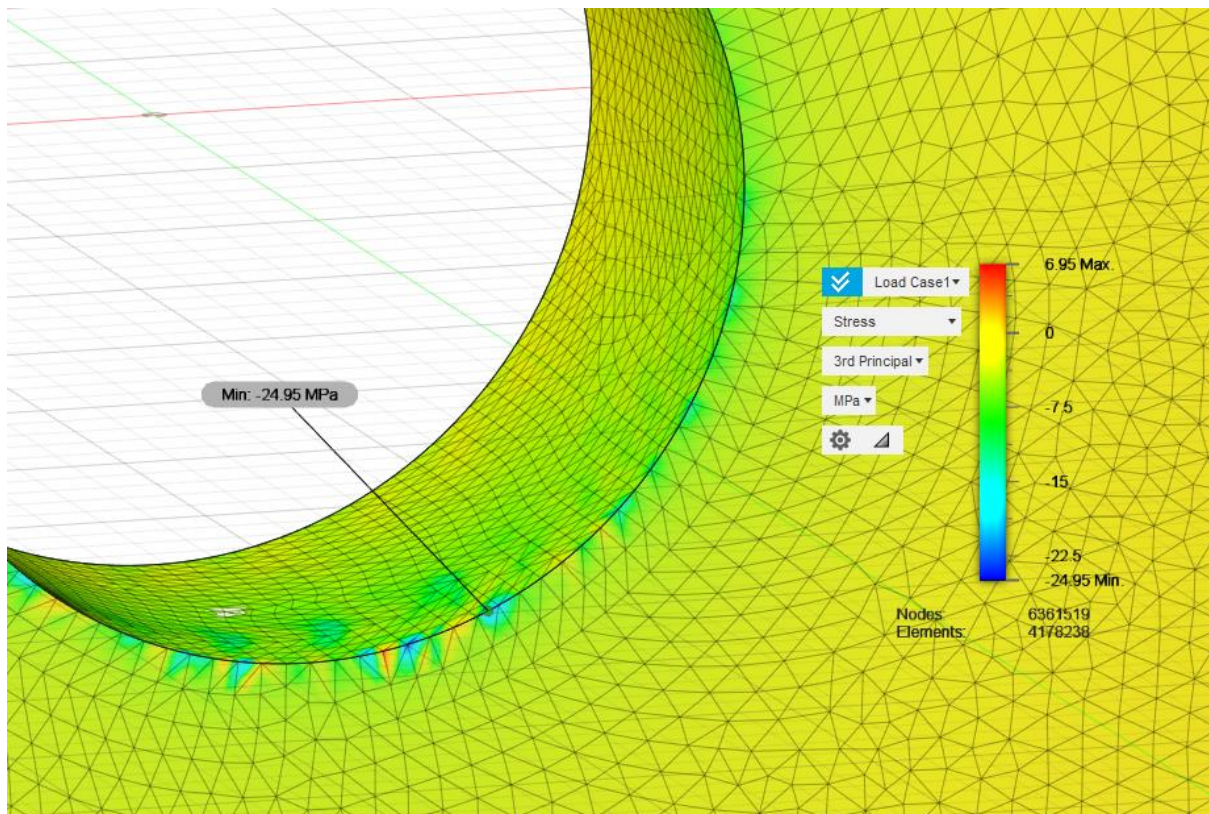


Figure 38 Max 3rd Principal Stress Original Swingarm

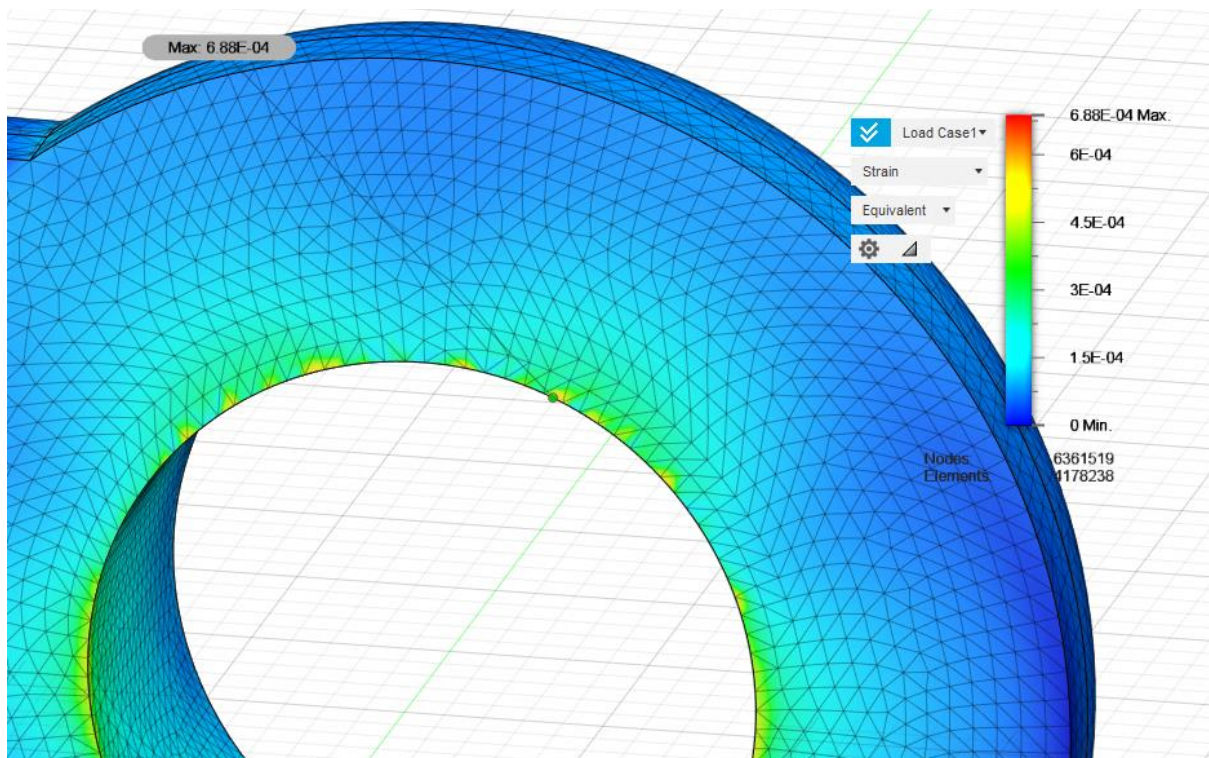


Figure 37 Max Equivalent Strain Original Swingarm

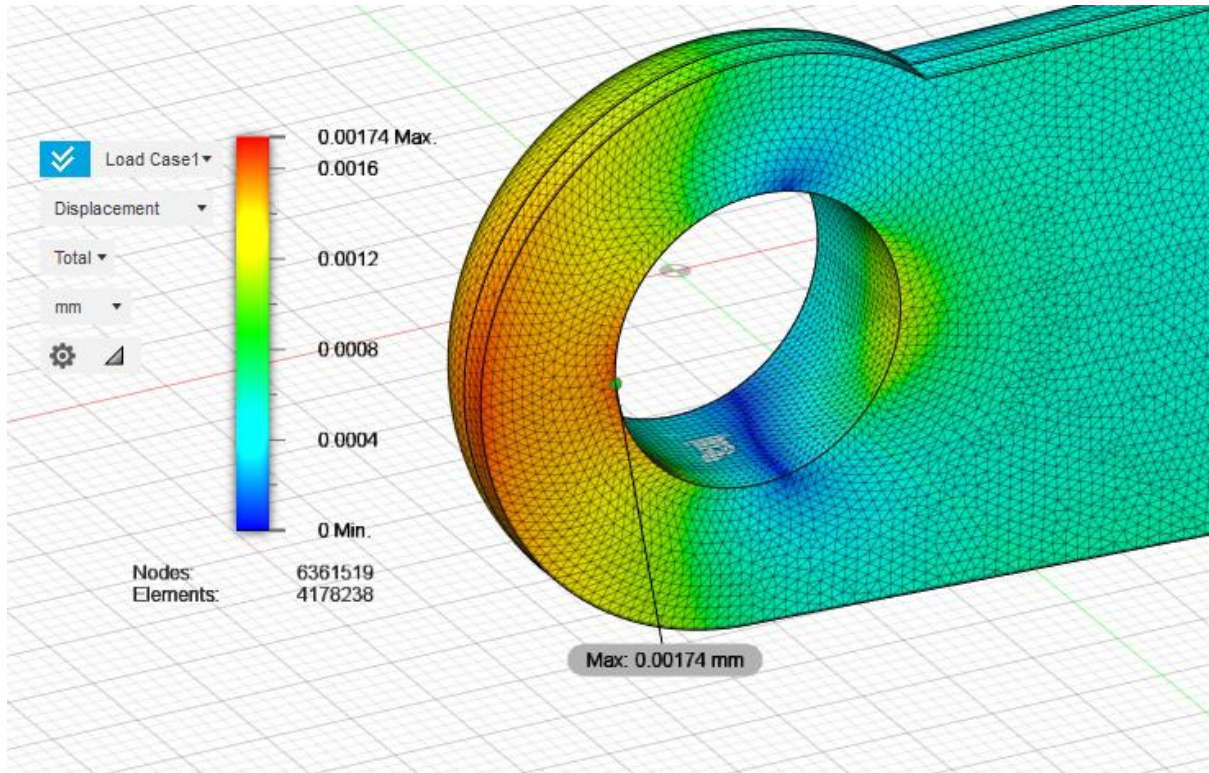


Figure 39 Max Displacement Original Swingarm

16.2 GENERATIVE DESIGN SWINGARM FEA

The FEA results of the GD swingarm with a 1mm mesh had the discrepancy of max VonMises Stress, and equivalent strain; the revision of mesh size to 0.75mm rectified this. The FEA results models can be found in Appendix 8, Appendix 9, and Appendix 10. The VonMises stress and 1st principal stress are 24.81MPa and 27.88MPa respectively; however, these values are at different locations. This could be due to there being higher levels of other stresses such as shear at the max von Mises location; hence the max tensile is in another location. The locations can be seen in Figure 40 and Figure 41. The locations of these stresses are at either rear axle pivot points but are both on the inner faces.

Generative Design Swing Arm FEA Results

	1mm Mesh	0.75mm Mesh
Measurable	Value	Value
VM Stress (Mpa)	25.05	24.81
1st Principal Stress	31.59	27.88
3rd Principal Stress	-26.96	-26.39
Equivalent Strain	5.967E-04	6.938E-04
1st Principal Strain	5.917E-04	6.862E-04
3rd Principal Strain	-5.796E-04	-6.437E-04
Displacement (mm)	1.412E-03	1.419E-03
Nodes	4306653	8254278
Elements	2992734	5799302
Mass (g)	279.374	279.374

Table 6 Generative Design Swingarm FEA Results

The 3rd principal stress value is 26.39MPa, which is deemed satisfactory and is at 180 degrees from the 1st principal stress however located on the other rear axle pivot where the max VonMises is found seen in Figure 44. This can be assumed to be due to the upper side of the rear axle pivot being in tension; therefore, the lower side must be in compression. The equivalent strain seen in Figure 43 is 6.938E-04, and 1st principal strain of 6.862E-04 seen in Figure 42 are located at the same location as Max von Mises stress. This is verification that the material is abiding Hooke's law when location and values are considered.

The 1st principal stress and 1st principal strain are located at different locations refer to Figure 41 and Figure 42. The 1st principal strain, however, is at the same location as the max VonMises stress. The maximum displacement was at the back of the rear axle pivot seen in Figure 45 with a value of 1.419E-04mm, which was expected due to the high load at that point. This could be seen as a discrepancy in the results of either the 1st principal stress or strain.

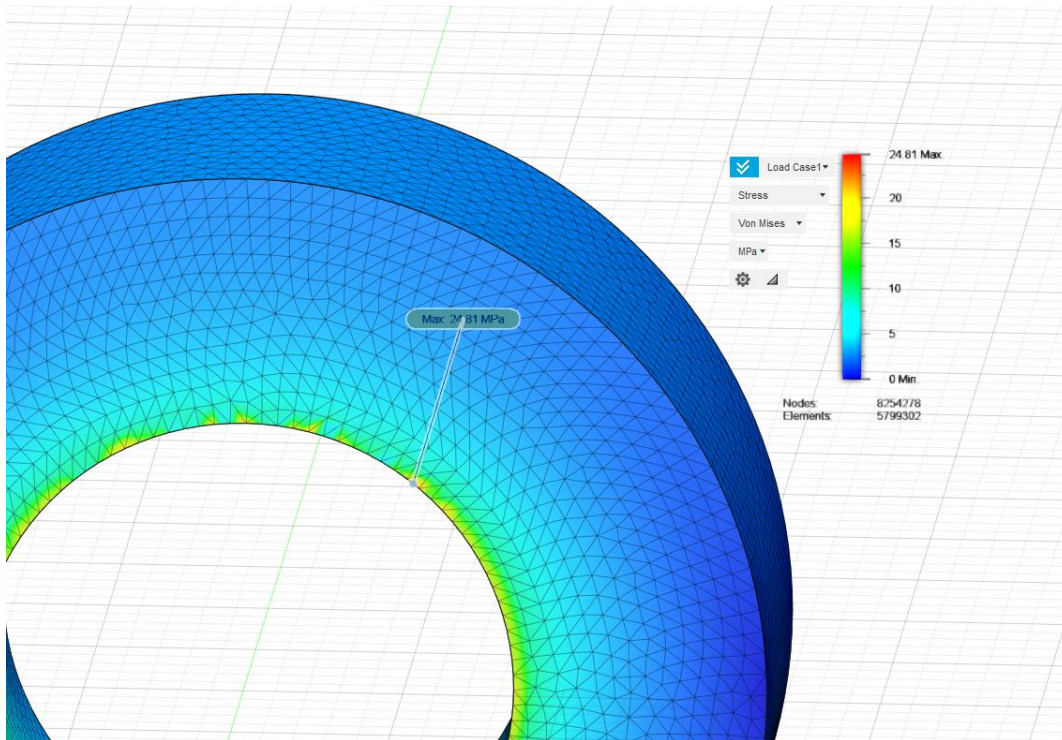


Figure 40 Max VonMises Stress Generative Design Swingarm

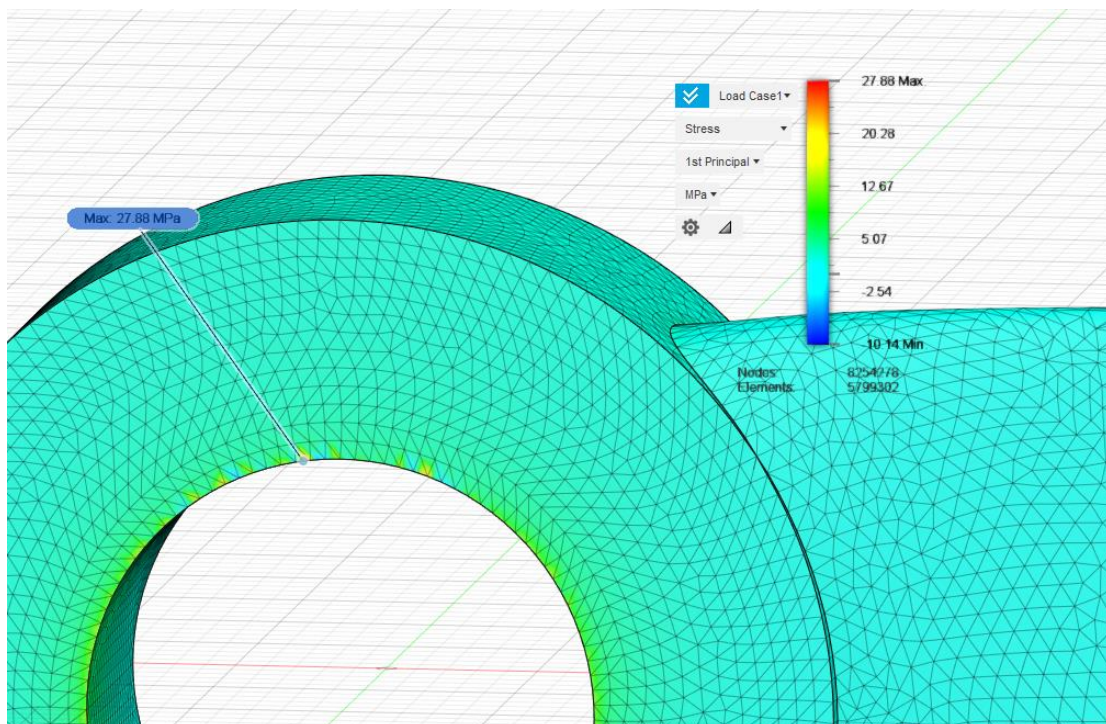


Figure 41 Max 1st Principal Stress Generative Design Swingarm

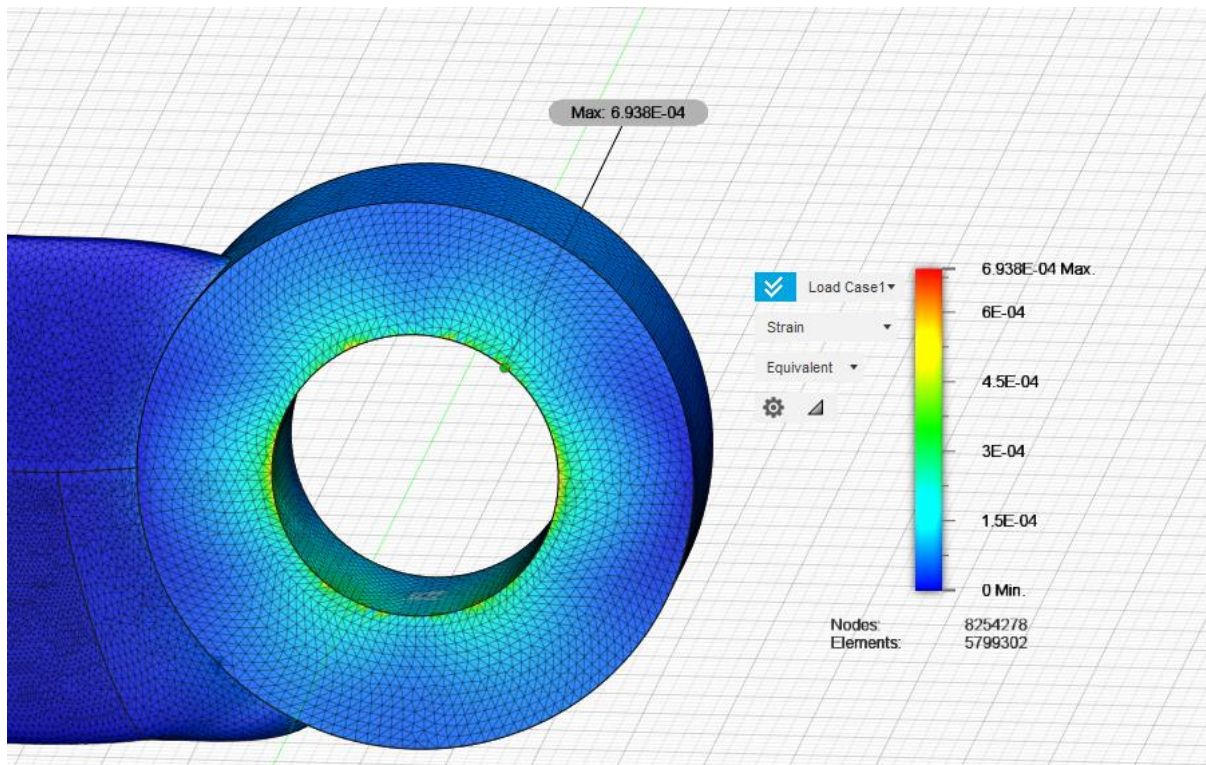


Figure 43 Max Equivalent Strain Generative Design Swingarm

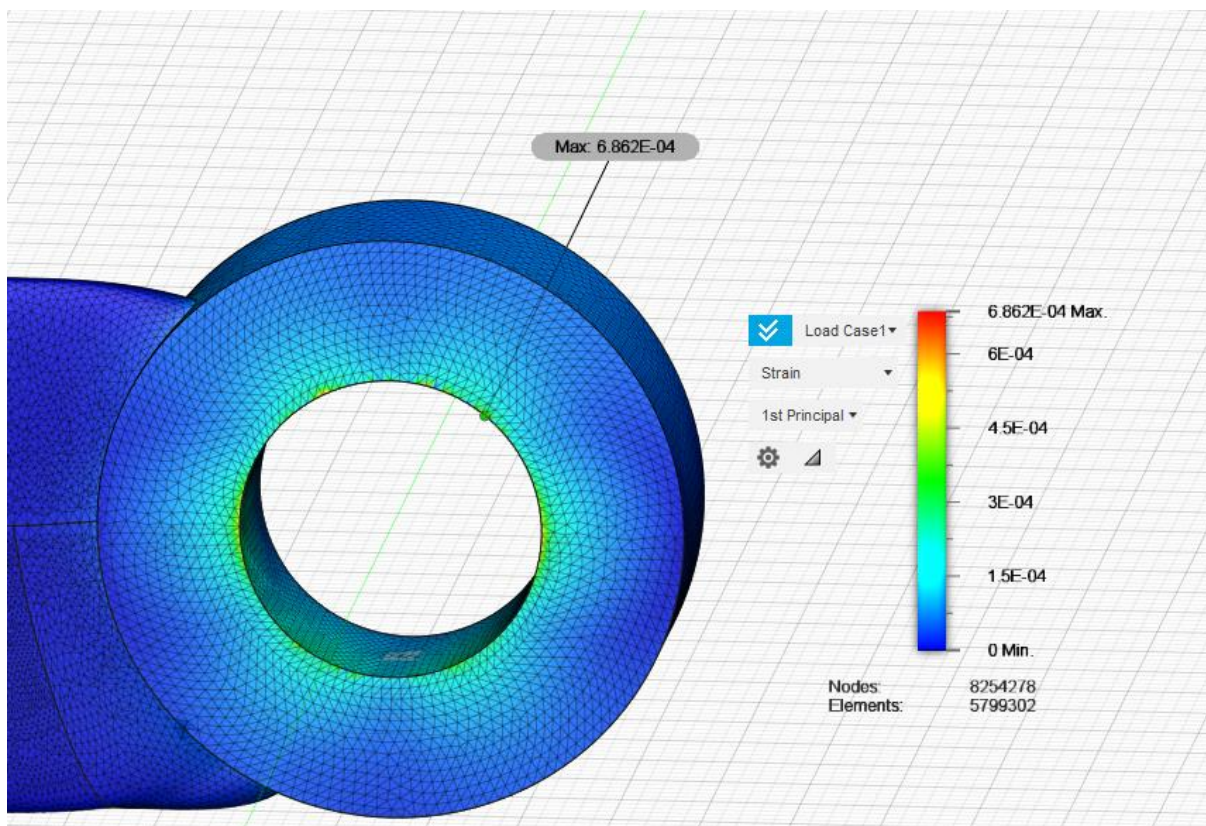


Figure 42 Max 1st Principal Strain Generative Design Swingarm

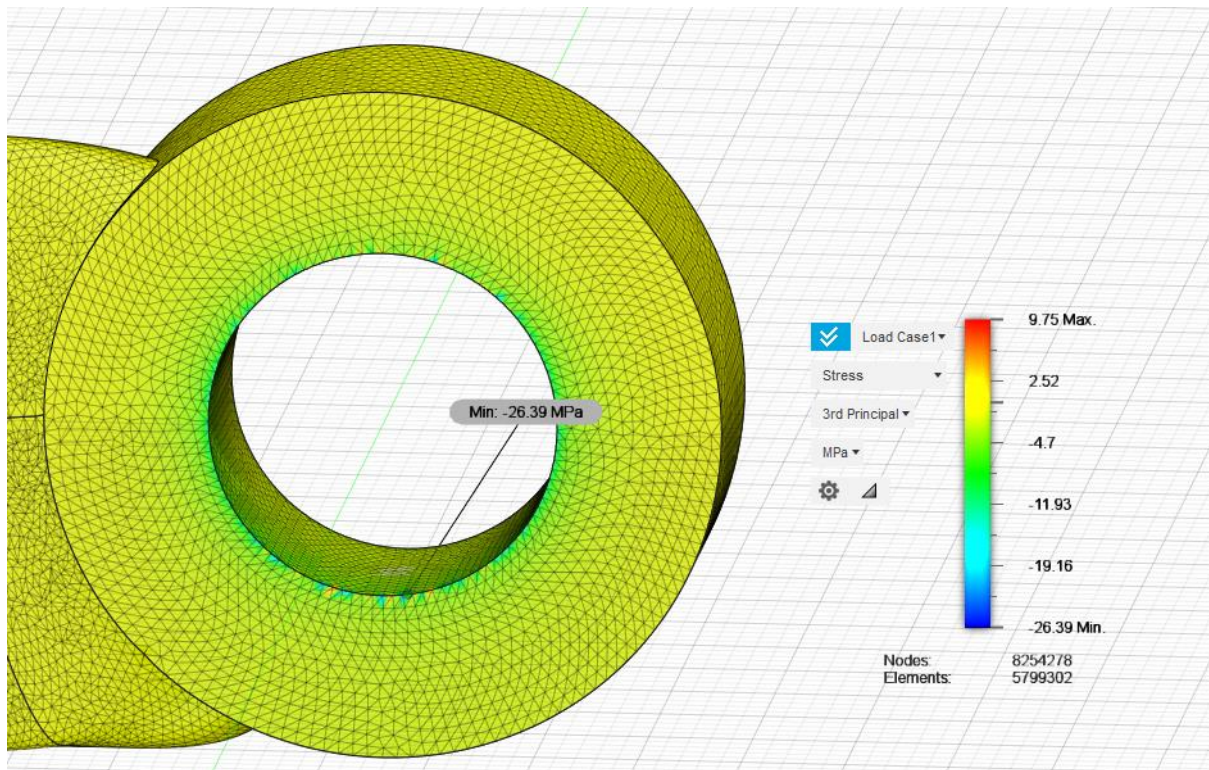


Figure 44 Max 3rd Principal Stress Generative Design Swingarm

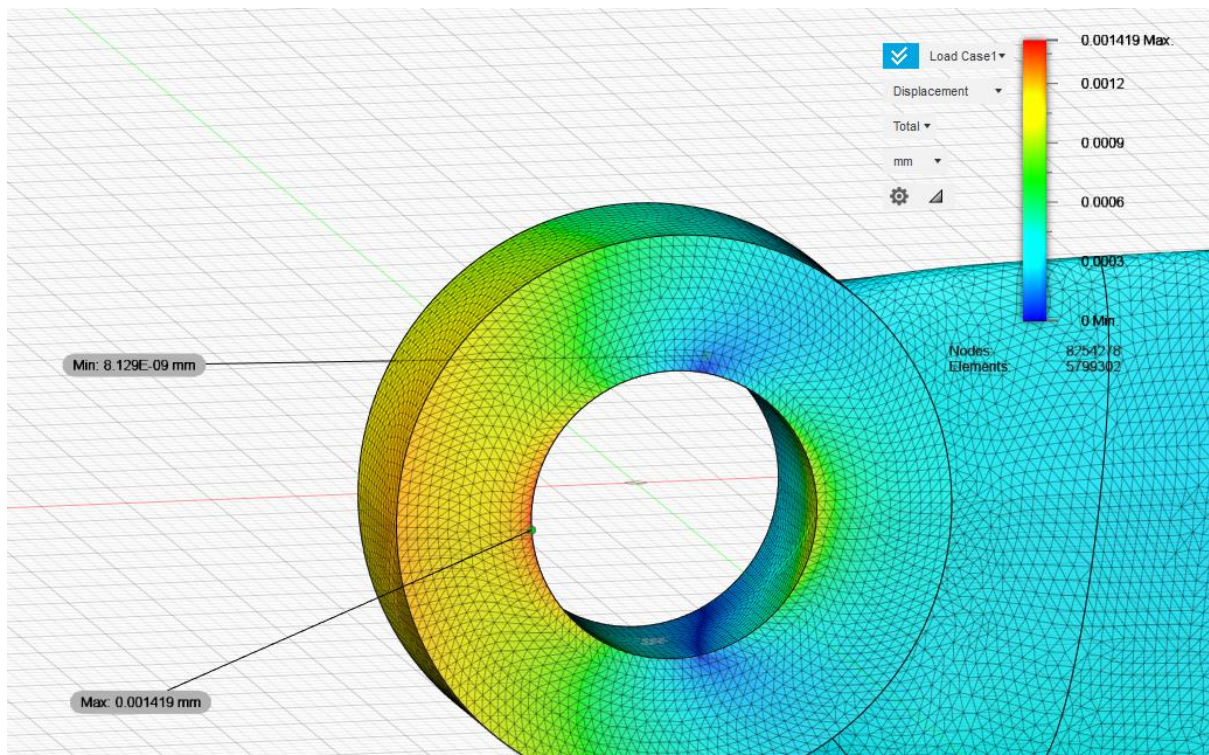


Figure 45 Max Displacement Generative Design Swingarm

16.3 ORIGINAL LINK ARM FEA

The original link arm with a 1mm mesh had different locations of Max von Mises stress and equivalent strain. The mesh was reduced to 0.75mm, yet this did not rectify the problem, a further reduction to 0.6mm did. The results are seen in Table 7 Original Link Arm FEA Results the decreased mesh size significantly increased the accuracy of the simulation, although at the cost of solve time. Full model results can be seen in Appendix 11,

Appendix 12 and Appendix 13. The maximum von Mises Stress was 61.39MPa, and the 1st principal stress was 40.07MPa both located at the rear axle pivot point seen in Figure 46 and Figure 47.

Original Link Arm FEA Results

Measurable	0.75mm Mesh	0.6mm Mesh
	Value	Value
VM Stress (Mpa)	51.27	61.39
1st Principal Stress	33.6	40.07
3rd Principal Stress	-32.24	-37.6
Equivalent Strain	1.481E-03	1.826E-03
1st Principal Strain	1.289E-03	1.567E-03
3rd Principal Strain	-1.276E-03	-1.594E-03
Displacement (mm)	1.465E-03	1.492E-03
Nodes	4253867	7878122
Elements	2964854	5559276
Mass (g)	259.672	259.672

The 3rd principal stress was 37.6MPa *Table 7 Original Link Arm FEA Results*

and was located close to the 1st principal stress seen in Figure 50. With all three stresses located in such proximity, it could explain why the von Mises stress is higher than the 1st principal stress.

The equivalent strain and 1st principle strain were 1.826E-03 and 1.567E-04, respectively and both located at the corresponding stress locations seen in Figure 49 and Figure 48. This is the verification that the material is acting abiding Hooke's law, thus deeming the results credible. The max displacement of 1.492E-03mm was found at the link pivot joint seen in Figure 52; the probable cause of this is the thin wall sections. A concerning result of the displacement is seen in Figure 51 at the midpoint of the body of the link arm displacement is 1.448E-03mm, while this value is relatively low. It is an indication that there is a lot of flex in this area.

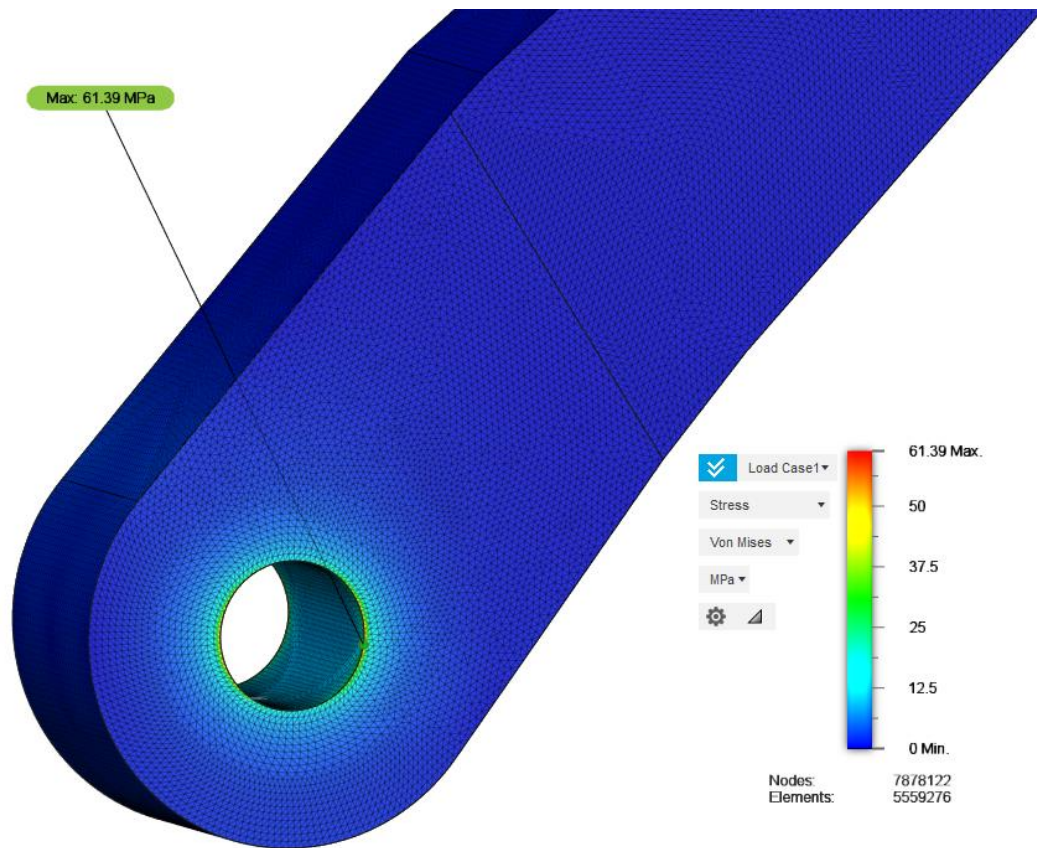


Figure 47 Max VonMises Stress Link Arm

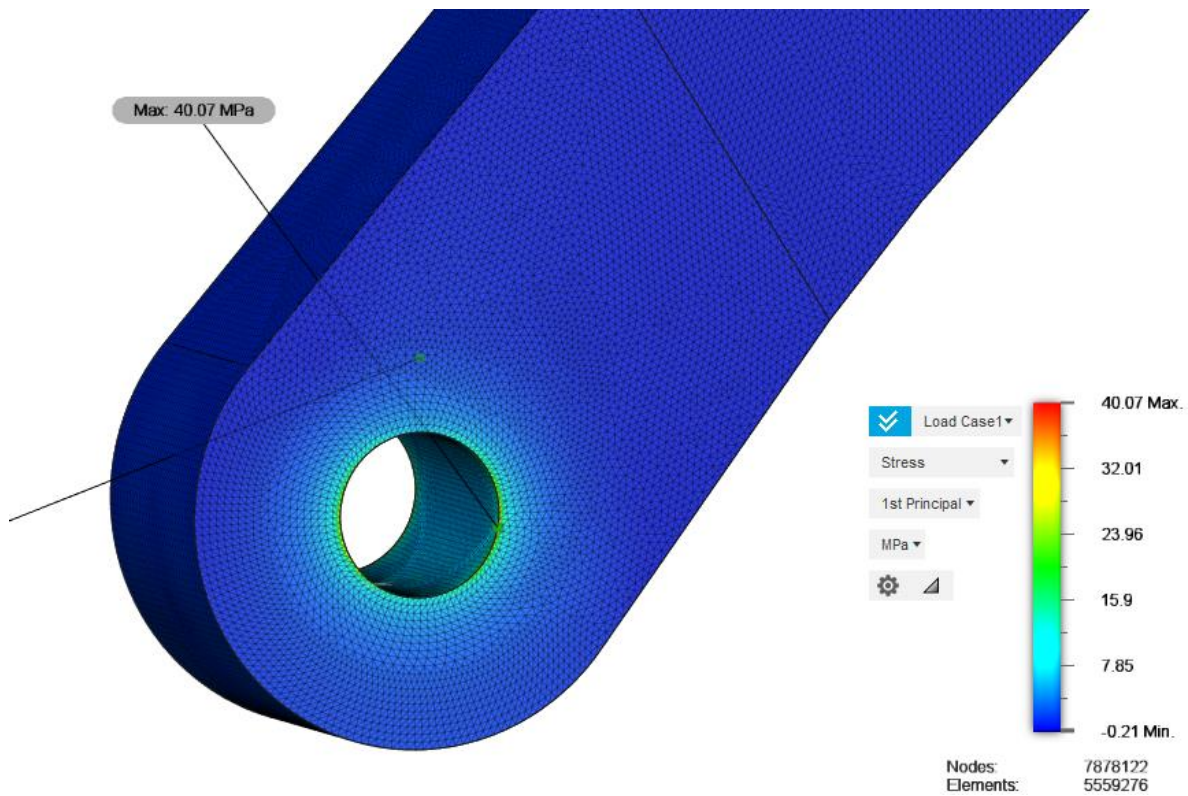


Figure 46 Max 1st Principal Stress Link Arm

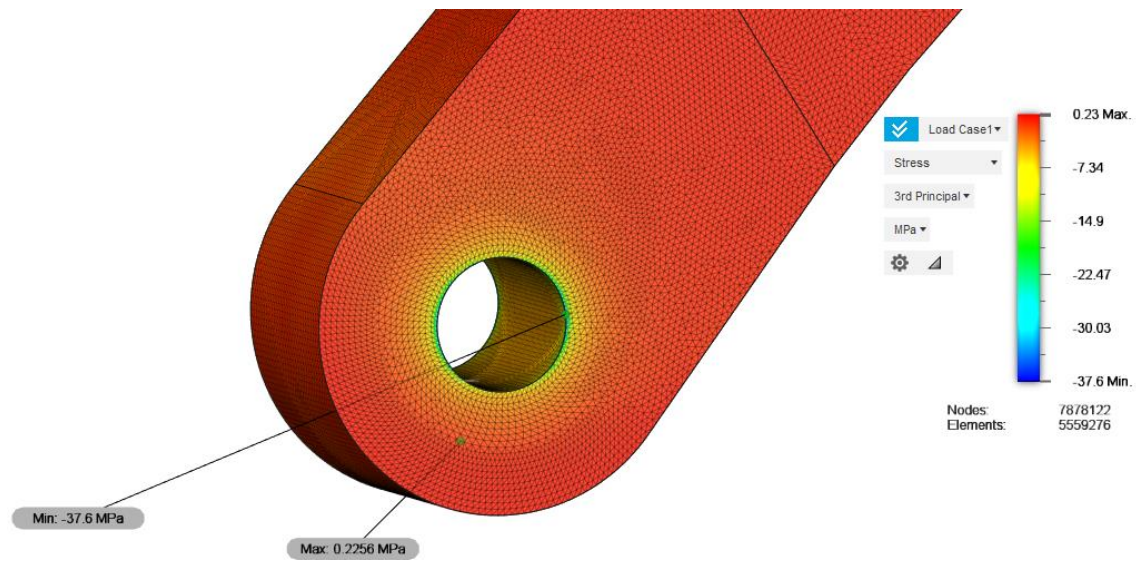


Figure 50 Max 3rd Principal Stress Link Arm

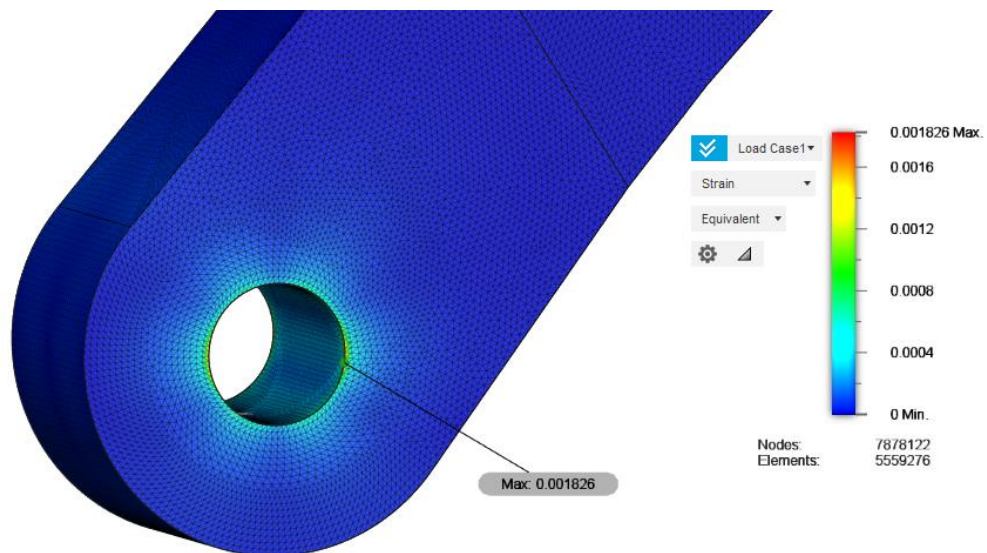


Figure 49 Max Equivalent Strain Link Arm

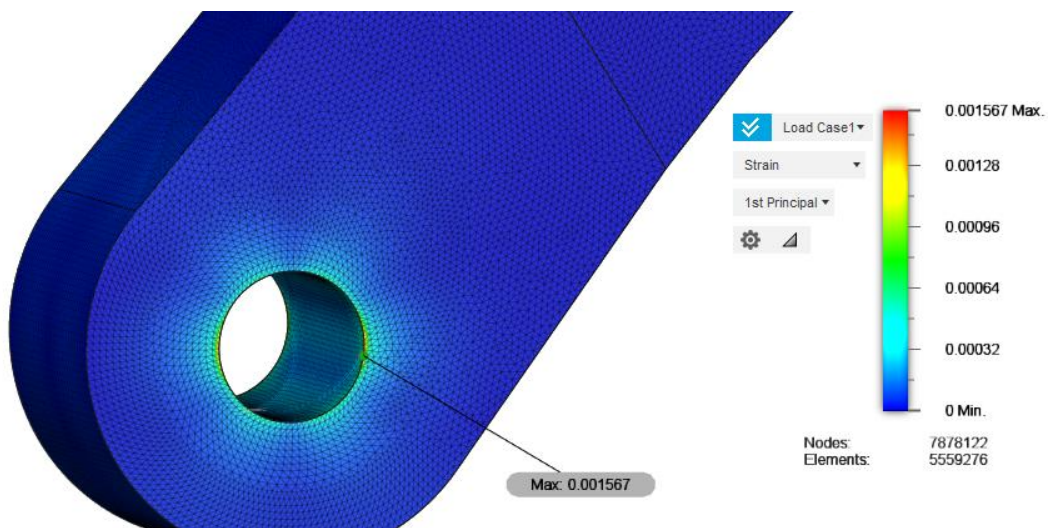


Figure 48 Max 1st Principal Strain Link Arm

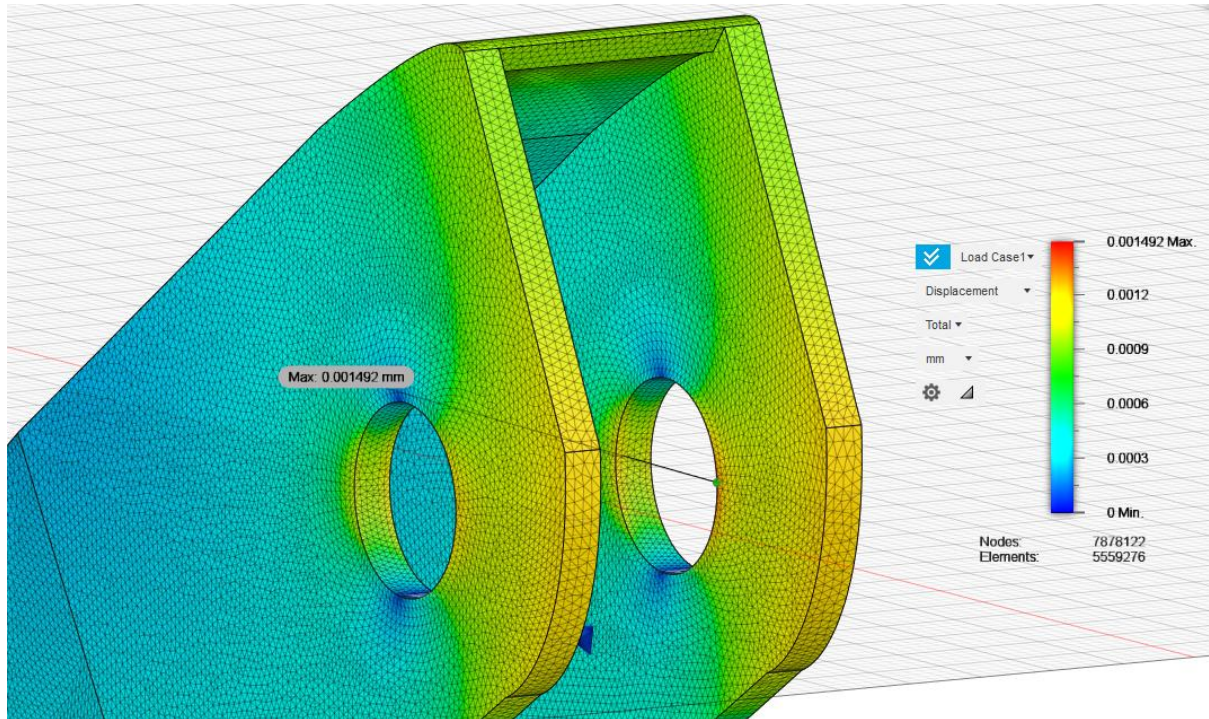


Figure 52 Max Displacement Link Arm

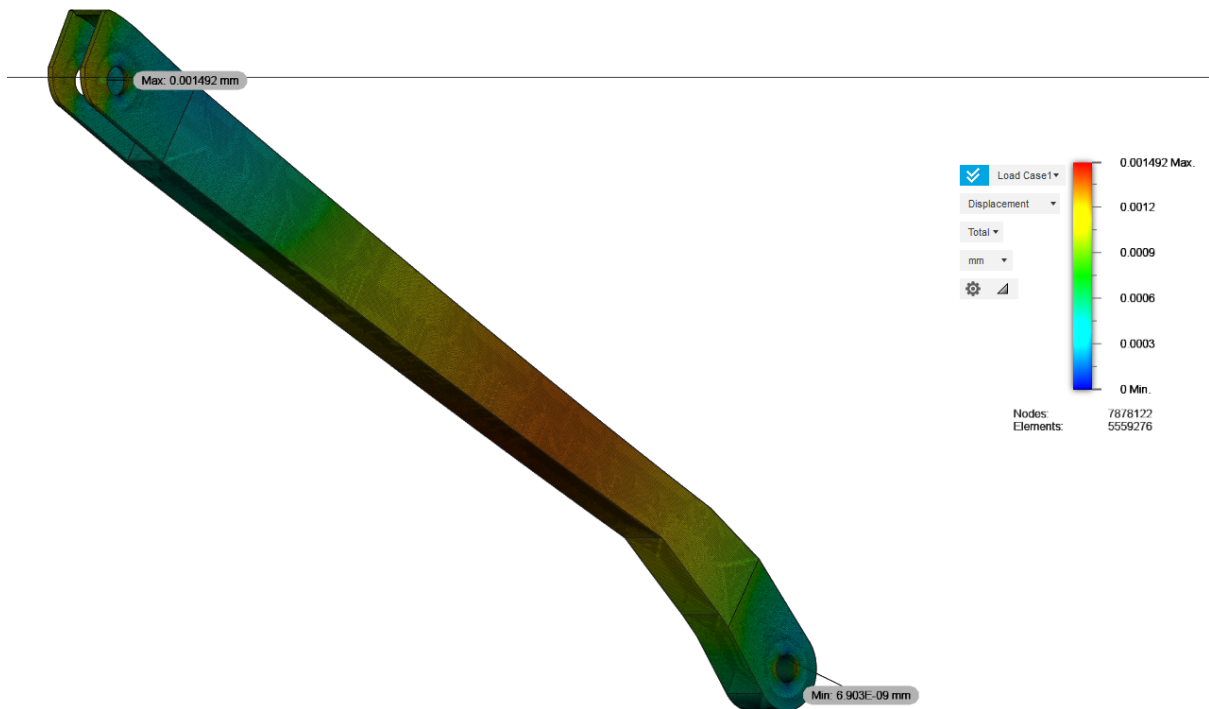


Figure 51 Displacement Side View Link Arm

16.4 GENERATIVE DESIGN LINK ARM FEA

The FEA results of the GD link arm are seen in Table 8 Generative Design Link Arm FEA Results, and FEA model results can be found in Appendix 14, Appendix 15, and Appendix 16. The max von Mises stress and 1st principal stress was 61.19MPa and 40.7MPa, respectively, both located at the same position seen in Figure 53 and Figure 54. With the max von Mises stress being higher than the 1st principal stress. The 3rd principal stress is 35.25MPa and is located one element from the 1st principal stress seen in Figure 55. The reason for the high von Mises stress could be due to all the stresses being so close to each other and von Mises being an absolute value of complex stresses.

The equivalent strain and 1st principal strain were 1.798E-03 and 1.567E-03 at

the same locations seen in Figure 56 and

Figure 58 as there corresponding stress. With the values of stress and strain coupled with the locations, it can be assumed to say that material was below the limit of proportionality, and the results can be said to be credible.

The displacement of 1.910E-03mm seen Figure 57 was an area of concern. With that amount of flex in the component, it could be prone to fatigue failure. While the component would not see such loading consistently, it will be exposed to multiple smaller loads but far more frequently. The lack of material there would be a revision in the next development phase.

Generative Design Link Arm FEA Results

	0.75 Mesh	0.6mm Mesh
Measurable	Value	Value
VM Stress (Mpa)	63.45	61.19
1st Principal Stress	38.63	40.7
3rd Principal Stress	-38.94	-35.25
Equivalent Strain	1.943E-03	1.798E-03
1st Principal Strain	1.661E-03	1.567E-03
3rd Principal Strain	-1.704E-03	-1.547E-03
Displacement (mm)	1.866E-03	1.910E-03
Nodes	2919088	4934851
Elements	2025935	3459326
Mass (g)	145.99	145.99

Table 8 Generative Design Link Arm FEA Results

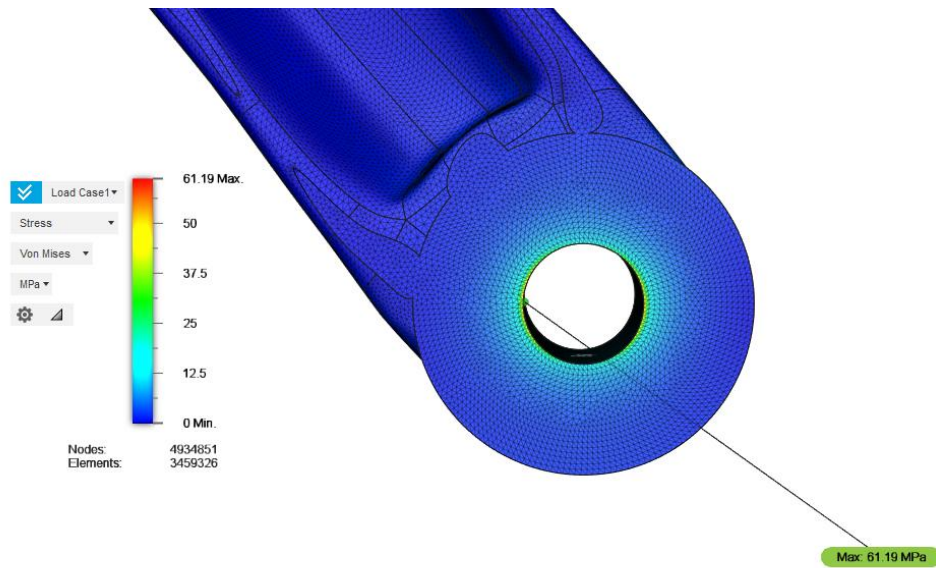


Figure 53 Max Von Mises Stress Generative Design Link Arm

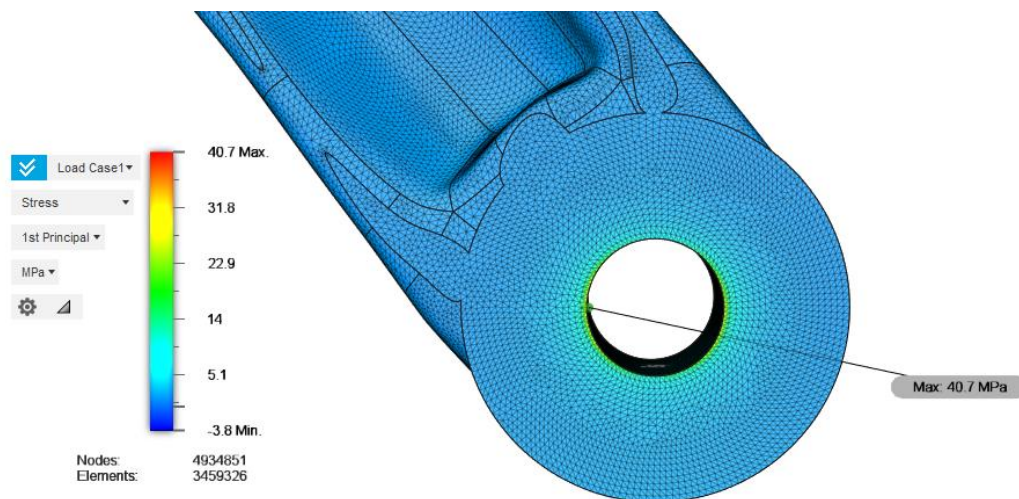


Figure 54 Max 1st Principal Stress Generative Design Link Arm

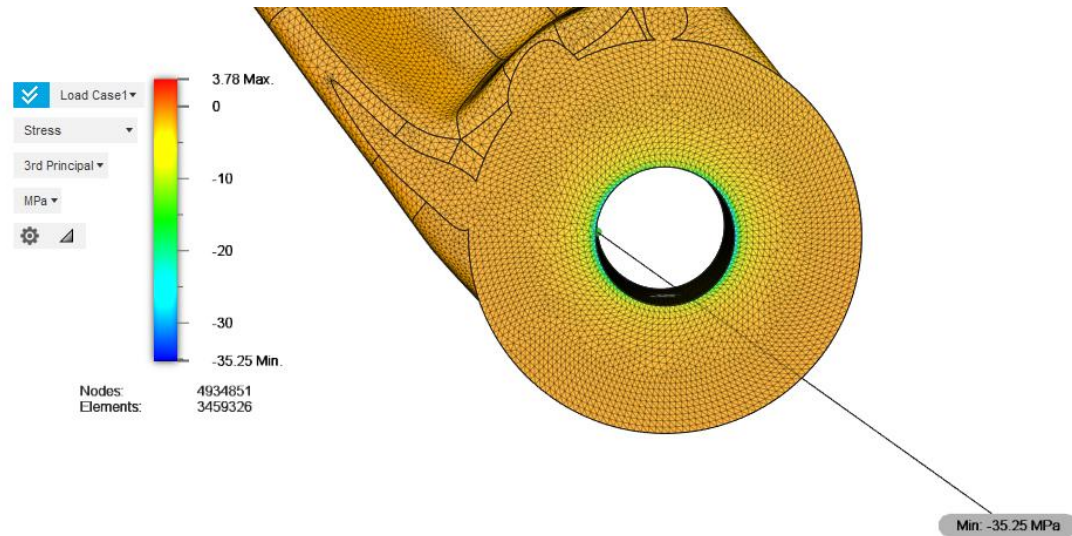


Figure 55 Max 3rd Principle Stress Generative Design Link Arm

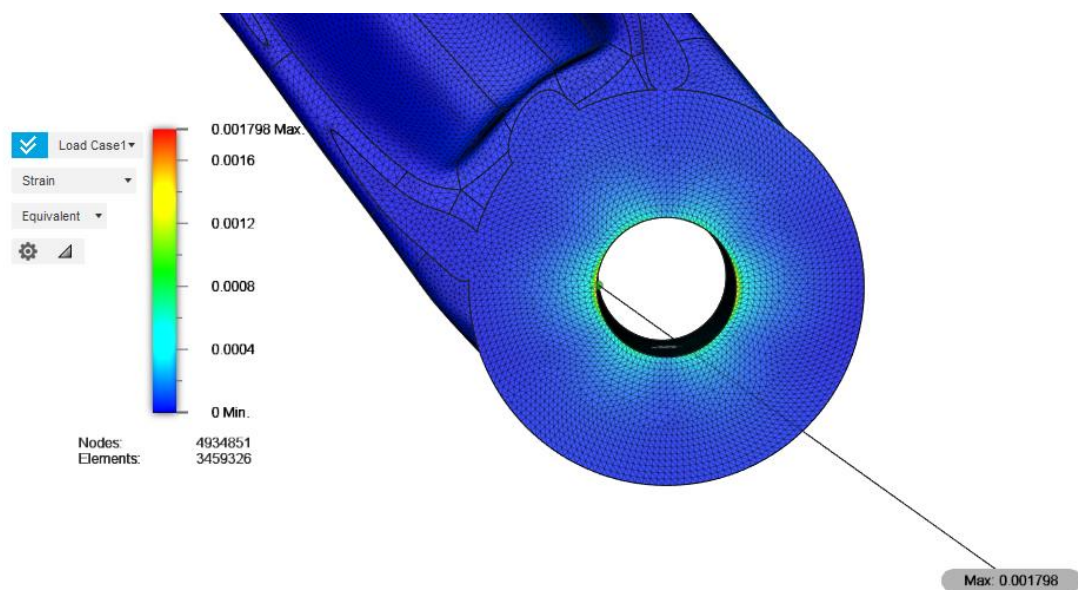


Figure 56 Max Equivalent Strain Generative Design Link Arm

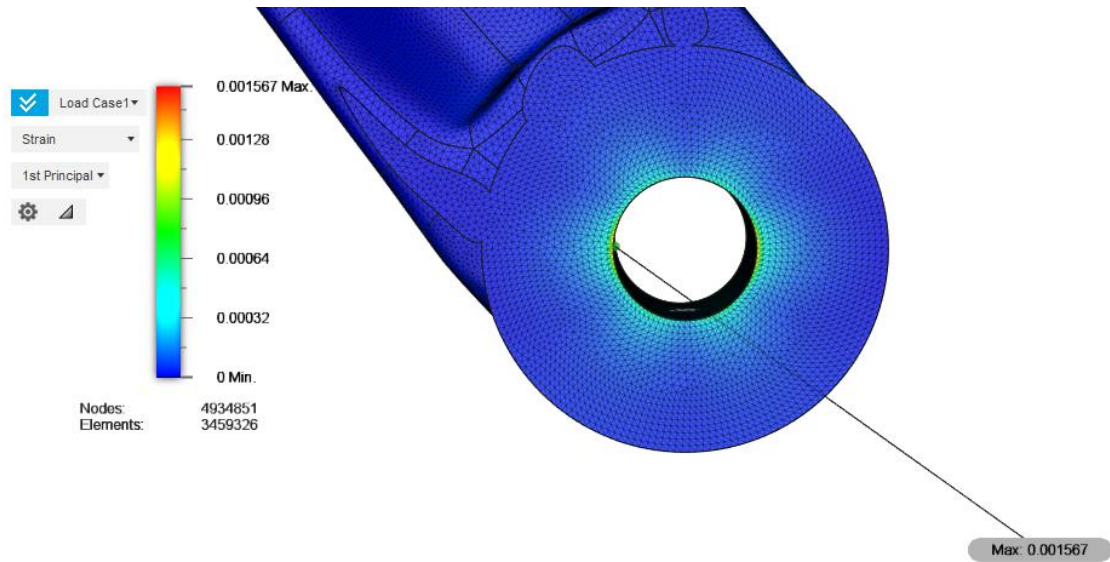


Figure 58 1st Principal Strain Generative Design Link Arm

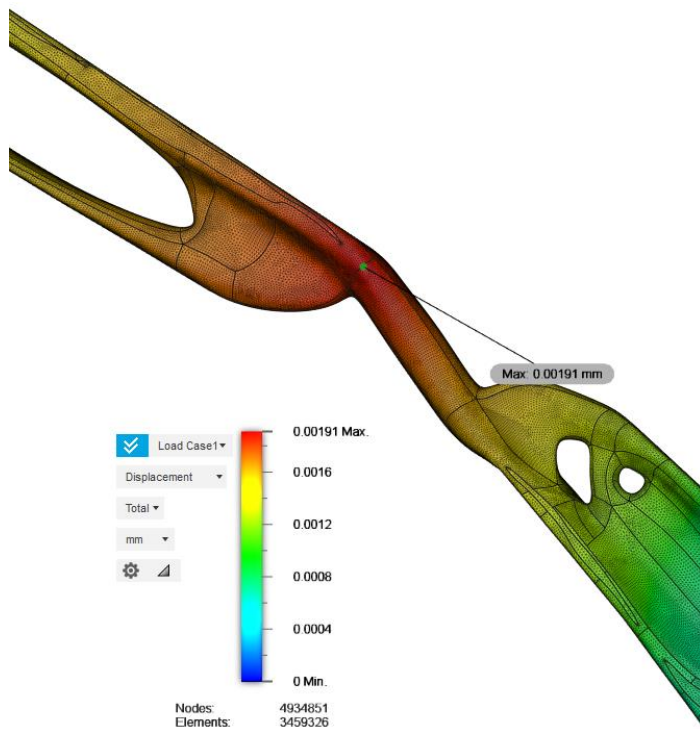


Figure 57 Max Displacement Generative Design Link Arm

16.5 FEA EVALUATION

Before the evaluation of components, it must be noted again that the original components FEA results are based upon assumptions. The real-life component may be designed to optimise the material properties thus may perform better in a real-world environment. This project changed the material of the component to give a standardised value so that a comparison can be made. Furthermore, stresses such as shear stress have not been considered in this comparison. Reports of the GD outcomes can be found in Appendix 19 and Appendix 20

16.5.1 Swingarm Comparison

The results of both FEA results of the swingarm can be seen in Table 9 the colours represent if the value was an improvement, equal or substandard. The GD swingarm only had a marginal improvement in tensile strain and displacement. However, all stress values had a marginal increase and addition of 40g of mass.

Swing Arm Comparison

	Original Swing Arm		GD Swingarm	
	Measurable	Value	Value	
All stresses and strains on both components were found to be on the face of the rear axle pivot. This was as expected due to the high load applied at that position.	VM Stress (Mpa)	22.9	24.81	
	1st Principal Stress	26.27	27.88	
	3rd Principal Stress	-24.95	-26.39	
	Equivalent Strain	6.880E-04	6.938E-04	
	1st Principal Strain	6.918E-04	6.862E-04	
	3rd Principal Strain	-6.380E-04	-6.437E-04	
	Displacement (mm)	1.740E-03	1.419E-03	
	Nodes	6361519	8254278	
	Elements	4178238	5799302	
	Mass (g)	239.116	279.374	

Table 9 Swingarm Comparison Matrix

It is important to note that the original component has inserts at pivot locations to seat bearings and fixing points. Therefore there will be less material at these positions; thus, stress values could be higher in a real-world scenario. In the next phase of development of the GD swingarm, these inserts can be set as the preserved geometry, which could change the design of the swingarm to reduce the

stress in these areas. This potentially could see improvements in the values compared to the original swingarm.

16.5.2 Link Arm Comparison

The results of both link arms can be seen in Table 10. The GD link arm has several improvements compared to the original. With only a minor increase of tensile stress but with a reduction in mass of 56%. With such improvements on original design so early in the development phase can only be seen as a success, with further geometry changes that GD can incorporate with the next iteration which the original design has already been optimised to.

The value of concern is the amount of displacement and the area of which it is located further detailed in section 16.4 and Figure 57. This would be a revision in the next development phase, with possible material constraints in that location.

Link Arm Comparison

	Original Link Arm	GD Link Arm
Measurable	Value	Value
VM Stress (Mpa)	61.39	61.19
1st Principal Stress	40.07	40.7
3rd Principal Stress	-37.6	-35.25
Equivalent Strain	1.826E-03	1.798E-03
1st Principal Strain	1.567E-03	1.567E-03
3rd Principal Strain	-1.594E-03	-1.547E-03
Displacement (mm)	1.492E-03	1.910E-03
Nodes	7878122	4934851
Elements	5559276	3459326
Mass (g)	259.672	145.99

Table 10 Link Arm Comparison Matrix

16.5.3 Von Mises & Maximum Principal

As explained in 13.1.2 von Mises and Maximum principal stress theories, each is more suited for different material types. Both values of von Mises and principal stress fell well below the assumed yield limit of the material so it can be justified that both scalars and values are credible. The location and values of von Mises stress and equivalent strain of each component verified that all components were abiding Hooke's law and within the linear solving range. Further investigation of material properties will need to be carried out to understand how the material fails. With this data, a decision on the relevant scalar can be made.

17 NEXT DEVELOPMENT STAGE

As this so far was the first phase of development, many considerations need to be taken for the linkage to become a physical component. For this reason, some recommendations of the development process are stated.

The next phase of development will start to incorporate inserts for bearings and fixing points. This will be done by revising the initial starting geometry in GD. These inserts will be at the areas of which there are high-stress concentrations so it could be a possibility that the outcome of that GD will be different.

Further geometry additions will be a brake calliper mount; this addition will need extensive research into loading. The braking load which will be applied will put a strain on the linkage, which if not correctly understood. This could change the characteristics of the bike, such as anti-rise, as explained in 12.4. This could lead to further iterations or a complete redesign. If the outcome has similarities to current designs, then some revision of the design may be considered around the areas of displacement to reduce the chance of fatigue failure.

Other loading conditions should also be considered in the next phase, due to the current loading conditions be assumed as static. Further investigation of industrial standard loading and possible real-world testing to find out new loading condition for such loading as impact simulation.

Material testing should be carried out to ensure the correct scalar is used and if the chosen material is a suitable option. The toughness of the material was highlighted as a critical attribute of a mountain bike material and will stop the damage from foreign bodies or unexpected impacts. Once the results of this are acceptable, then extra stress values such as shear stress should be considered in the FEA results.

Once the development has incorporated all these aspects, then further simulation should be carried out. Simulations of anisotropic materials in areas such as non-linear, fatigue, impact, frequency and thermal should be carried out on the component, followed by a complete assembly simulation to see

if components have an interference with the compliance of the components. This simulation will give a better understanding of the motion forces such angular momentum of the wheels, suspension compliance, acceleration and deacceleration. All these forces will affect the design of the components which should be incorporated in the GD.

Linkage simulation with new components should be carried out to ensure that the new linkage components do not change the characteristics of the bike. Once all these simulations have been carried out and deemed to be satisfactory, then a physical prototype can be made and tested. Furthermore, a manufacturing process study should take place to see what areas of the design if any have a constrain the process.

18 COST ESTIMATION

Using the GD components and the Anisoprint AM process for manufacturing the cost can be estimated. Using the Anisoprints Aura slicing software, the components were sliced to give an estimation of print time and material used details can be found in Appendix 17 and Appendix 18. The

link arm print time was 68hours and 38 minutes with a 218g of PETG filament and 10g of CCF. The swingarm had a print time of 77hours and 4 minutes with 213g of PETG and 8.18g of CCF found in Table 11.

Costs of Swingarm

Material Cost	Swingarm	Link Arm
PTEG @ £0.03 per g	£6.60	£6.84
CCF @ £0.43 per m	£24.08	£31.82
Energy £0.04 per 5h	£0.64	£0.56
Total	£31.32	£39.22

Table 11 Cost of Components

While the cost of components seen relatively low, without a comparison of the cost of original parts it is very difficult to compare. Bike companies do not release such data to the public; however, the retail of a Scott Spark swingarm is 1,090GBP (Westbrook Cycles, 2020). This does give some indication of either the amount of profit the bike companies make or the cost of the component. The cost of the PROM IS 500 has been neglected from these calculations. The reason for this is due to the volume of output not being known; therefore, the cost cannot be shared per unit.

19 CONCLUSION

To conclude, the aims of the project was to see if the use of advanced design and manufacturing techniques can be a replacement for the established method. The GD components have fared well against the original designs with regards to the FEA values and considering that the GD parts are in the first development stage. The reduction in design iterations has been exceptional and is one a key feature that GD has over traditional design methods. If the equivalent was designed using SO, then the time taken would be in the hundreds of hours compared to the time it took to pick the best design option. In regards to the GD outcomes, the link arm, outperformed the current design in almost all measured values. With further development, this component could be a viable option as a replacement. The swingarm did not perform well against the original component, but the original component has been through hours of development and it a tried and tested component. If an equal amount of time and investment went it the design of the component using GD, then it would outperform its traditional counterpart; this is evident in the many examples throughout this project.

The manufacturing of the GD components is where the most substantial improvements could be made. The manufacturing time estimations is an area with revision of the selected process could see a reduction. The times could be seen as reasonable compared to the Athertons bike manufacturing time of two weeks. However, this could only be a manufacturing option if there were multiple 3D printers, printing simultaneously to meet the demand. This will be the case if this becomes the primary manufacturing method. It would further reduce the labour needed due to the autonomous nature of AM. The price estimation of the components with regards to the material can be said to a reasonably low; however, further research into component price would be needed, but this is not information that companies would usually release to the public domain.

It should be noted that the GD models have been made with limited resources when compared to the development budgets that the big bike companies have. These companies have departments

dedicated to the design of these components; while the development of these components was carried out by a single person with a non-industrial CAD package. If this is considered then, the GD components can be seen as a success. With the current results and information, it could be said that the GD components could replace the originals if manufactured to a competitive price. The GD components have highlighted with knowledge of an industry and a reasonable level of competency of CAD what can be achieved.

Having said that GD was not used to its full potential in this project. The most significant limitations of the GD in this project was the part it was redesigning. GD was improving an existing design essentially, due to the constraints of the other components. To fully utilise GD to the fullest, the restrictions of current designs must not be incorporated. GD has the potential to redesign the whole bike and maybe for the better. GD has the capabilities of not only designing the bike but designing the factory and process of how it is manufactured. The limitations of GD is the imagination of the user. The improvements of GD is already evident in industries such as the aerospace industry where the savings of weight of the new components is equating to millions saved in fuel costs. The traditional thinking of density is equal to strength is gone, GD is the proof of that. Organic structures are now a common outcome of GD, and while humans have thought that man-made structures are better, GD proves that nature was right all along. When the algorithm matures, and the adoption of this technology is used widely in other industries, then it is a possibility become endless.

The application of GD would only be possible with new processes such as AM. It allows for parts to be produced, which before would never have been imagined. Internal cavities and organic webbing are becoming the norm now. With the investment in AM, the growth of the industry will be exponential. Advancements in materials and printers will only keep increasing, with speed and accuracy challenging traditional methods already within such a short amount of time. The next decade will be an exciting time with regards to the application of AM in mass production.

The implementation of AM in the bike industry by the Athertons has highlighted the advantages of the technology. The ability to customise the bike to order with no extra cost or time is a unique selling point that no other bike company offers. The age of one size fits all is gone, giving riders the ability to choose a size that fits them will be the new standard in the coming years. The hybrid approach of printing the lugs and bonding with carbon fibre tubes is the start of the implementation of AM in the bike industry. Retrospectively that approach would be best suited in this project, after understanding the load paths, and the stress concentrations minimal load is transferred through the body of the component. Carbon fibre tubing as the body would be sufficient, and GD could be used to design the lugs in the same way the Athertons have and printed using a more developed AM method. This would significantly reduce the print time compared to what was estimated in this project. Therefore, based on the findings, the status quo of the tube method of manufacturing bikes currently is the most cost-effective method with the available manufacturing technologies.

For GD and AM to be the direct replacement for traditional methods, there must be value-added or cost savings to the process. The bike industry, like many others, is based on profit, if this method costs more due to the limitations of volume with the same attributes, why would any bike company make the change. Unfortunately, profit stunts the growth of innovation. GD and AM have the capabilities of developing anything in the bike industry, but until there is a real need for change due to other factors or a competitive edge gained from this technology, then the change to these techniques will take some time.

20 REFERENCES

- 3D GBIRE, 2020. *www.3dgbire.com*. [Online]
Available at: <https://3dgbire.com/products/petg-rpetg-black-filament-1-75mm?variant=7743510773813>
[Accessed 12 April 2020].
- Abbey, T., 2018. *www.ptc.com*. [Online]
Available at: <https://www.ptc.com/en/cad-software-blog/what-is-topology-optimization>
[Accessed 29 March 2020].
- Akella, R., 2018. *www.newequipment.com*. [Online]
Available at: <https://www.newequipment.com/research-and-development/article/22059780/what-generative-design-is-and-why-its-the-future-of-manufacturing>
[Accessed 25 March 2020].
- All3DP, 2019. *www.all3dp.com*. [Online]
Available at: <https://all3dp.com/2/fused-deposition-modeling-fdm-3d-printing-simply-explained/>
[Accessed 27 March 2020].
- ALL3DP, 2020. *www.all3dp.com*. [Online]
Available at: <https://all3dp.com/2/the-3d-printer-filament-recycler-s-guide/>
[Accessed 18 March 2020].
- Allied Cycle Works, 2018. *www.cyclingtips.com*. [Online]
Available at: <https://cyclingtips.com/2018/01/how-carbon-fibre-bicycle-frames-are-made/>
[Accessed 28 April 2020].
- Alupro, 2020. *www.alupro.org.uk*. [Online]
Available at: <https://alupro.org.uk/consumers/how-is-aluminium-recycled/>
[Accessed 14 April 2020].
- AMFG, 2019. *www.AMFG.ai*. [Online]
Available at: <https://amfg.ai/wp-content/uploads/2019/08/The-Additive-Manufacturing-Landscape-2019-Whitepaper.pdf>
[Accessed 1 April 2020].
- Anisoprint, 2020. *www.anisoprint.com*. [Online]
Available at: <https://anisoprint.com/product-cf>
[Accessed 27 March 2020].
- Anisoprint, 2020. *www.anisoprint.com*. [Online]
Available at: <https://anisoprint.com/product-aura>
[Accessed 15 April 2020].
- Anisoprint, 2020. *www.anisoprint.com*. [Online]
Available at: <https://anisoprint.com/product-prom>
[Accessed 17 April 2020].
- Aniwaa, 2020. *www.aniwaa.com*. [Online]
Available at: <https://www.aniwaa.com/product/3d-printers/anisoprint-prom-is-500/>
[Accessed 16 April 2020].

- Arevo, 2018. *www.arevo.com*. [Online]
Available at: https://arevo.com/news_item/arevo-unveils-first-3d-printed-carbon-fiber-ebike/
[Accessed 15 April 2020].
- Askeland, D., 1993. *The Science and Engineering of Materials*. 2 ed. London: Chapman & Hall.
- Atherton Bikes, 2019. *www.athertonbikes.com*. [Online]
Available at: <https://www.athertonbikes.com/technology>
[Accessed 25 March 2020].
- Atherton Bikes, 2020. *www.athertonbikes.com*. [Online]
Available at: <https://www.athertonbikes.com/technology>
[Accessed 29 April 2020].
- Autodesk, 2019. *www.autodesk.com*. [Online]
Available at: <https://adsknews.autodesk.com/news/autodesk-airbus-generative-design-aerospace-factory>
[Accessed 15 April 2020].
- Autodesk, 2020. *www.autodesk.com*. [Online]
Available at: <https://www.autodesk.com/industry/manufacturing/resources/mechanical-engineer/what-is-generative-design>
[Accessed 22 March 2020].
- Autodesk, 2020. *www.autodesk.com*. [Online]
Available at: <https://knowledge.autodesk.com/support/simulation-mechanical>
[Accessed 2 April 2020].
- Bank of England, 2020. *www.bankofengland.co.uk*. [Online]
Available at: <https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator>
[Accessed 5 May 2020].
- Barthelat, F., 2014. Designing nacre-like materials for simultaneous stiffness,. *Journal of the Mechanics and Physics of Solids*, 73(1), pp. 22-37.
- Bayer, C., 2019. *www.enduro-mtb.com*. [Online]
Available at: <https://enduro-mtb.com/en/orbea-rallon-m-ltd-19-review/>
[Accessed 14 October 2019].
- Bhasin, V. & Bodla, M., 2018. *Impact of 3D Printing on Global Supply*, Massachusetts: MIT.
- Bicycle Retailer, 2020. *www.bicycleretailer.com*. [Online]
Available at: <https://www.bicycleretailer.com/international/2020/03/30/giant-hits-record-revenue-2019-braces-rocky-year-ahead#.Xr-odahKhhE>
[Accessed 6 April 2020].
- Bicycle Universe, 2020. *www.bicycleuniverse.com*. [Online]
Available at: <https://bicycleuniverse.com/where-are-bikes-made/>
[Accessed 115 MARCH 2020].
- Bikeradar, 2018. *www.bikeradar.com*. [Online]
Available at: <https://www.bikeradar.com/features/the-ultimate-guide-to-mountain-bike-rear-suspension-systems/>
[Accessed 14 December 2019].
- Bloomberg, 2019. *www.bloomberg.com*. [Online]
Available at: <https://www.bloomberg.com/news/articles/2019-06-17/world-s-top-bicycle-maker->

says-era-of-made-in-china-is-over

[Accessed 28 April 2020].

Bougherara, H., Saleem, M., Shah, S. & Toubal, L., 2018. Stress analysis of a carbon fiber-reinforced epoxy plate with a hole undergoing tension: A comparison of finite element analysis, strain gages, and infrared thermography. *Journal of Composite Materials*, 1(1), pp. 1-12.

Bourell, D. et al., 2017. Materials for additive manufacturing. *CIRP Annals*, 66(2), pp. 659-681.

Brandt, M., 2017. *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications*. 1 ed. London: Woodhead Publishing Ltd.

Britannica, 2020. *www.britannica.com*. [Online]

Available at: <https://www.britannica.com/science/conservative-force>

[Accessed 29 March 2020].

Britannica, 2020. *www.britannica.com*. [Online]

Available at: <https://www.britannica.com/science/Hookes-law>

[Accessed 2 April 2020].

Bu, Y., Xiang, Z., Wu, X. & Chen, C., 2010. Optimal design of mountain bicycle based on biomechanics. *Transactions of Tianjin University*, 16(1), pp. 45-49.

Carbon3d, 2020. *www.carbon3d.com*. [Online]

Available at: <https://www.carbon3d.com/white-papers/injectionmoldingcosts/>

[Accessed 15 April 2020].

Chadwick, P., 2012. *Continuum mechanics: concise theory and problem*. 2 ed. New York: Courier Coporation.

Chang, K.-H., 2015. *Structural Design Sensitivity Analysis*. 1 ed. London: Elsevier.

Chua, C., Leong, K. & Lim, C., 2003. *Rapid Prototyping*. 2 ed. Singapore: World Scientific.

CISION, 2018. *www.prnewswire.com*. [Online]

Available at: <https://www.prnewswire.com/news-releases/global-and-china-carbon-fiber-and-cfrp-industry-report-2018-2022-300682977.html>

[Accessed 14 April 2020].

Clarke, C., 2017. *Behind the Bike HB160* [Interview] (21 August 2017).

Collotta, M., Solazzi, L. & Pandini, S., 2017. New design concept of a downhill mountain bike frame made of a natural composite material. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 232(1), pp. 50-56.

Cycling Industry, 2017. *www.cyclingindustry.com*. [Online]

Available at: <https://cyclingindustry.news/where-can-the-bicycle-industry-go-to-recycle-its-carbon-waste/>

[Accessed 12 April 2020].

Cycling Industry, 2019. *www.cyclingindustry.com*. [Online]

Available at: <https://cyclingindustry.news/one-third-of-new-bike-customers-are-planning-to-spend-over-500/>

[Accessed 1 March 2020].

Dassault, 2017. *www.solidworks.com*. [Online]

Available at: <https://blogs.solidworks.com/tech/2017/07/needs-mesh-controls->

[anyway.html#_ga=2.157382076.763274582.1573940097-8f5c6790-8ec5-11e9-9da1-1f7a9cb301a7](#)
[Accessed 15 November 2019].

Dieter, G., 1991. *Engineering Design*. 1 ed. Singapore: McGraw-Hill.

Dino, I. G., 2012. CREATIVE DESIGN EXPLORATION BY PARAMETRIC. *METU Journal of the Faculty of Architecture*, 29(1), pp. 207-224.

Dirt Mountainbike, 2017. www.dirtmountainbike.com. [Online]
Available at: <https://dirtmountainbike.com/uncategorized/starling-cycles-murmur.html>
[Accessed 21 April 2020].

Dutt, D., Natarajan, V., Wilson, A. & Robinson, R., 2020. www.deloitte.com. [Online]
Available at: <https://www2.deloitte.com/us/en/insights/industry/automotive/industry-4-0-future-of-automotive-industry.html>
[Accessed 16 April 2020].

Elkington, M. et al., 2015. Hand layup: understanding the manual process. *Advance Manufacturing: Polymers & Composites Science*, 1(3), pp. 138-151.

Enduro-MTB, 2019. www.enduro-mtb.com. [Online]
Available at: <https://enduro-mtb.com/en/mtb-suspension-kinematics/>
[Accessed 19 December 2019].

EOS, 2019. www.eos.com. [Online]
Available at: <https://eos.materialdatacenter.com/eo/>
[Accessed 29 March 2019].

EOS, 2019. www.eos.info. [Online]
Available at: <https://www.eos.info/material>
[Accessed 22 March 2019].

Farmer, B., 2019. *The Tech Behind the New Atherton Bikes* [Interview] (7 April 2019).

FEA for all, 2017. www.feaforall.com. [Online]
Available at: <http://feaforall.com/linear-static-analysis-fea/>
[Accessed 14 November 2019].

Foale, T., 2002. *Motorcycle Handling and Chassis Design: The Art and Science*. 2nd ed. Madrid: Tony Foale Designs.

Ford Motor Company, 2019. *Ford Production System Hand Book*. Bridgend: Ford Motor Company.

Ford Motor Company, 2020. www.henryford.com. [Online]
Available at: <https://www.henryford.com/hcp/academic/pathology/production-system/what-is>
[Accessed 3 May 2020].

GE, 2018. www.ge.com. [Online]
Available at: <https://www.ge.com/reports/future-manufacturing-take-look-inside-factory-3d-printing-jet-engine-parts/>
[Accessed 6 March 2020].

GE, 2020. www.ge.com. [Online]
Available at: <https://www.ge.com/additive/additive-manufacturing/industries/aviation-aerospace>
[Accessed 27 March 2020].

Giant Bicycles, 2018. www.giant-bicycles.com. [Online]
Available at: <https://www.giant-bicycles.com/gb/news/aluminium-or-carbon-mtb-frame-which-one->

[to-choose/22809](#)

[Accessed 10 March 2020].

Gibson, I., Rosen, D. & Stucker, B., 2014. *Additive manufacturing technologies*. 17 ed. New York: Springer.

Goldratt, E., 2009. Standing on the shoulders of giants: production concepts versus production applications. The Hitachi Tool Engineering example. *Gestao & Producao*, 16(3), pp. 1-10.

Gonzalez, J., 2011. *Interview with director of suspension at Trek* [Interview] (17 Januray 2011).

GSC, 2017. www.solidoworks.com. [Online]

Available at: https://blogs.solidworks.com/tech/2017/07/needs-mesh-controls-anyway.html#_ga=2.157382076.763274582.1573940097-8f5c6790-8ec5-11e9-9da1-1f7a9cb301a7 [Accessed 15 November 2019].

Hope Tech, 2019. www.hopetech.com. [Online]

Available at: <https://www.hopetechhb.com/> [Accessed 26 September 2019].

Hughes , C., 2018. *The Worlds First 3D Printed Bike*. [Interview] (1 June 2018).

Hughes, T., 1987. *The Finite Element Method: Linear Static and Dynamic Finite Element Analysis*. 1 ed. Stanford: Dover Publications.

Hutton, D. V., 2003. *Fundamentals of Finite Element Analysis*. 1 ed. New York: McGraw-Hill.

iMakr, 2020. www.imakr.com. [Online]

Available at: <https://www.imakr.com/anisoprint/anisoprint-composite-carbon-fibre-ccf-spool> [Accessed 12 May 2020].

Inagaki, M., 2000. *New Carbon: Control of Structure and Function*. 1 ed. Oxford: Elsevier Science.

ISO, 2020. www.iso.org. [Online]

Available at: <https://www.iso.org/standard/59908.html> [Accessed 4 May 2020].

i-track suspension, 2020. www.i-tracksuspension.com. [Online]

Available at: <http://www.i-tracksuspension.com/suspensiontheory2.html> [Accessed 25 Febuary 2020].

Jiang, D. & Smith, D., 2017. Anisotropic mechanical properties of oriented carbon fiber filled polymer composites produced with fused filament fabrication. *Additive Manufacturing*, 18(1), pp. 84-94.

Jones , R., 2009. *Deformation Theory of Plasticit*. 1 ed. Blacksburg: Bulls Ridge.

Kanbanize, 2020. www.kanbanize.com. [Online]

Available at: <https://kanbanize.com/lean-management/value-waste/7-wastes-of-lean> [Accessed 1 May 2020].

Keyuan, Z., 2015. Regulation of waste dumping at sea: The Chinese practice. *Ocean & Coastal Management*, 52(1), pp. 383-389.

King, J., 2017. www.3dprintheq.com. [Online]

Available at: <https://3dprintheq.com/cost-running-desktop-3d-printer/> [Accessed 14 May 2020].

Kokkonen, L., 2018. *Carbon vs Aluminium* [Interview] (2 March 2018).

- Kokkonen, L., 2019. *Pole Bicycles* [Interview] (5 December 2019).
- Kroutromanos, I., 2018. *Fundamentals of Finite Element Analysis: Linear Finite Element Analysis*. 1 ed. Blackburg: Wiley.
- Kurowski, P. M., 2012. *www.kisi.deu.edu*. [Online]
Available at: http://kisi.deu.edu.tr/zeki.kiral/MEE5049_2014/Failure_Assesment.pdf
[Accessed 15 November 2019].
- Leitao, A., Fernandes, R. & Santos, L., 2013. Pushing the Envelope: Stretching the Limits of Generative Design. *Conference: XVII Conference of the Iberoamerican Society of Digital Graphics*, 1(1), pp. 235-238.
- Levy, M., 2012. *www.pinkbike.com*. [Online]
Available at: <https://www.pinkbike.com/news/santa-cruz-bicycles-test-lab.html>
[Accessed 4 March 2020].
- Levy, M., 2018. *www.pinkbike.com*. [Online]
Available at: <https://www.pinkbike.com/news/orbea-rallon-m-ltd-review.html>
[Accessed 14 October 2019].
- Levy, M., 2018. *www.pinkbike.com*. [Online]
Available at: <https://www.pinkbike.com/news/orbea-rallon-m-ltd-review.html>
[Accessed 5 October 2019].
- Levy, M., 2019. *www.pinkbike.com*. [Online]
Available at: <https://www.pinkbike.com/news/review-orbeas-rally-on-linkage-for-the-rallon.html>
[Accessed 5 October 2019].
- Liu, G. R. & Quek, S. S., 2014. *The Finite Element Method*. 2 ed. Singapore: Elsevier.
- Liu, Y., 2013. *Effects of Mesh Density on Finite Element Analysis*, Louisiana: SAE World Congress.
- Liu, Y. & Glass, G., 2013. *Effects of Mesh Density on Finite Element Analysis*, Louisiana: SAE International.
- Market Research Future, 2020. *www.marketresearchfuture.com*. [Online]
Available at: [marketresearchfuture.com/reports/mountain-bike-market-5165](https://www.marketresearchfuture.com/reports/mountain-bike-market-5165)
[Accessed 16 March 2020].
- Markforged, 2020. *www.markforged.com*. [Online]
Available at: <https://markforged.com/materials/carbon-fiber/>
[Accessed 12 March 2020].
- Materials Today, 2017. *www.materialstoday.com*. [Online]
Available at: <https://www.materialstoday.com/carbon-fiber/news/new-way-to-recycle-carbon-fiber-composites/>
[Accessed 12 April 2020].
- MBR, 2020. *www.mbr.co.uk*. [Online]
Available at: <https://www.mbr.co.uk/news/best-enduro-mountain-bikes-326155>
[Accessed 28 April 2020].
- McCarthy, J. M. & Soh, G. S., 2011. *Geometric Design of Linkages*. 2 ed. New York: Springer-Verlag.
- McEwen, J., 2019. *Is Boutique Best? Starling Cycles* [Interview] (9 December 2019).

- Midas, 2019. *www.midasoft.com*. [Online]
Available at: <https://www.midasoft.com/mechanical-blog-1/linear-static-analysis>
[Accessed 15 November 2019].
- MIT, 2020. *www.MIT.edu*. [Online]
Available at: http://courses.csail.mit.edu/6.S080/lectures/02_all.pdf
[Accessed 18 January 2020].
- Mizutani, T., Okabe, Y. & Takeda, N., 2003. Quantitative evaluation of transverse cracks in carbon fiber reinforced plastic quasi-isotropic laminates with embedded small-diameter fiber Bragg grating sensors. *Smart Materials and Structures*, 12(6), p. 898.
- Monden, Y., 2012. *Toyota Production System: An Integrated Approach to Just-In-Time*. 4 ed. Boca Raton: CRC Press.
- Mostafa, R., 2019. Mostafa, R. Simultaneous manufacturing shape optimization for minimum cost of milling using interior point method. *Advance Manufacturing Technology*, 31(1), pp. 1531-1538.
- Mouritz, A., 2012. *Introduction to Aerospace*. 1 ed. Cambridge: Woodhead Publishing.
- Murdick, N., 2018. *The Cost of Mountain Biking* [Interview] (16 October 2018).
- NASA, 2010. *www.nasa.gov*. [Online]
Available at: <https://www.grc.nasa.gov/www/k-12/UEET/StudentSite/engines.html>
[Accessed 5 March 2020].
- NSMB, 2018. *www.nsmb.com*. [Online]
Available at: <https://nsmb.com/articles/aerospace-perspective-carbon/>
[Accessed 1 May 2020].
- Orbea, 2019. *www.orbea.com*. [Online]
Available at: <https://www.orbea.com/int-en/bicycles/mountain/rallon>
[Accessed 26 September 2019].
- Orbea, 2019. *www.orbea.com*. [Online]
Available at: <https://www.orbea.com/gb-en/blog/orbea-rallon2020-suspension-updates>
[Accessed 14 October 2019].
- Payne, A., 2017. *Behind the Bike HB160* [Interview] (21 August 2017).
- Pearce, K., 2020. *www.autodesk.com*. [Online]
Available at: <https://academy.autodesk.com/inspiration/blog/cycling-and-academia-team-explore-thousands-design-solutions-swingarm>
[Accessed 14 March 2020].
- Pereira, T., Kennedy, J. & Potgieter, J., 2019. A comparison of traditional manufacturing vs additive manufacturing, the best method for the job. *Procedia Manufacturing*, 30(1), pp. 11-18.
- Perez, C., 2016. *www.medium.com*. [Online]
Available at: <https://medium.com/intuitionmachine/the-alien-look-of-deep-learning-generative-design-5c5f871f7d10#.qi2lzhswg>
[Accessed 28 March 2020].
- Pinkbike, 2020. *www.pinkbike.com*. [Online]
Available at: <https://www.pinkbike.com/news/definitions-what-is-anti-squat.html>
[Accessed 29 March 2020].

Pole Bicycles, 2019. *www.polebicycles.com*. [Online]
Available at: <https://polebicycles.com/why-arent-we-going-for-carbon-frames/>
[Accessed 18 April 2020].

Pole, 2015. *www.polebicycles.com*. [Online]
Available at: <https://polebicycles.com/what-is-anti-squat-and-pedal-kickback/>
[Accessed 5 Januray 2020].

Qingxi, H. et al., 2018. Manufacturing and 3D printing of continuous carbon fiber prepreg filament. *Journal of Materials Science*, 53(3), pp. 1887-1898.

Rao, S. S., 2018. *The Finite Element Method in Engineering*. 6 ed. Coral Gables: Elsevier.

RedBull, 2017. *www.redbull.com*. [Online]
Available at: <https://www.redbull.com/gb-en/quiz-alloy-versus-carbon-on-mtb>
[Accessed 21 March 2020].

RedBull, 2018. *www.redbull.com*. [Online]
Available at: <https://www.redbull.com/gb-en/enduro-mtb-racing-explained>
[Accessed 5 March 2020].

Redbull, 2020. *www.redbull.com*. [Online]
Available at: <https://www.redbull.com/se-en/tags/mtb>
[Accessed 14 March 2020].

Redbull, 2020. *www.redbull.com*. [Online]
Available at: [redbull.com/gb-en/energydrink/history-of-red-bull#1988](https://www.redbull.com/gb-en/energydrink/history-of-red-bull#1988)
[Accessed 19 April 2020].

Report Linker, 2020. *www.globenewswire.com*. [Online]
Available at: <https://www.globenewswire.com/news-release/2020/04/07/2013205/0/en/The-Global-Mountain-Bike-Market-is-expected-to-grow-by-2-52-bn-during-2020-2024-progressing-at-a-CAGR-of-5-during-the-forecast-period.html>
[Accessed 24 April 2020].

Reuleaux, F., 1963. *The kinematics of machinery: outlines of a theory of machines*. 1 ed. New York: Dover Publications.

Richards, K. L., 2014. *Design Engineer's Reference Guide: Mathematics, Mechanics, and Thermodynamics*. 1 ed. Boca Raton: CRC Press.

Roylance, D., 2008. *Mechanical Properties of Materials*. 1 ed. Massachusetts: MIT.

Ruto, A., 2020. *www.autodesk.com*. [Online]
Available at: <https://www.autodesk.com/autodesk-university/content/generative-design-for-formula-1-car-design>
[Accessed 27 March 2020].

Santa Cruz Cycles, 2012. *www.santacruzcycles.com*. [Online]
Available at: <https://www.santacruzcycles.com/en-GB/news/340>
[Accessed 8 March 2020].

Scott, S., 2019. *www.bikeradar.com*. [Online]
Available at: <https://www.bikeradar.com/reviews/bikes/mountain-bikes/full-suspension-mountain-bikes/orbea-rallon-m10-myo-review/>
[Accessed 14 October 2019].

Scott, S., 2020. *www.bikeradar.com*. [Online]
Available at: <https://www.bikeradar.com/features/are-bikes-getting-more-expensive-or-just-better/>
[Accessed 28 April 2020].

Seepersad, C. et al., 2012. A designer's guide for dimensioning and tolerancing SLS parts. In *Solid Freeform Fabrication Symposium*, 14(1), pp. 921-931.

Simscale, 2019. *www.simscale.com*. [Online]
Available at: <https://www.simscale.com/docs/content/simwiki/fea/what-is-von-mises-stress.html>
[Accessed 15 November 2019].

Slocum, A., 2008. *www.MIT.edu*. [Online]
Available at:
<https://web.mit.edu/2.75/fundamentals/FUNdaMENTALs%20Book%20pdf/FUNdaMENTALs%20Topic%204.PDF>
[Accessed 18 January 2020].

Smell, M., 2017. *Cloud & Solve Speed of Autodesk* [Interview] (3 April 2017).

Solidworks, 2019. *www.solidworks.com*. [Online]
Available at:
https://help.solidworks.com/2012/English/SolidWorks/cworks/ID_Solid_Mesh.htm?id=60d2224ca7e64c9fb63bb111ad57387c
[Accessed 16 November 2019].

Specialized, 2020. *www.specialized.com*. [Online]
Available at: <https://www.specialized.com/us/en/carbon-fiber-recycling-program>
[Accessed 19 April 2020].

Stanciu, M., Curtu, I. & Savin, A., 2017. A Finite Element Approach for Inter-Laminar Damage of the Carbon Fiber Reinforced Polymer due to Impact. *Procedia Engineering*, 181(1), pp. 249-256.

Statista, 2019. *www.statista.com*. [Online]
Available at: <https://www.statista.com/topics/1448/bicycle-industry-in-the-us/>
[Accessed 14 March 2020].

Sutton, M., 2017. *www.cyclingindustry.com*. [Online]
Available at: <https://cyclingindustry.news/are-carbon-bike-makers-dumping-in-the-ocean-and-do-consumers-care/>
[Accessed 20 April 2020].

The Guardian, 2017. *www.theguardian.com*. [Online]
Available at: <https://www.theguardian.com/sustainable-business/2017/mar/22/carbon-fibre-wonder-material-dirty-secret>
[Accessed 14 April 2020].

Tonelli, P. & Mouret, J.-B., 2013. On the Relationships between Generative Encodings, Regularity, and Learning Abilities when Evolving Plastic Artificial Neural Networks. *PloS One*, 8(11), pp. 1-10.

Toyota, 2020. *www.toyota.com*. [Online]
Available at: <https://global.toyota/en/company/vision-and-philosophy/production-system/>
[Accessed 3 May 2020].

UCI, 2019. *www.uci.org*. [Online]
Available at: <https://www.uci.org/news/2019/the-evolution-of-mountain-bike-and-its-many-formats>
[Accessed 1 April 2020].

- Vincent, J., 2017. *www.theverge.com*. [Online]
Available at: <https://www.theverge.com/2017/4/11/15256008/3d-printed-titanium-parts-boeing-dreamliner-787>
[Accessed 15 March 2020].
- Vinoski, J., 2018. *www.forbes.com*. [Online]
Available at: <https://www.forbes.com/sites/jimvinoski/2018/09/03/will-a-robot-take-my-manufacturing-job-yes-no-and-maybe/#43768bd1123f>
[Accessed 24 March 2020].
- von Mises, R., 1913. Mechanik der festen Korper im plastisch ferormablen Zustand. *Gottin Nachr Math Phys*, 1(1), pp. 582-592.
- Wade, P., 2016. *www.biketart.com*. [Online]
Available at: <https://www.biketart.com/blog/2016/11/its-all-in-the-weave-carbon-fibre-frames-explained/>
[Accessed 7 March 2020].
- Weagle, D., 2011. *Interview with the Dave Weagle* [Interview] (17 January 2011).
- Westbrook Cycles, 2020. *www.westbrookcycles.co.uk*. [Online]
Available at: <https://www.westbrookcycles.co.uk/scott-spark-rc-700-sl-swingarm-2017-p337430>
[Accessed 10 May 2020].
- Woon, S. Y., Querin, O. & Steven, G., 2001. Structural application of a shape optimization method based on a genetic algorithm. *Structural and Multidisciplinary Optimization*, 22(1), pp. 57-64.
- Zhang, J. et al., 2020. Performance of 3D-Printed. *Materials*, 13(2), pp. 471-478.

21 APPENDIX

MATERIAL DATASHEET

Composites



Plastic Matrix	Test (ASTM)	Onyx	Onyx FR	Nylon W
Tensile Modulus (GPa)	D638	1.4	1.3	1.7
Tensile Stress at Yield (MPa)	D638	36	29	51
Tensile Strain at Yield (%)	D638	25	33	4.5
Tensile Stress at Break (MPa)	D638	30	31	36
Tensile Strain at Break (%)	D638	58	58	150
Flexural Strength (MPa)	D790 ¹	81	79	50
Flexural Modulus (GPa)	D790 ¹	3.6	4.0	1.4
Heat Deflection Temp (°C)	D648 B	145	145	41
Flame Resistance	UL94	—	V-0 ²	—
Izod Impact - notched (J/m)	D256-10 A	330	—	110
Density (g/cm ³)	—	1.2	1.2	1.1

Fiber Reinforcement	Test (ASTM)	Carbon	Kevlar®	Fiberglass	HSHT FG
Tensile Strength (MPa)	D3039	800	610	590	600
Tensile Modulus (GPa)	D3039	60	27	21	21
Tensile Strain at Break (%)	D3039	1.5	2.7	3.8	3.9
Flexural Strength (MPa)	D790 ¹	540	240	200	420
Flexural Modulus (GPa)	D790 ¹	51	26	22	21
Flexural Strain at Break (%)	D790 ¹	1.2	2.1	1.1	2.2
Compressive Strength (MPa)	D6641	320	97	140	192
Compressive Modulus (MPa)	D6641	54	28	21	21
Compressive Strain at Break (%)	D6641	0.7	1.5	—	—
Heat Deflection Temp (°C)	D648 B	105	105	105	150
Izod Impact - notched (J/m)	D256-10 A	960	2000	2600	3100
Density (g/cm ³)	—	1.4	1.2	1.5	1.5

Dimensions and Construction of Plastic Test Specimens:

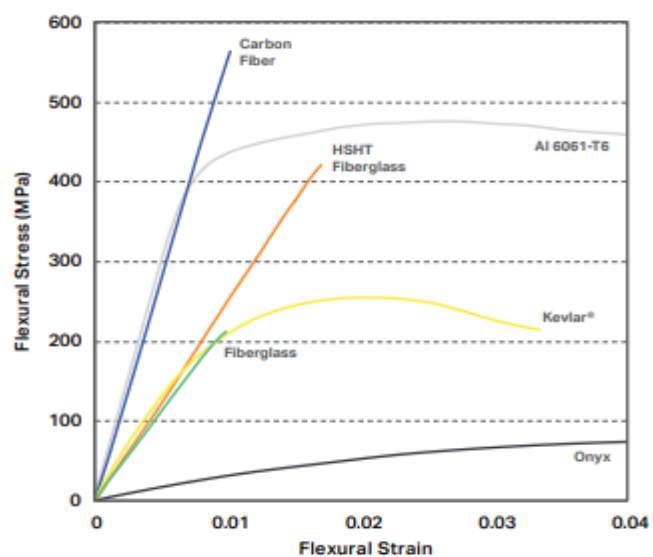
- Tensile test specimens: ASTM D638 type IV beams
- Flexural test specimens: 3-pt. Bending, 4.5 in (L) x 0.4 in (W) x 0.12 in (H)
- Heat-deflection temperature at 0.45 MPa, 66 psi (ASTM D648-07 Method B)

All Markforged composite machines are equipped to print Onyx. Nylon White is available on the Mark Two and X7. Onyx FR is available on X3, X5, and X7.

Markforged parts are primarily composed of plastic matrix. Users may add one type of fiber reinforcement in each part, enhancing its material properties.

1. Measured by a method similar to ASTM D790. Thermoplastic-only parts do not break before end of flexural test.

2. Onyx FR is UL 94 V-0 Blue Card certified down to a thickness of 3mm.



CCF-1.5K Carbon Composite Fiber Properties

Effective Diameter, mm	VF, %	Elastic Modulus, GPa	Tensile Strength, MPa
0.35	60	149	2206

Dual-matrix Composite Properties

Parameter	CCF-1.5K-PETG
Density, g/cm ³	1.4
Tensile modulus in fiber direction, GPa	64
Poisson ratio 31	0.36
Tensile ultimate stress in fiber direction, MPa	860
Compressive ultimate stress in fiber direction, MPa	290
Flexural Strength along axis 1 under bending in plane 1-3, MPa	520

About

Additive manufacturing of composite parts reinforced with continuous fibers is based on dual-matrix composite co-extrusion technology (Composite Fiber Co-extrusion, CFC) and allows manufacturing of strong, lightweight and complex-shaped parts with tailored material properties.

CCF

- 30 times stiffer and stronger than normal plastic
- Strength-to-weight ratio is more than 5 times higher than for 2024-T351 Aluminum
- Stiffness-to-weight ratio is more than 5 times higher than for 2024-T351 Aluminum
- 7 times lighter than steel and strong as stainless steel

CBF

- 15 times stiffer and stronger than normal plastic
- Strength-to-weight ratio is more than 2 times higher than for 2024-T351 Aluminum
- 5 times lighter than steel and strong as stainless steel

Appendix 2 Anisoprint Composite Carbon Fiber Properties

Specification

Laminate Composition

In 3mm thickness, this resin infused high strength panel is composed of the following carbon fabric layers:

- 200gsm 2/2 Twill 3k Carbon
- 300gsm ±45 Biaxial Carbon
- 650gsm 2/2 Twill Carbon
- 200gsm 2/2 Twill 3k Carbon
- 650gsm 2/2 Twill Carbon
- 300gsm ±45 Biaxial Carbon
- 200gsm 2/2 Twill 3k Carbon

In 2mm thickness, the sheets are composed of the following carbon fabric layers:

- 200gsm 2/2 Twill 3k Carbon
- 300gsm ±45 Biaxial Carbon
- 650gsm 2/2 Twill Carbon
- 300gsm ±45 Biaxial Carbon
- 200gsm 2/2 Twill 3k Carbon

In 1mm thickness, the sheets are composed of the following carbon fabric layers:

- 200gsm 2/2 Twill 3k Carbon
- 300gsm ±45 Biaxial Carbon
- 200gsm 2/2 Twill 3k Carbon

Resin matrix is high-performance epoxy throughout. Panels are post-cured at 70°C for maximum mechanical performance.

Nominal Thickness	Average Thickness	Average weight
1mm Sheet	0.9mm (± 0.2mm)	1.28kg/m ²
2mm Sheet	1.7mm (± 0.2mm)	2.40kg/m ²
3mm Sheet	2.8mm (± 0.2mm)	4.08kg/m ²

Property	1mm Thick	2mm Thick	3mm Thick	Test Details
Tensile Modulus at 0°/90°	37200MPa (74400 psi)	43900MPa (87800 psi)	47400MPa (94800 psi)	DIN EN ISO 527-4 Tested in-house at Easy Composites
Tensile Modulus at 45°	32300MPa (64600 psi)	34500MPa (69000 psi)	27100MPa (54200 psi)	
Tensile Strength at 0°/90°	503MPa (1006 psi)	558MPa (1116 psi)	644MPa (1288 psi)	
Tensile Strength at 45°	557MPa (1114 psi)	622MPa (1244 psi)	443MPa (886 psi)	
Percentage Elongation at 0°/90°	2.27%	0.0291	0.0388	DIN EN ISO 14125 Tested in-house at Easy Composites
Percentage Elongation at 45°	3.13%	0.0411	0.041	
Youngs Modulus at 0°/90° Gloss Side in Compression	32.4 GPa (4699223 psi)	35.1 GPa (5090625 psi)	10.3 GPa (1493889 psi)	
Youngs Modulus at 0°/90° Gloss Side in Tension	31.6 GPa (4583193 psi)	35.3 GPa (5119632 psi)	10.5 GPa (1522896 psi)	
Density	1152 kg/m ³	1020 kg/m ³	1269 kg/m ³	-
Glass Transition Temperature (T _g)	80°C (176°F)			-

Appendix 3 Easy Composites Carbon Fibre Sheet DataSheet



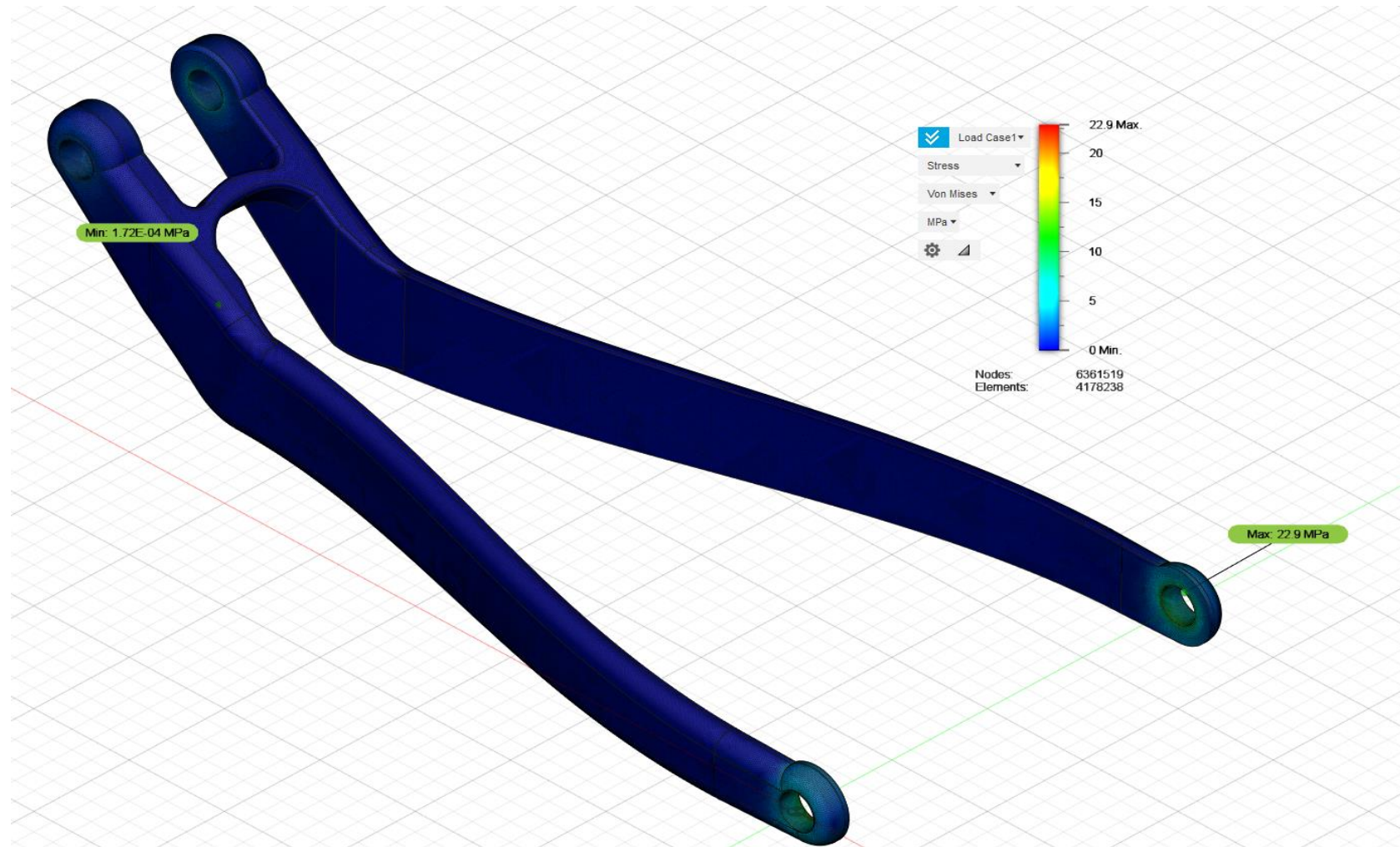
Mechanical Properties of Carbon Fibre Composite Materials, Fibre / Epoxy resin (120°C Cure)

Fibres @ 0° (UD), 0/90° (fabric) to loading axis, Dry, Room Temperature, Vf = 60% (UD), 50% (fabric)

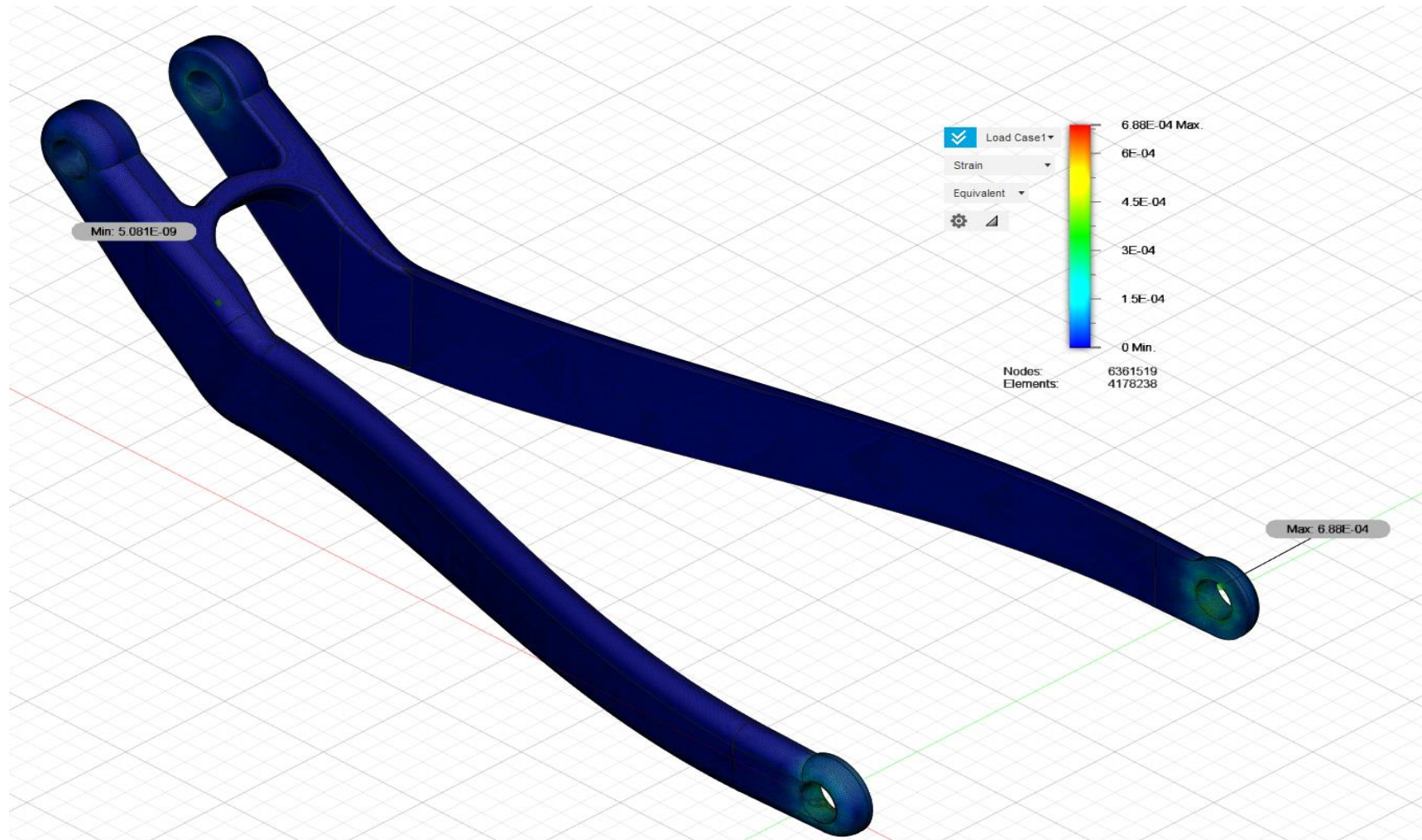
	Symbol	Units	Std CF Fabric	HMCF Fabric	E glass Fabric	Kevlar Fabric	Std CF UD	HMCF UD	M55** UD	E glass UD	Kevlar UD	Boron UD	Steel S97	Al. L65	Tit. dtd 5173
Young's Modulus 0°	E1	GPa	70	85	25	30	135	175	300	40	75	200	207	72	110
Young's Modulus 90°	E2	GPa	70	85	25	30	10	8	12	8	6	15	207	72	110
In-plane Shear Modulus	G12	GPa	5	5	4	5	5	5	5	4	2	5	80	25	
Major Poisson's Ratio	v12		0.10	0.10	0.20	0.20	0.30	0.30	0.30	0.25	0.34	0.23			
Ult. Tensile Strength 0°	Xt	MPa	600	350	440	480	1500	1000	1600	1000	1300	1400	990	460	
Ult. Comp. Strength 0°	Xc	MPa	570	150	425	190	1200	850	1300	600	280	2800			
Ult. Tensile Strength 90°	Yt	MPa	600	350	440	480	50	40	50	30	30	90			
Ult. Comp. Strength 90°	Yc	MPa	570	150	425	190	250	200	250	110	140	280			
Ult. In-plane Shear Stren.	S	MPa	90	35	40	50	70	60	75	40	60	140			
Ult. Tensile Strain 0°	ext	%	0.85	0.40	1.75	1.60	1.05	0.55		2.50	1.70	0.70			
Ult. Comp. Strain 0°	exc	%	0.80	0.15	1.70	0.60	0.85	0.45		1.50	0.35	1.40			
Ult. Tensile Strain 90°	eyt	%	0.85	0.40	1.75	1.60	0.50	0.50		0.35	0.50	0.60			
Ult. Comp. Strain 90°	eyc	%	0.80	0.15	1.70	0.60	2.50	2.50		1.35	2.30	1.85			
Ult. In-plane shear strain	es	%	1.80	0.70	1.00	1.00	1.40	1.20		1.00	3.00	2.80			
Thermal Exp. Co-ef. 0°	Alpha1	Strain/K	2.10	1.10	11.60	7.40	-0.30	-0.30	-0.30	6.00	4.00	18.00			
Thermal Exp. Co-ef. 90°	Alpha2	Strain/K	2.10	1.10	11.60	7.40	28.00	25.00	28.00	35.00	40.00	40.00			
Moisture Exp. Co-ef 0°	Beta1	Strain/K	0.03	0.03	0.07	0.07	0.01	0.01		0.01	0.04	0.01			
Moisture Exp. Co-ef 90°	Beta2	Strain/K	0.03	0.03	0.07	0.07	0.30	0.30		0.30	0.30	0.30			
Density		g/cc	1.60	1.60	1.90	1.40	1.60	1.60	1.65	1.90	1.40	2.00			

** Calculated figures

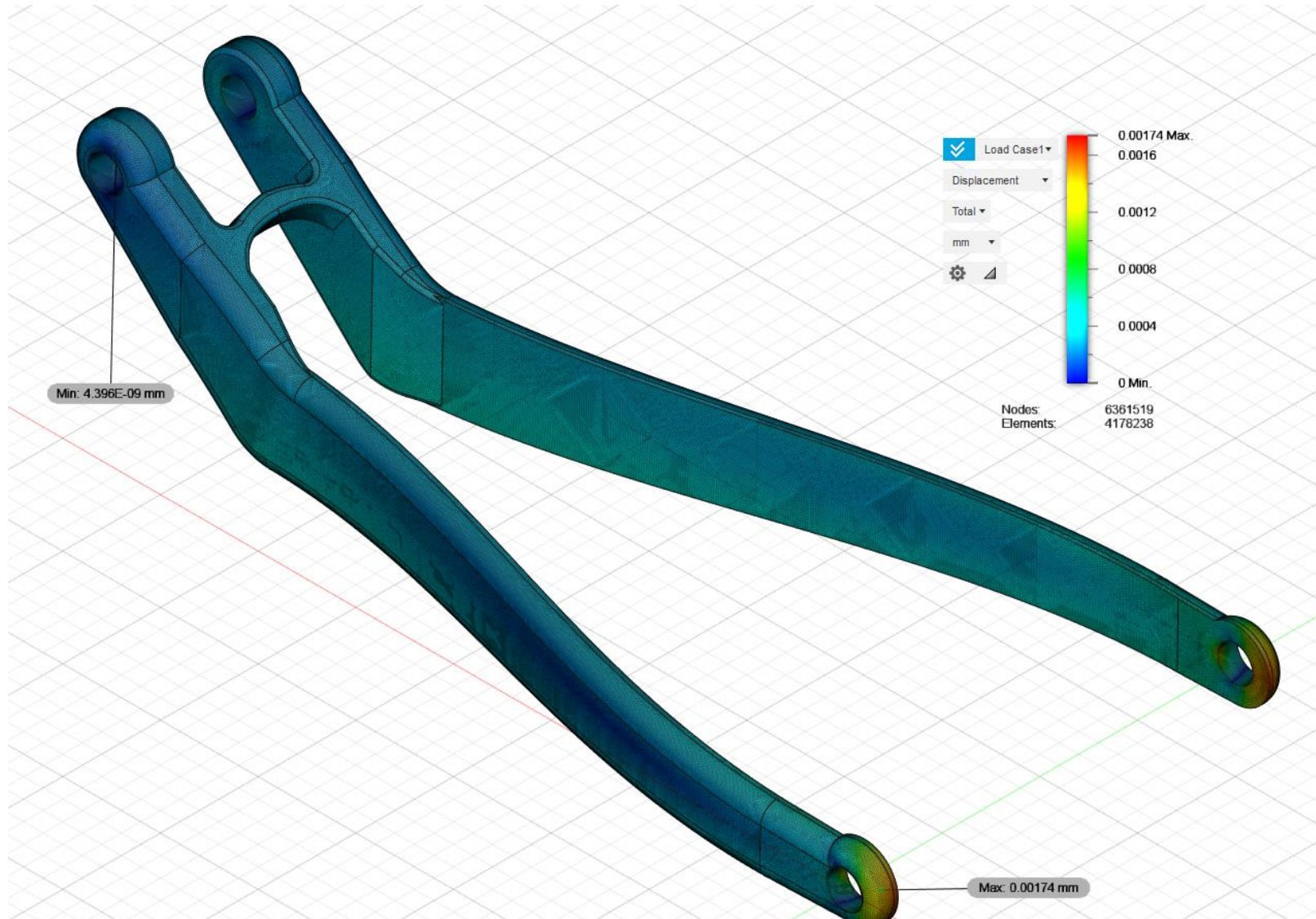
Appendix 4 Performance Composites Carbon Fiber Sheet Data Sheet



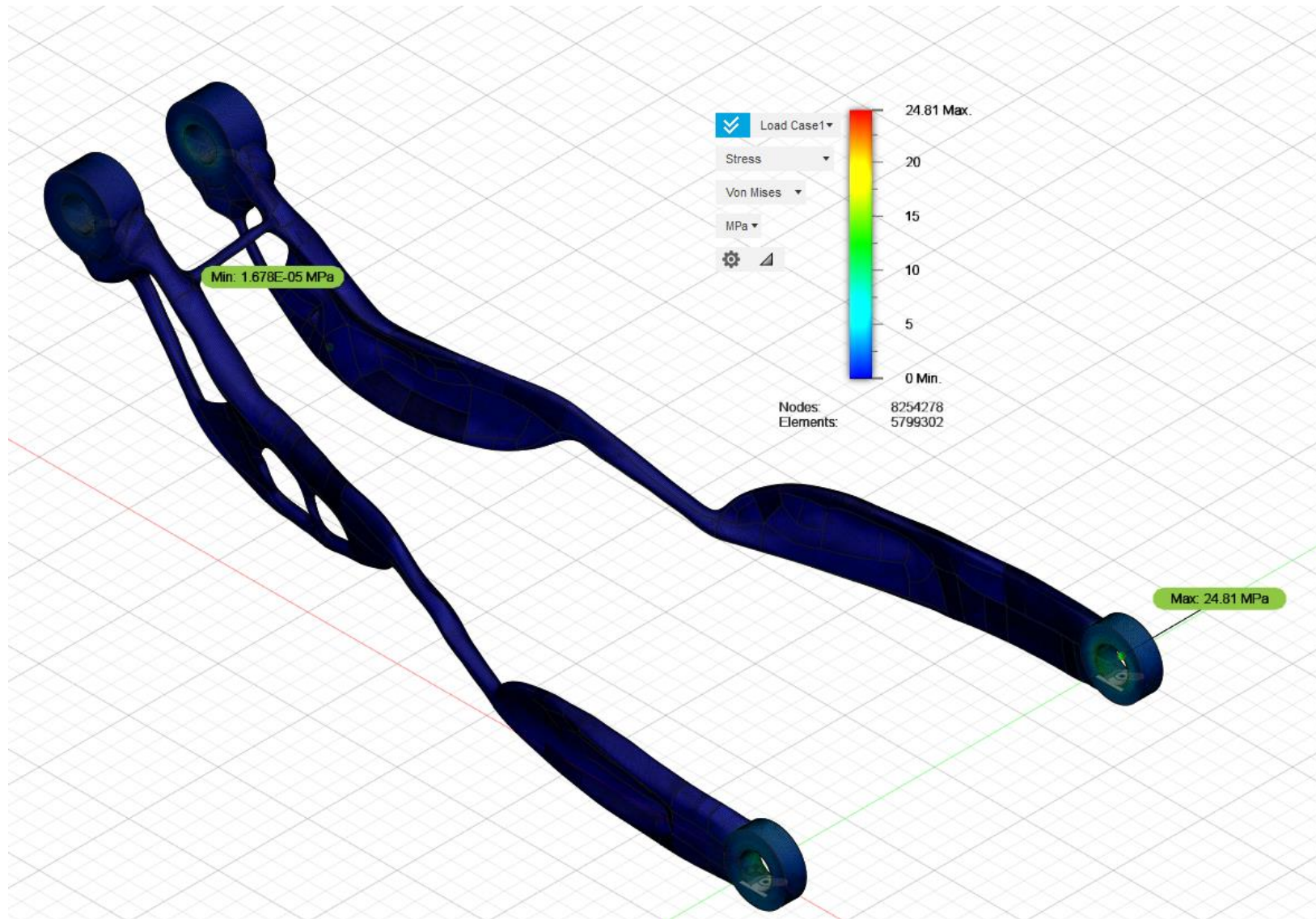
Appendix 5 Max VonMises Stress FEA Results Swingarm



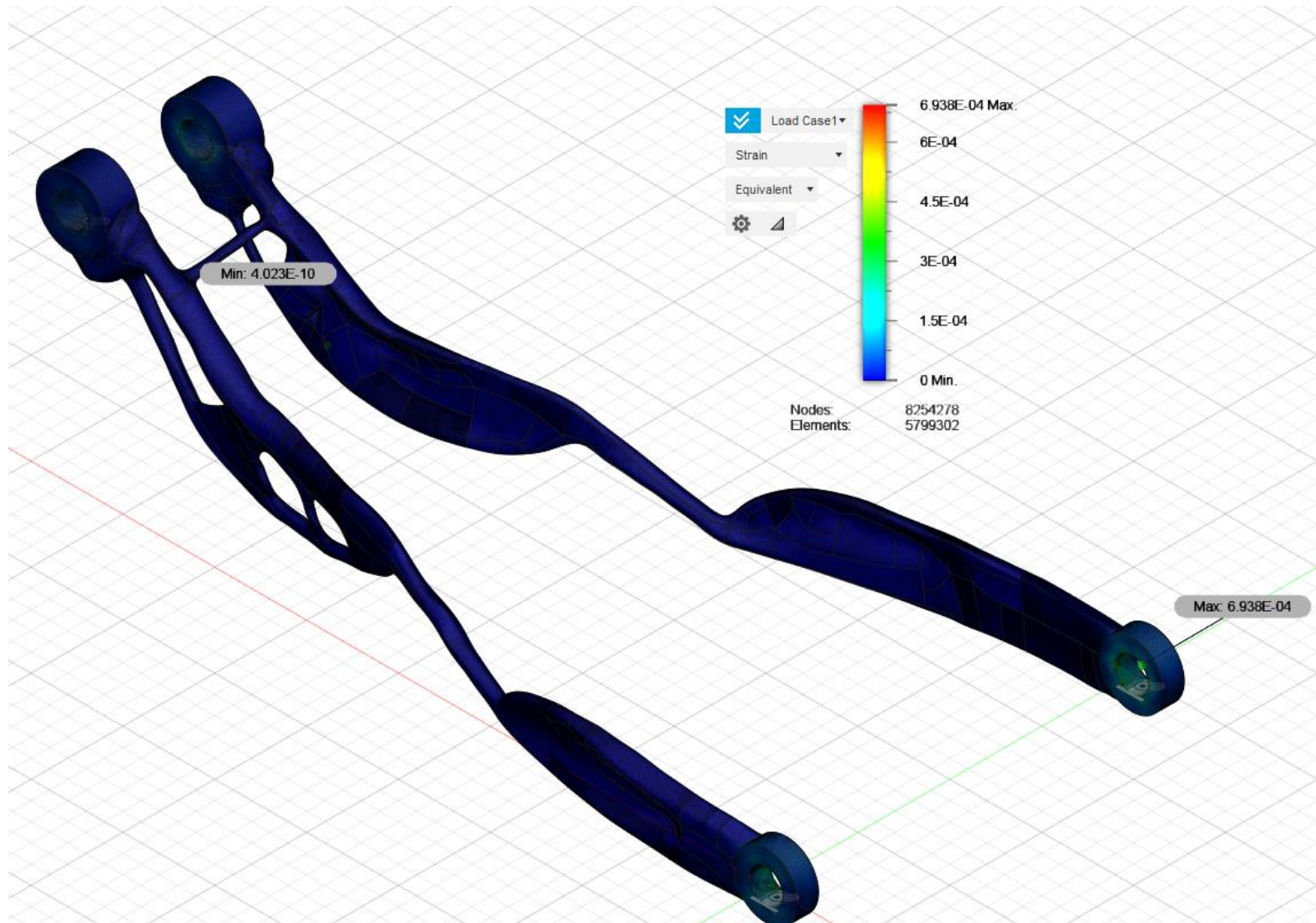
Appendix 6 Max Equivalent Strain FEA Results Swingarm



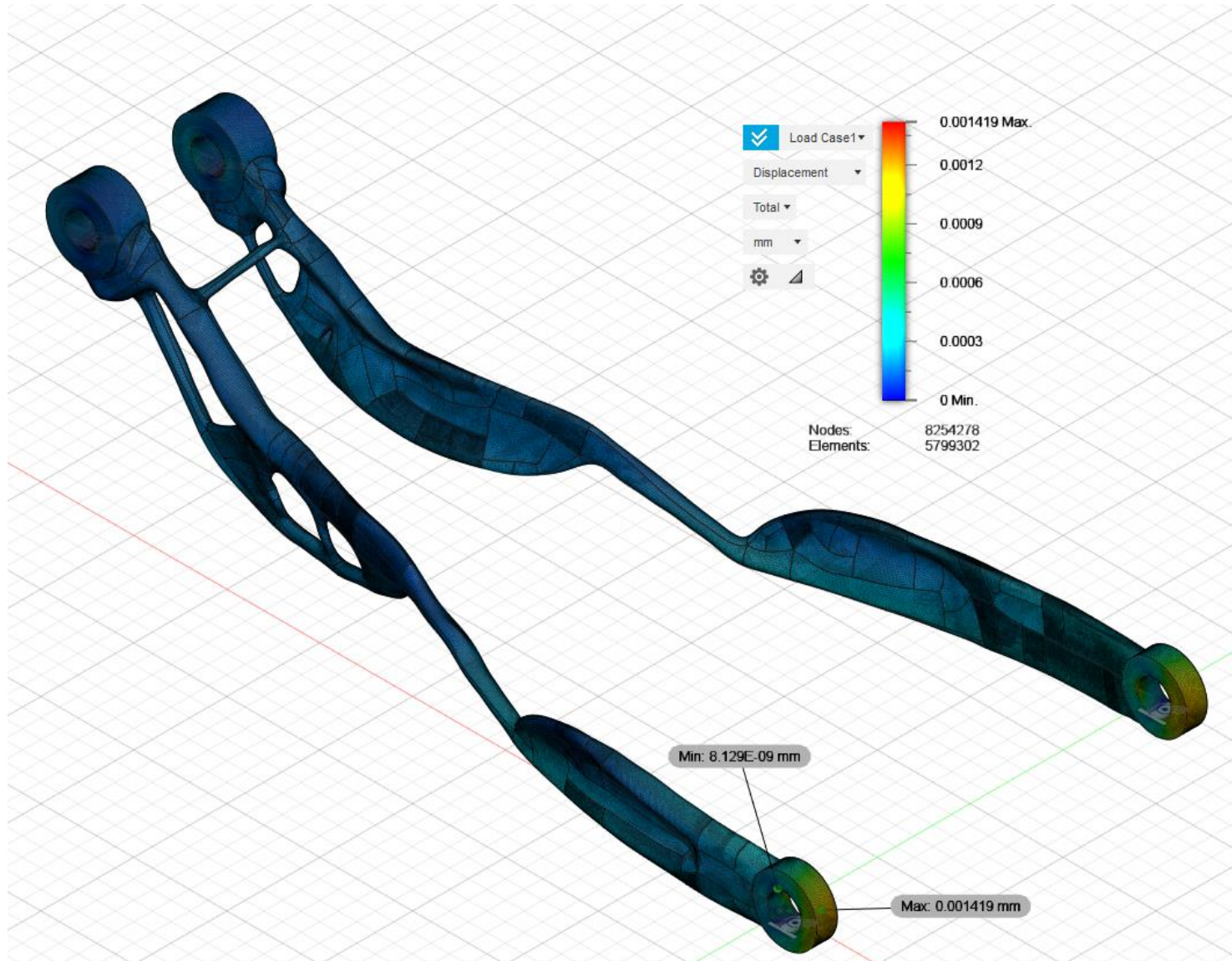
Appendix 7 Max Displacement FEA Results Swingarm



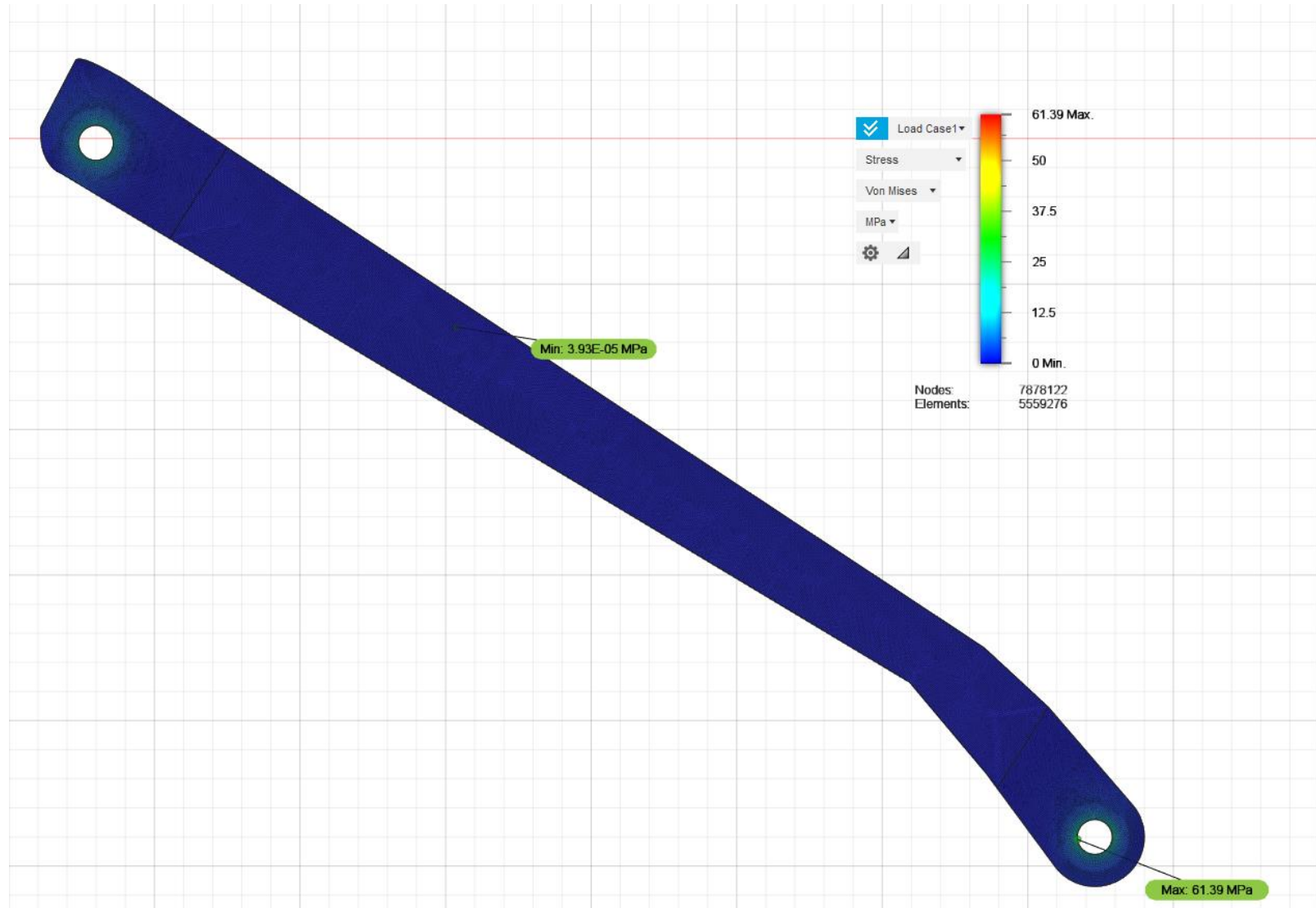
Appendix 8 Max VonMises Stress FEA Results Generative Design Swingarm



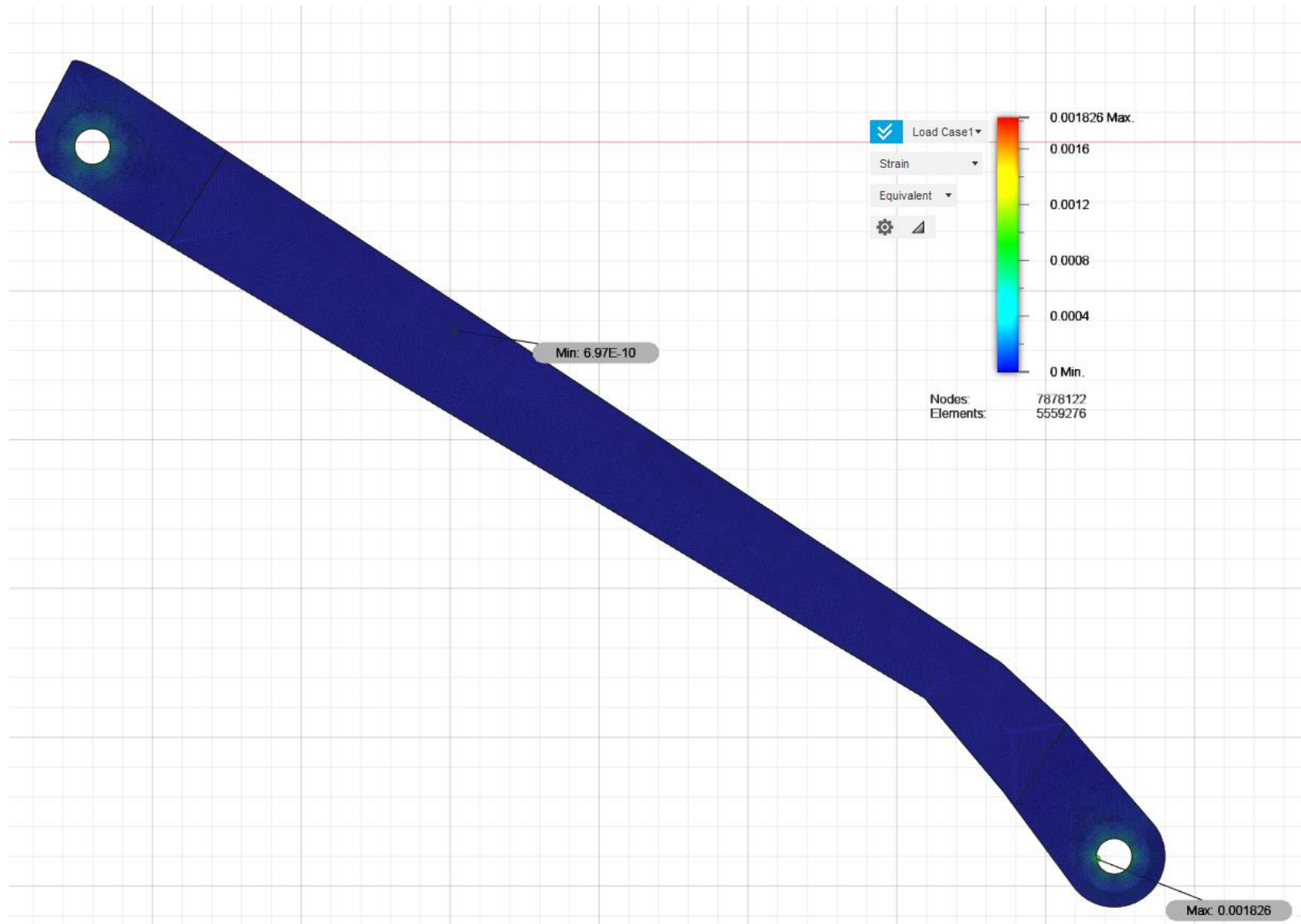
Appendix 9 Max Equivalent Strain FEA Results Generative Design Swingarm



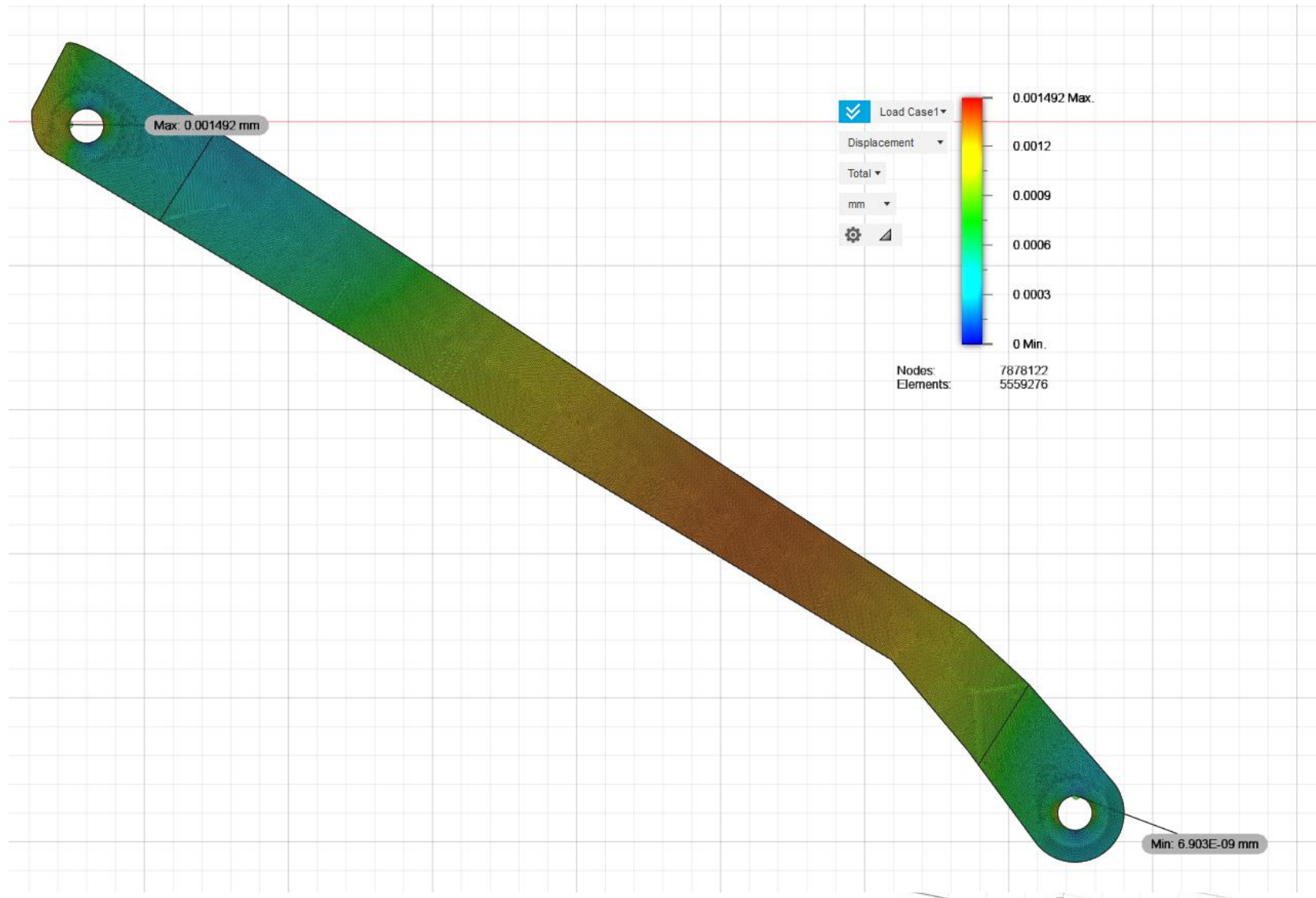
Appendix 10 Max Displacement FEA Results Generative Design Swingarm



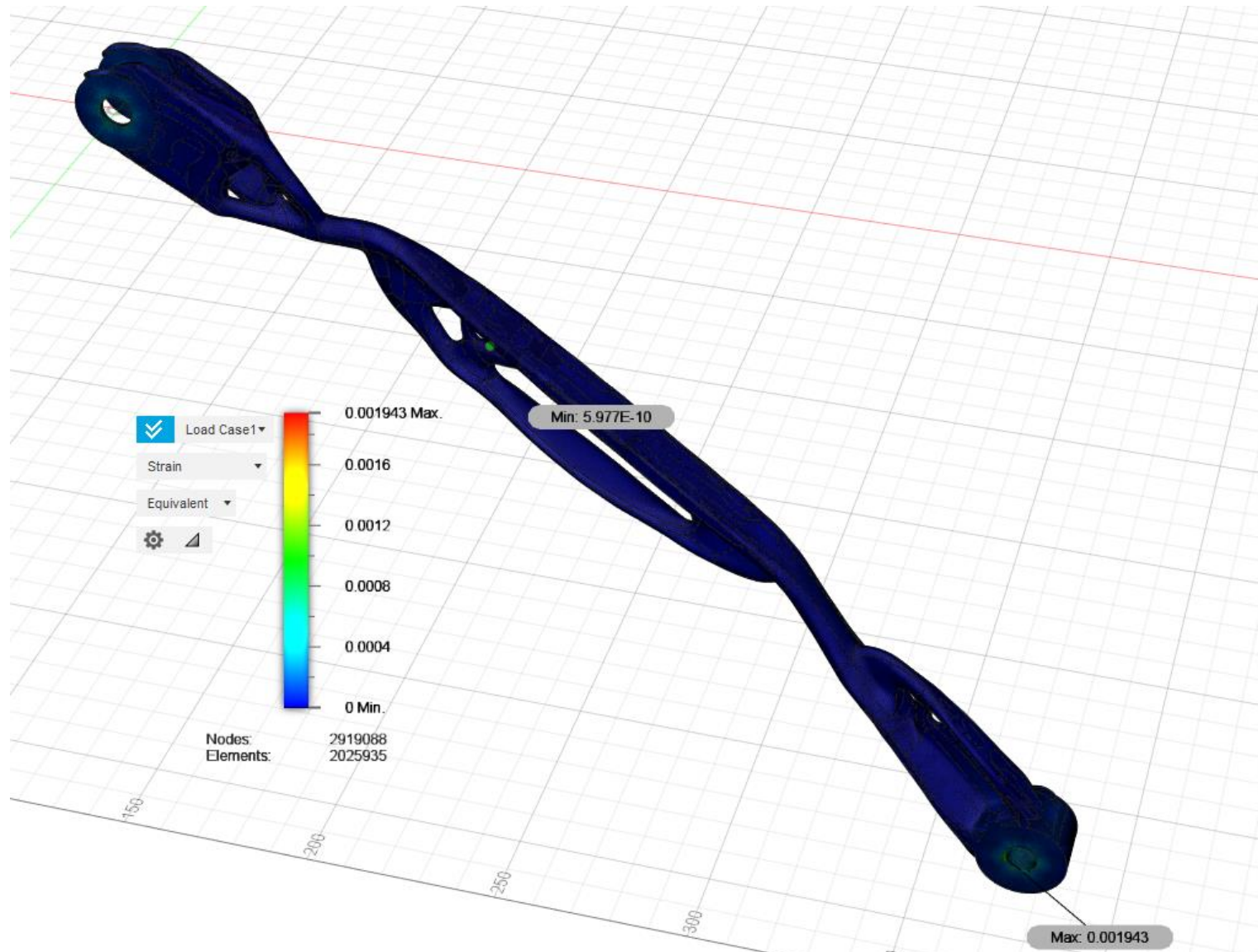
Appendix 11 Max Von Mises Stress FEA Results Linkarm



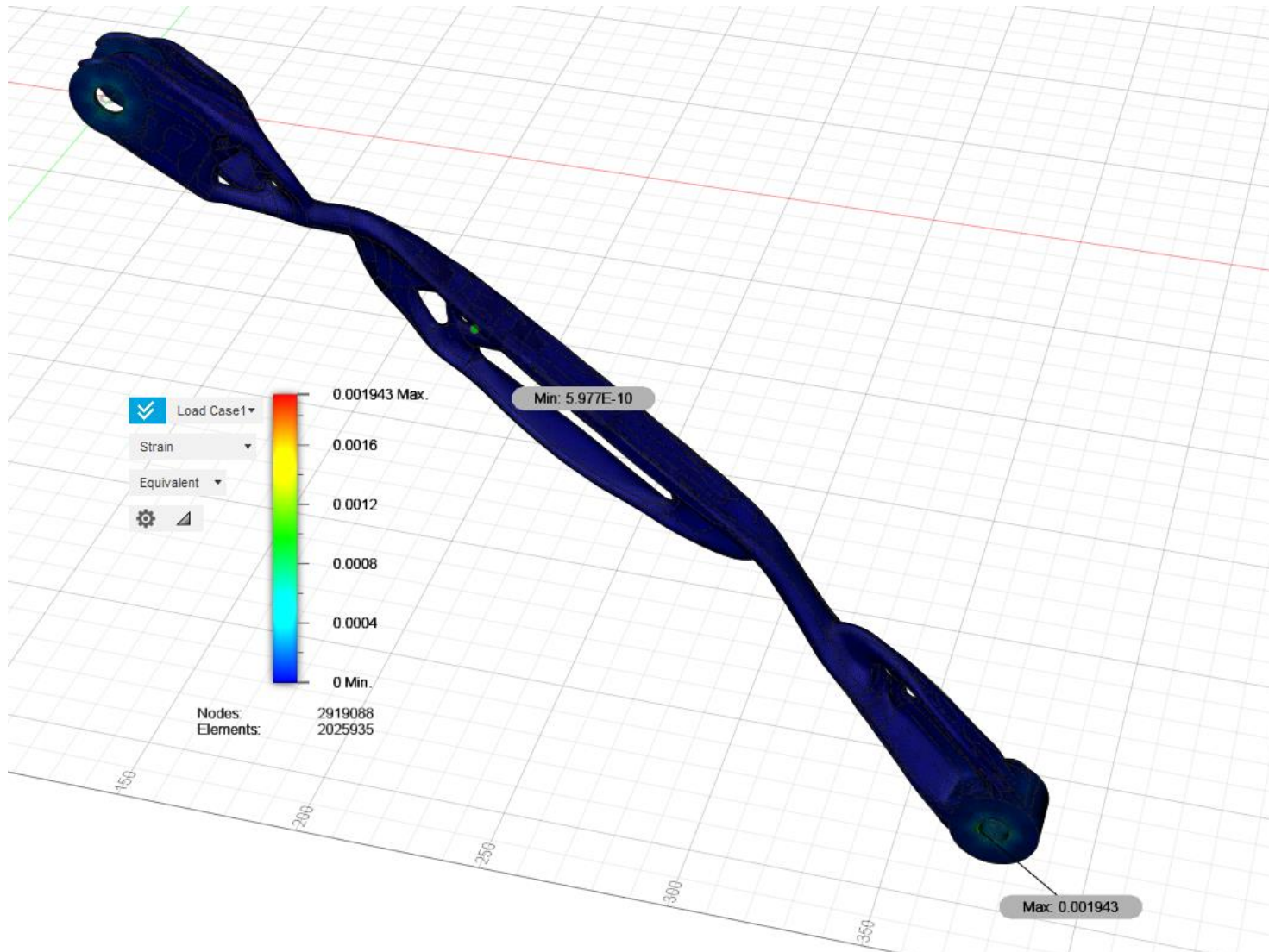
Appendix 12 Max Equivalent Strain FEA Results Linkarm



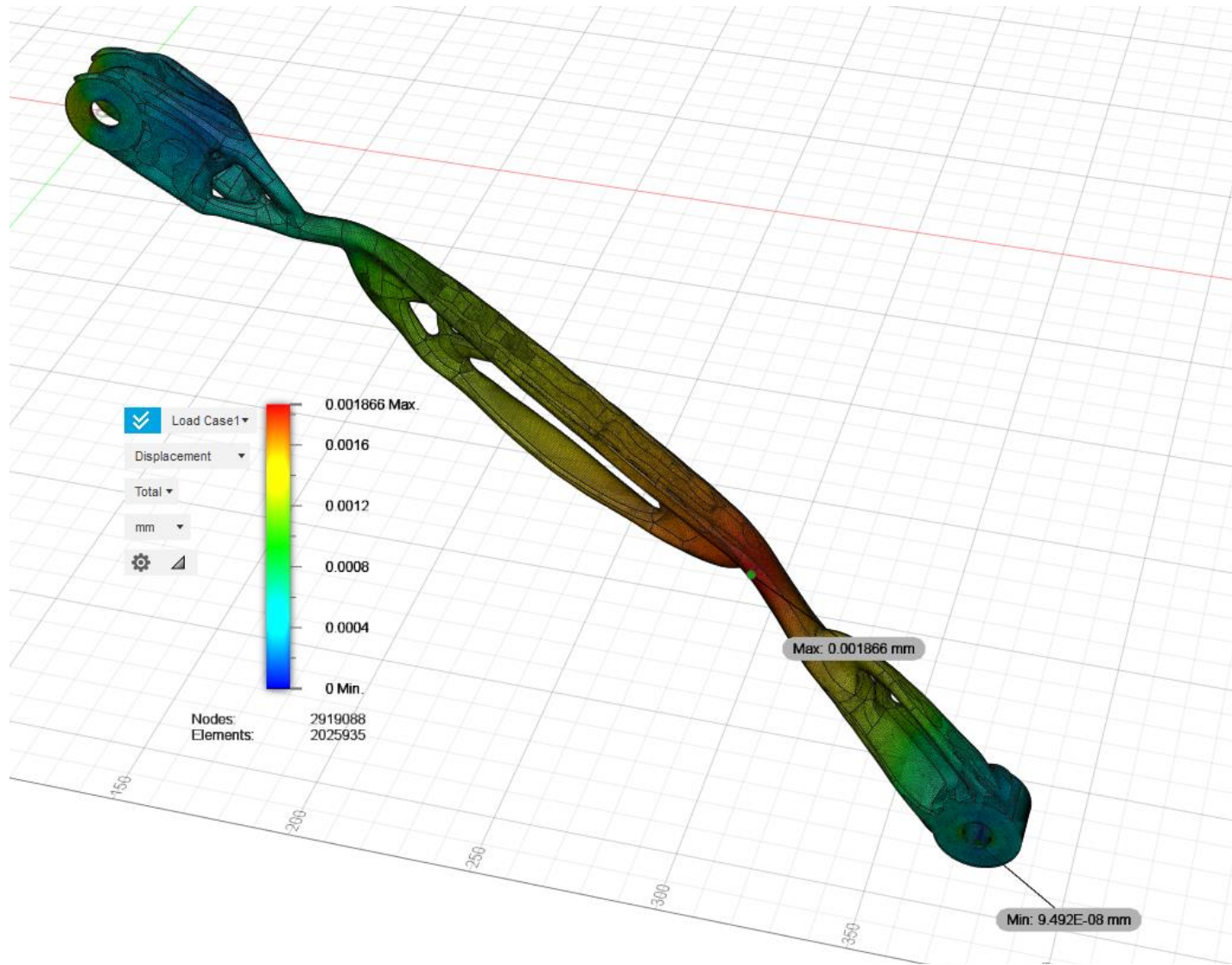
Appendix 13 Max Displacement FEA Results Linkarm



Appendix 14 Max Von Mises Stress FEA Results Generative Design Link Arm



Appendix 15 Max Equivalent Strain FEA Results Generative Design Link Arm



Appendix 16 Max Displacement FEA Results Generative Design Link Arm

PRINT TIME 68h:38min

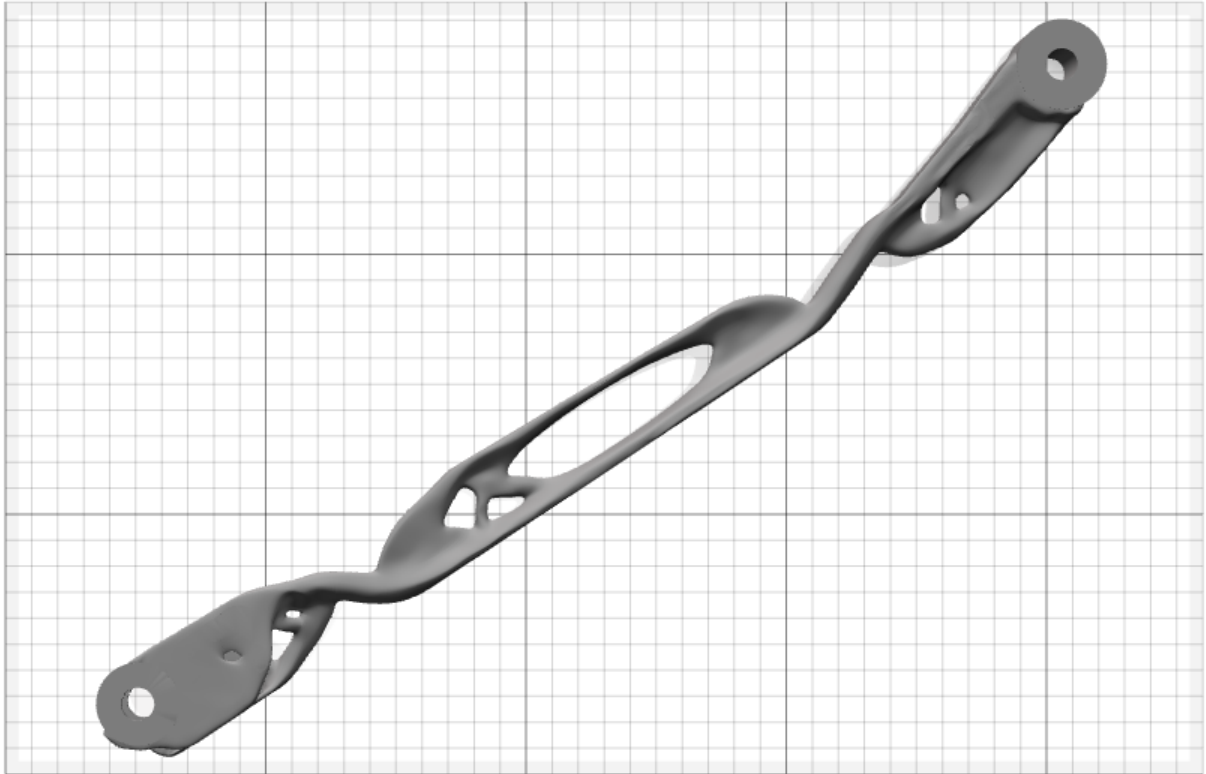
PLASTICS

PETG [ESUN] 73.9m (218.6g)

COMPOSITES

PETG [Generic] 3.3m (10.4g)

CCF 1.5k 73.3m (10.6g)



Appendix 17 Link Arm Print Time

PRINT TIME 77h:4min

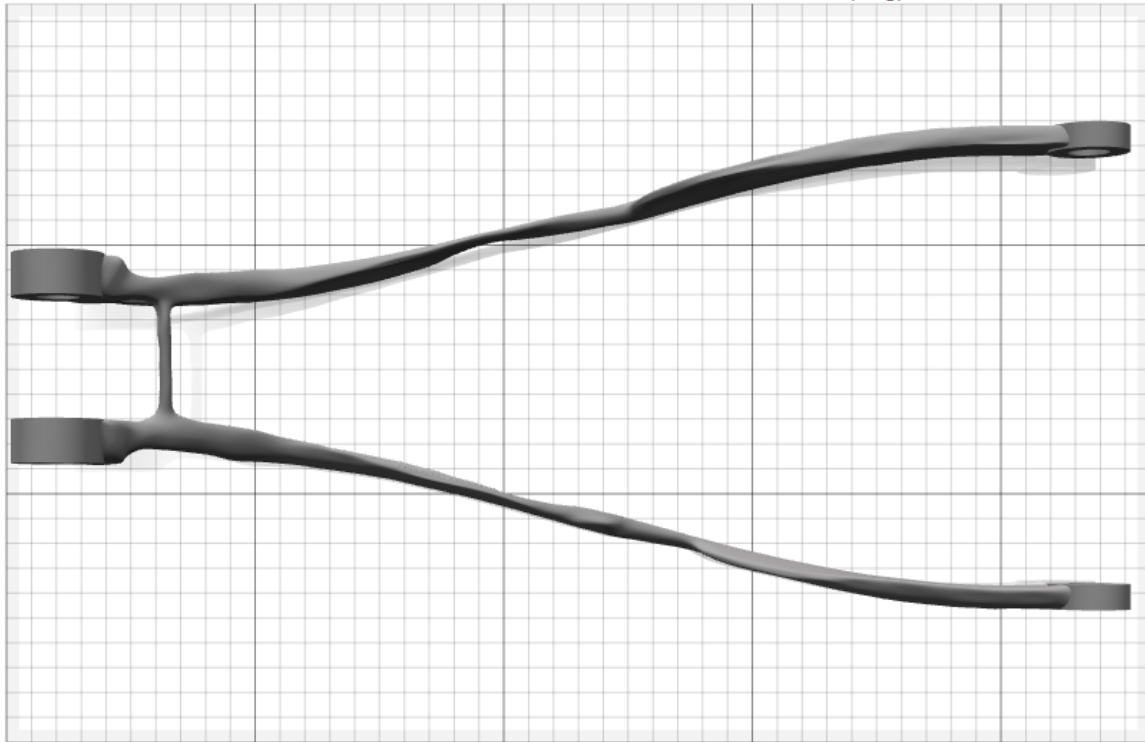
PLASTICS

PETG [ESUN] 72.1m (213.2g)

COMPOSITES

PETG [Generic] 2.5m (7.8g)

CCF 1.5k 55.5m (8.1g)



Appendix 18 Swingarm Print Time



Appendix 19 Link Arm Generative Design Report

Link Arm Generative Design Report

Analyzed File	Link arm single mk2 v4
Version	Autodesk Fusion 360 (2.0.8335)
Creation Date	2020-05-21, 18:43:25
Author	William May-White

☐ Project Properties

Title	Studies
Author	Will

☐ Simulation Model 1:1

☐ **Study 1 - Static Stress**

☐ **Study Properties**

Study Type	Static Stress
Last Modification Date	2020-05-15, 09:18:14

☐ Settings

☐ **General**

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

☐ **Damping**

☐ **Mesh**

Average Element Size (% of model size)	
Solids	-
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	0.6 mm
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

☐ **Adaptive Mesh Refinement**

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

☐ Materials

Component	Material	Safety Factor
Body8	MF CCF	Yield Strength

☐ **Contacts**

☐ **Bonded**

Component1:1	MF CCF	Yield Strength
Component2:1	MF CCF	Yield Strength

☐ **MF CCF**

Density	1.43E-06 kg / mm ³
Young's Modulus	60000 MPa
Poisson's Ratio	0.38
Yield Strength	540 MPa
Ultimate Tensile Strength	800 MPa
Thermal Conductivity	0.105 W / (mm C)
Thermal Expansion Coefficient	9.93E-06 / C
Specific Heat	1129 J / (kg C)

Name
[S] Bonded4 [[]]
[S] Bonded5 [[]]
[S] Bonded6 [[]]

☐ Mesh

Type	Nodes	Elements
Solids	4934851	3459326

☐ Load Case1

 **Solve result of this load case is out of date.**

☐ Constraints

☐ **Pin1**

Type	Pin
Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ **Pin2**

Type	Pin
Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ **Pin3**

Type	Pin
Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ **Loads**

☐ **Force1**

Type	Force
Magnitude	3500 N
X Value	0 N
Y Value	0 N
Z Value	3500 N
X Angle	0 deg
Y Angle	0 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force2**

Type	Force
Magnitude	3500 N
X Value	0 N
Y Value	-1479 N
Z Value	3172 N
X Angle	0 deg
Y Angle	180 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force3**

Type	Force
Magnitude	3500 N
X Value	0 N
Y Value	1479 N
Z Value	3172 N
X Angle	0 deg
Y Angle	180 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force4**

Type	Force
Magnitude	2000 N
X Value	0 N
Y Value	0 N
Z Value	-2000 N
X Angle	0 deg
Y Angle	180 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force5**

Type	Force
Magnitude	2000 N
X Value	0 N
Y Value	-845.2 N

Z Value	-1813 N
X Angle	0 deg
Y Angle	205 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force6**

Type	Force
Magnitude	2000 N
X Value	0 N
Y Value	-845.2 N
Z Value	-1813 N
X Angle	0 deg
Y Angle	-155 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ Results

☐ **Result Summary**

Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	3.916	15
Stress		
Von Mises	1.727E-05 MPa	137.9 MPa
1st Principal	-117 MPa	228.9 MPa
3rd Principal	-218.7 MPa	140.1 MPa
Normal XX	-140.7 MPa	149.8 MPa
Normal YY	-203.5 MPa	203.2 MPa
Normal ZZ	-143.7 MPa	167.6 MPa
Shear XY	-18.75 MPa	24.05 MPa
Shear YZ	-60.07 MPa	51.38 MPa
Shear ZX	-27.77 MPa	29.34 MPa
Displacement		
Total	1.14E-07 mm	0.004821 mm
X	-8.878E-04 mm	0.001141 mm
Y	-0.001049 mm	6.602E-04 mm
Z	-0.004797 mm	0.00397 mm
Reaction Force		
Total	0 N	133.1 N
X	-62.67 N	66.67 N
Y	-12.62 N	16.12 N
Z	-120.2 N	116.9 N
Strain		
Equivalent	5.266E-10	0.003509
1st Principal	-1.754E-04	0.003139
3rd Principal	-0.003627	7.091E-05
Normal XX	-5.257E-04	5.9E-04
Normal YY	-0.001807	0.001518
Normal ZZ	-0.001169	0.001172
Shear XY	-8.623E-04	0.001107
Shear YZ	-0.002763	0.002363
Shear ZX	-0.001277	0.00135
Contact Pressure		
Total	0 MPa	121.3 MPa
X	-56.59 MPa	52.33 MPa
Y	-52.29 MPa	58.15 MPa
Z	-91.84 MPa	111 MPa

☐ **Safety Factor**

☐ **Safety Factor (Per Body)**

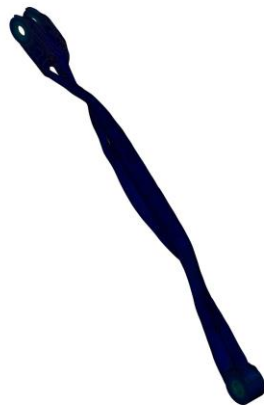
0  8



☐ **Stress**

☐ **Von Mises**

[MPa] 0  61.19



☐ **1st Principal**

 40.7



[

MPa] -3.8

☐ **3rd Principal**

 3.78



[

MPa] -35.25

☐ **Displacement**

☐ **Total**

[mm] 0  0.00191





Appendix 20 Link Arm Generative Design Report

Swingarm Generative Design Report

Analyzed File	Swing Arm Final v14
Version	Autodesk Fusion 360 (2.0.8335)
Creation Date	2020-05-21, 18:44:18
Author	William May-White

☐ Project Properties

Title	Studies
Author	Will

☐ Simulation Model 1:1

☐ 0.75 Study 3 - Static Stress

☐ Study Properties

Study Type	Static Stress
Last Modification Date	2020-05-11, 16:44:56

☐ Settings

☐ General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

☐ Damping

☐ Mesh

Average Element Size (% of model size)	
Solids	-
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	0.75 mm
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

☐ Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

☐ Materials

Component	Material	Safety Factor
Body9	MF CCF	Yield Strength
Body10	Aluminum 6061 T6 80 Hot Formed	Yield Strength
Body11	Aluminum 6061 T6 80 Hot Formed	Yield Strength

☐ MF CCF

Density	1.43E-06 kg / mm ³
Young's Modulus	60000 MPa
Poisson's Ratio	0.38
Yield Strength	540 MPa
Ultimate Tensile Strength	800 MPa
Thermal Conductivity	0.105 W / (mm C)
Thermal Expansion Coefficient	9.93E-06 / C
Specific Heat	1129 J / (kg C)

☐ Aluminum 6061 T6 80 Hot Formed

Density	2.7E-06 kg / mm ³
Young's Modulus	72700 MPa
Poisson's Ratio	0.33
Yield Strength	313 MPa
Ultimate Tensile Strength	340 MPa
Thermal Conductivity	0.167 W / (mm C)
Thermal Expansion Coefficient	2.36E-05 / C
Specific Heat	896 J / (kg C)

☐ Contacts

☐ Bonded

Name
[S] Bonded1 [Body9] [Body10]
[S] Bonded2 [Body9] [Body10]
[S] Bonded3 [Body9] [Body11]
[S] Bonded4 [Body9] [Body11]

☐ Mesh

Type	Nodes	Elements
Solids	8254278	5799302

☐ Load Case1

☐ Constraints

☐ Pin1

Type	Pin
------	-----

Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ **Pin2**

Type	Pin
Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ **Pin3**

Type	Pin
Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ Pin4

Type	Pin
Radial	Yes
Axial	Yes
Tangential	No

☐ **Selected Entities**



☐ Loads

☐ Force1

Type	Force
Magnitude	2000 N
X Value	3.674E-13 N
Y Value	0 N
Z Value	-2000 N
X Angle	-180 deg

Y Angle	0 deg
Z Angle	0 deg
Force Per Entity	No

Type	Force
------	-------

☐ **Selected Entities**



☐ Force2

☐ Type	Force
Magnitude	2000 N
X Value	3.559E-13 N
Y Value	-845.2 N
Z Value	-1813 N
X Angle	-180 deg
Y Angle	0 deg
Z Angle	0 deg
Force Per Entity	No

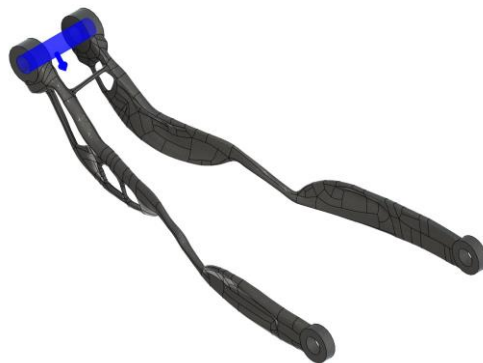
☐ **Selected Entities**



☐ Force3

Magnitude	2000 N
X Value	3.559E-13 N
Y Value	845.2 N
Z Value	-1813 N
X Angle	-180 deg
Y Angle	0 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force4**

Type	Force
Magnitude	3500 N
X Value	0 N
Y Value	0 N
Z Value	3500 N
X Angle	0 deg
Y Angle	0 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force5**

Type	Force
Magnitude	3500 N
X Value	0 N
Y Value	1479 N
Z Value	3172 N
X Angle	0 deg
Y Angle	25 deg
Z Angle	0 deg
Force Per Entity	No

☐ **Selected Entities**



☐ **Force6**

Type	Force
Magnitude	3500 N
X Value	0 N
Y Value	-1479 N

Z Value	3172 N
X Angle	0 deg
Y Angle	-25 deg
Z Angle	0 deg
Force Per Entity	No

☐ Selected Entities



☐ Results

☐ Result Summary

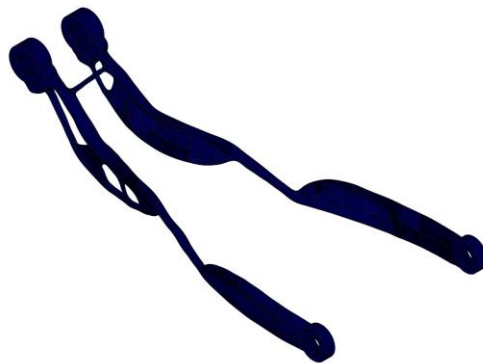
Name	Minimum	Maximum
Safety Factor		
Safety Factor (Per Body)	0.3397	15
Stress		
Von Mises	1.678E-05 MPa	921.4 MPa
1st Principal	-228.2 MPa	1029 MPa
3rd Principal	-1156 MPa	241.4 MPa
Normal XX	-390.6 MPa	373.7 MPa
Normal YY	-1032 MPa	926.4 MPa
Normal ZZ	-321.8 MPa	347.2 MPa
Shear XY	-198.3 MPa	196.6 MPa
Shear YZ	-410.7 MPa	384.5 MPa
Shear ZX	-90.23 MPa	96.42 MPa
Displacement		
Total	8.129E-09 mm	0.4612 mm
X	-0.003613 mm	0.003616 mm
Y	-0.06243 mm	0.06243 mm
Z	-0.007068 mm	0.4612 mm
Reaction Force		
Total	0 N	348.8 N
X	-244 N	171.7 N

Y	-176.7 N	218.3 N
Z	-291 N	287.2 N
Strain		
Equivalent	4.023E-10	0.01834
1st Principal	-3.886E-06	0.01756
3rd Principal	-0.01832	3.729E-06
Normal XX	-0.001778	0.001789
Normal YY	-0.01153	0.01078
Normal ZZ	-0.004657	0.004939
Shear XY	-0.007255	0.007192
Shear YZ	-0.01503	0.01407
Shear ZX	-0.003302	0.003528
Contact Pressure		
Total	0 MPa	436.2 MPa
X	-98.19 MPa	91.97 MPa
Y	-388.6 MPa	364.6 MPa
Z	-224.6 MPa	64.18 MPa

☐ Safety Factor

☐ Safety Factor (Per Body)

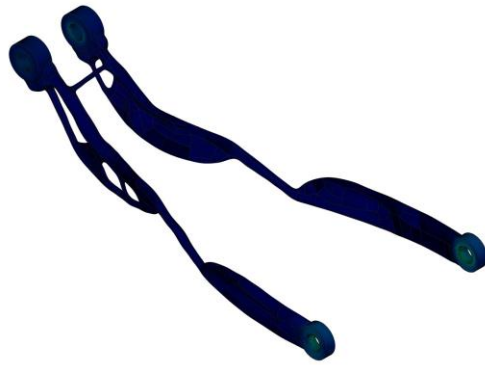
0  8



☐ Stress

☐ Von Mises

[MPa] 0  24.81



☐ 1st Principal

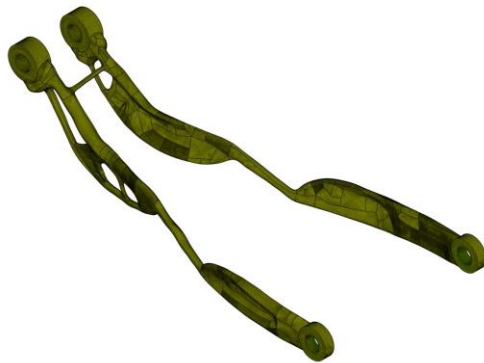
 27.88



[MPa] -10.14

☐ 3rd Principal

 9.75



[MPa] -26.39

☐ Displacement

☐ Total

[mm] 0  0.001419

