

Design, Analysis and 3D Printing of the Rear Axle of a Single-Axle Heavy Truck

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ABSTRACT

A Rear axle of a single axle heavy truck has been designed using CATIA V5. A Finite Element analysis of the axle has been carried out on ANSYS Static Structural tool using Mechanical APDL to obtain the maximum deformation, the maximum stress and strain, the minimum factor of safety, the life cycle and the fatigue sensitivity of the axle. The product is then scaled down and sliced using Ultimaker Cura software and the tool path and G-Code is generated for FDM 3D printing. The part is then printed using an FDM 3D printer for further testing.

Keywords: Rear Axle, Heavy Truck, Stress Distribution, Finite element analysis, Life Cycle, Fatigue Analysis, 3D printing

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INTRODUCTION

The rear axle, which is also called the dead axle, is the final member of the power train. In the majority of automobiles, the real axle is the driving axle [1]. It is situated in between the driving wheels and the differential gear, and transmits power from the differential to the driving wheels. It consists of two half shafts connected to the differential gear, one for each wheel. The sun gear of the differential is connected to the inner end of each half shaft and the outer ends are connected to the wheel. The rear axle and differential gear are completely encased in a housing which protects them from the environment. The rear axle supports the major load of the truck. Another function of the dead axle is that it rotates for transferring power from the engine to the wheels. Rear axles are classified either as a banjo axle or a split axle (Figure 1). A split axle is one in which split shafts are used with a central casing, called a housing, that contains the differential gear which is fitted with a tube at every side to carry the

half axles and bearing. A banjo-type axle, like the one used in our design and shown in Figure 2, is an axle in which a tubular axle section casing is built up of steel pressings and then welded together and suitably strengthened to withstand the bending load. The centre of this casing along with the axle tube on one side resembles a banjo. The final drive assembly is then mounted in detachable malleable iron housing and is secured by a ring of bolts to the axle casing. The axle shafts are slid into this assembly from the road wheel end of the casing [2].

The main components of the rear axle are the housing, the front plate, the back plate, the disc, the spindle, the shaft, the wheel rim and the differential. Most of the parts of the axle are made from carbon steel except for the wheel rim which is made from aluminium alloy. This axle is designed for a class 8 heavy truck [3]. Heavy trucks weigh more than 15,000 kg with load (Class 8) [4]. The particular type of axle being used in this work is a banjo

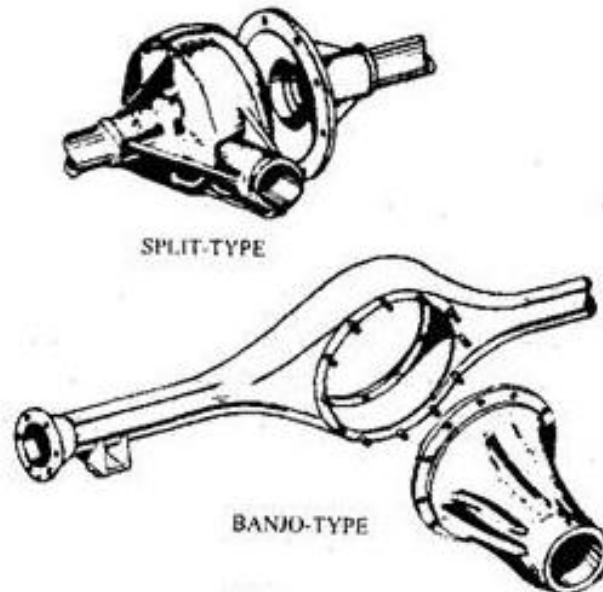


Fig. 1. Types of axle.



Fig. 2. Render of our banjo rear axle.

axle with leaf springs and an anti-torsion bar. Also, for the axle shaft and hub arrangement, a fully floating axle hub is used. In this arrangement, the axle hub incorporates a flanged sleeve, positioned over an axle casing. A flange is provided for accommodating the road wheels. Two bearings, which are widely spaced, are installed between the hub and its casing to support the hub assembly. However, in this paper, we will mostly be focusing on the housing.

LITERATURE REVIEW

A finite element analysis of the entire axle without the differential is done to find the reaction of the main housing to the forces exerted on it by the weight of the truck and the load it is carrying. This load is transferred to the axle at two areas where the leaf springs are attached. The CAD model of a traditional truck banjo axle is

imported to the CAE software to perform a finite element analysis. Then the locations of the stress with its distribution pattern, the strain experienced, the deformations and the factor of safety of the various parts will be obtained from the analysis. Then the model will be scaled down, sliced and the G-code for the tool path will be generated using the 3D printing software. The von Mises stresses, displacement contours, the deformation contours and the factor of safety contours for all the parts of the axle have been generated. It was observed that stresses, displacements and deformations were found to be within the prescribed limits and the structure would be able to withstand the load under the conditions prescribed. As can be seen further on, most of the research focuses on the static analysis of the truck axle and its various components. A fatigue analysis is also done to estimate the life of the rear axle and the number of loading cycles it could undergo without succumbing to failure. The safety factor of various parts is also calculated. The stress life of the component was calculated using the Goodman mean stress theory with fully reversed type loading and with an equivalent (von Mises) stress component. In this work, CAD model of rear axle is

made and optimized for weight on CATIA V5 software by cutting weight wherever unnecessary, while keeping the majority of the structure rigid. The drafting for dimensions is done on Solidworks, which also gives an exploded view of all the parts along with a bill of materials. The total weight of the dead axle of the heavy truck is 843 kg as given by the CATIA V5 software. Ultimate Cura software is used to slice the scaled-down version of the dead axle. The printing parameters such as infill percentage, type of infill, number of shells, layer height (which determines print quality), the print and travel speed, the support structures, rafts, their types and build volume for the 3D printer are specified and a solid-scaled model of the axle is produced so as to get a feel for the part.

METHODOLOGY

Initially, a 3D model of the dead axle is designed on the CAD software CATIA V5 based on traditional banjo-type axles of heavy trucks. Parts are individually designed and then assembled. It is then visually optimized to reduce the weight of parts based on required thickness. Drafting of the parts is done on Solidworks. An engineering drawing of the assembly where its exploded view along with a bill of materials is made. Next, the step file of the assembly is imported to the static structural analysis system of the ANSYS Workbench which is a CAE software. Here, initially, the assembly is meshed. Then the supports are set and the loads are placed along with other constraints. The solution parameters are set and an analysis is carried out to obtain the stress distribution, the strain, the deformation, the life cycle and the factor of safety of the various parts. The results are then analysed to check whether the axle was able to withstand the vertical load and the effect of the load and if it was increased on the other components of the axle. Next, the assembly is scaled down and sliced using

Ultimaker Cura 3D printing software. The printing parameters are putted and the G-code of the tool path is generated by the software. This G-code is fed to a 3D printer via the computer itself through a USB cable or using an SD card. The 3D printer then prints the part. Post-processing on the part is done, i.e. removing the rafts and the supports to get the final 3D printed part (Figure 3).

MODELLING

The CAD model of the various parts of the dead axle is made using CATIA V5 CAD software. A full-scale model of all the parts of the axle, excluding the differential, is made on the software. The assembly of the parts is also done on CATIA V5. Major focus is given to the housing of axle, as it is the part that directly takes the vertical loads. It comprised thin-walled shells with a uniform thickness of 10 mm all over. The assembly as a whole comprises the housing, the front plate, the back plate, the discs, the tyres, the spindles, the shafts, the wheel rims, and nuts and bolts of various diameters and lengths. Each of the above parts is made individually and then assembled into a single product file. Table 1 shows the bill of materials of the assembly and shows the material of each of the parts.

Figure 4 shows the CAD model of the rear axle without the tyres, along with centre of gravity of the assembly highlighted by the intersection of the red, blue and green lines that signify the axes. The thick blue arrows signify the contact between the tyres and the road, and are the locations at which fixed supports are given to the axle. The thick red arrows signify the load acting on the housing, resulting from the weight and load of the truck. The white squares show where the leaf springs will be attached to the housing and the area at which the load will act. These areas of action are 75 mm × 100 mm. The total mass of the dead axle assembled with all the parts is 843 kg and the total volume is 0.172 m³ (Figures 5 and 6).

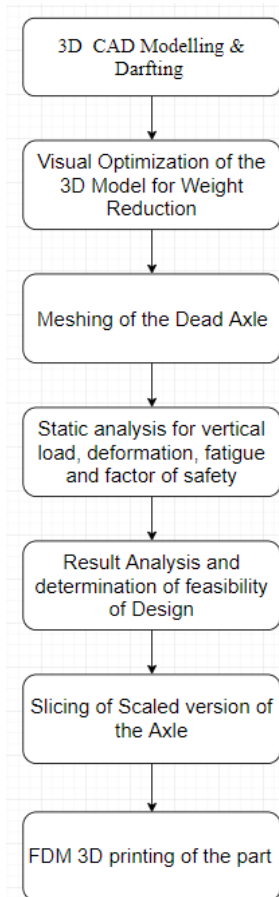


Fig. 3. Flowchart of the workflow.

Meshing of the CAD Model by the CAE Tool for Structural Analysis

The CAD model assembly, without the tyres, is imported to ANSYS in STEP file format. Meshing of the surfaces, faces, edges and volumes of all the parts was carried out by the inbuilt meshing tool. A high amount of smoothing is done to the CAD model to get better mesh quality. A tetrahedron-type mesh is used with a proximity and curvature sizing function. The curvature normal angle is 18° . The defeature size is 0.269530 mm. The total number of nodes obtained after meshing is 31,706,734 and the total number of elements in the mesh is 20,618,325. To check the quality of the mesh, an orthogonal quality data was reviewed and plotted. The minimum value for the orthogonal quality mesh element was 0.092118, which was acceptable as it did not fall below 0.05. The average value was above 0.7. The orthogonal quality of the mesh plot can be seen in Figures 7–9.

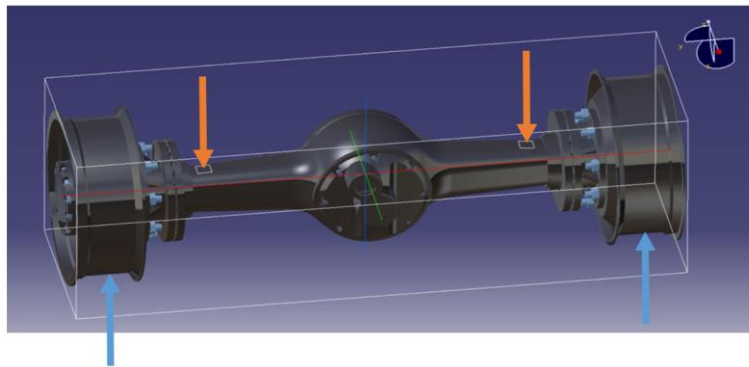


Fig. 4. CAD model with arrows showing loads and supports.

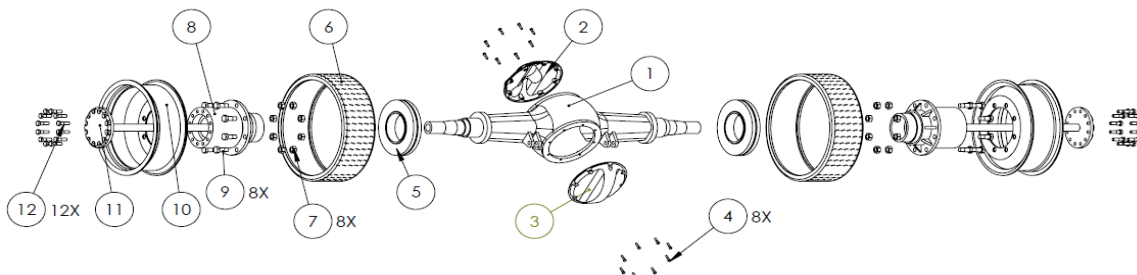


Fig. 5. Exploded view.

Table 1: Bill of Materials.

ITEM NO.	DESCRIPTION	QUANTITY	MATERIAL
1	HOUSING	1	CARBON STEEL
2	FRONTPLATE	1	CARBON STEEL
3	BACKPLATE	1	CARBON STEEL
4(8X)	8 M16x65 HEX HEAD BOLT	2	CARBON STEEL
5	DISC	2	CARBON STEEL
6	TYRE	2	RUBBER
7(8X)	8 M42 HEX NUT	2	CARBON STEEL
8	SPINDLE	2	CARBON STEEL
9(8X)	8 M42x160 HEX HEAD BOLT	2	CARBON STEEL
10	WHEEL RIM	2	ALUMINIUM ALLOY
11	SHAFT	2	CARBON STEEL
12(12X)	12 M30x110 HEX HEAD BOLT	2	CARBON STEEL

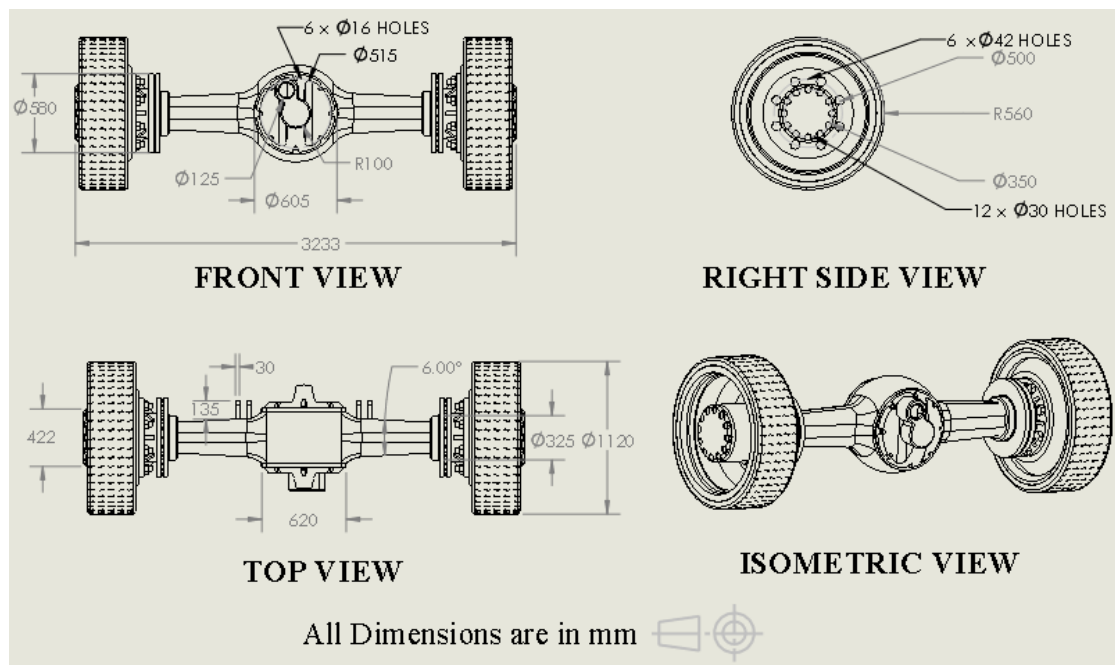


Fig. 6. Orthographic projection of the rear axle.

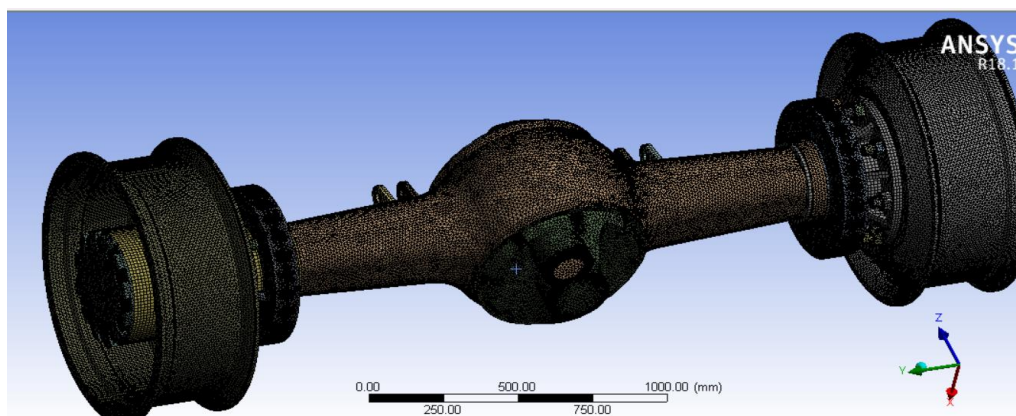


Fig. 7. Mesh generated for the axle.

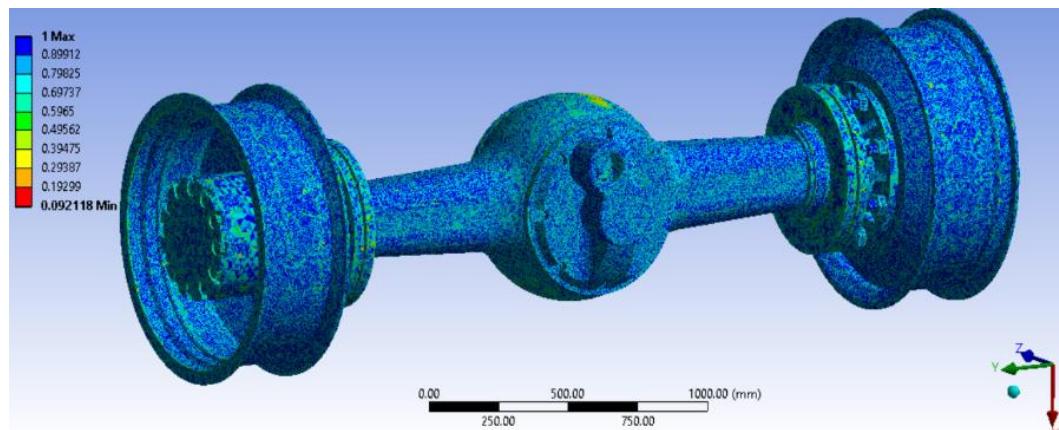


Fig. 8. Orthogonal mesh quality plot.

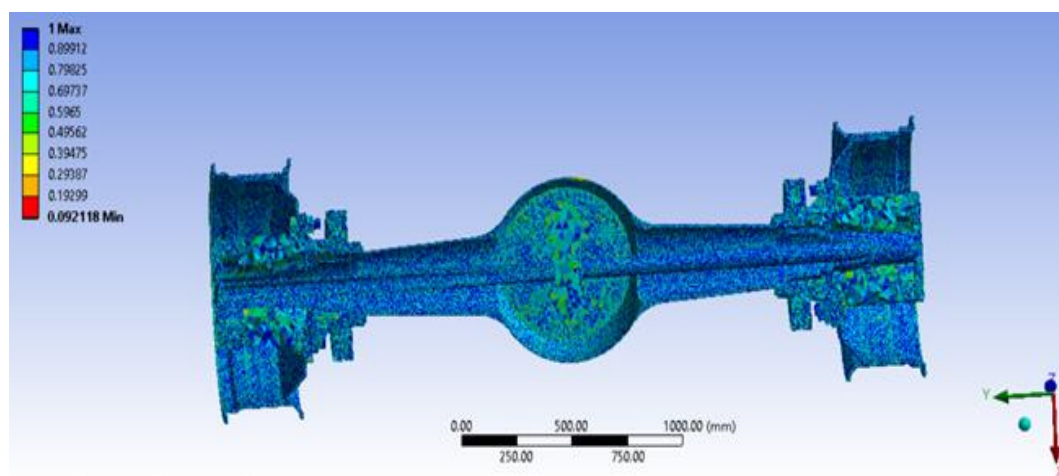


Fig. 9. Sectioned orthogonal mesh quality plot.

Table 2. Material properties.

Material	Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Ultimate strength (MPa)
6061-T6 (Aluminium Alloy)	68.9	0.33	276	310
SAE 1020 (Carbon Steel)	205	0.29	350	420

Materials Used and Their Properties

A majority of parts of the dead axle such as the housing, the spindle, the shaft, the front plate and the back plate are made of the same material, being carbon steel. However, the wheel rims are made of aluminium alloy, more specifically aluminium 6061-T6 (Table 1).

LOADING CONDITIONS

Loads were applied at the points where the leaf spring was attached to the housing,

and supports were given at the bottom region of the wheel rims, where the tyres contacted the ground. The load given was used to determine whether the rear axle could support the maximum legally permissible loading condition that could be applied on it by the weight of the truck and its carrying load. A bending moment occurs on the housing during the loading press. According to guidelines about axle load calculation by SCANIA [5], a Swedish manufacturer of commercial trucks, about 60%–65% of the total weight of the truck and its load is borne by the steering axle, which is the rear axle of the truck in this case. The curb weight or kerb weight of a vehicle refers to the actual weight of a vehicle including all the factory-installed equipment, facilities, vehicle fluids and 90% full fuel tank. The gross vehicle weight rating or gross

vehicle mass is the maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and the cargo [6]. These weights have been illustrated in Table 3.

Table 3. Load conditions on the truck.

Curb weight	90 KN
Load weight	110 KN
Gross weight	200 KN

Table 4. Load Conditions on the Axles.

Load on Rear Axle	120 KN
Load on Front Axle	80 KN

The loads on the axles of the truck are shown in Table 4. The load of 120 KN on the rear axle is equally distributed, therefore a load of 60KN each, acts at the points where the leaf springs would be attached to the housing.

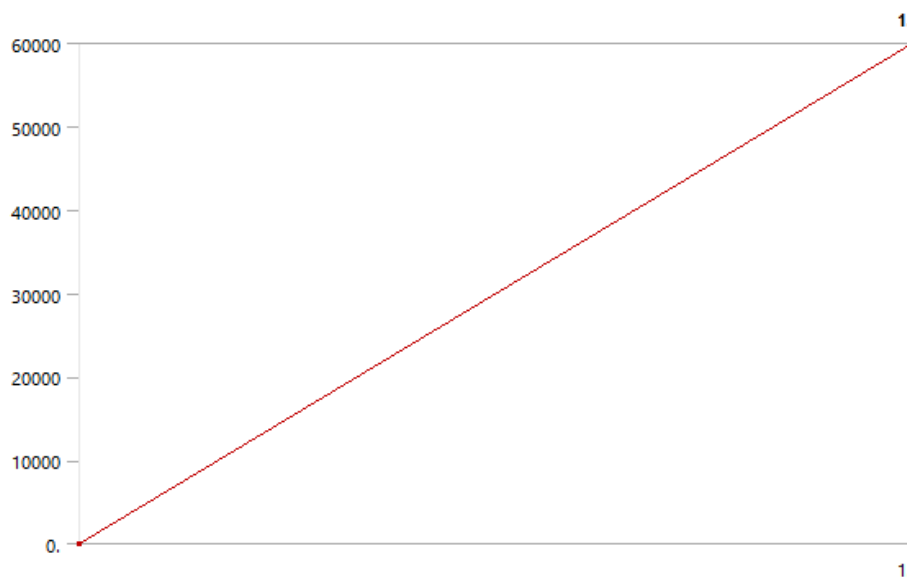


Fig. 10: Loading Vs Time Graph.

RESULTS AND DISCUSSIONS

Equivalent von-Mises Stress and Strain

Equivalent stress is related to the principal stresses by the following equation:

$$\sigma_e = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right]^{\frac{1}{2}} \quad (1)$$

Equivalent von Mises stress is used as it allows any arbitrary 3D stress state to be represented as a single positive stress value. Equivalent stress is part of the maximum equivalent stress failure theory used to predict yielding in a ductile material [7].

The von Mises or equivalent strain ϵ_e is computed as follows:

$$\epsilon_e = \frac{1}{1+\nu'} \left(\frac{1}{2} \left[(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2 \right] \right)^{\frac{1}{2}} \quad (2)$$

where ν' is the effective Poisson's ratio, which is defined as follows: Material Poisson's ratio for elastic and thermal strains computed at the reference temperature of the body. The results of the equivalent von Mises stress analysis, using the ANSYS mechanical APDL, converged after applying the force for 1 second. The stress on every component of the rear axle is shown in Figure 11.

Equivalent von-Mises Stress

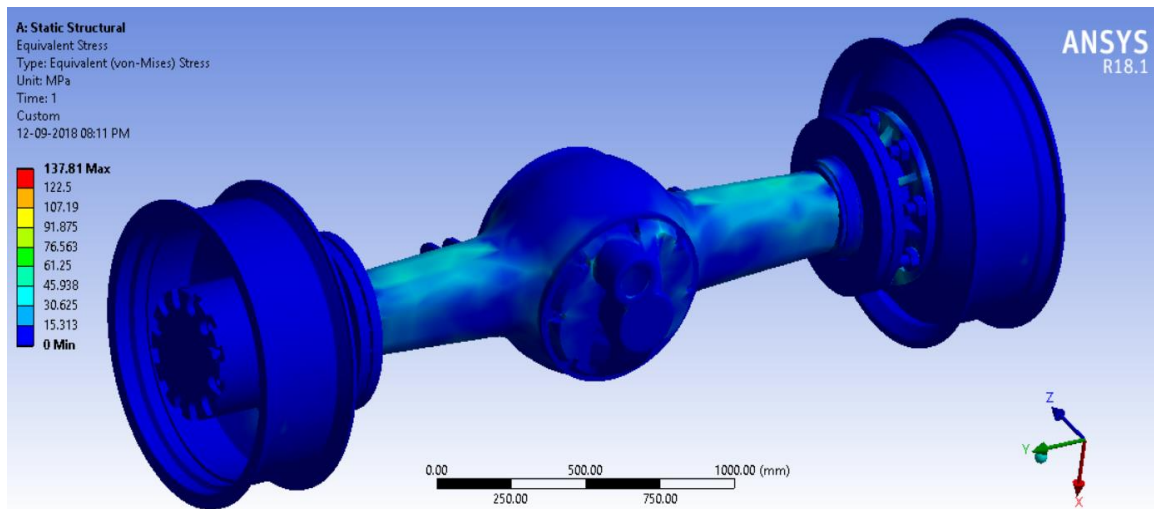


Fig. 11. Real-scale full equivalent stress distribution graphic.

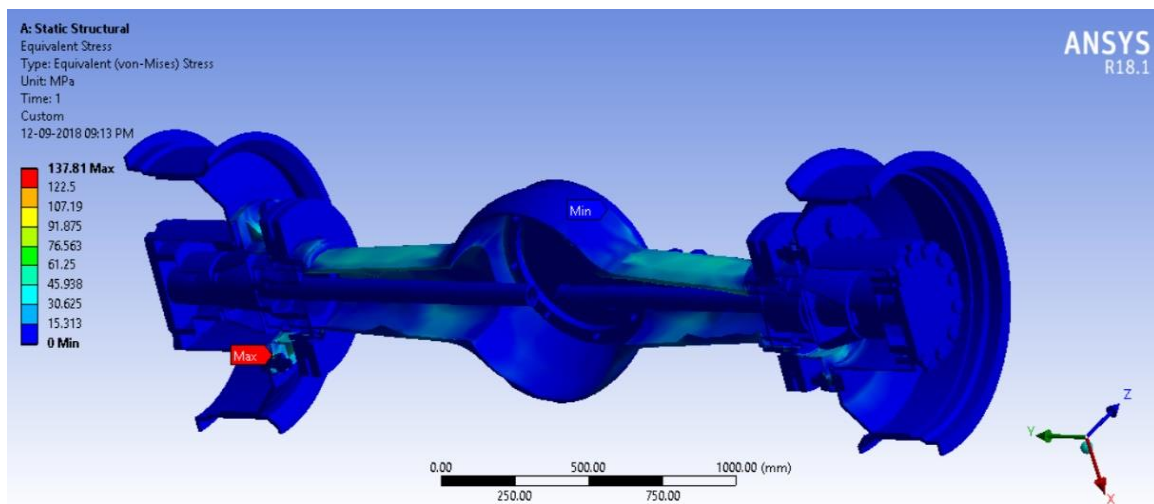


Fig. 12. Real-scale sectioned equivalent stress distribution graphic with points where minimum and maximum stresses are exerted.

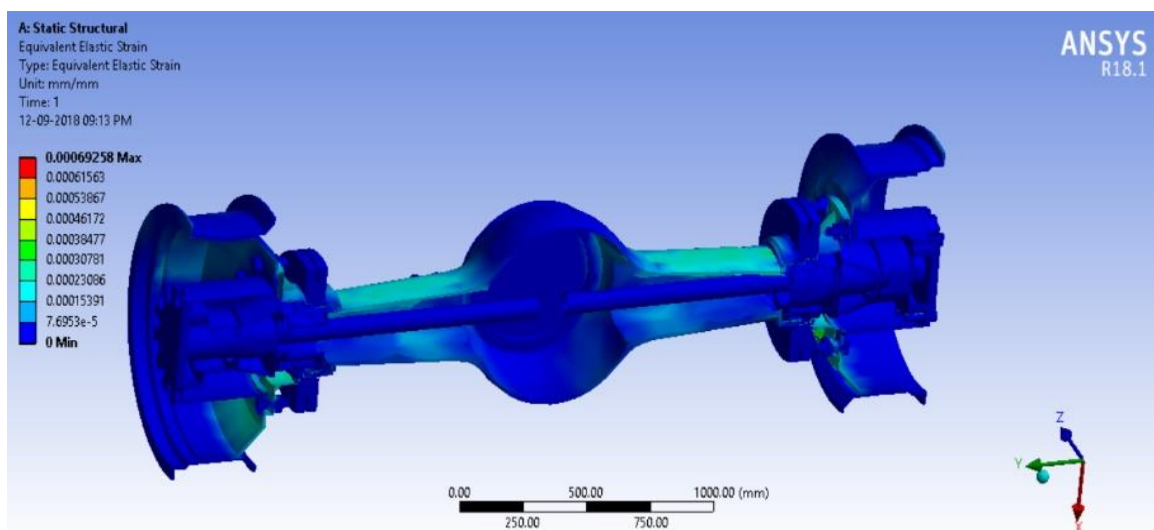


Fig. 13. Sectioned strain distribution.

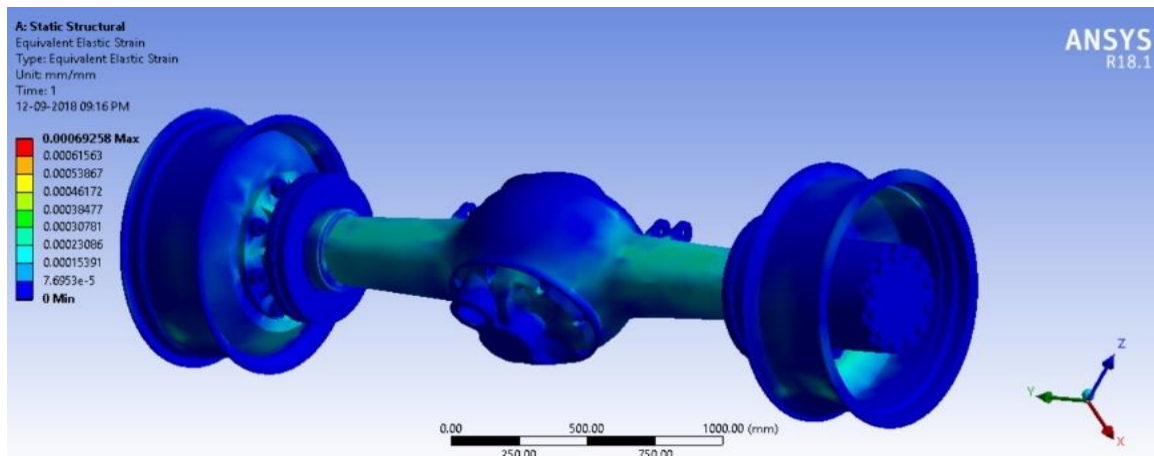


Fig. 14. Full equivalent strain distribution.

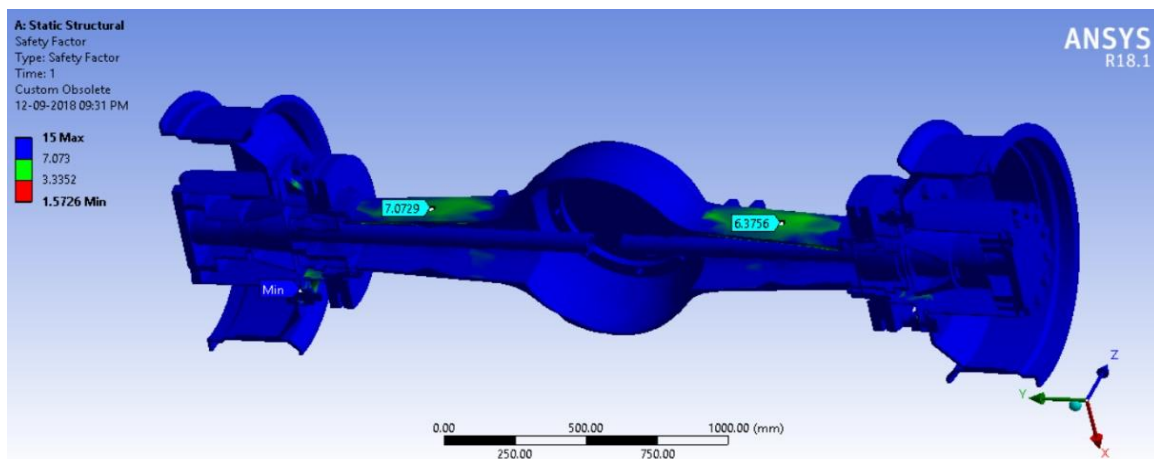


Fig. 15. Sectioned factor of safety graphic plot.

What can be observed in figures 10 and 11 are that the maximum equivalent stress, pointed in red in figure 12, exerted on the axle is 137.81 MPa. This value is under the value of the yield strength of both the carbon steel and the aluminium alloy. Also, it can be observed that the maximum stress occurs at the interface of a bolt (fastener). This occurs due to stress concentration in that region, because of the build-in pressure due to its multiple sharp edges causing stress to build. The minimum strain occurs at the crown region of the housing; the oval shape of this region allows smooth flow of stress.

Equivalent von Mises Strain

From the observations made from the real-scale graphics in Figures 13 and 14, strain

analysis is that the equivalent elastic strain is almost negligible with that maximum value being 6.9258×10^{-4} mm.

Factor of Safety

Factor of safety is a term describing the load-carrying capability of a system or a part beyond the expected or actual loads. It is essentially how much stronger the system or a part is than it needs to be for an intended load (Figure 15).

The minimum factor of safety is 1.5726 which is at the interface of the bolt. This can be remedied; however, the more prominent factor of safety values is for the two top faces of the housing. Therefore, the more prominent factor of safety value is around 6.

Total Deformation

The total deformation gives us the direction and values of deformation at the different regions of the various components in all three axes. A scaled-up

value is used to show the extent and direction of the deformation. The results shown in Figures 16 and 17 have been scaled 2700 times to show the graphical deformation.

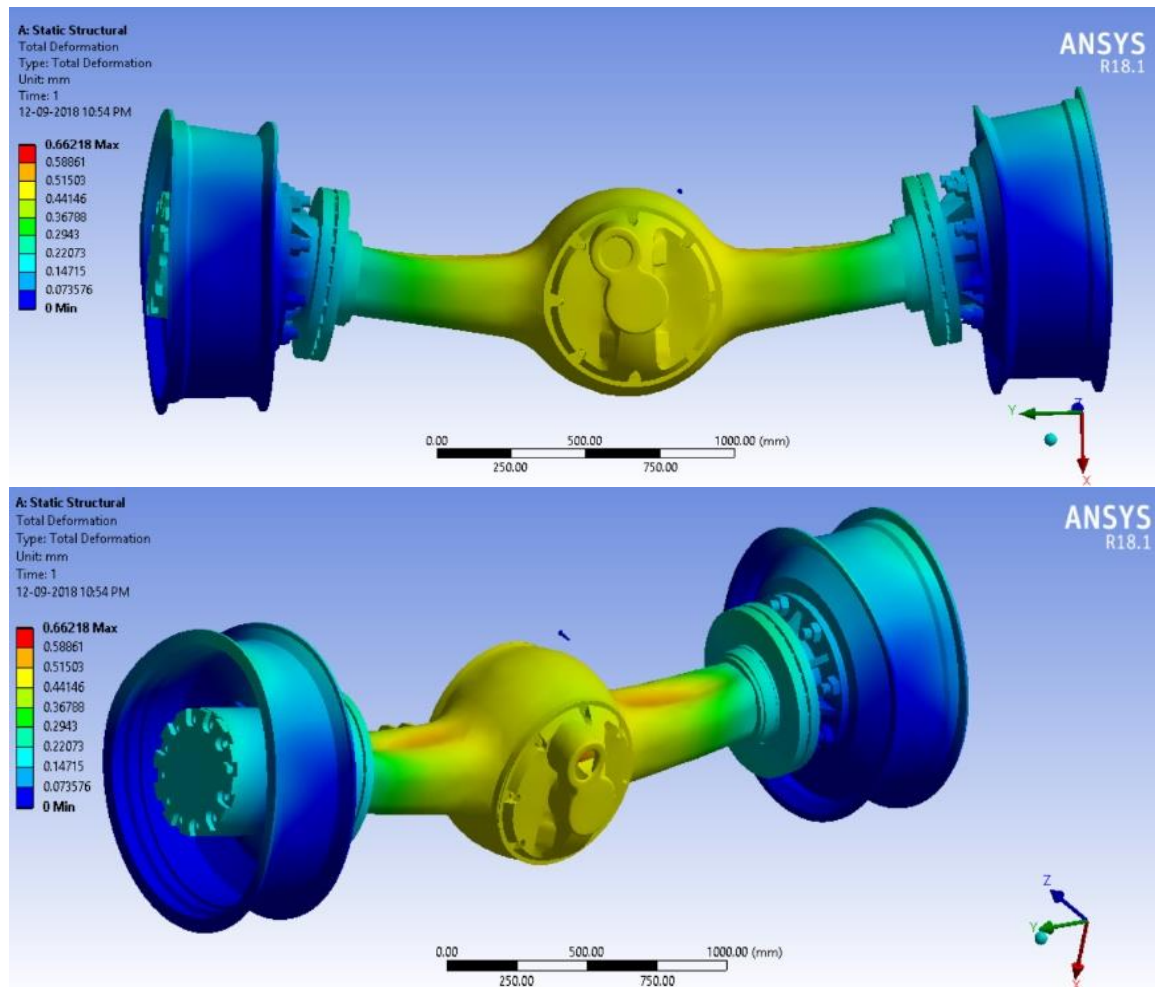
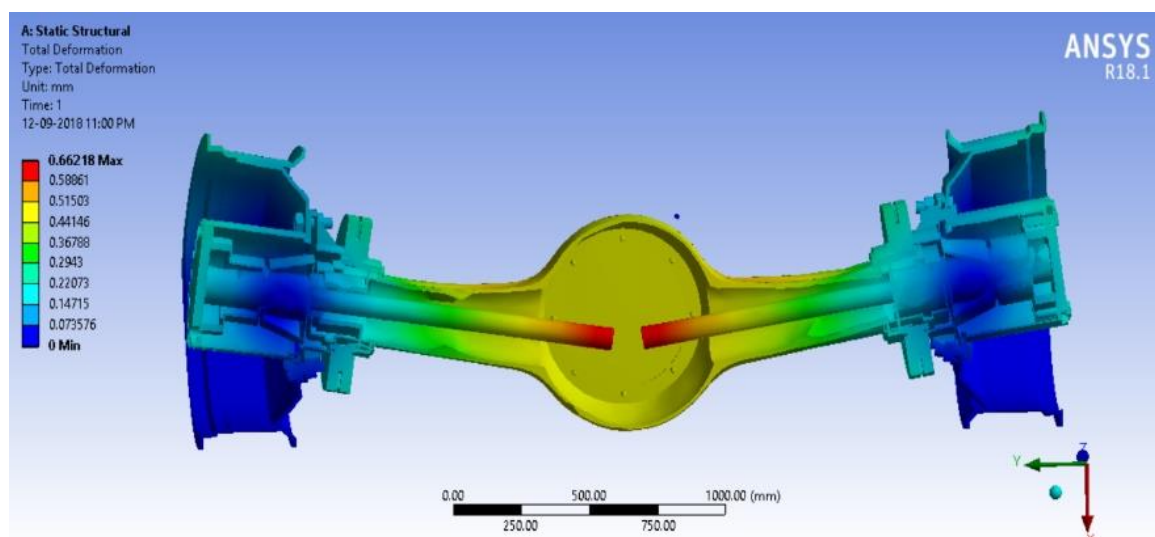


Fig. 16. Scaled-up and predicted full total deformation results with two perspectives.



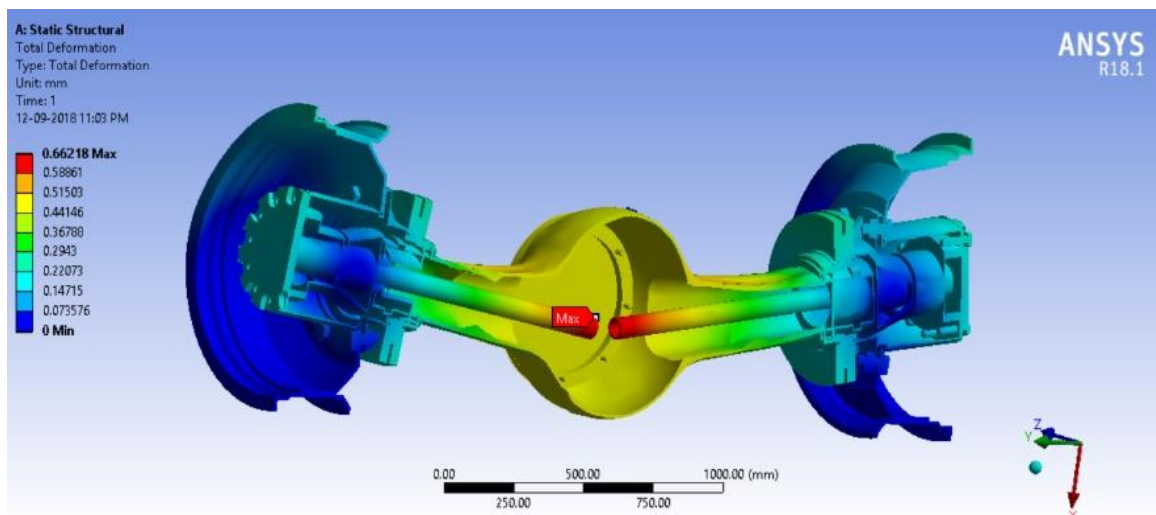


Fig. 17. Scaled-up and predicted Sectioned total deformation results with two perspectives.

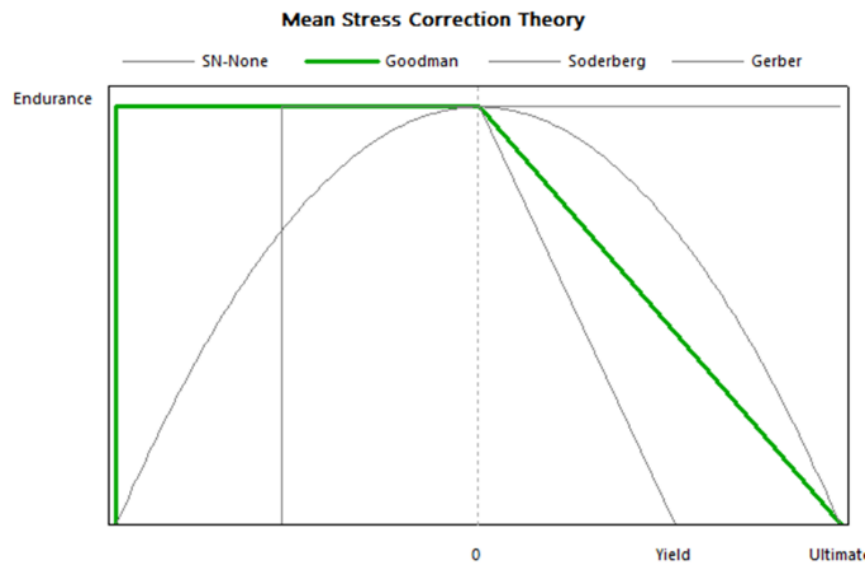


Fig. 18. Goodman mean stress theory graph.

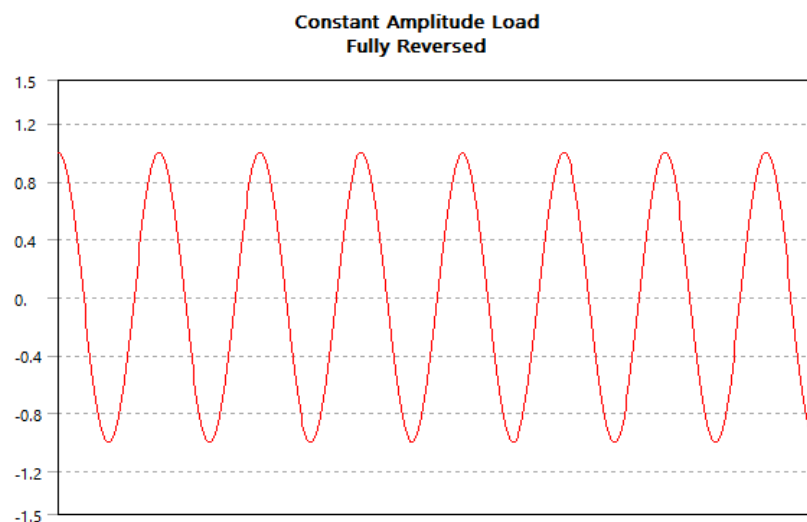


Fig. 19. Fully reversed-type loading.

The maximum total deformation occurs at the differential facing ends of the two pieces of the shaft as shown in Figure 16. The maximum total deformation value is 0.66218 mm. The scaled deformation graphic shows how the major parts of the axle would buckle and deform under their ultimate load.

Fatigue Analysis

Fatigue is the weakening of a material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading (Figures 18 and 19).

Life Cycle

It is observed from the fatigue analysis for life cycle in Figure 19 that most parts of the rear axle have a life cycle of between 4.6594×10^6 and 1.0033×10^6 , and the wheel rims have a greater life cycle of 1×10^8 . The minimum value is 1.0049×10^5 due to the bolt interface. The life cycle of all the components is shown in Table 5.

Safety Factor: The lower fatigue factor of safety values for the housing of the axle is around 2.3 as seen in Figures 21 and 22.

The graph in Figure 23 shows how the fatigue results for the life cycle change as a function of the loading at the critical location on the scoped region.

FDM 3D Printing

For the scaled-down printing of the part, significant changes needed to be made to

the CAD model of the rear axle. First, all the internal features of the CAD needed to be removed as only the external features would be accessible after the part was printed. Unfortunately, there is no effective method or file-saving format in which it is possible to save the product in such a manner that all components whose significant dimensions will be less than 0.5 mm after scaling down need to be removed. Therefore, all fasteners such as the nuts and bolts were deleted from the CAD file. It is possible just to save the external faces by converting them to surfaces; however, this causes problems as often; many faces of the components are not produced. Therefore, the internal features of the individual part need to be cut manually. The next step is to remove all the shell features and make the parts solid inside. If this is not possible, the thickness of the parts is increased to the maximum instead. This can be done using the thickness tool in CATIA V5. After the modifications to the CAD model is done, the product/assembly file is saved as a STEP file as CATIA cannot save a product file as an STL file. The STEP file is then imported into Solid works and then saved as an STL file with a fine quality. The STL file is then imported into the Ultimaker Cura Slicing software where it is scaled down to 6% of its initial size and placed on the build plate. Scaling it to a lower value would cause the thickness of certain parts to become lower than what the FFF 3D printer would be able to handle (Figures 24-26 and Table 5).

Table 4. Component life cycle.

Part	Life cycle
Housing	1,000,000
Wheel rims	100,000,000
Shafts	1,000,000
Spindles	1,000,000
Discs	1,000,000
Back plate	1,000,000
Front plate	1,000,000

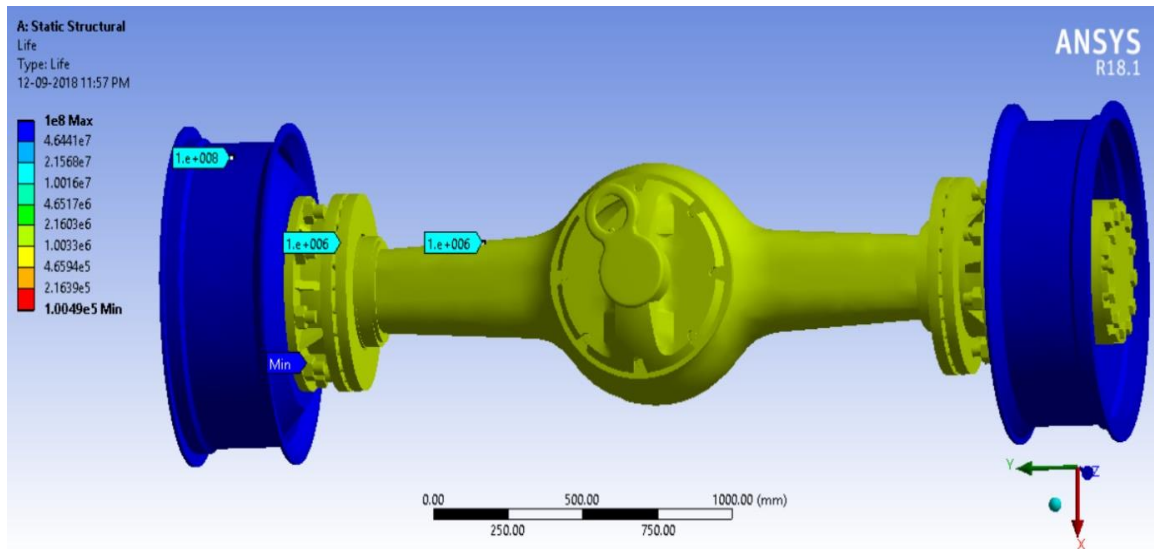


Fig. 20. Life cycle graphic plot.

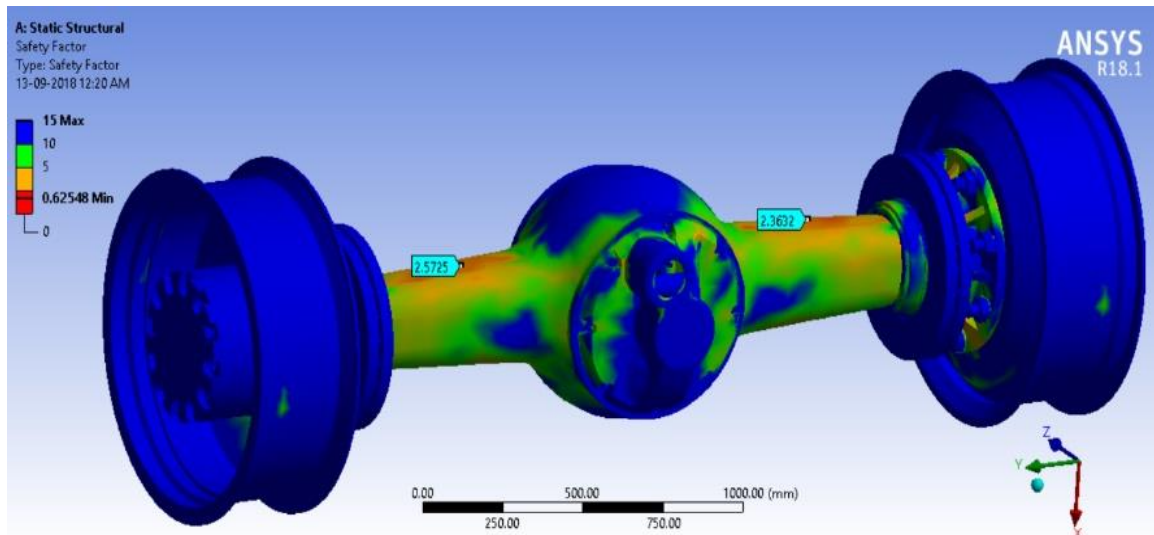


Fig. 21. Full fatigue safety factor.

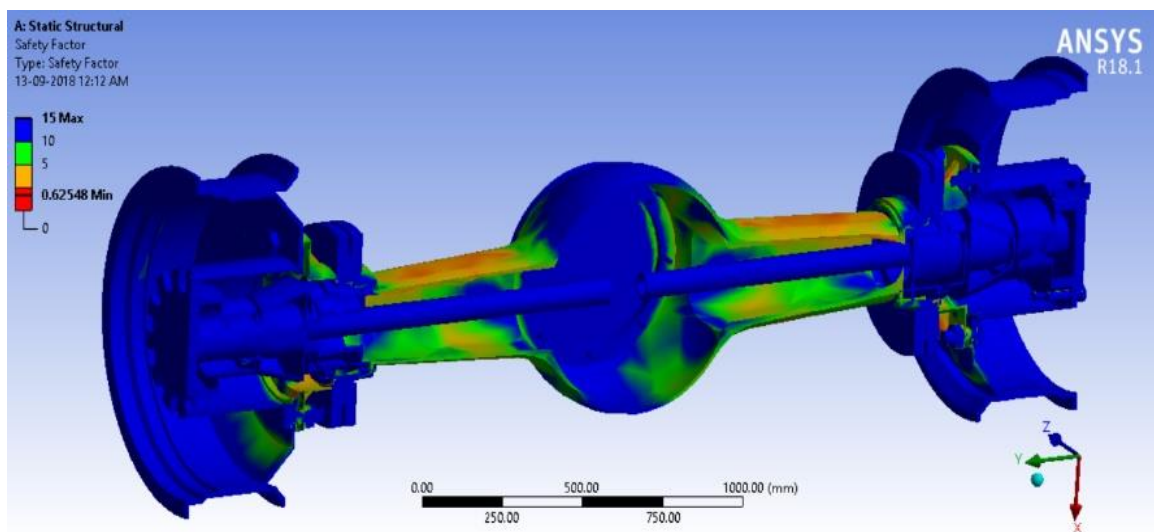


Fig. 22. Sectioned fatigue safety factor.

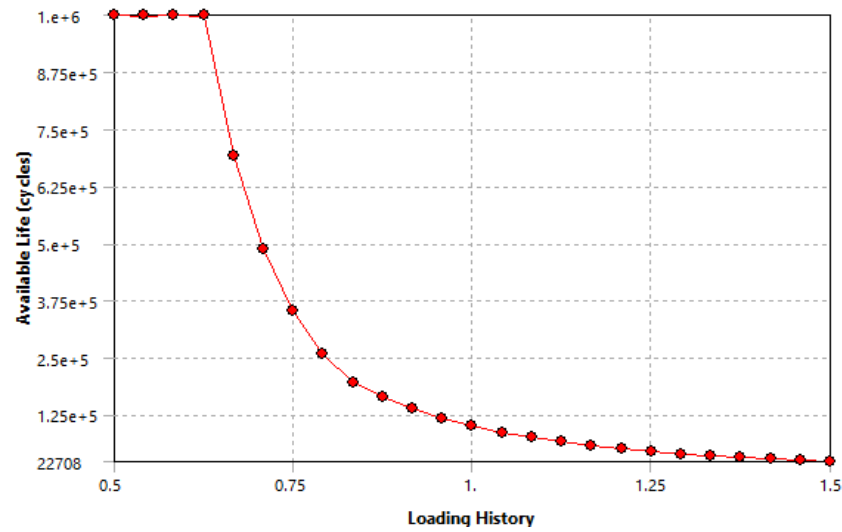


Fig. 23. Fatigue sensitivity graph.

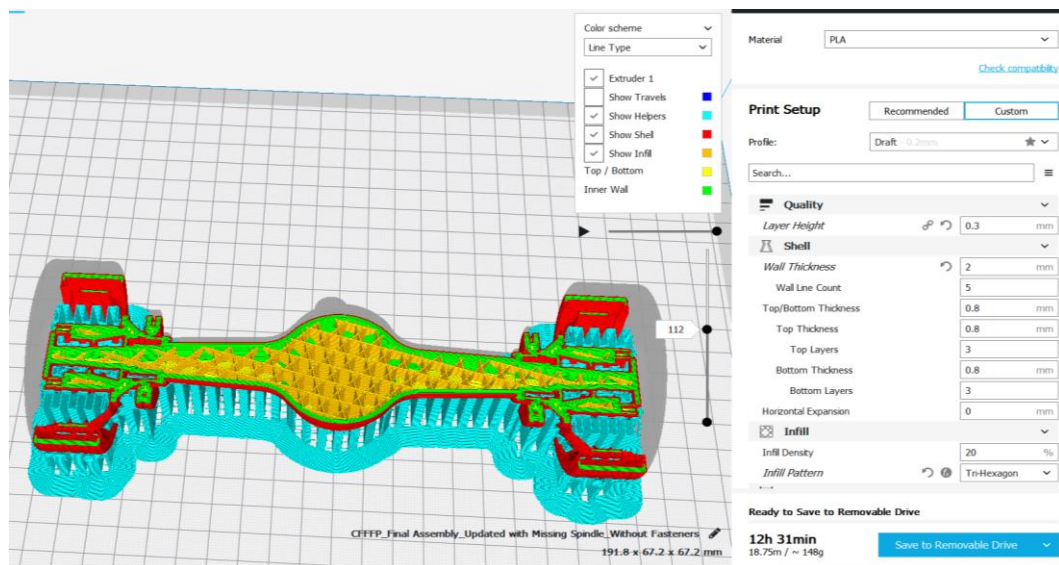


Fig. 24. Sliced layer view halfway.

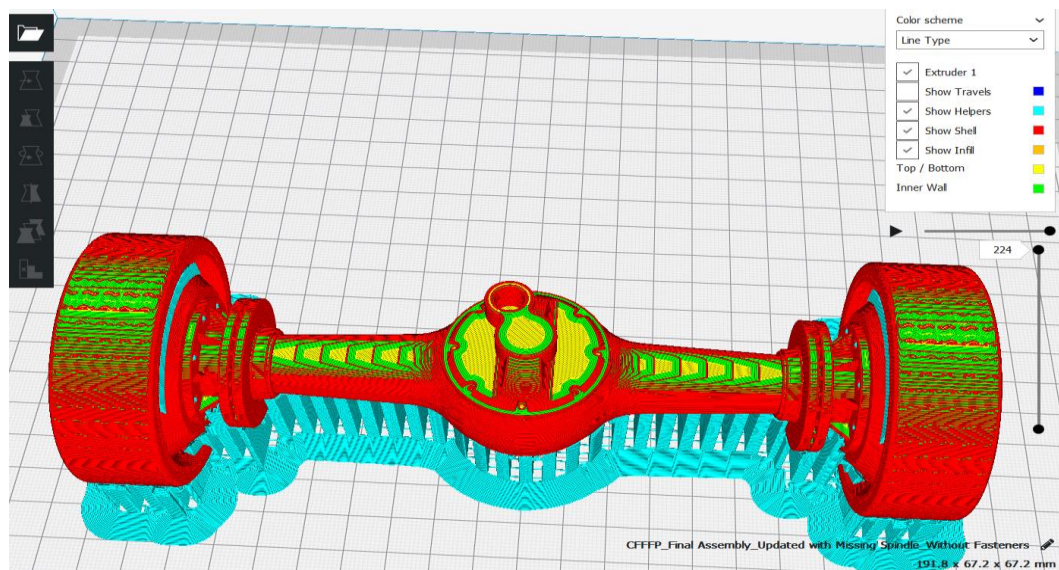


Fig. 25. Sliced layer view full path.



Fig. 26. 3D printed axle assembly.

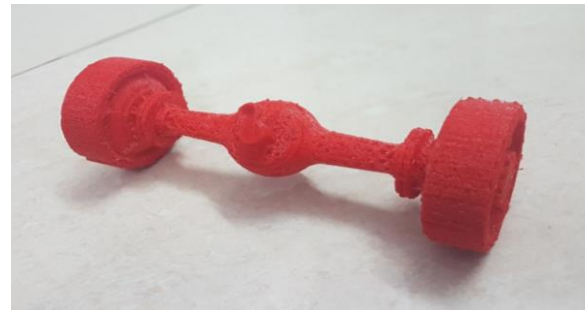


Fig. 27: 3D Printed Final Part Without Supports.

Table 5. Printing parameters.

Parameters	Value
Layer height	0.3 mm
Wall thickness	2 mm
Number of shells	2
Infill type	Tri-hexagon
Infill percentage	20%
Print speed	35mm/s
Printing temperature	210°C
Support overhang angle	50°
Filament diameter	1.75 mm
Nozzle diameter	0.4 mm

CONCLUSION

A fatigue analysis is done on the axle, using the Goodman mean stress theory with a fully reversed-type loading and with an equivalent (von Mises) stress component to determine the life and safety factor of the axle. Also, to check the sensitivity of the axle to fatigue, a fatigue sensitivity graph is plotted for the available life cycles against the loading history. Axle assembly was printed by using PLA material with overhang supports and used rafts for greater build plate adhesion. The total print time of the part comes to around 12 hours and 31 minutes and the the dimensions of the print are 67.2 mm × 191.8 mm × 67.2 mm.

Abbreviations and Acronyms

1. FFF – Fused Filament Fabrication

2. APDL - ANSYS Parametric Design Language
3. CAD – Computer Aided Design
4. STL – Standard Tessellation Language
5. STEP - Standard for the Exchange of Product model data
6. CAE – Computer Aided Engineering
7. MPa – Mega Pascal
8. KN – Kilo Newton
9. mm – Millimetre
10. FDM-Fused Deposition Modelling

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