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Generative Design Optimization Process for Developing an E-bike Frame Using SolidThinking Inspire

Proyecto de Investigación

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Ingeniería Mecánica

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RESUMEN

"Generative Design" (GD) es una nueva tendencia para el diseño de producto. Este tipo de tecnología utiliza "Simulation-Driven Design", que implica un proceso de optimización iterativo, el cual imita al proceso evolutivo de la naturaleza. El siguiente trabajo muestra el potencial de este nuevo tipo de tecnología emergente para optimizar diseños ya existentes. Para lograr esto se escogió optimizar el cuadro de una bicicleta eléctrica (E-Bike) utilizando "SolidThinking Inspire". Una de las grandes diferencias con respecto a otros procesos de diseño es que parte desde un nuevo enfoque, donde no se considera ninguna suposición o limitación por parte del proceso de manufactura. En este proceso simplemente se considera un espacio inicial de diseño para el cuadro y múltiples escenarios de carga que simulan condiciones de manejo. En este caso los escenarios de carga fueron hechos en base a la norma europea EN14766. En cada escenario de carga, el programa presentó una solución diferente, el cual muestra cómo la forma de un cuerpo cambia en base a las fuerzas que se aplican a él. En el diseño final se combinaron todos los escenarios de carga, para obtener la mejor estructura que satisfaga a todos los escenarios de carga previamente establecidos. Este diseño final fue postprocesado y analizado mediante elementos finitos en SolidThinking Inspire. Este proceso de optimización logró reducir el 24% de peso con respecto a la estructura tradicional de tubos de los cuadros de bicicletas eléctricas actuales. Esta reducción de peso manteniendo los estándares de seguridad mejoran el rendimiento de la E-Bike y muestran el potencial de GD que revolucionará muchas industrias

Palabras clave: Generative Design, E-Bike, Topology Optimization, Lattice Optimization, SolidThinking Inspire, Multiples escenarios de carga, EN14766, FEA

ABSTRACT

Generative Design (GD) is a new trend for product design. This technology uses simulation-driven design, which involves an iterative optimization process that imitates natural evolution. The following work demonstrates how GD can be used to improve any existing design. Specifically, this project demonstrates the complete GD methodology for developing an E-Bike frame using SolidThinking Inspire. This new approach for designing an E-Bike frame does not require prior assumptions or manufacturing constraints for generating the frame. It simply considers an initial design space and multiple load cases that simulate riding conditions. These load cases were based on the European Standard EN14766. In each load case, a different solution is presented in order to understand how a body is shaped by the forces that are applied to it. A final design was generated by merging every load case to generate the best overall structure. This final design is then post processed and validated using Finite Element Analysis (FEA) within SolidThinking Inspire. This optimization process reduced 24% of the mass of traditional tube structure frames. This large weight reduction greatly improved the E-Bike's efficiency while maintaining all safety requirements. This exemplified the potential of GD as an emerging technology that will revolutionize many industries.

Key words: Generative Design, E-Bike, Topology Optimization, Lattice Optimization, SolidThinking Inspire, Multiple Load Cases, EN14766, FEA

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INTRODUCTION

Generative Design (GD) is one of the most promising technologies that has been recently developed in computer aided design (CAD). This new type of technology completely changes how products are made, by giving multiple solutions for accomplishing a specific goal according to the designer's criteria. This iterative process takes advantage of today's advanced computing power that that continues to develop rapidly. This optimization process will ensure maximum performance by evolving the initial design, imitating nature's evolutionary approach for solving problems. In GD, multiple complex forms are developed and tested until the program reaches the most optimal solution. More common use of this process will lead to more efficient products. This can have a big impact on many industries by reducing energy consumption and improving product strength and durability. GD is the future and the next big step in the evolution of design (Keane, Generative Design: The Road to Production, 2018).

One of the main inspirations for this emerging technology is nature. The optimization process of GD has already occurred for millions of years through natural evolution including Natural Selection (Autodesk, 2018). Most human inventions have been inspired by nature itself. However, using artificial intelligence and the development of complex iterative algorithms, we can now recreate this evolutionary process using computational science. This provides the opportunity to recreate and optimize a variety of products.

GD is revolutionizing and improving efficiency in many fields, from racings cars to industrial machinery equipment to aerospace engineering design. This technology provides solutions with multiple variations, allowing designers to achieve their goals with more flexibility than before. GD lets the machine do the work which, resulting in the improvement from previous generation models. Many industries are starting to implement this technology to optimize their products. Companies like General Motors, Airbus, and Under Armour have done this with amazing results (Keane, The New Age of Highly Efficient Products Made with Generative Design, 2017). Many focused on generating weight efficient products while meeting the structural requirements of stiffness and deformation.

The principal companies that have been involved in developing this type of GD software are Autodesk, Dassault Systèmes, Altair Engineering, and NTopology. Each company has incorporated GD into its own products in different ways: Autodesk in Fusion 360 and plans for future projects like Dreamcatcher (Autodesk, 2018); Dassault Systèmes in Catia 3D Experience and topology optimization in SolidWorks (Dassault Systemes, 2018); Altair Engineering in SolidThinking Inspire (SolidThinking, 2018); NTopology in Elements (NTopology, 2018). Each company uses its own protected GD algorithms and routines that are hidden within the software. From the previously mentioned, the company with the most clearly articulately GD steps is SolidThinking Inspire. For this reason, the focus of this paper is SolidThinking Inspire.

SolidThinking Inspire is a product of Altair. This software has a variety of applications, including 3D modeling, simulating, analyzing, and optimizing parts and assemblies. It includes GD and topology optimization allowing multiple material selection and loading cases. The main inputs required by this software are the design space, design parameters, loading cases, properties of the material, and user-established goals. This software allows the user to create and test structurally efficient concepts on the same platform. Using one software for the entire design process reduces costs and time when compared to using multiple. The main features of SolidThinking Inspire for GD are topology and lattice optimization which can be used together for improving product efficiency. This GD module was inspired by a bone growth algorithm that was developed at the University of Michigan (Wasserman, 2015). This algorithm was then introduced to OpiStruct which is the backbone of SolidThinking Inspire.

While there are many products left to optimize using GD, the aim of this paper is to improve the existing designs of electric bikes (E-bikes) in order to reduce weight while maintaining stiffness. The following work presents the complete GD for an E-bike frame using SolidThinking Inspire 2018.1. Furthermore, it compares multiple loading case inputs to choose the optimal design from the structures obtained with the GD algorithm. Each possible solution is then compared among the previous solutions and analyzed using finite element methods to validate the results. These solutions are then tested based on overall displacements, factors of safety, percent yields, tensions/compressions, max shear stresses, von Mises stresses, and major principal stresses. In addition to optimizing an E-bike, the present work shows how the methodology of GD can be used to improve any existing design.

DESIGN METHODOLOGY

GD uses computer aided-engineering (CAE) which is based in simulation-driven design. This new trend for designing parts takes advantage of numerical tools, evolution algorithms, and other optimization strategies. From the user point of view, the design workflow follows a simple methodology that consists of 3 main steps: define the initial geometry, establish the structural set-up, and define the optimization goals. The methodology used for designing this E-Bike frame starts by defining the initial components and geometry.

Hardware Selection

The electric motor is the first component one must consider for the initial design. For the scope of this study, a mid-drive E-bike kit was used. This kit, shown in Fig 1, included the electric motor, cranks, chainring, and electric controller with a display (LUNA CYCLE, 2016).

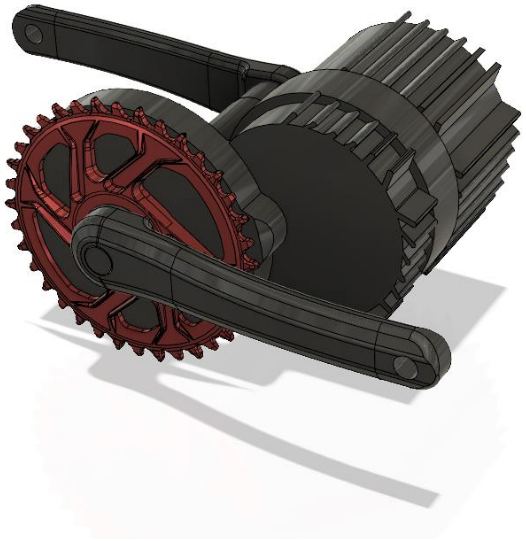
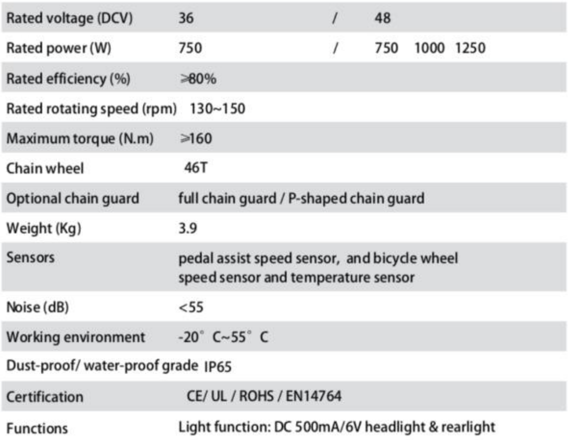


Fig 1. Bafang BBSHD 1000 Mid Drive

As the most important part of the bike, this kit provides the E-bike with pedal assist and throttle control. It is fitted into the bottom bracket of the bicycle and is easily installed. The specifications for this motor were obtained from the user manual shown on Fig 2 (LUNA CYCLE, 2016).



Rated voltage (DCV)	36	/	48
Rated power (W)	750	/	750 1000 1250
Rated efficiency (%)	≥80%		
Rated rotating speed (rpm)	130~150		
Maximum torque (N.m)	≥160		
Chain wheel	46T		
Optional chain guard	full chain guard / P-shaped chain guard		
Weight (Kg)	3.9		
Sensors	pedal assist speed sensor, and bicycle wheel speed sensor and temperature sensor		
Noise (dB)	<55		
Working environment	-20° C~55° C		
Dust-proof/ water-proof grade	IP65		
Certification	CE/ UL / ROHS / EN14764		
Functions	Light function: DC 500mA/6V headlight & rearlight		

Fig 2. Bafang BBSHD specifications

The second most important component of the E-bike design is the battery. This supplies energy to the electric motor and controller. As shown in Fig 3, the battery chosen for this study was a SAMSUNG E-Bike Mighty Mini Cube 52V battery specially made for E-bikes.

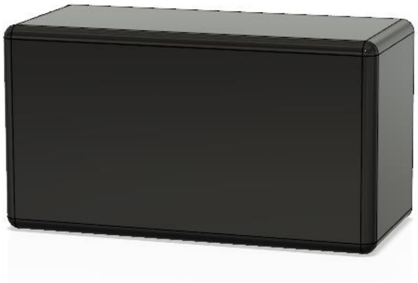
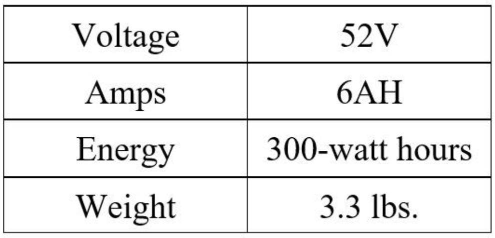


Fig 3. SAMSUNG Mighty Mini Cube 52V

This battery was chosen because of its high performance and light weight (LUNA CYCLE, 2016). Depending on the desired distance range, the E-bike can carry up to 2 batteries. The technical specifications of the battery are shown in Fig 4.



Voltage	52V
Amps	6AH
Energy	300-watt hours
Weight	3.3 lbs.

Fig 4. 52V SAMSUNG Mighty Mini Cube 52V

Mechanical Selection

In terms of kinematics, the mechanical components of the E-bike are the front fork and the rear shock. These make up the suspension system which is used for absorbing the impact of rough riding conditions, while going uphill or downhill. Due to demanding off-road conditions, top suspension components where selected for achieving 200mm of travel front and 240mm rear. For the rear shock, a ROCKSHOX Vivid R2C was selected, as shown in Fig 5. It has a total length of 240mm and a stroke of 76mm.

Fig 5. ROCKSHOX Vivid R2C

For the front fork, a ROCKSHOX BoXXer RC was selected, shown in Fig 6.

Fig 6. ROCKSHOX BoXXer RC

Additionally, in order to adjust seat height while riding, a dropper post was added. This study uses a ROCKSHOX Reverb, shown in Fig 7.

Fig 7. ROCKSHOX Reverb

Geometry

In order to locate the E-bike's main components, a 3D model layout was made in Fusion 360. The main parts of the frame are the bottom bracket, the head tube, and the seat tube. The locations and angles are shown in Fig 8. The main objective for the design of the E-bike's geometry was to get a slack head angle, with a short reach and wheelbase for improving maneuverability.

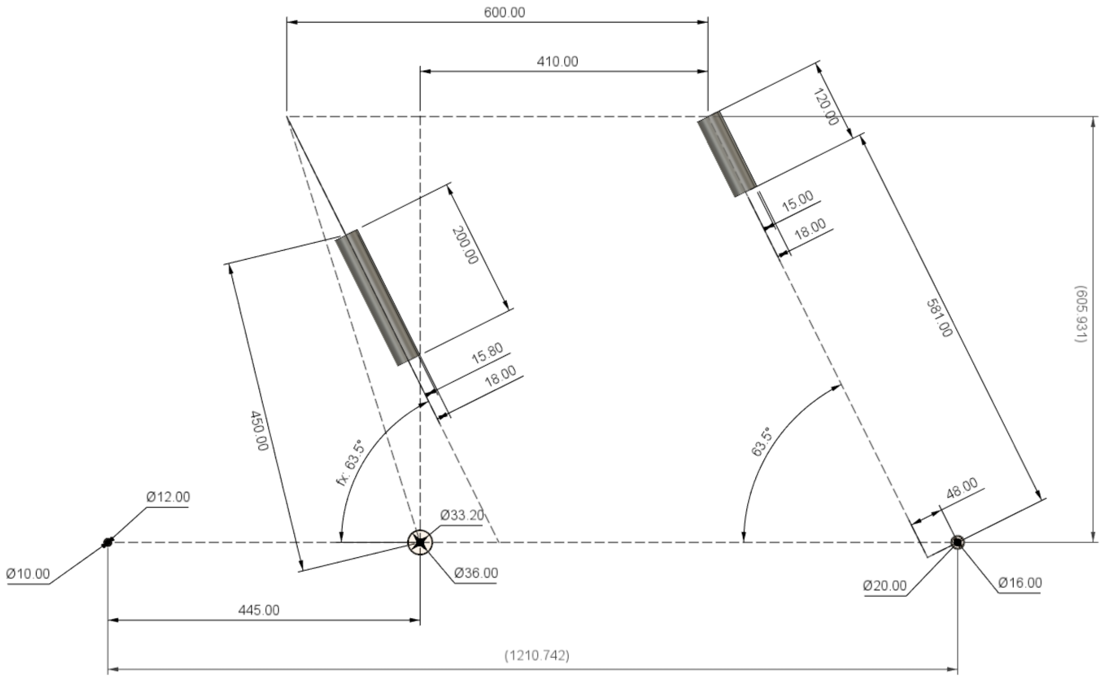


Fig 8. Frame geometry layout

For the next part of the methodology, the frame, rear arm, bottom link, and top link were design based on a virtual pivot point (VPP) linkage used by the top downhill bikes. A renowned bike company, Intense, used to call this linkage the JS Tuned Suspension system; meanwhile, another well-known brand, Santa Cruz, called it VPP. These two famous companies used to share a patent for this system for their high-end downhill bikes the Intense M16 and the Santa CruzV10; however, it is now expired. This linkage gives high efficiency, fine tuning, balanced braking, structural integrity, and low maintenance (INTENSE, 2016). In summary, the chosen hardware and mechanical components, along with the design space, are shown in Fig 9.

Fig 9. Frame components and design space

European Standards

For assuring the rider's safety, the E-bike needs to fulfill a series of safety requirements. These involve different types of testing methods specifically established for mountain biking. For the scope of this project, the bike was tested and validated based on the European Standard EN14766. This assured strength and durability of the E-bike's frame (European Commitee For Standardization, 2005). The tests considered for this project's load cases are shown in the following Figs 10-14.

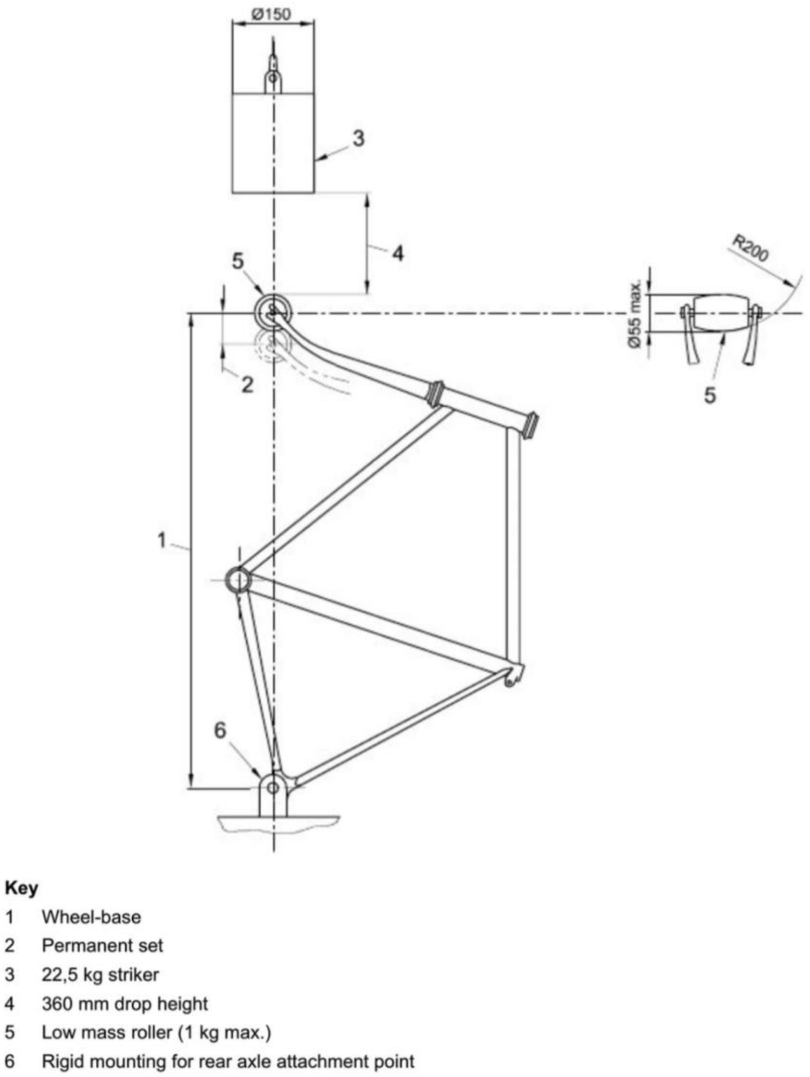
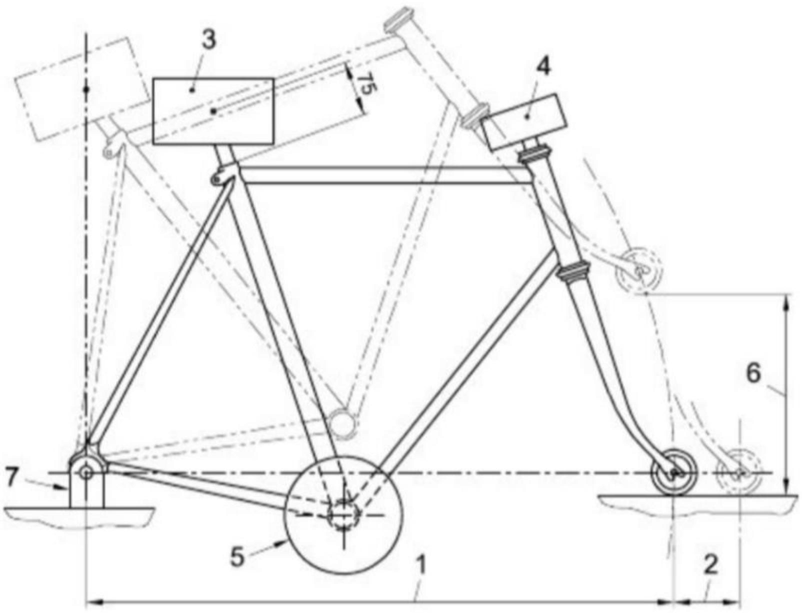


Fig 10. Frame and front fork impact test 1



Key

1 Wheel-base

2 Permanent set

3 30 kg mass

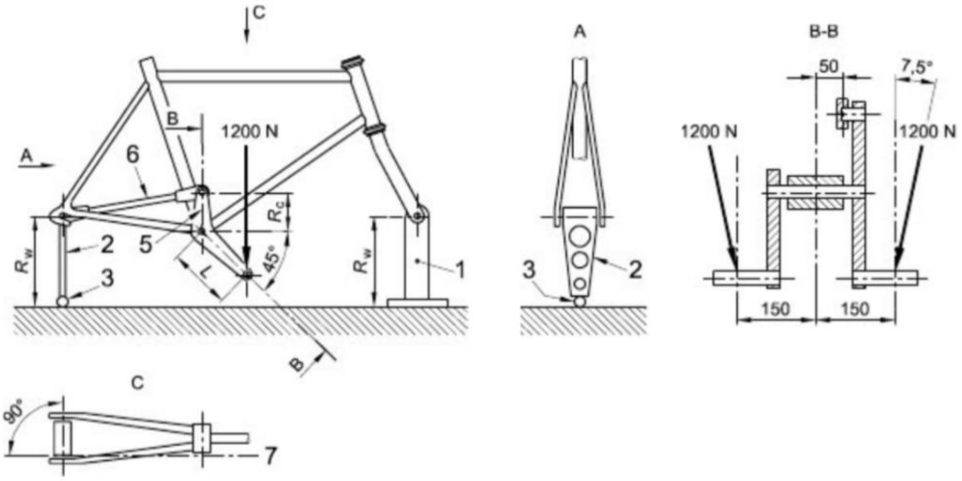
4 10 kg mass

5 50 kg mass

6 300 mm drop height

7 Rigid mounting for rear axle attachment point

Fig 11. Frame and front fork impact test 2



Key

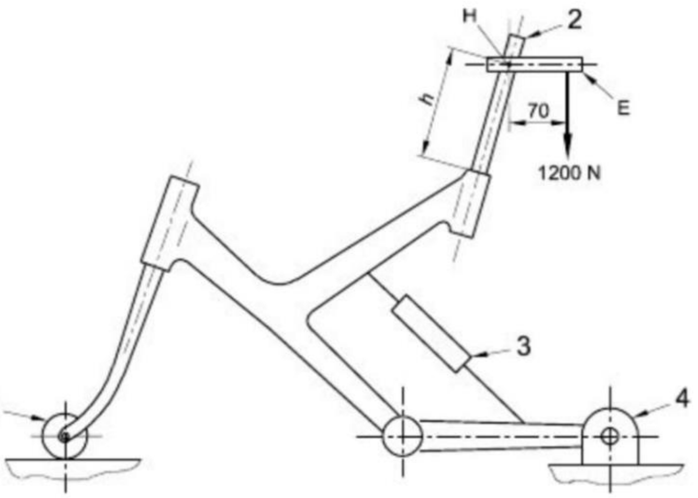
R_w	Height of rigid mount and vertical link
R_c	Length of vertical arm (75 mm)
L	Length of crank replacement (175 mm)
1	Rigid mount
2	Vertical link
3	Ball-joint
4	Adaptor assembly
5	Vertical arm
6	Tie-rod
7	Centre-line of tie-rod

Fig 12. Frame fatigue test with pedaling force 2

Key

1	Free-running guided roller
2	Rigid, pivoted mounting for rear axle attachment point

Fig 13. Frame fatigue test horizontal forces



Key

1 Free-running roller

2 Steel bar

3 Locked suspension unit or solid link for pivoted chain-stays

4 Rigid, pivoted mounting for rear axle attachment point

Fig 14. Frame fatigue test with a vertical force

Considering all the safety requirements by the EN14766, the set-up, simulation configuration, and the optimization goals in SolidThinking Inspire are explained in the following section.

OPTIMIZATION PROCESS

Optimization

SolidThinking Inspire Workflow is a simple and user-friendly optimization software. The first step in the optimization process of the E-bike frame was to import or draw the initial geometry within this software. In this case, the previously defined geometry was imported as a .step file. The next step was to separate the design space from the design parameters. For this process, the partition tool within the Geometry tab was used. This tool automatically detects the different types of features on the 3D model and splits the initial body into multiple bodies. This process is shown in Fig 15.

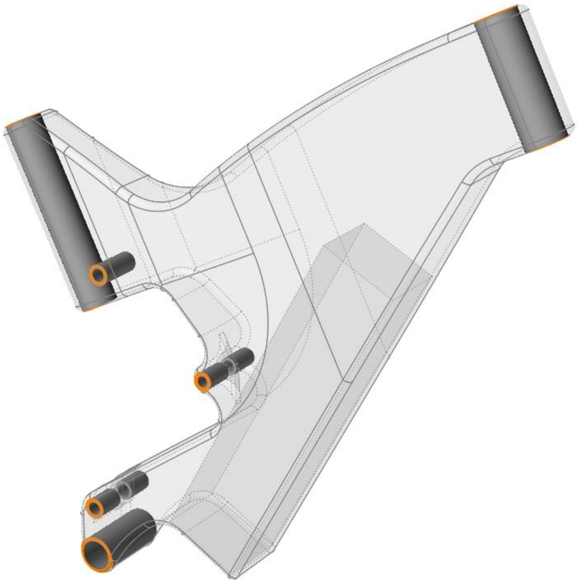


Fig 15. Partition tool for Frame

Once the partition was done, the design space was selected. The following step was to check the contacts within the assembly. SolidThinking Inspire automatically detects the contacts within the assembly and assigns different categories to each. In this case, the bonded contacts were automatically added after the partition process as seen in Fig 16.

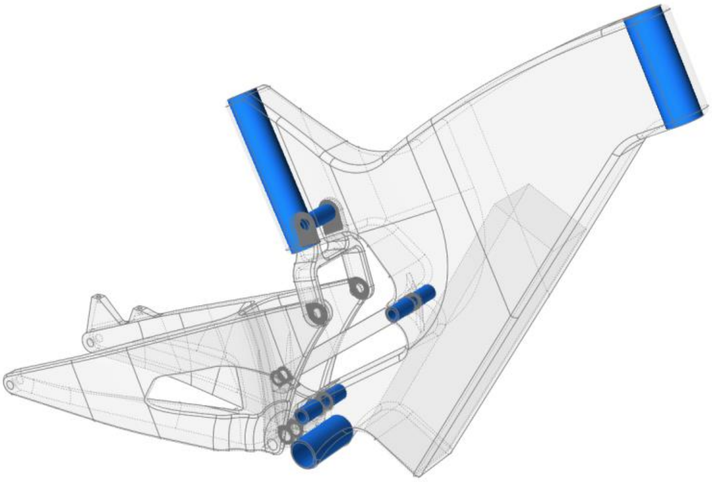


Fig 16. Frame’s Contacts

The next step was to set up the linkage joints. The Joints tool automatically detects and classifies different features to set the joints depending on the degrees of freedom needed for the assembly. The joints for the VPP system in this project are pins that match the Aligned Holes feature. In this way, the pins were automatically added as shown in Fig 17.

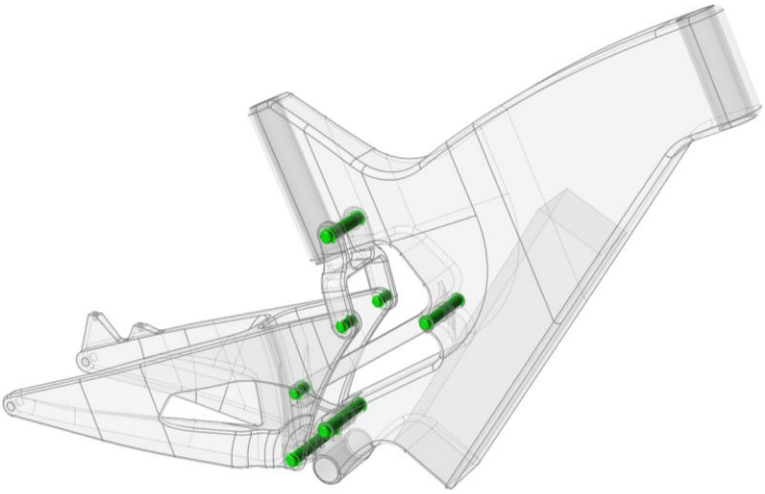


Fig 17. Frame’s Joints

The following step was to define the supports for the simulation. This set up was based on the EN14766 that simulates ridding conditions in Fig 18.

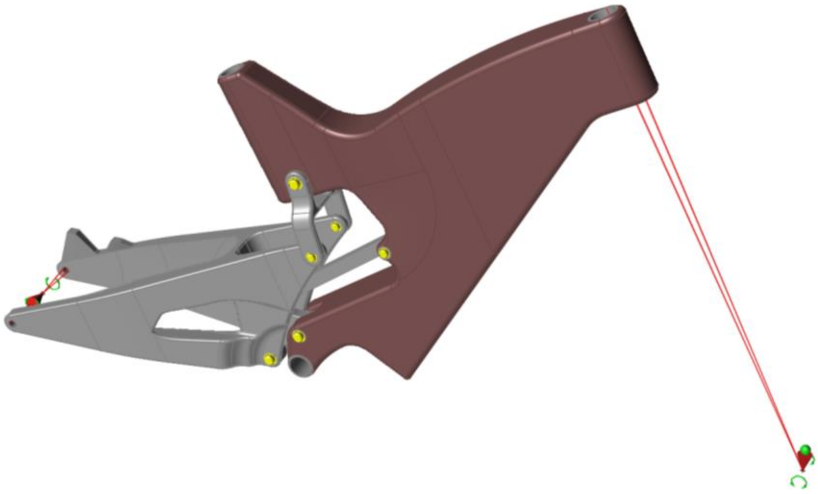


Fig 18. Frame’s Supports

Once the structure was supported, the load cases were defined considering the maximum load that the frame could handle. These load cases are summarized in Table 1 below.

Table 1. Load Cases Frame

Load Case	Name	Description	Direction
1	BB* load	3000N BB	-z
2	Saddle load	2000N Saddle	-z
3	Handlebar load	500N on each side	-z
4	Front impact	1500N Front axis	y
5	Side impact	500N Front axis	x
6	Pull	1000N Saddle	x1 y1 z0
7	Heavy Pedaling	1000N Pedal and handlebars same side	-z, z
8	Aggressive Cornering	1000N Pedal and handlebars alternated	-z, -z

*BB: Bottom Bracket

The load cases detailed above are shown in Fig 19.

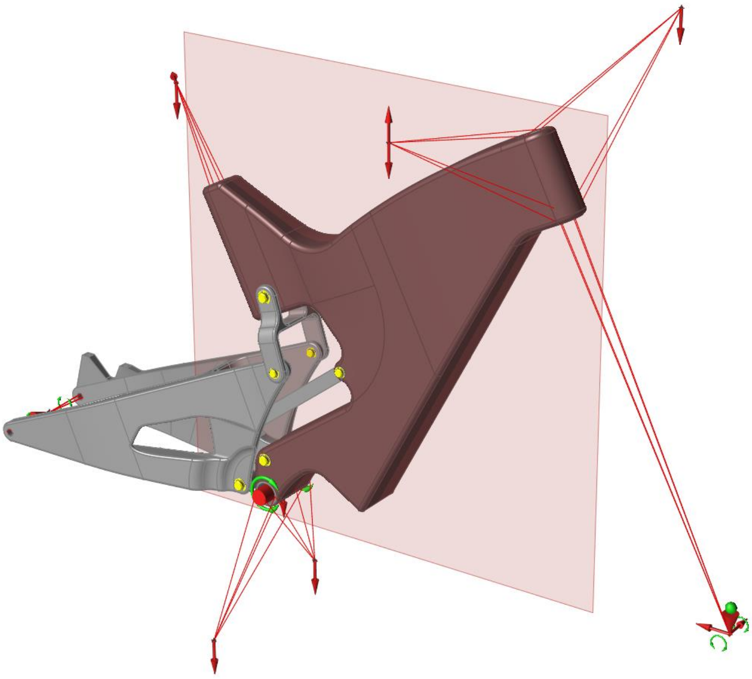


Fig 19. Load Cases

Additionally, some load cases are not symmetrical and have to be mirrored to obtain a rigid structure on both sides. To do this, a Shape Control was set to apply a symmetric control on the plane YZ. Once the load cases were defined, the Analysis tool was used to verify the motion constraints by the linkage. After the analysis was completed, the Topology optimization could take place. This process needs a lot of computational power depending on the thickness constraint established for the simulation. Despite using a high-end PC, the simulation runtime can take between 12 to 24 hours for each run.

In this first optimization stage, the Topology optimization parameters were set for a target mass of 10% with the minimum thickness constraint for every load case defined separately. The results for the topology optimization are shown in Figs 20-27.

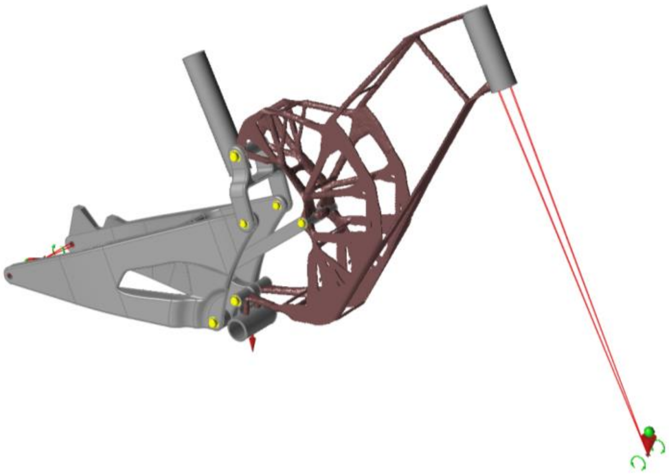


Fig 20. Topology optimization Load Case 1

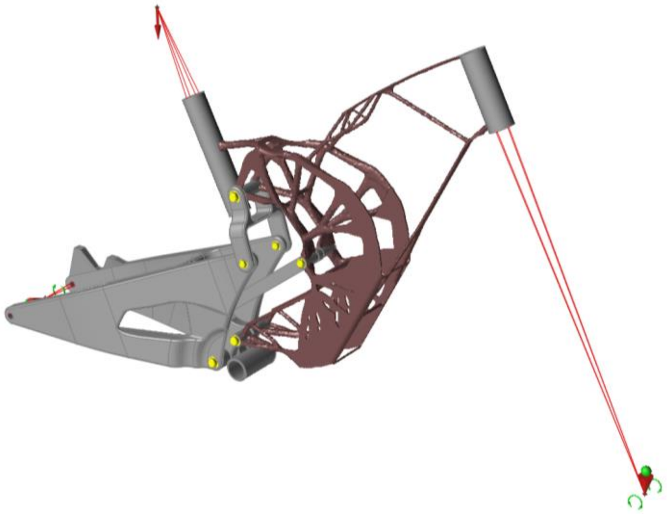


Fig 21. Topology optimization Load Case 2

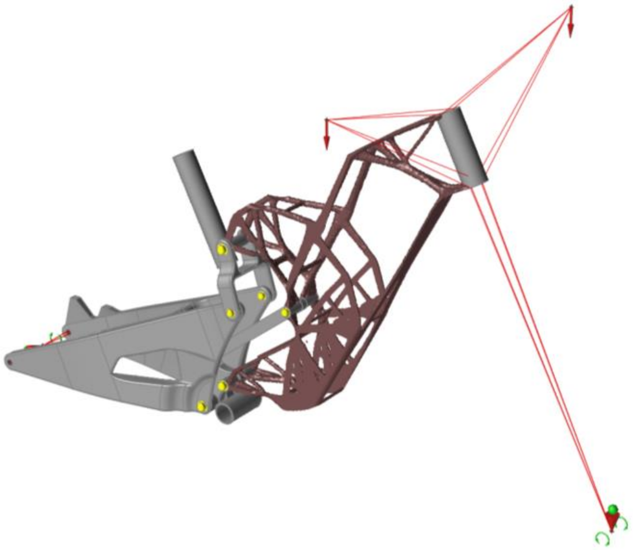


Fig 22. Topology optimization Load Case 3

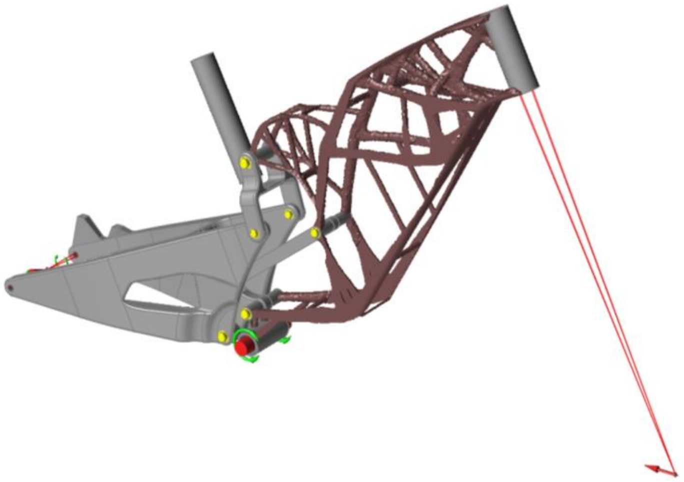


Fig 23. Topology optimization Load Case 4

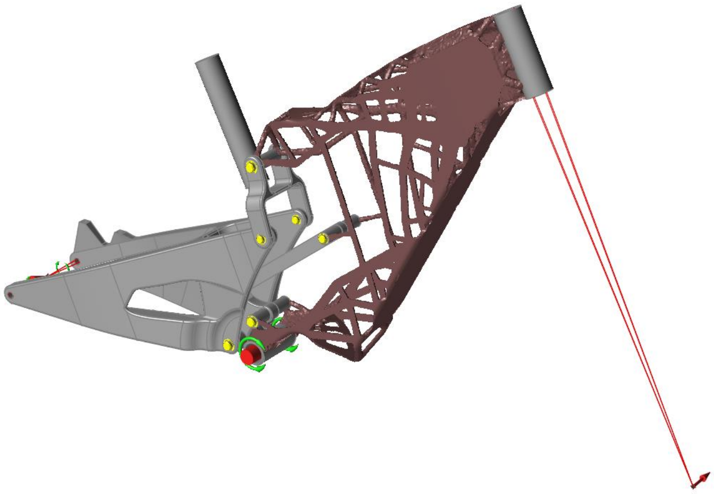


Fig 24. Topology optimization Load Case 5

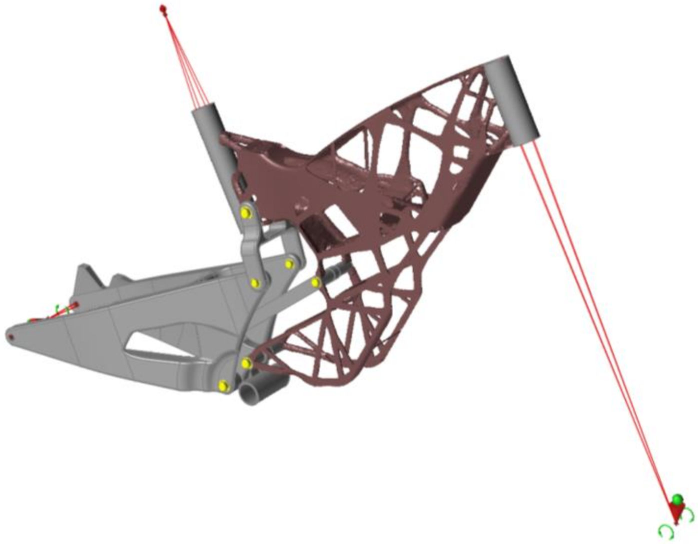


Fig 25. Topology optimization Load Case 6

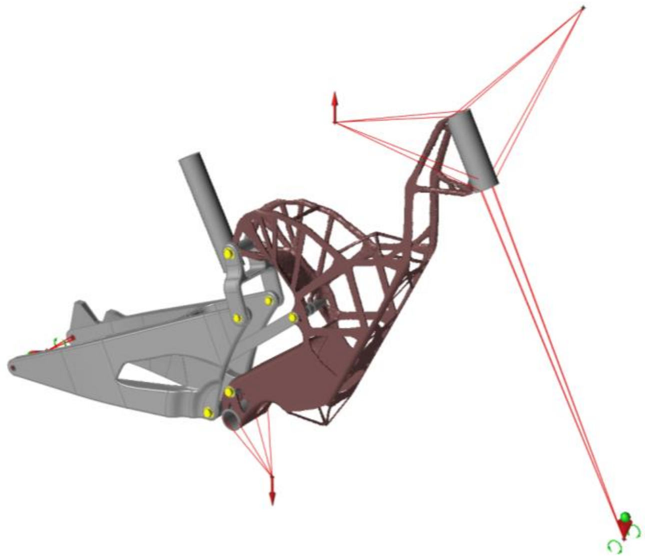


Fig 26. Topology optimization Load Case 7

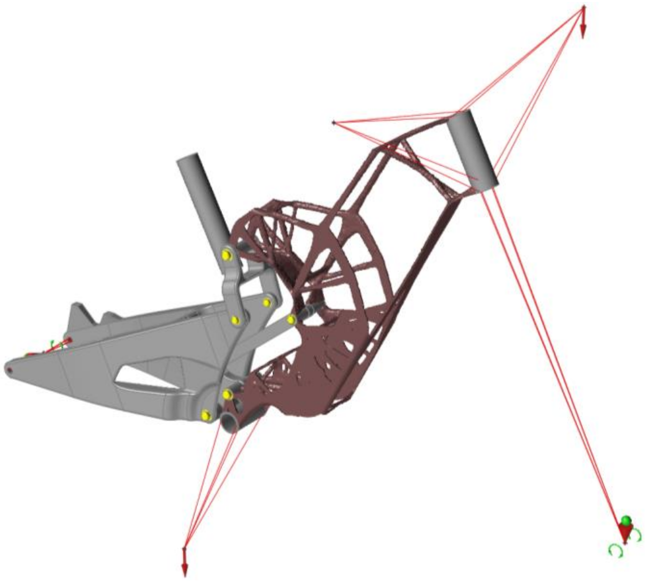


Fig 27. Topology optimization Load Case 8

To obtain the most accurate results, all the above optimized structures were combined into one model. This provide an overall compliance for every load case. This final Topology Optimization was set with the smallest thickness constraint available in SolidThinking Inspire and with a target mass of 5% of the original total mass. The result of the final Topology Optimization is shown in Fig 28.

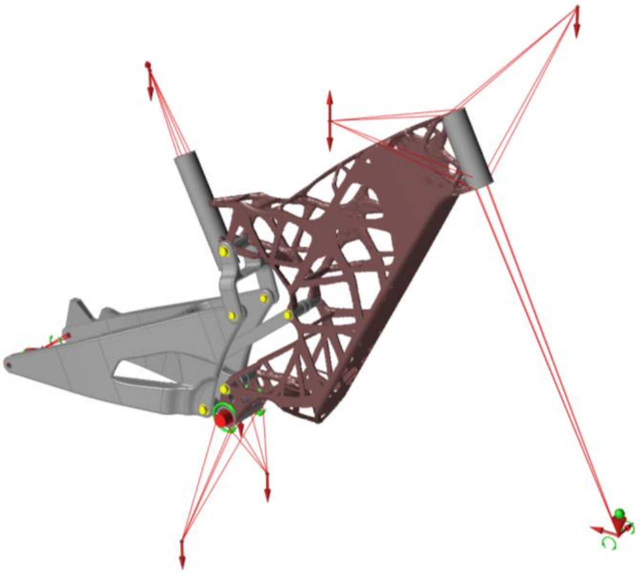
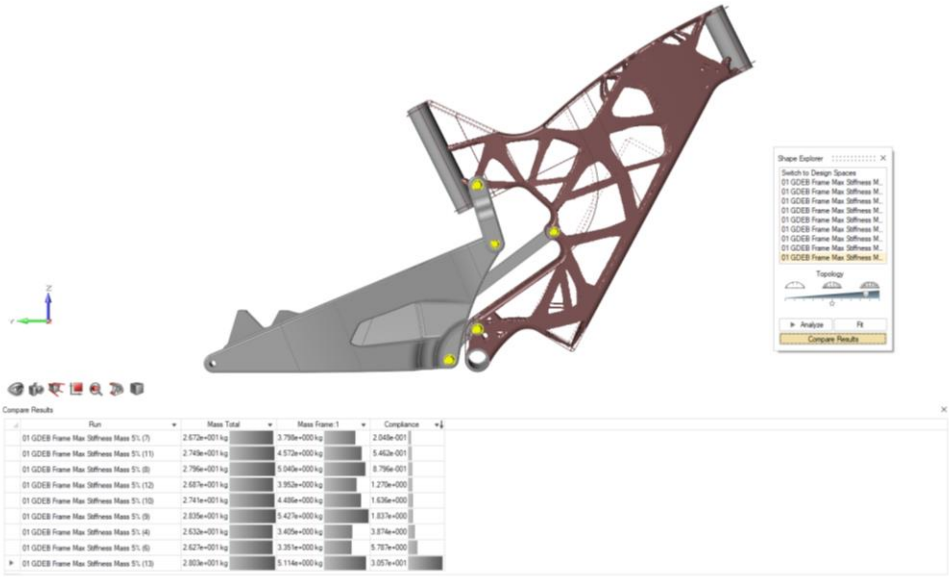


Fig 28. Final Topology optimization

A comparison chart of all the topology optimization was used to determine the best design solution for the system. As a result, the combined load case was chosen because it had the highest compliance score as shown in Fig 29.



Compare Results

Run	Mass Total	Mass Frame:1	Compliance
01 GDEB Frame Max Stiffness Mass 5% (7)	2.672e+001 kg	3.798e+000 kg	2.048e-001
01 GDEB Frame Max Stiffness Mass 5% (11)	2.749e+001 kg	4.572e+000 kg	5.462e-001
01 GDEB Frame Max Stiffness Mass 5% (8)	2.796e+001 kg	5.040e+000 kg	8.796e-001
01 GDEB Frame Max Stiffness Mass 5% (12)	2.687e+001 kg	3.952e+000 kg	1.270e+000
01 GDEB Frame Max Stiffness Mass 5% (10)	2.741e+001 kg	4.486e+000 kg	1.636e+000
01 GDEB Frame Max Stiffness Mass 5% (9)	2.835e+001 kg	5.427e+000 kg	1.837e+000
01 GDEB Frame Max Stiffness Mass 5% (4)	2.632e+001 kg	3.405e+000 kg	3.874e+000
01 GDEB Frame Max Stiffness Mass 5% (6)	2.627e+001 kg	3.351e+000 kg	5.787e+000
▶ 01 GDEB Frame Max Stiffness Mass 5% (13)	2.803e+001 kg	5.114e+000 kg	3.057e+001

Fig 29. Final Topology optimization

This same process was done for the rear arm. For this case, the design space was changed, and the supports were redefined. The new set up with the modified load cases is shown in Table 2 below.

Table 2. Load Cases Rear Arm

Load Case	Name	Description	Direction
1	BB load	3000N BB	-z
2	Rear wheel Skid	500N Rear Axle	y
3	Rear Braking	250N Rear Brake Mount	-y' (tangent to the rotor)
4	Acceleration	200Nm Right side	x
5	Side Drift	250N Tire contact point	x

These modified supports are shown in Fig 30.

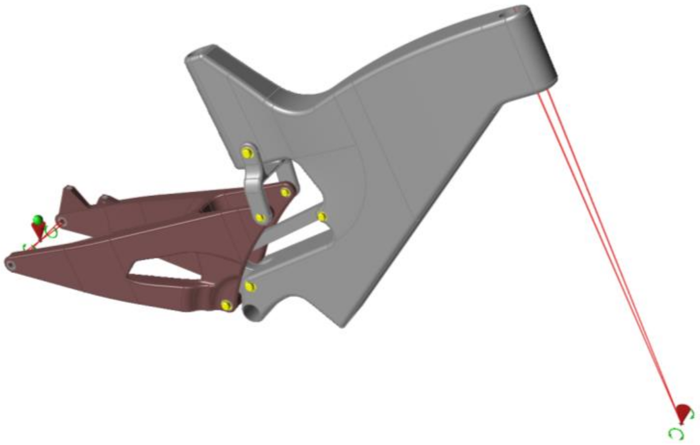


Fig 30. Rear Arm Set up

The Topology optimization results for the following load cases are shown on the following Figs 31-35.

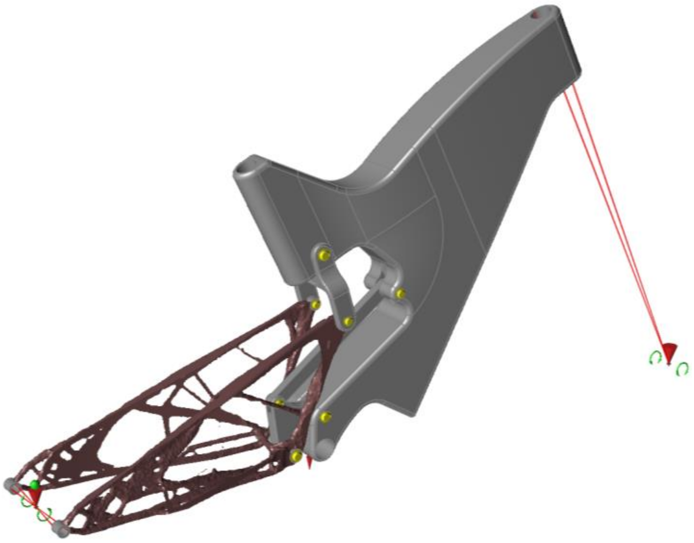


Fig 31. Topology optimization Load Case 1

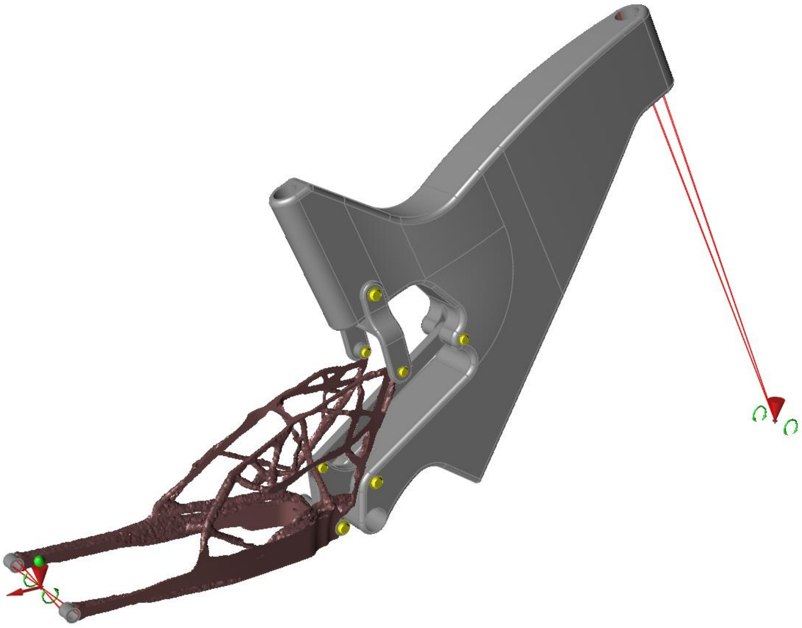


Fig 32. Topology optimization Load Case 2

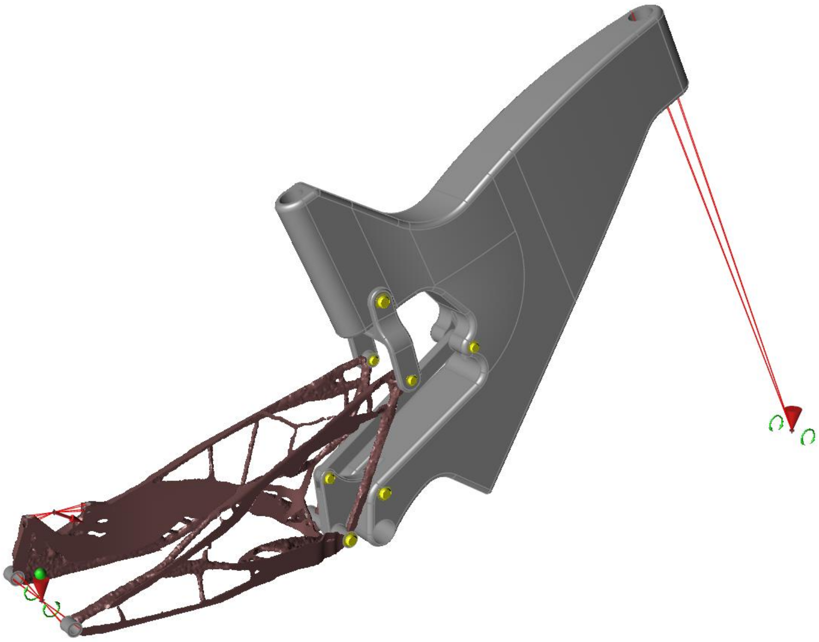


Fig 33. Topology optimization Load Case 3

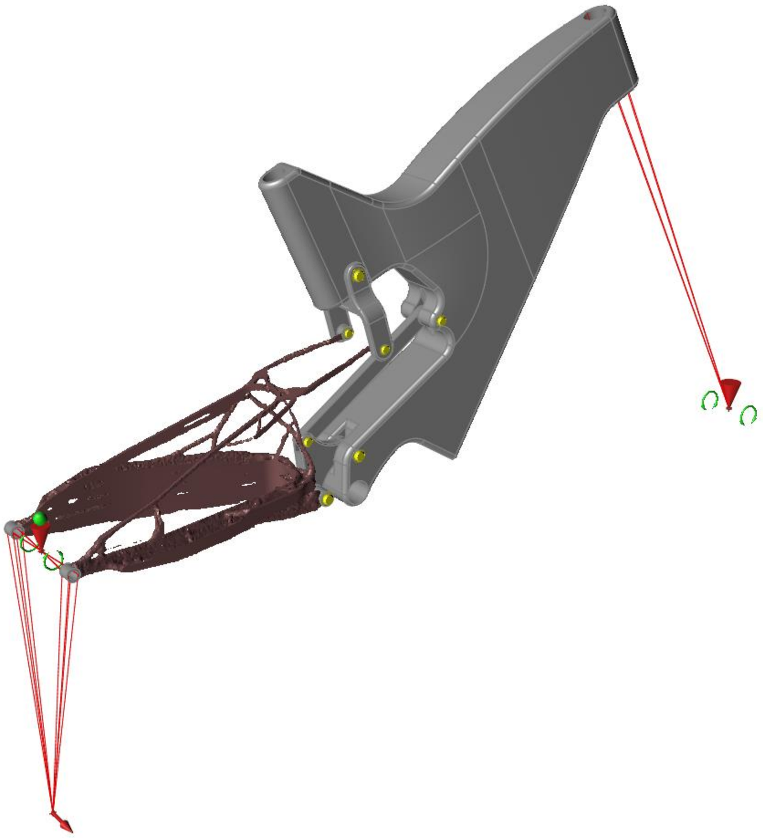


Fig 34. Topology optimization Load Case 4

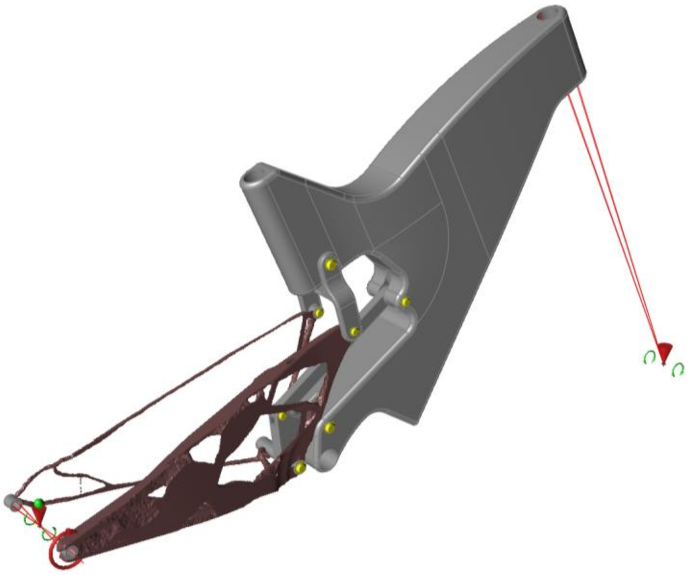


Fig 35. Topology optimization Load Case 5

Finally, the result obtained by combining all the load cases is shown in Fig 36.

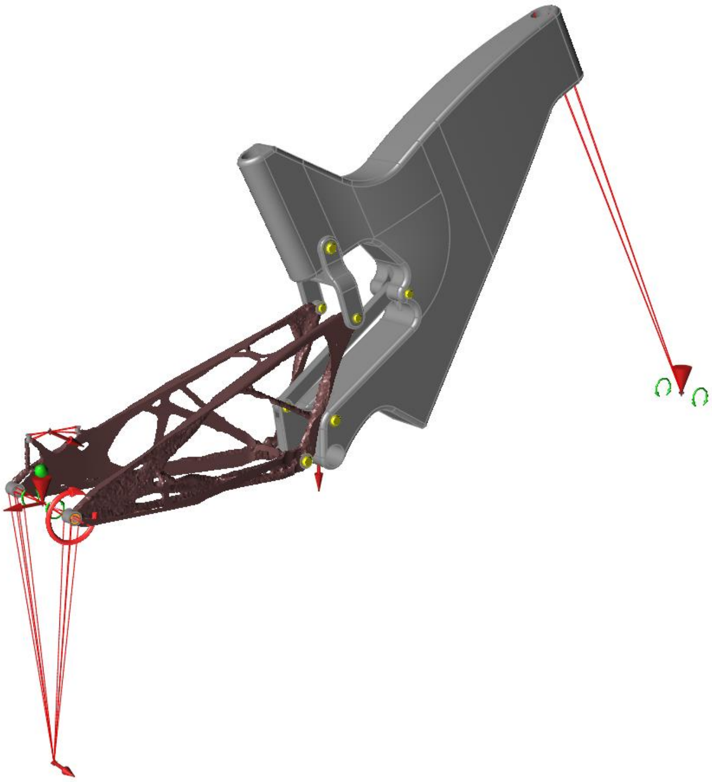
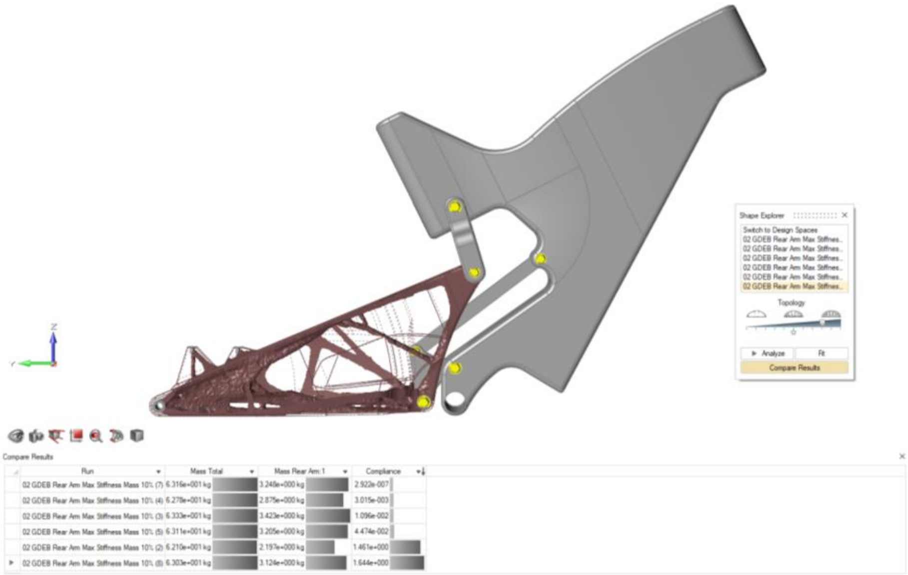


Fig 36. Final Topology optimization Rear Arm

As before, a comparison chart of all the topology optimization was used to determine the best design solution for the system. The combined load case was chosen again because it had the highest compliance score as shown in Fig 37.



Compare Results

	Run	Mass Total	Mass Rear Arm:1	Compliance
	02 GDEB Rear Arm Max Stiffness Mass 10% (7)	6.316e+001 kg	3.248e+000 kg	2.922e-007
	02 GDEB Rear Arm Max Stiffness Mass 10% (4)	6.278e+001 kg	2.875e+000 kg	3.015e-003
	02 GDEB Rear Arm Max Stiffness Mass 10% (3)	6.333e+001 kg	3.423e+000 kg	1.096e-002
	02 GDEB Rear Arm Max Stiffness Mass 10% (5)	6.311e+001 kg	3.205e+000 kg	4.474e-002
	02 GDEB Rear Arm Max Stiffness Mass 10% (2)	6.210e+001 kg	2.197e+000 kg	1.461e+000
▶	02 GDEB Rear Arm Max Stiffness Mass 10% (8)	6.303e+001 kg	3.124e+000 kg	1.644e+000

Fig 37. Final Topology optimization Rear Arm

For the optimization of the links, the Topology Optimization process was done with the same load cases and parameters as the one used for the Rear Arm. The top and bottom links results are shown in Fig 38-39.

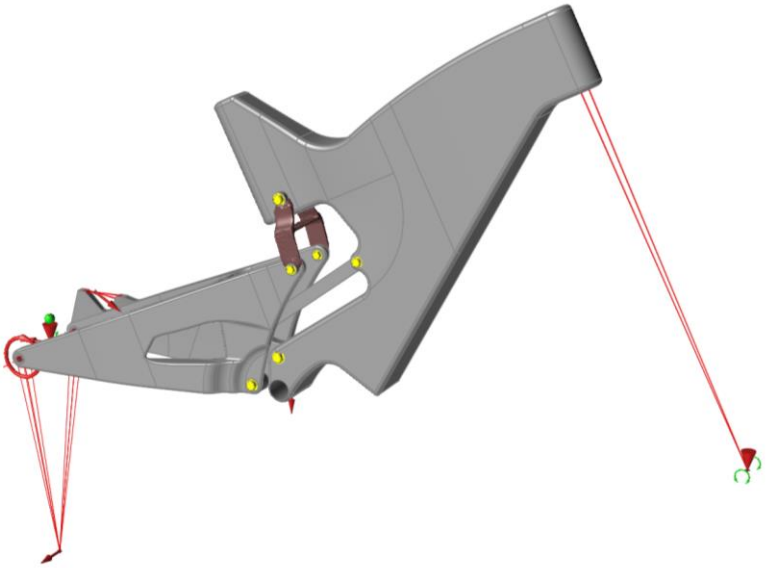


Fig 38. Final Topology optimization Top Link

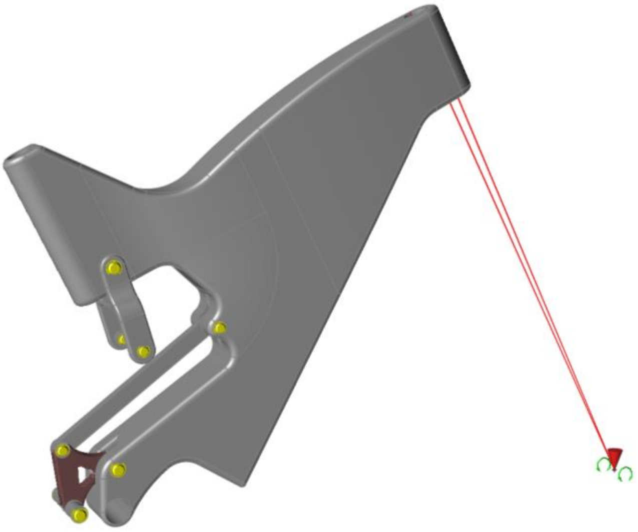


Fig 39. Final Topology Optimization Bottom Link

PolyNurbs

Once all the parts were optimized, the results were post processed using PolyNurbs. This tool uses freeform commands and shapes for softening the obtained results. The post process results are shown on the following Figs 40-43.

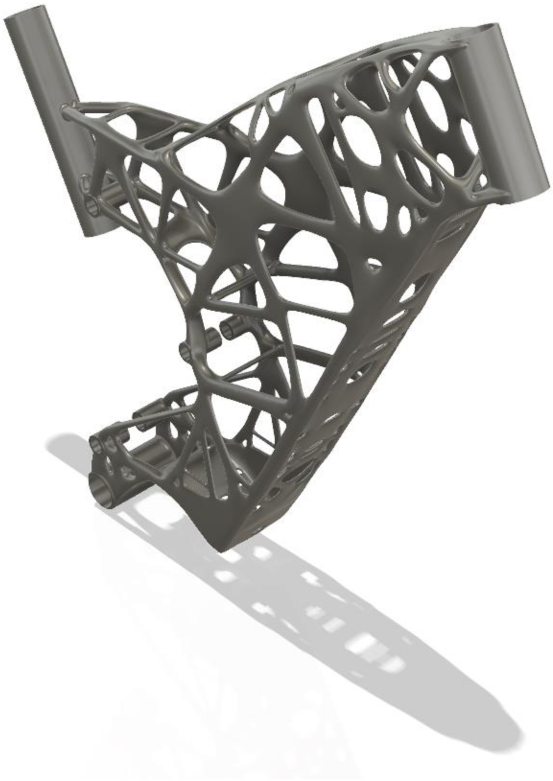


Fig 40. Frame PolyNurbed

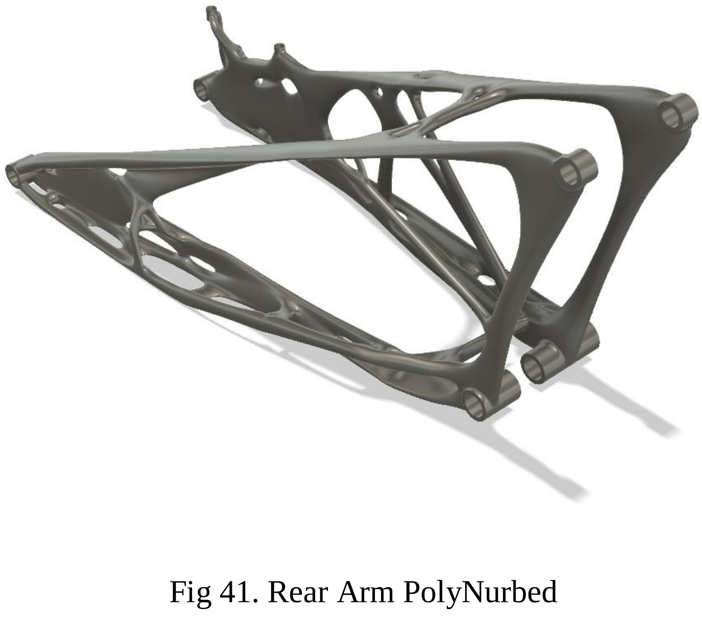


Fig 41. Rear Arm PolyNurbed

Fig 42. Top Link PolyNurbed

Fig 43. Lower Link PolyNurbed

The final assembly is shown in Fig 44.

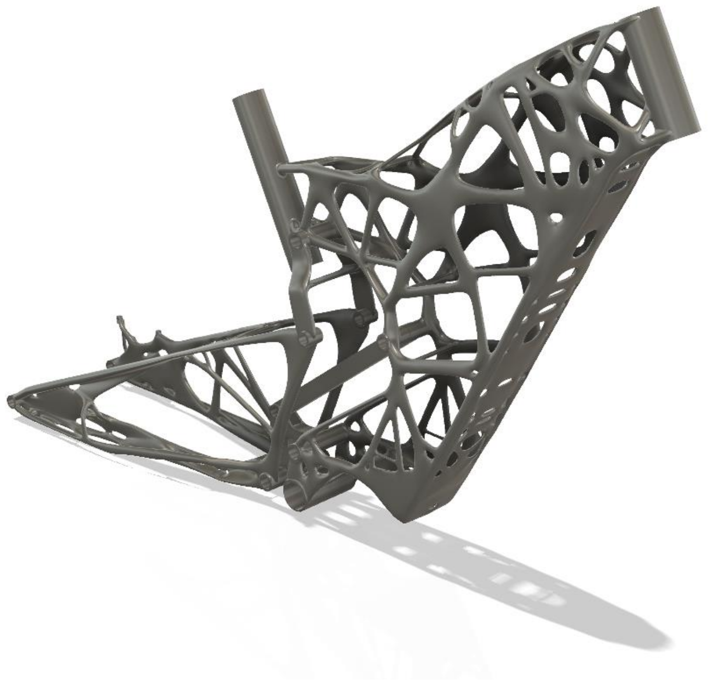


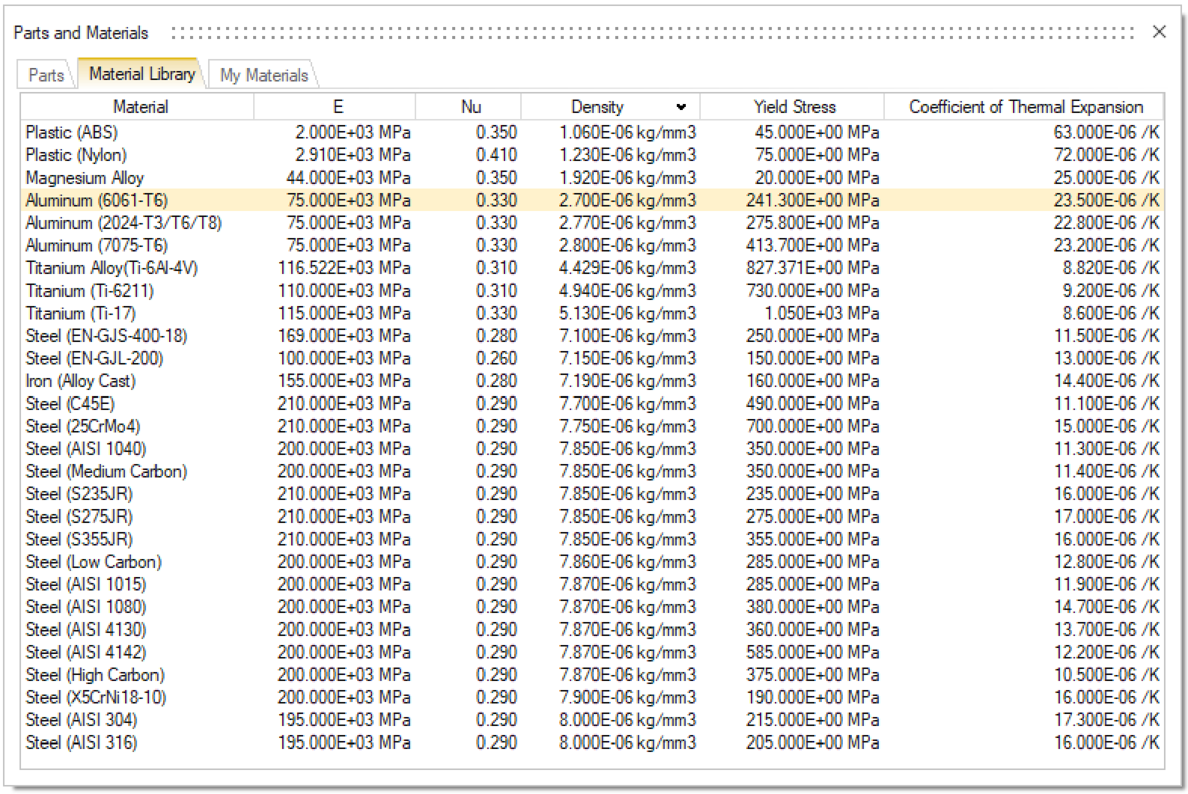
Fig 44. Final post processed model

The following section details how this final model was analyzed to verify if it met the safety standards previously set.

ANALYSIS AND VALIDATION

FEA

Once the whole frame was optimized, the analysis and validation process took place. The postprocessed parts were imported again to SolidThinking Inspire for setting up the finite element analysis (FEA). The first step of this analysis was to set up the material. Aluminum 6061-T6 was selected because it is very common in the mountain bike industry due to its low density and considerably high Yield Stress. As a result of using Aluminum 6061-T6, the designed frame has a light weight and high durability. The properties of the selected material are shown in the following Fig 45.



Material	E	Nu	Density	Yield Stress	Coefficient of Thermal Expansion
Plastic (ABS)	2.000E+03 MPa	0.350	1.060E-06 kg/mm3	45.000E+00 MPa	63.000E-06 /K
Plastic (Nylon)	2.910E+03 MPa	0.410	1.230E-06 kg/mm3	75.000E+00 MPa	72.000E-06 /K
Magnesium Alloy	44.000E+03 MPa	0.350	1.920E-06 kg/mm3	20.000E+00 MPa	25.000E-06 /K
Aluminum (6061-T6)	75.000E+03 MPa	0.330	2.700E-06 kg/mm3	241.300E+00 MPa	23.500E-06 /K
Aluminum (2024-T3/T6/T8)	75.000E+03 MPa	0.330	2.770E-06 kg/mm3	275.800E+00 MPa	22.800E-06 /K
Aluminum (7075-T6)	75.000E+03 MPa	0.330	2.800E-06 kg/mm3	413.700E+00 MPa	23.200E-06 /K
Titanium Alloy(Ti-6Al-4V)	116.522E+03 MPa	0.310	4.429E-06 kg/mm3	827.371E+00 MPa	8.820E-06 /K
Titanium (Ti-6211)	110.000E+03 MPa	0.310	4.940E-06 kg/mm3	730.000E+00 MPa	9.200E-06 /K
Titanium (Ti-17)	115.000E+03 MPa	0.330	5.130E-06 kg/mm3	1.050E+03 MPa	8.600E-06 /K
Steel (EN-GJS-400-18)	169.000E+03 MPa	0.280	7.100E-06 kg/mm3	250.000E+00 MPa	11.500E-06 /K
Steel (EN-GJL-200)	100.000E+03 MPa	0.260	7.150E-06 kg/mm3	150.000E+00 MPa	13.000E-06 /K
Iron (Alloy Cast)	155.000E+03 MPa	0.280	7.190E-06 kg/mm3	160.000E+00 MPa	14.400E-06 /K
Steel (C45E)	210.000E+03 MPa	0.290	7.700E-06 kg/mm3	490.000E+00 MPa	11.100E-06 /K
Steel (25CrMo4)	210.000E+03 MPa	0.290	7.750E-06 kg/mm3	700.000E+00 MPa	15.000E-06 /K
Steel (AISI 1040)	200.000E+03 MPa	0.290	7.850E-06 kg/mm3	350.000E+00 MPa	11.300E-06 /K
Steel (Medium Carbon)	200.000E+03 MPa	0.290	7.850E-06 kg/mm3	350.000E+00 MPa	11.400E-06 /K
Steel (S235JR)	210.000E+03 MPa	0.290	7.850E-06 kg/mm3	235.000E+00 MPa	16.000E-06 /K
Steel (S275JR)	210.000E+03 MPa	0.290	7.850E-06 kg/mm3	275.000E+00 MPa	17.000E-06 /K
Steel (S355JR)	210.000E+03 MPa	0.290	7.850E-06 kg/mm3	355.000E+00 MPa	16.000E-06 /K
Steel (Low Carbon)	200.000E+03 MPa	0.290	7.860E-06 kg/mm3	285.000E+00 MPa	12.800E-06 /K
Steel (AISI 1015)	200.000E+03 MPa	0.290	7.870E-06 kg/mm3	285.000E+00 MPa	11.900E-06 /K
Steel (AISI 1080)	200.000E+03 MPa	0.290	7.870E-06 kg/mm3	380.000E+00 MPa	14.700E-06 /K
Steel (AISI 4130)	200.000E+03 MPa	0.290	7.870E-06 kg/mm3	360.000E+00 MPa	13.700E-06 /K
Steel (AISI 4142)	200.000E+03 MPa	0.290	7.870E-06 kg/mm3	585.000E+00 MPa	12.200E-06 /K
Steel (High Carbon)	200.000E+03 MPa	0.290	7.870E-06 kg/mm3	375.000E+00 MPa	10.500E-06 /K
Steel (X5CrNi18-10)	200.000E+03 MPa	0.290	7.900E-06 kg/mm3	190.000E+00 MPa	16.000E-06 /K
Steel (AISI 304)	195.000E+03 MPa	0.290	8.000E-06 kg/mm3	215.000E+00 MPa	17.300E-06 /K
Steel (AISI 316)	195.000E+03 MPa	0.290	8.000E-06 kg/mm3	205.000E+00 MPa	16.000E-06 /K

Fig 45. Material Library

Once the material was defined, the loads for generating the frame were applied to the optimized structure for each load case. This set-up is shown on Fig 46.

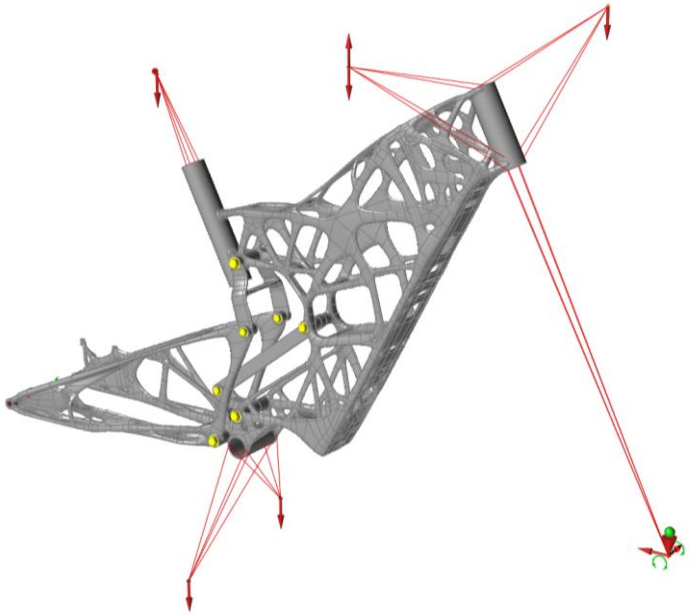


Fig 46. Loading Conditions for the Optimized Structure

With the set-up complete, the FEA analysis was set to solve every load case with the finest meshing available. The FEA has a Result Envelope option that shows all the combined results for every load case, as shown in the following Figs 47-52.

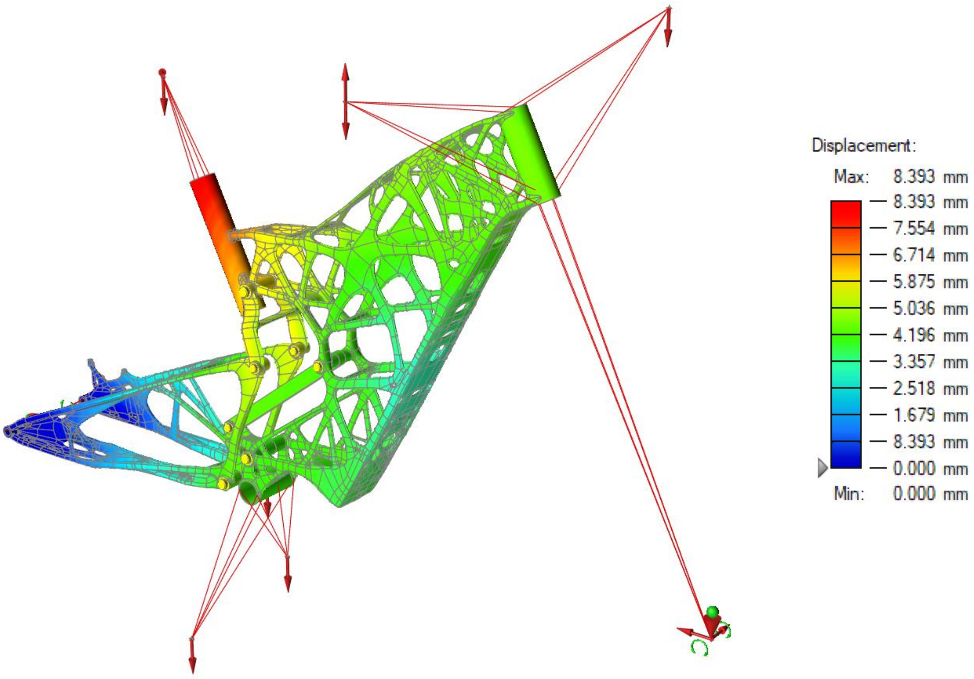


Fig 47. Displacements

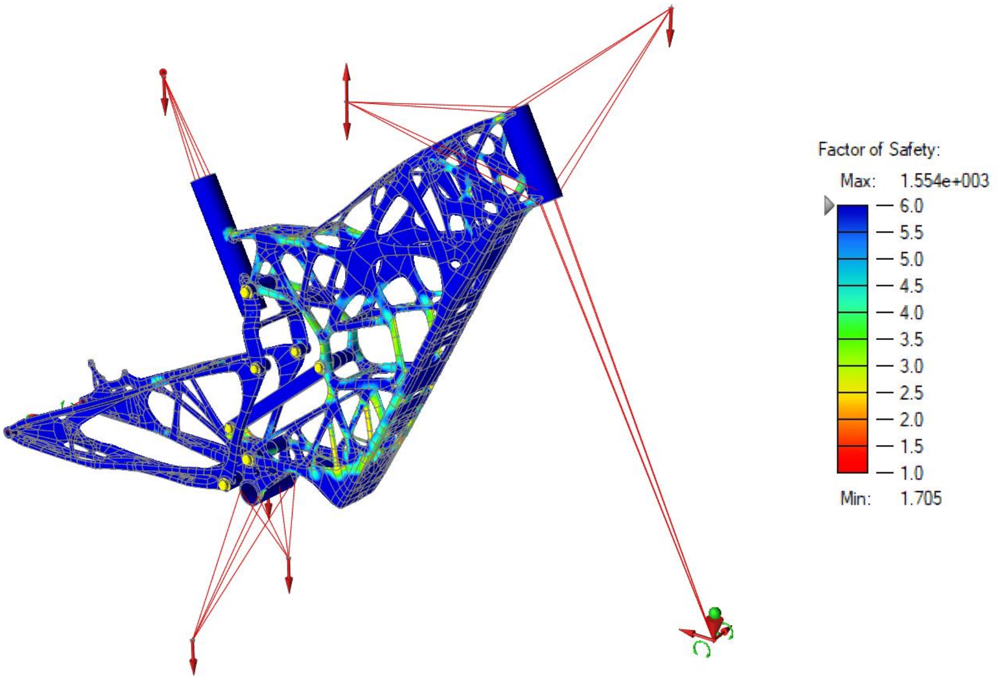


Fig 48. Factory of Safety

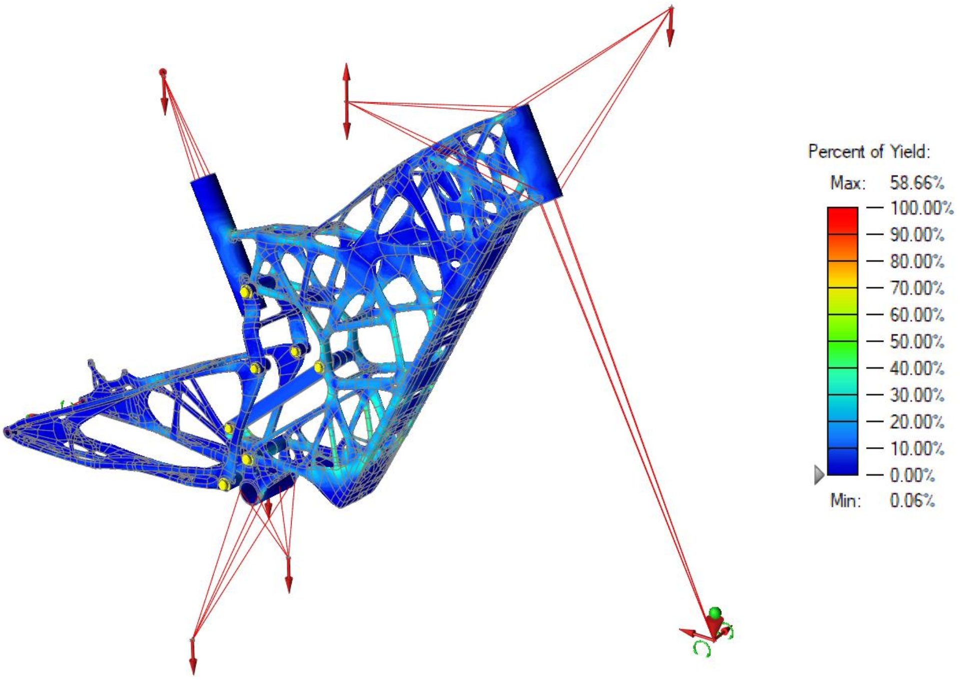


Fig 49. Percent of Yield

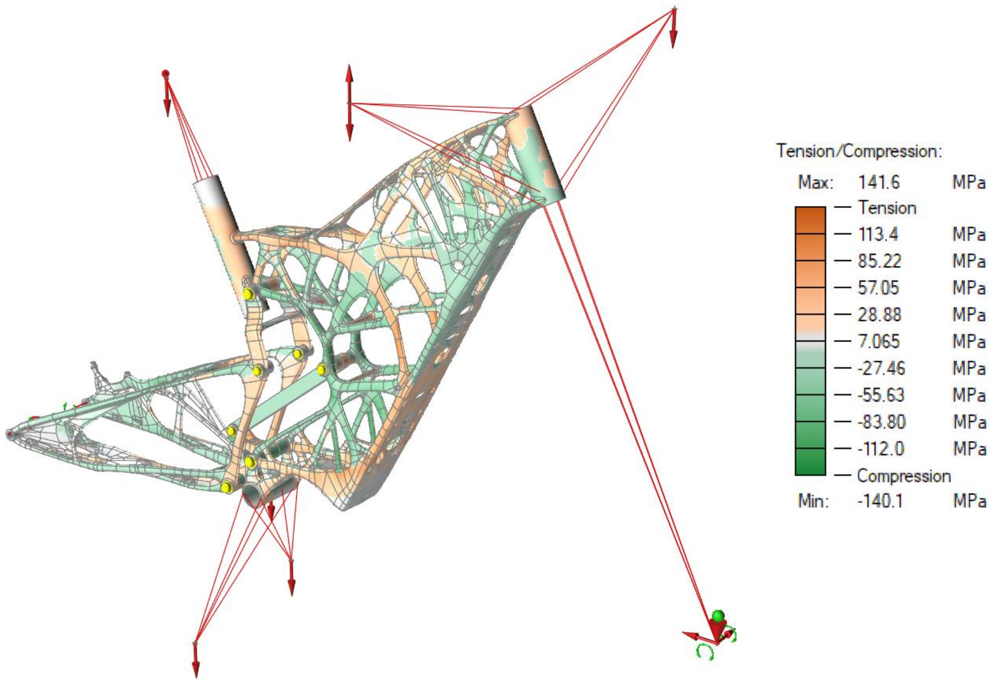


Fig 50. Tension/Compression

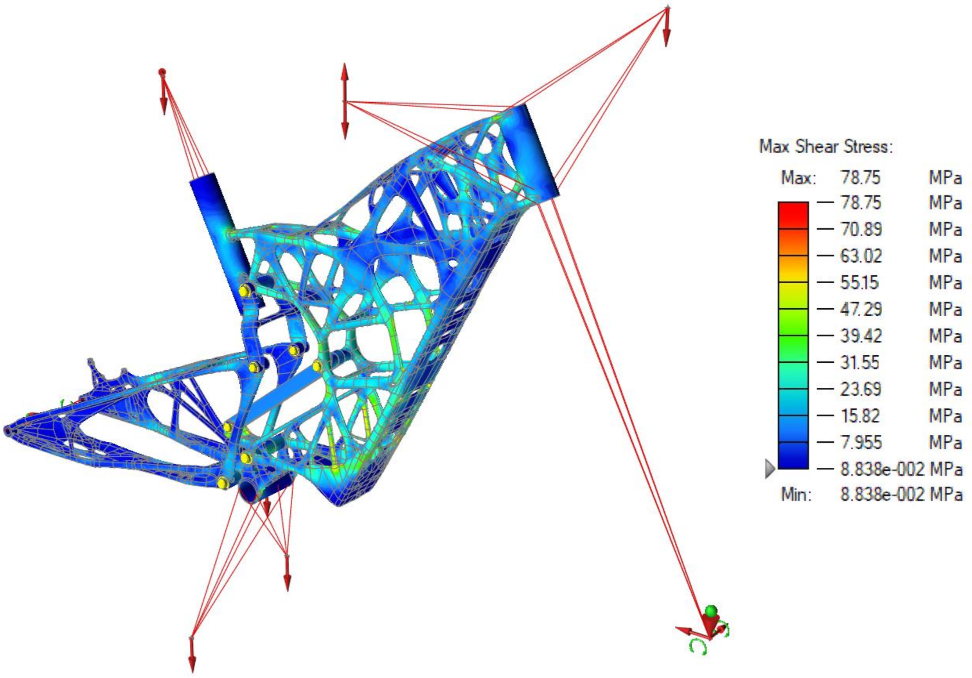


Fig 51. Max Shear Stress

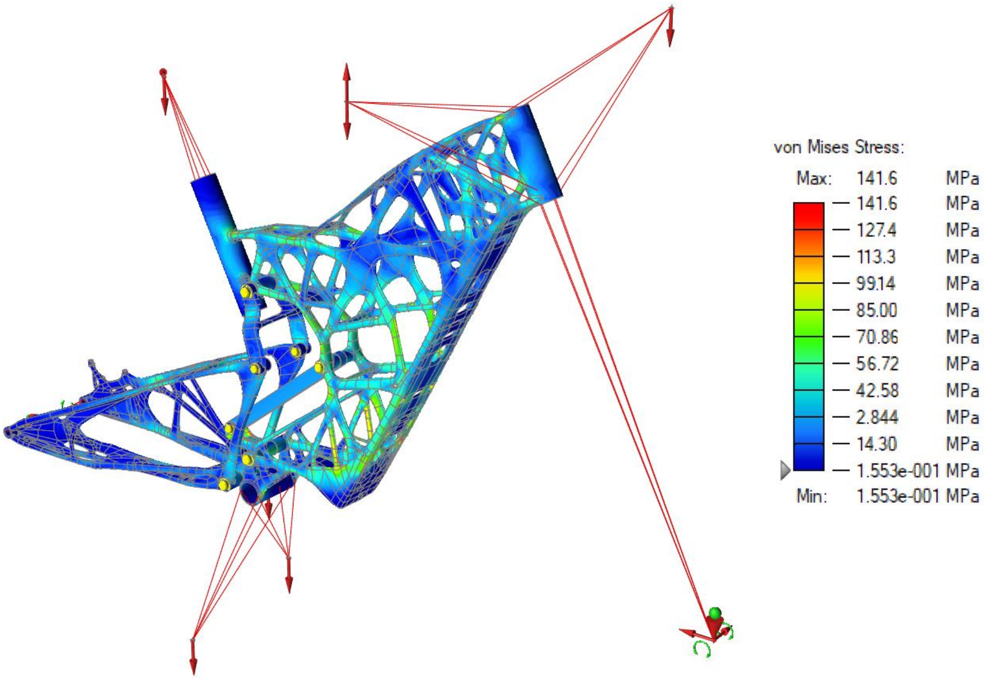


Fig 52. von Mises Stress

The critical sections which contain the minimum factor of safety are shown on the following Figs 53-54.

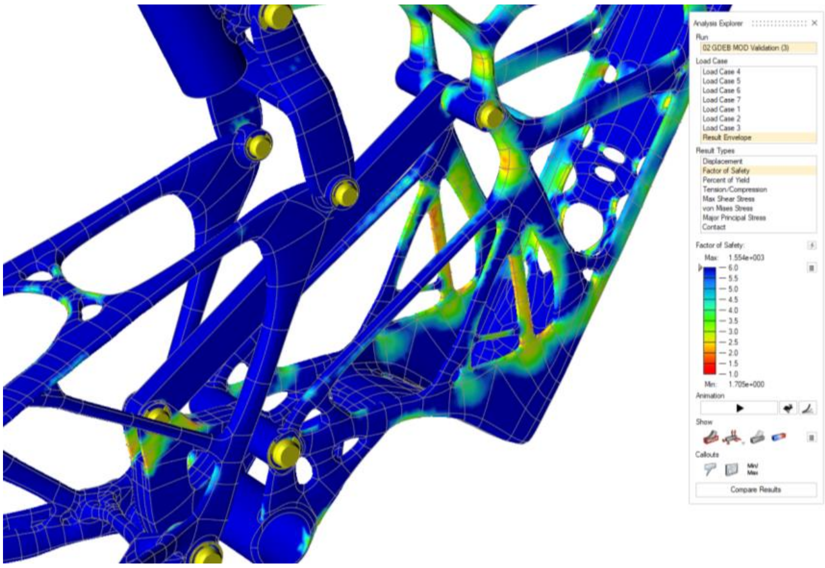


Fig 53. Critical sections Factor of Safety FEA

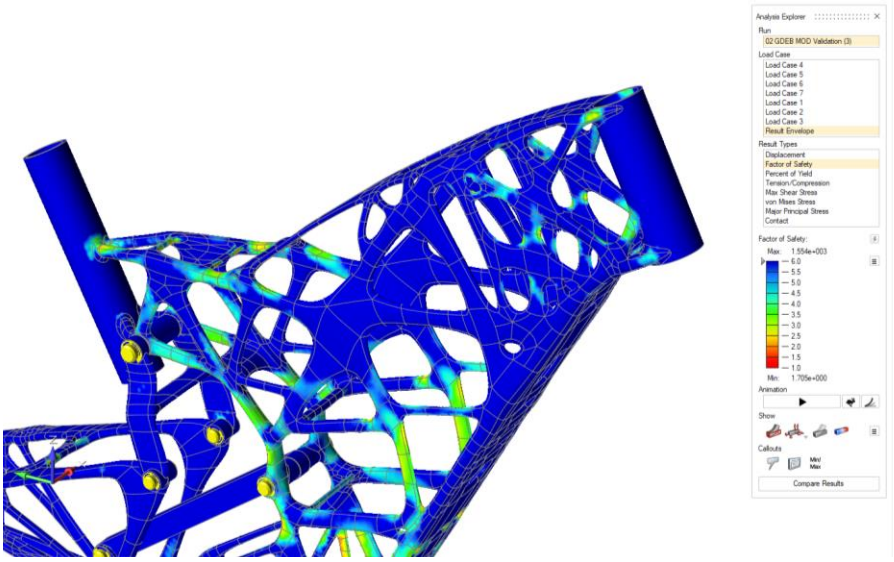


Fig 54. Critical sections Factor of Safety FEA

The following Fig 55. shows the tension and compression zones in a lateral view. The green part corresponds to the compression zones, meanwhile the orange zones correspond to the tension zones.

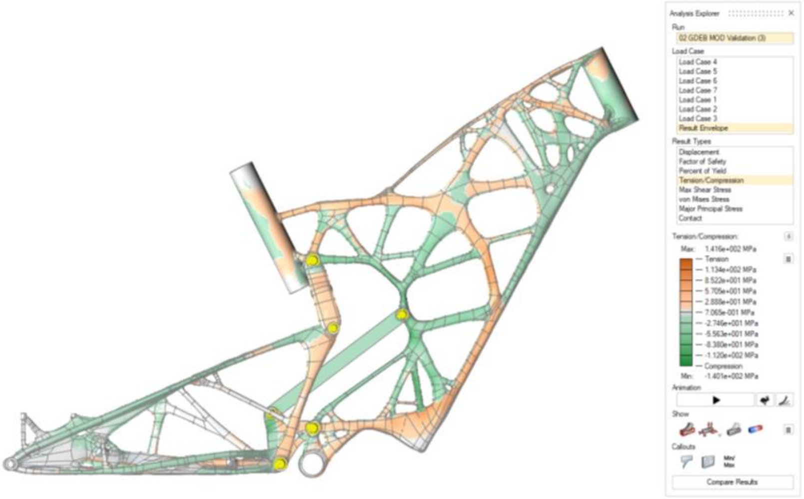


Fig 55. Tension/Compression Lateral View

The summary for the minimum and maximum results for the FEA is shown in Table 3.

Table 3. FEM analysis results

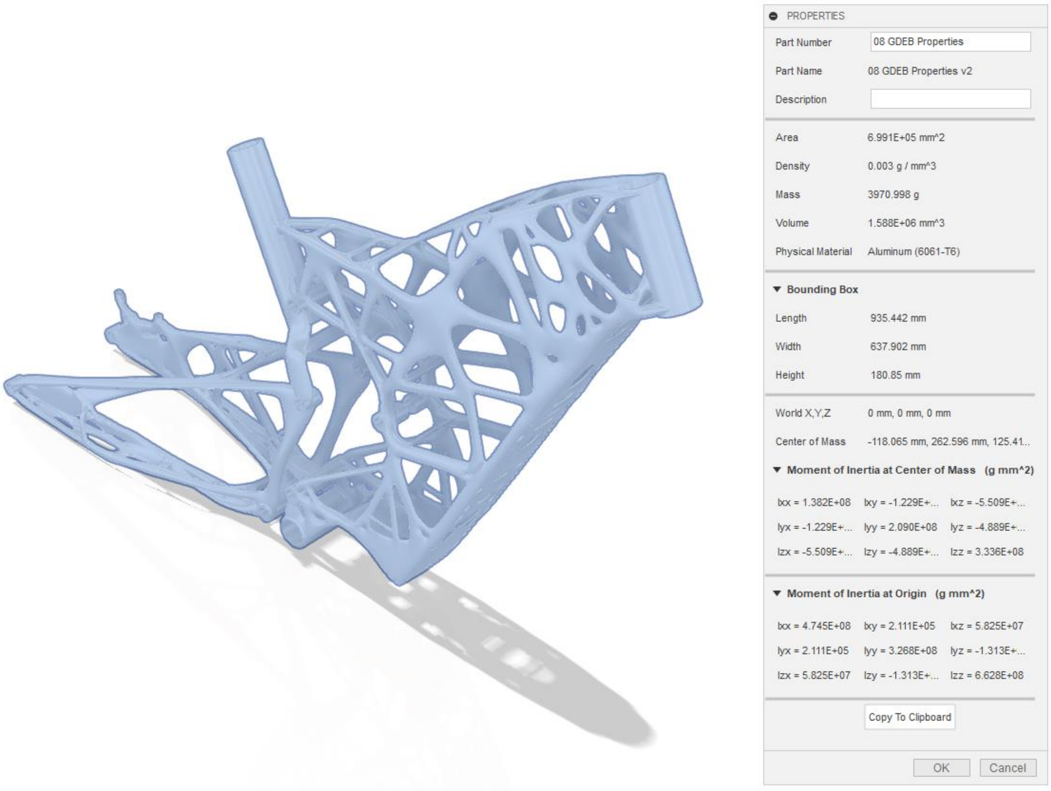
	Min	Max
Displacements	-	8.393 mm
Factor of Safety	1.705	-
Percent of Yield	-	58.66%
Tension/Compression	-140.1 MPa	141.6 MPa
Max Shear Stress	-	78.75 MPa
Von Mises Stress	-	141.6 MPa

The overall results from the validation process are detailed in the next section.

RESULTS: FINAL DESIGN

Properties

After the validation process, the areas with the minimum factor of safety were reinforced with more material. Next, the frame’s 3D model was exported to Fusion 360. The frame’s physical properties are shown in the following Figs 56-57.



Part Number	08 GDEB Properties
Part Name	08 GDEB Properties v2
Description	
Area	6.991E+05 mm^2
Density	0.003 g / mm^3
Mass	3970.998 g
Volume	1.588E+06 mm^3
Physical Material	Aluminum (6061-T6)

Bounding Box

Length	935.442 mm
Width	637.902 mm
Height	180.85 mm
World X,Y,Z	0 mm, 0 mm, 0 mm
Center of Mass	-118.065 mm, 262.596 mm, 125.41...

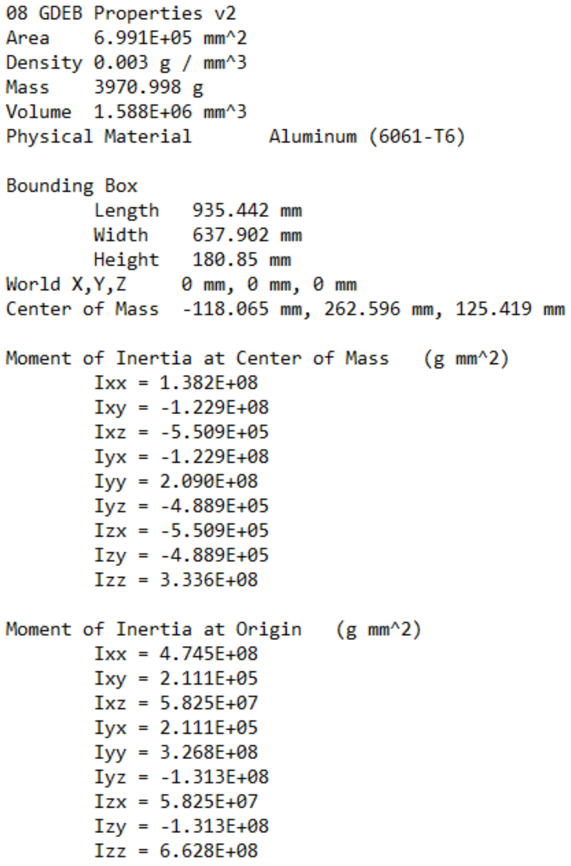
Moment of Inertia at Center of Mass (g mm^2)

Ixx = 1.382E+08 Ixy = -1.229E+... Ixz = -5.509E+...
Iyx = -1.229E+... Iyy = 2.090E+08 Iyz = -4.889E+...
Izx = -5.509E+... Izy = -4.889E+... Izz = 3.336E+08

Moment of Inertia at Origin (g mm^2)

Ixx = 4.745E+08 Ixy = 2.111E+05 Ixz = 5.825E+07
Iyx = 2.111E+05 Iyy = 3.268E+08 Iyz = -1.313E+...
Izx = 5.825E+07 Izy = -1.313E+... Izz = 6.628E+08

Fig 56. Physical Properties



```
08 GDEB Properties v2
Area    6.991E+05 mm^2
Density 0.003 g / mm^3
Mass    3970.998 g
Volume  1.588E+06 mm^3
Physical Material       Aluminum (6061-T6)

Bounding Box
        Length   935.442 mm
        Width    637.902 mm
        Height   180.85 mm
World X,Y,Z     0 mm, 0 mm, 0 mm
Center of Mass  -118.065 mm, 262.596 mm, 125.419 mm

Moment of Inertia at Center of Mass   (g mm^2)
        Ixx = 1.382E+08
        Ixy = -1.229E+08
        Ixz = -5.509E+05
        Iyx = -1.229E+08
        Iyy = 2.090E+08
        Iyz = -4.889E+05
        Izx = -5.509E+05
        Izy = -4.889E+05
        Izz = 3.336E+08

Moment of Inertia at Origin   (g mm^2)
        Ixx = 4.745E+08
        Ixy = 2.111E+05
        Ixz = 5.825E+07
        Iyx = 2.111E+05
        Iyy = 3.268E+08
        Iyz = -1.313E+08
        Izx = 5.825E+07
        Izy = -1.313E+08
        Izz = 6.628E+08
```

Fig 57. Exported Physical Properties

The final weight of the E-Bike Frame was 3.97kg using Aluminum (60601-T6), a 1.25 kg less than the conventional tube frame version. This is a 23.913% weight reduction from the production models currently available that comply with all EN14766 safety standards.

Final Model

After that, all the E-bike components were added to the frame in order to see how the E-Bike would appear. The final assembly is shown in Fig 58.

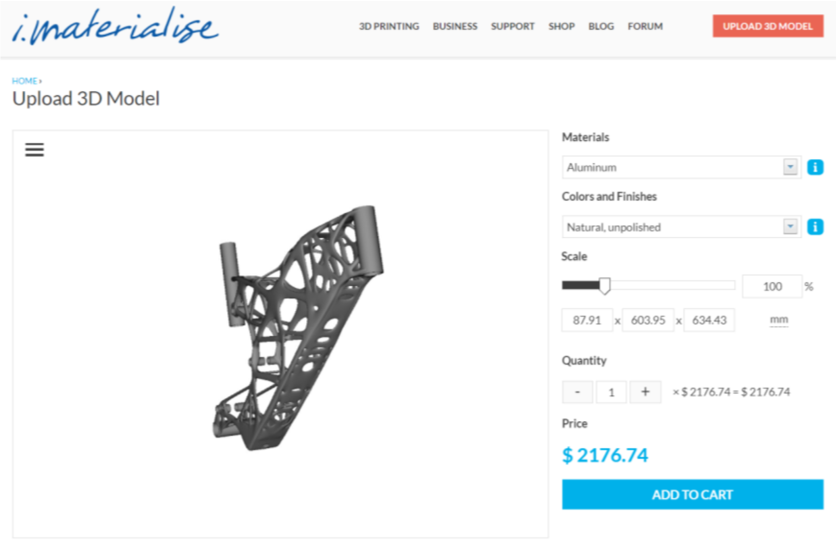
Fig 58. Final Assembly

The E-Bike’s cost analysis is shown in the next section.

BUDGET

3D Printed Parts

The most important parts to consider for the budget were the 4 components of the frame. It is possible to manufacture these complex parts using 3D printing, specifically direct metal laser sintering (DMLS). The quotes for 3D printing the 4 full-scale aluminum components were determined online through i.materialise. These quotes are shown in the following Figs 59-62.



Materials

Aluminum

Colors and Finishes

Natural, unpolished

Scale

100 %

87.91 x 603.95 x 634.43 mm

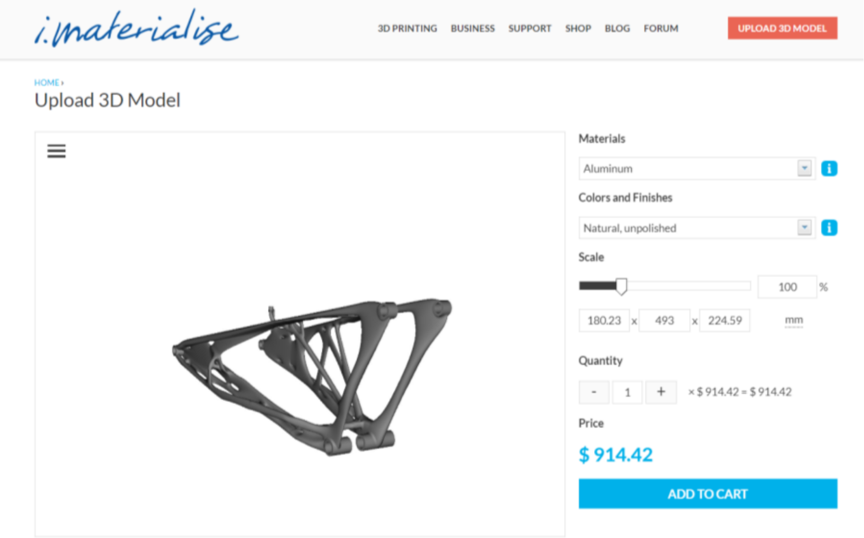
Quantity

1 × $ 2176.74 = $ 2176.74

Price

$ 2176.74

Fig 59. Frame DMLS quote



Materials

Aluminum

Colors and Finishes

Natural, unpolished

Scale

100 %

180.23 x 493 x 224.59 mm

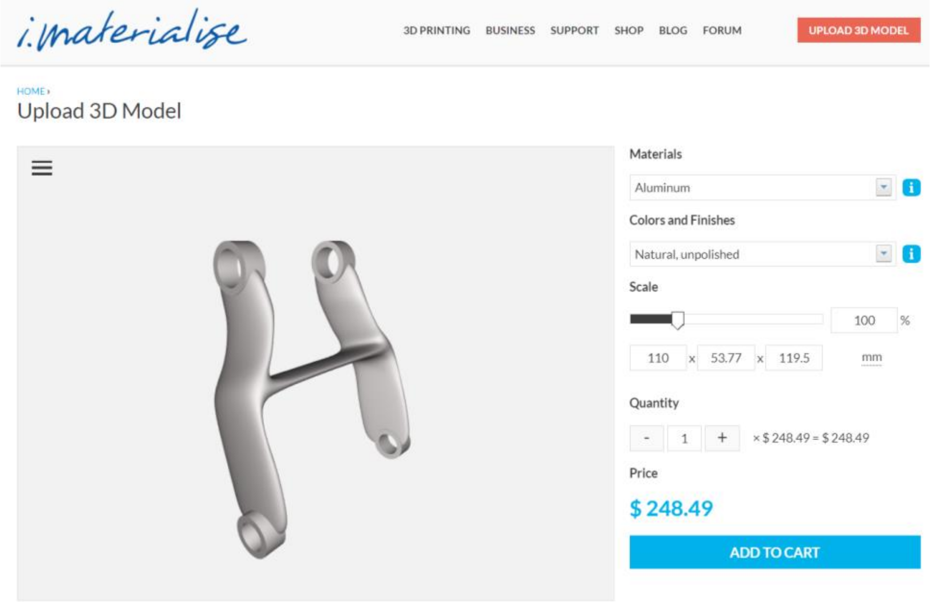
Quantity

1 × $ 914.42 = $ 914.42

Price

$ 914.42

Fig 60. Rear Arm DMLS quote



Upload 3D Model

Materials: Aluminum

Colors and Finishes: Natural, unpolished

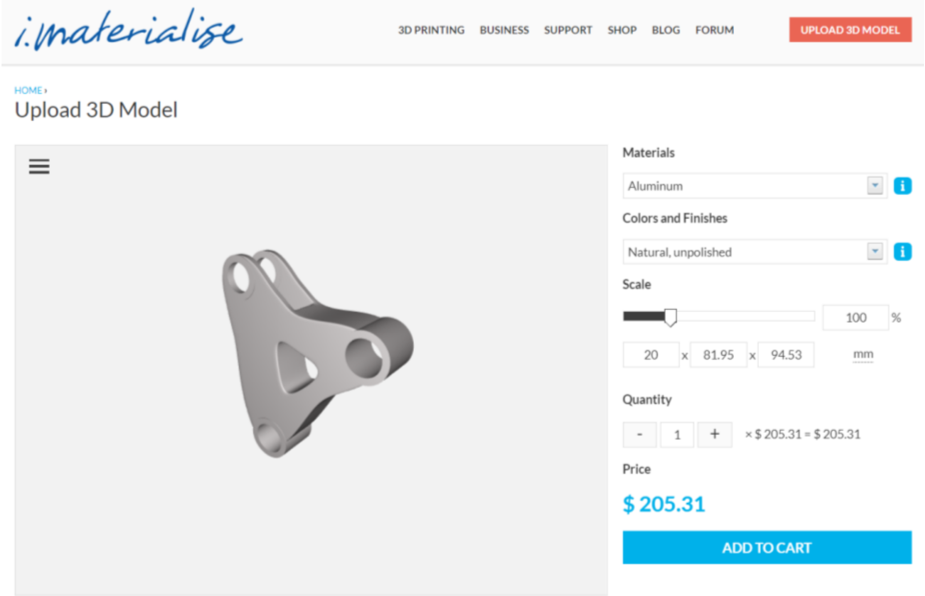
Scale: 100 %

110 x 53.77 x 119.5 mm

Quantity: 1 × $ 248.49 = $ 248.49

Price: $ 248.49

Fig 61. Top Link DMLS quote



Upload 3D Model

Materials: Aluminum

Colors and Finishes: Natural, unpolished

Scale: 100 %

20 x 81.95 x 94.53 mm

Quantity: 1 × $ 205.31 = $ 205.31

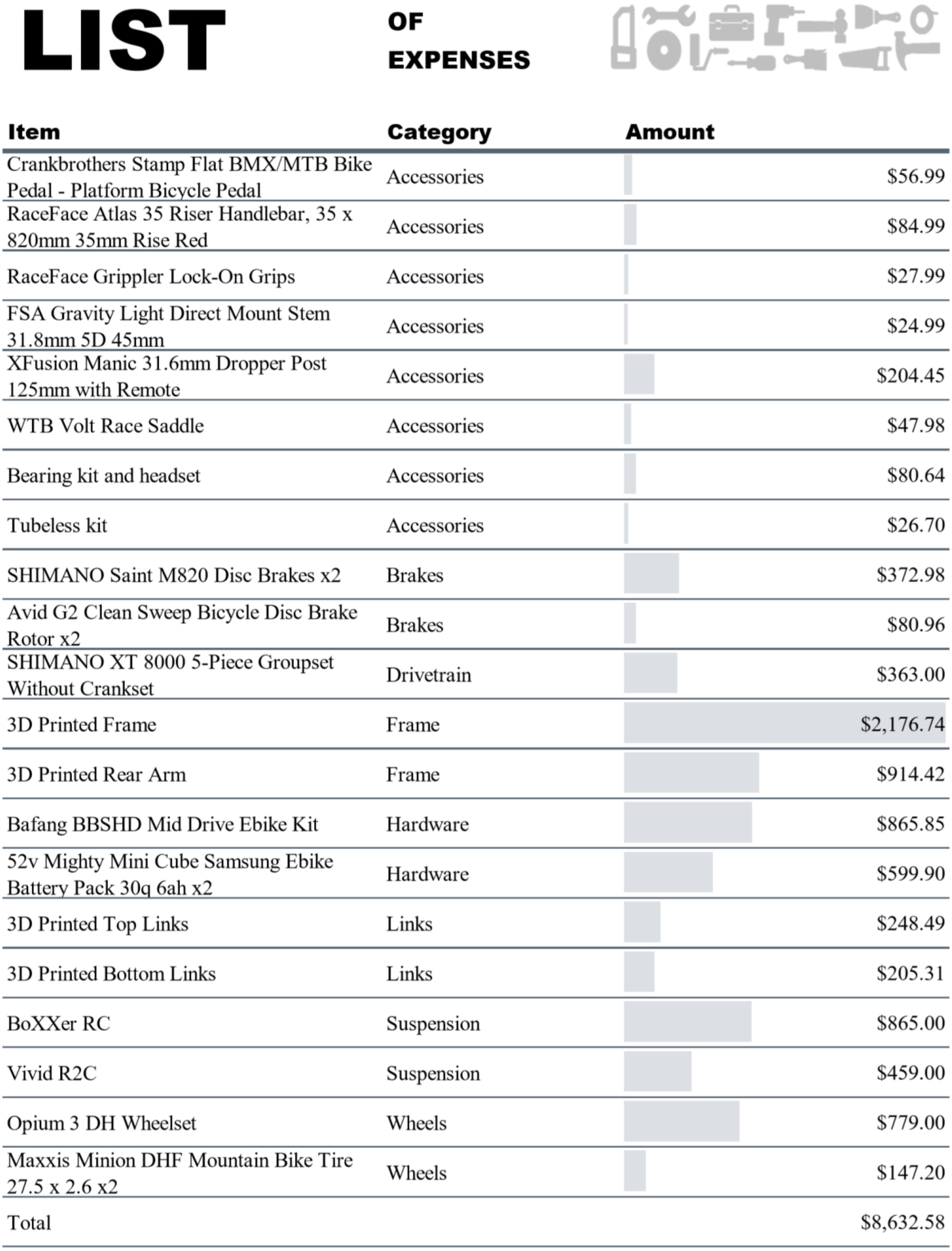
Price: $ 205.31

Fig 62. Bottom Link DMLS quote

Total

Together, these 4 components cost $3533.96. Considering the other E-Bike components as well, a list of total expenses is shown in the following Table 4.

Table 4. List of Expenses



LIST OF EXPENSES

Item	Category	Amount
Crankbrothers Stamp Flat BMX/MTB Bike Pedal - Platform Bicycle Pedal	Accessories	$56.99
RaceFace Atlas 35 Riser Handlebar, 35 x 820mm 35mm Rise Red	Accessories	$84.99
RaceFace Grippler Lock-On Grips	Accessories	$27.99
FSA Gravity Light Direct Mount Stem 31.8mm 5D 45mm	Accessories	$24.99
XFusion Manic 31.6mm Dropper Post 125mm with Remote	Accessories	$204.45
WTB Volt Race Saddle	Accessories	$47.98
Bearing kit and headset	Accessories	$80.64
Tubeless kit	Accessories	$26.70
SHIMANO Saint M820 Disc Brakes x2	Brakes	$372.98
Avid G2 Clean Sweep Bicycle Disc Brake Rotor x2	Brakes	$80.96
SHIMANO XT 8000 5-Piece Groupset Without Crankset	Drivetrain	$363.00
3D Printed Frame	Frame	$2,176.74
3D Printed Rear Arm	Frame	$914.42
Bafang BBSHD Mid Drive Ebike Kit	Hardware	$865.85
52v Mighty Mini Cube Samsung Ebike Battery Pack 30q 6ah x2	Hardware	$599.90
3D Printed Top Links	Links	$248.49
3D Printed Bottom Links	Links	$205.31
BoXXer RC	Suspension	$865.00
Vivid R2C	Suspension	$459.00
Opium 3 DH Wheelset	Wheels	$779.00
Maxxis Minion DHF Mountain Bike Tire 27.5 x 2.6 x2	Wheels	$147.20
Total		$8,632.58

DISCUSSION

The results obtained through Generative Design (GD) allow the designer to see how a body can be shaped directly by the forces that are applied to it. As used in this project, this iterative process demonstrates how organic forms are the most optimal solution in every case of study. The bone growth algorithm used in GD illustrates how every set-up has a different solution depending on its configuration. Different traits from all the previous solutions are inherited in the final design. This optimization process requires many steps, because it is completed without any previous assumption of how the geometry should appear; thus, it is a revolutionary approach.

Additionally, the FEA analysis used in this project showed how the optimization process functions: by showing the critical zones and detailing how the stress was distributed along the structure. After this analysis, the final design was tested by spreading the stress of the compression zones in different branches. These were then connected to generate a truss-like structure.

This optimization process not only achieved the optimal design through SolidThinking Inspire, but it also reduced the frame weight considerably. The 23.913% weight reduction compared to traditional tube structure bikes is a large improvement in design efficiency. For this reason, GD is revolutionizing many industries.

FUTURE WORK

Lattice Optimization

The optimization process of GD can be further improved using lattice optimization. This uses the same principle of topology optimization; however, instead of adding or removing material, this technology uses lattice beams to fill in the structure. This optimization process can be used in a topology optimized shape to obtain an even greater reduction in weight. Some lattice optimization simulation runs were tested on the E-Bike frame, resulting in a reduction of almost 40% of the topology optimized model as shown in Figs 63-65.

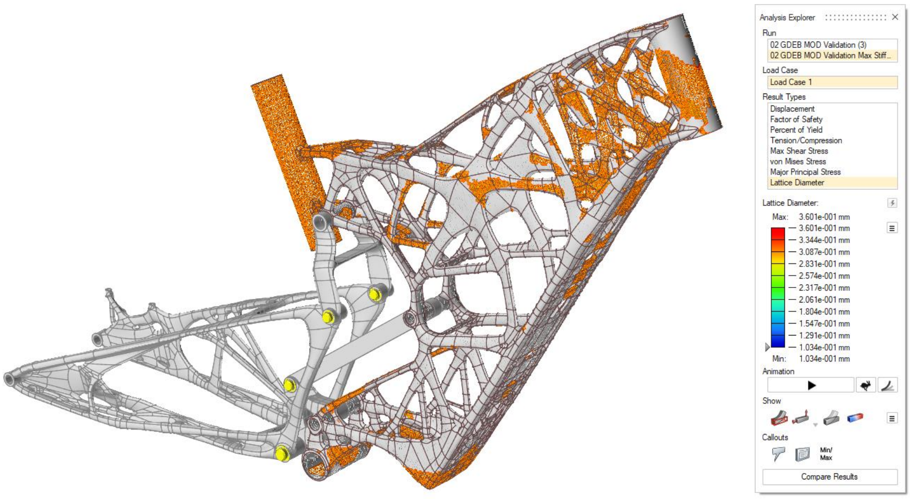


Fig 63. Lattice Optimization zones

Fig 64. Lattice Optimization seat-tube

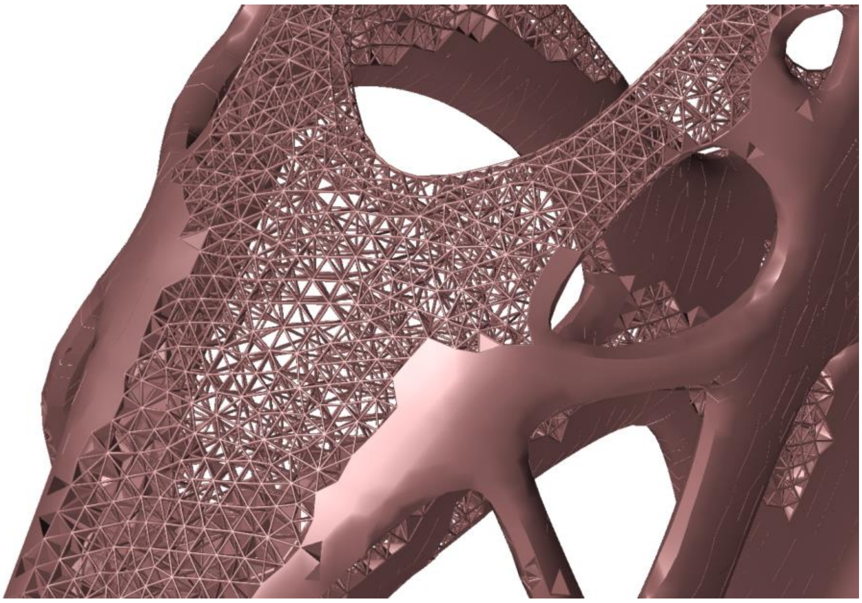


Fig 65. Lattice Optimization zoom-in

This optimal design can only be achieved due to 3D printing technology that can create this lattice structure. This type of optimization is still under development and will improve topology optimized shapes by replacing solid parts with lattice structures.

CONCLUSION

The optimization process used in this project demonstrates the potential of GD to revolutionize many industries. It reduced the mass of the tradition E-Bike frame by 23.913%, while still meeting the same safety requirements. This new approach for designing clearly shows that most of the existing products can still be optimized. The technology available before GD only allowed the user to translate their ideas, but now it can synthesis geometry. This is a big step for engineering, because now computers can come up with new designs all by themselves. This fact allows designers to explore the entire solution space for a desired set-up. This will augment the capacity of designers and engineers to another level for achieving lightweight high-performance products.

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