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Problem Statement:

The suspension of a 4-wheel Formula student vehicle experiences extreme static and fluctuating forces. During cornering extreme compressive and tensile loads are induced in the wishbone structure of suspension. Currently, many formula students team uses steel and aluminum alloys for their wishbone structure which may be cheap, however, it has a low fatigue life and it is very heavy. The overall weight of a formula student car is quintessential, therefore it is essential to optimize components to reduce the weight. Our aim was to compare the different materials used for wishbone structure by simulating them under realistic loads on ANSYS software and find the most favorable material.

Introduction

The suspension is an extremely important aspect of a vehicle. It consists of tires, shock absorbers, and other connections that allow the car and the wheel to have relative motion. These connections can be made in many different ways and their various designs are called suspension systems. One of these suspension systems mainly used in open-wheel racing cars is known as The Double Wishbone Suspension System. This suspension system consists of two control arms called the upper and lower A-arm. These A-arms connect the hub of the wheel to the mainframe of the vehicle. The connections between the upper and lower A-arm and the mainframe are different, therefore, by varying the length of one arm, the camber of the tires can be altered. Due to this significant feature, A-arms are used as opposed to other suspension designs such as the H-arm.

Formula Student (FS) is a university-level design competition where teams from universities all around the world design and build open-wheel race cars. One of the most important design challenges they face is to reduce the overall weight of the car. Many FS teams around the world still choose to use various steel alloys that go with the material of their main body frame. However, steel alloys are quite heavy and have a short fatigue life. Steel systems that are used however can be easily shaped and have a lower probability of sudden failure. Upon extreme loads, steel tubes are more likely to bend and channel the load by internal deformation.

Many teams nowadays are moving more towards composite wishbones. Many FS teams have even developed carbon fiber monocoque chassis which provide for a significant weight reduction. Professional Formula racing cars and even a few FS teams have successfully developed Carbon Fibre wishbones. Carbon fibre when manufactured properly can provide enhanced strength. The specialty of carbon fibre lies in its feature that whilst providing extremely high strengths it remains very light. Carbon fiber components have also proven to be very stiff and therefore provide greater stiffness in the suspension, however, under extreme loads, these components can exhibit immediate structural failure.

Literature review:

Paper Title	Citation	Findings
Designing Composite Suspension Arms for a Formula SAE Vehicle.	McDonald, Martin & Joyce, Peter & Hamilton, Leonard. (2011). Designing Composite Suspension Arms for a Formula SAE Vehicle.	- Designed and tested a composite A-arm under compressive loads to see the feasibility of using composites as a viable material. - It was found that the Composite A-arm was more prone to immediate failure. - Composite A-arm gave a 50% weight reduction as compared to conventional steel tubes.
Composite Suspension Arm Optimization for the City Vehicle XAM 2.0	Airale, Andrea & Carello, Massimiliana. (2014). Composite Suspension Arm Optimization for the City Vehicle XAM 2.0. Design and Computation of Modern Engineering Materials, Advanced Structured Materials.	- FEM-based analysis of composite A-arm for use in XAM 2.0 Prototype EV. Maximum load and desired stiffness value were used in order to design the A-arm. - Only a 5% overall weight reduction was noticed in the prototype XAM 2.0. - However, stiffness increased by 75% which gave a significant dynamic performance improvement.
Design of a Carbon fiber suspension system for FSAE application.	Cobi, Alban. (2012). Design of a carbon fiber suspension system for FSAE applications. (MIT)	- The author designed and tested the suspension of the formula car, particularly the upper and lower wishbone structure made up of Carbon fiber. - Reduced weight, maintained structural integrity - Conducted a pull test on an Instron machine which pulled the wishbone till failure. - CRPF wishbone resulted in 40% weight saving. He further developed a relationship between bond length and force per area to pull out an aluminum insert from carbon fiber.
Lightweighting of Wishbone Finite Element Analysis	Wang, S., Chong, P. L., & Hughes, D. (2020). Lightweighting of Wishbone Finite Element Analysis. Engineering Transactions, 68.	- lightweight wishbone structure for a family-size car made up of Carbon/Epoxy without compromising material strength. - Siemens NX to conduct lateral braking force and vertical. - Performed better or on par with the wishbone structure is made of high carbon steel. - Achieved a weight reduction of 54.6%.

Design and Analysis of Wishbones in Double Wishbone Suspension System: Technical Note	Gopal, Arunkumar. (2018). Design and Analysis of Wishbones in Double Wishbone Suspension System:. International Journal of Vehicle Structures and Systems. 10.	- The author designed and analyzed the wishbone used in the double-wishbone suspension system. - Utilizes Pugh's matrix approach to optimize material selection for the wishbone. - The author concluded that the Alumina matrix composite is a preferred material. - Proceed to analyze wishbone in ANSYS and compare AISI 1040 with metal matrix composite material. - Concluded, it yielded better durability and strength than conventional.
Modeling and Analysis of Lower Wishbone for Independent Suspension System for Commercial Vehicles	Udhayakumar, R., & Raman, S. (2014). Modeling and Analysis of Lower Wishbone for Independent Suspension System for Commercial Vehicles. Journal Of Chemical And Pharmaceutical Sciences, (ISSN: 0974-2115).	- The author modeled and analyzed the lower wishbone for an independent suspension system for commercial vehicles. - Redesign the existing wishbone and compare the composite wishbone structure to steel. - In conclusion, the deflection of the composite lower wishbone arm is greater than the steel lower wishbone arm at the same loading condition. - Utilizing composite material saved 18% of weight. Proposed redesigning of suspension to have higher stiffness.

Through the literature review, we conjecture that the lower or upper wishbone structure's design made of composite material improved the suspension system's static loading capacity. Moreover, composite material use also resulted in a reduction in the weight of the whole car, which is quintessential in formula students and can give a competitive edge. However, there was a lack of research that evaluated the fatigue characteristics of the composite wishbone arm. The reliability and durability of the wishbone arm subjected to fluctuating stresses are essential for the FSAE team.

Methodology

The methodology of this project was based on a series of logical steps. Several research papers were studied in order to gain a better understanding of the subject. Based on these papers, several parameters were decided and the following procedure was defined:

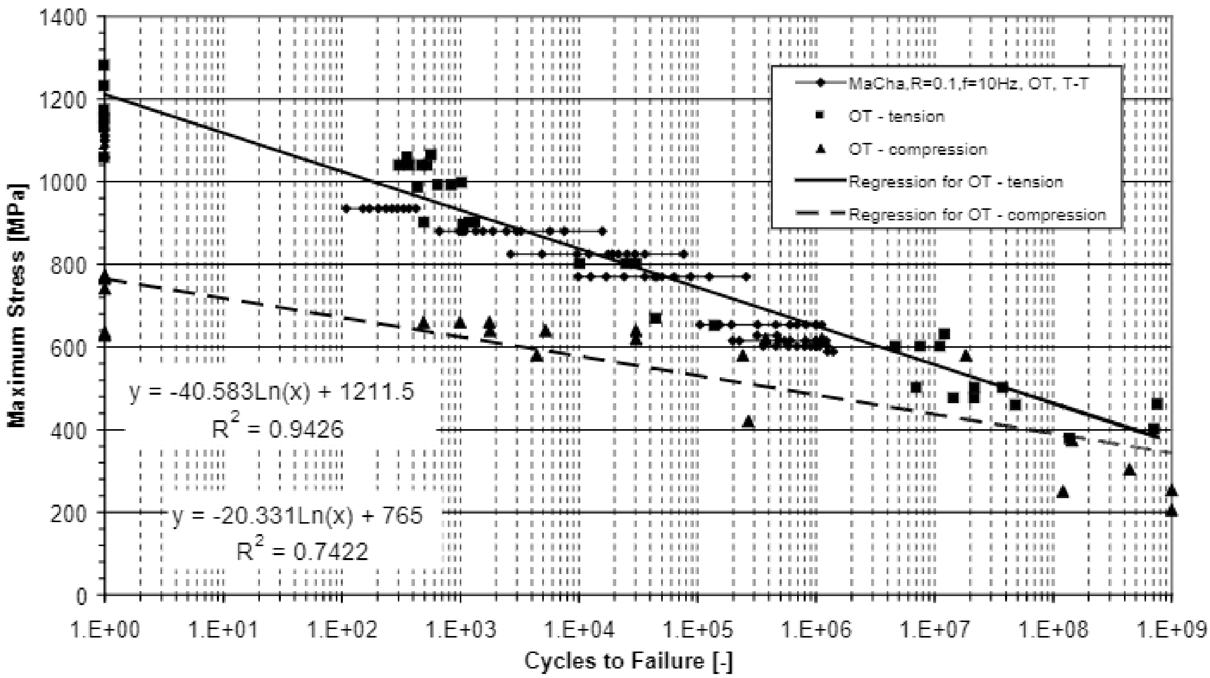
1. The force diagram of the suspension system was established. The various loads acting on the upper A-arms during cornering were found in existing research.

2. Following this, different stress correction curves such as Gerber, Goodman, and Soderberg methods were studied which were imperative to the fatigue analysis.

3. The CAD of the upper A-Arm was created using SOLIDWORKS.

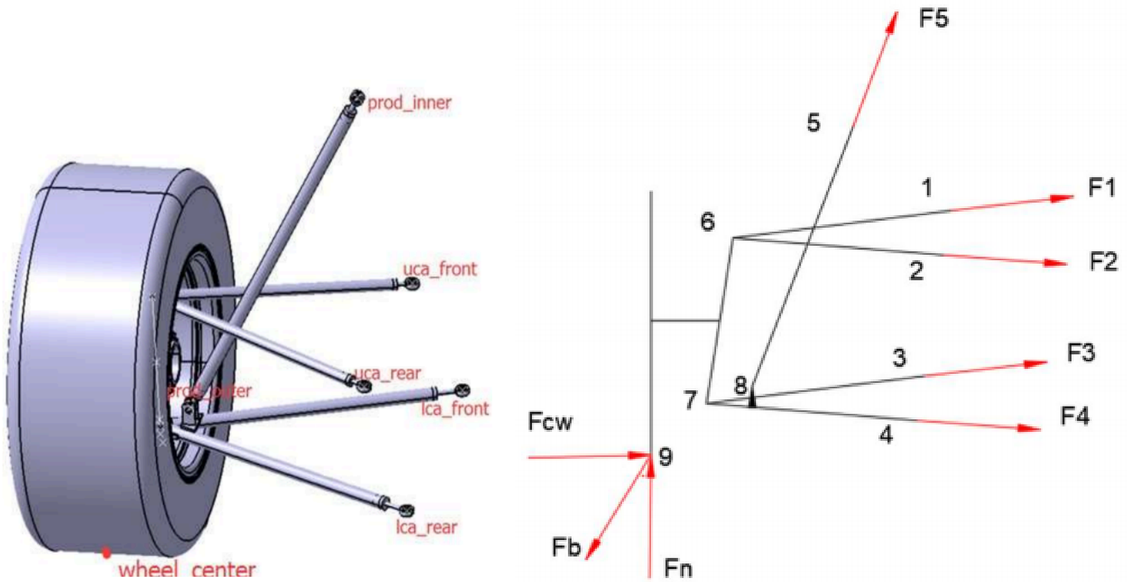
4. Simulation of Aluminium 6061 and Steel upper A-arms were conducted on ANSYS software. Two static structural analyses were conducted. One with compressive loads and the other using bending loads.

5. Fatigue simulation of carbon fiber components is extremely difficult due to the behavior of single fiber strands present in the component. Furthermore, the strength and quality of a carbon fibre component also depend on the epoxy used for making the component. However, many researchers have successfully predicted the fatigue life of Carbon fiber composite to about 8% (always underestimated) by assuming the entire process as quasi-static (Brod, 2018) (Adarsh D.K., 2014). Further, to simplify the process, the carbon fibre component was treated as one single part and the behaviour of individual fibres was neglected. The SN-curve was obtained from experimental data from a research paper (Silvain, 2006).



6. Lastly, the simulated stress values and the fatigue life values of the three different materials are compared. Further analysis based on ease of manufacturing and the economical aspect of these materials are analyzed.

Forces in the Wishbone of a Formula Student Vehicle



In a research paper (Rui, 2019), we identified that the suspension of Formula Student cars uses an independent suspension structure. The research paper analyzed the suspension and wheel as one system. Researchers utilize various force-measuring devices to find the maximum force experienced by the upper and lower wishbone arm. In the figure, F1 is the force in the front point of the upper transverse arm and F2 is the force in the rear point of the upper transverse arm. It is similar to the lower wishbone arm which is F3 and F4. For simulation, it was assumed that the forces F1 and F2 are equal and F3 and F4 are equal.

In the research paper (McDonald, 2011), the researcher used a Formula student car of weight 220 kilograms or 2200N, and they assumed that the driver weighed approximately 80 kilograms or 800N. We further assumed that:

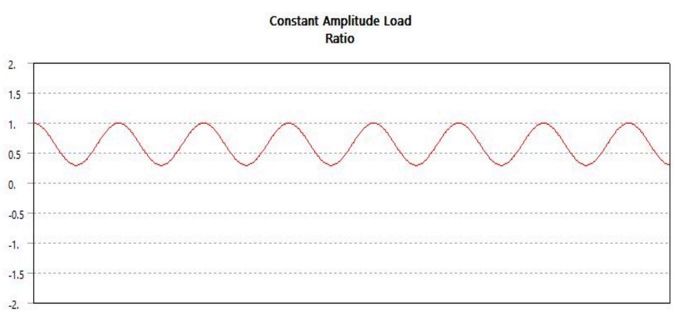
- The maximum acceleration of a car is 2G.
- Only part of the maximum weight car can transfer to a single tire.
- All components in the suspension are rigid bodies.
- A suspension system is a quasi-static process.

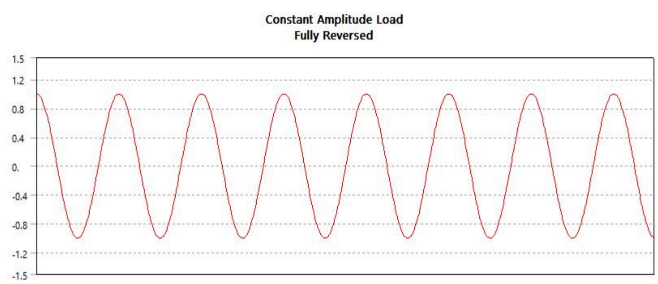
- The difference in force experienced in the front and rear upper A-arm is negligible.
- The tensile load in the wishbone is relatively less compared to the compared load.
- Maximum bending and compressive loads are generated when turning and braking.

The researcher found that the following forces on the upper arm of the wishbone:

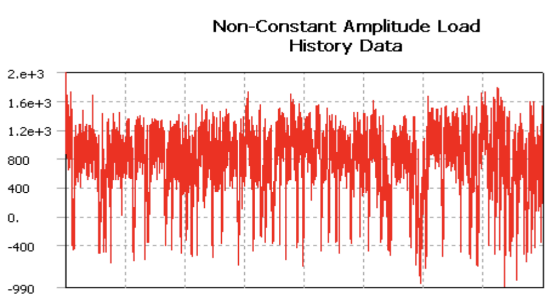
- Forces during braking /acceleration:
  - The peak compressive load on the upper A-arm = 9000N
  - The peak bending load on the upper A-arm = 1100N
- Forces during uniform turning:
  - The peak compressive load on the upper A-arm = 2300N
  - The peak bending load on the upper A-arm = 960N

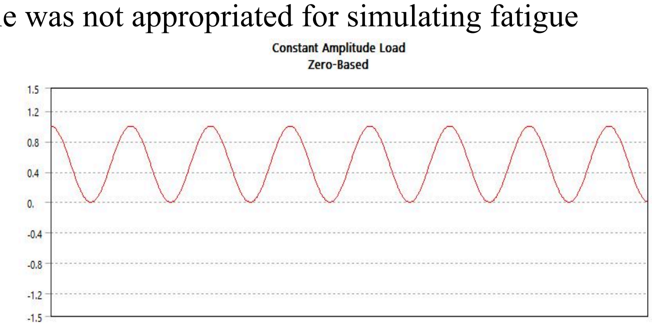
For the fatigue analysis, the most accurate result will be obtained if historical data for the wishbone load is available. However, due to the current situation, it is not possible. We decided to use ANSYS's inbuilt features for fluctuating load using fatigue tools present in Static Structural analysis. We assumed that the tensile forces on the wishbone are minimal compared to





compressive forces. Hence a fully reversed cycle was not appropriated for simulating fatigue





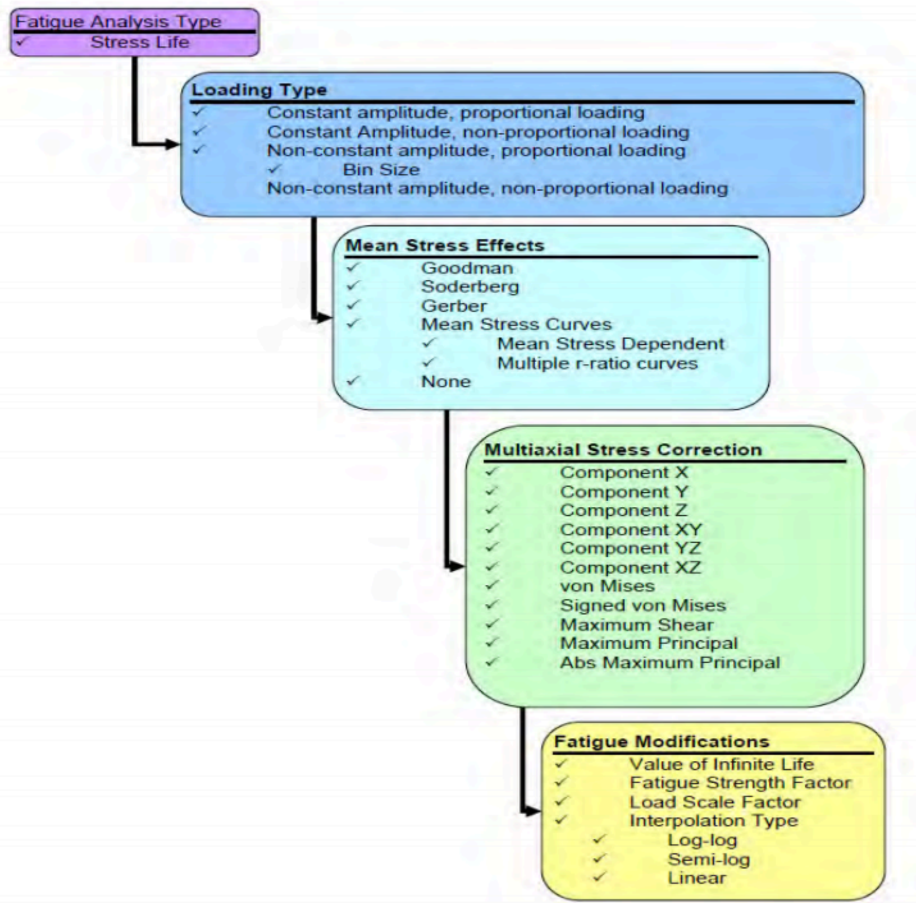
cycle in the wishbone component. We decided to utilize zero-based constant amplitude fluctuating load to simulate the real-life condition that a formula student car may experience while driving a circuit. When using the zero-based fatigue cycle, the mean stress is non-zero, so stress correction needs to be applied to predict fatigue life accurately.

Stress life model vs Strain life Model

A structure or component subjected to a repeated stress cycle may lead to continuous brittle fracture in the component, ultimately leading to its total failure; this phenomenon is called fatigue. Fatigue can occur for a structure at a stress lower than its ultimate strength. As a formula student car experiences constant acceleration and deceleration, turning, and braking, all the car's structural components are subjected to fluctuating load. Hence understanding the fatigue behavior of a component is quintessential for reliable and optimal car design. Moreover, the budget for formula student teams is scarce and the longevity of essential components is quintessential from an economic point of view.

Fatigue life is the number of stress cycles a component can withstand before its total failure. There are two different methods used for fatigue analysis of a structure; Stress life and Strain life method. Although both models present their advantages and limitations, usually stress life models are used to predict high cycle fatigue (HCF), and the strain life model is used to predict low cycle fatigue (LCF). High cycle fatigue and Low cycle fatigue are distinguished based on the number of load cycles required for the crack to occur in a structure; an order of 10^5 cycles commonly differentiates them.

We decided to use the classical stress life method as an S-N curve to analyze the fatigue life of the wishbone used in a formula student. It relates the number of load cycles to failure (N) to the stress amplitude in uniaxial loading. Moreover, some materials can theoretically never experience fatigue if stresses are under a certain threshold, known as the endurance limit. The workflow to contact a fatigue analysis using the stress life model is shown in the flowchart below.

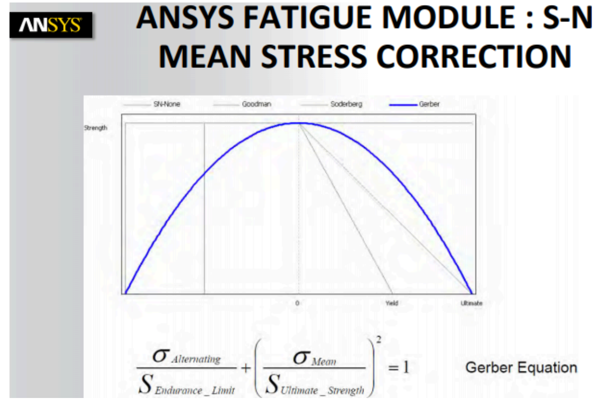


Mean Stress Correction

The mean stress for a wishbone component is non-zero, as the load cycle is not fully reversed. There is a need to use mean stress correction to predict the fatigue life of the component accurately. There are numerous mean stress correction methods, including Gerber Correction, Goodman Correction, and Soderberg Correction.

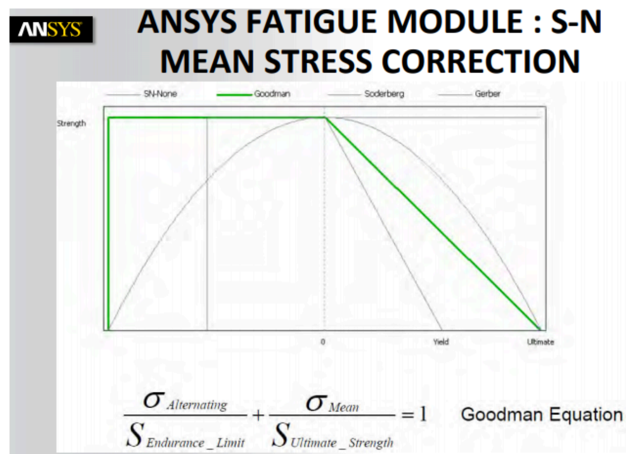
Gerber Correction Method:

Gerber proposed a parabolic correction. The curve is drawn between the endurance limit and ultimate tensile strength. It is a non-conservative method and it is generally used for fatigue analysis of ductile material. We used the Gerber method for the analysis of Steel alloy and aluminum components.



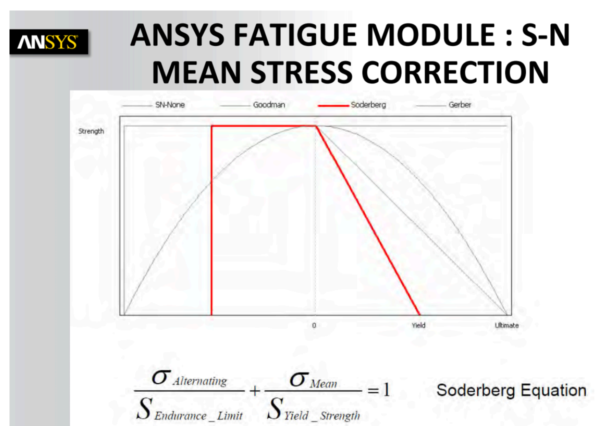
Goodman Correction Method:

Goodman proposed a linear correction. It is a straight line connecting endurance limits and ultimate strength. It is a conservative method and is used for fatigue analysis of ductile or brittle materials. We assumed that carbon fiber epoxy material is a brittle material, hence using Goodman correction for its analysis.



Soderberg Correction Method:

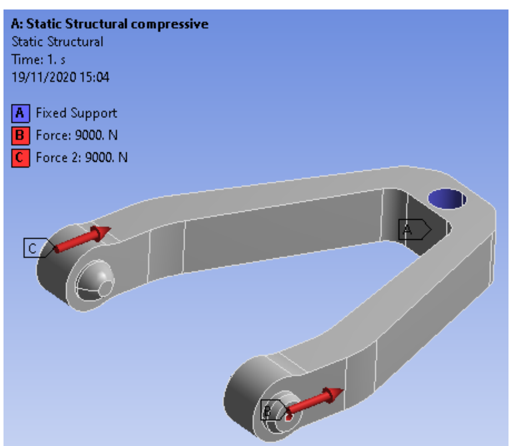
Soderberg proposed a similar correction method to Goodman, but Soderberg's correction method is based on the yield strength of the material instead of ultimate strength. It is a very conservative method, and it is generally used for ductile material subjected to bending. However, we decided not to use this method as it doesn't fit our needs.

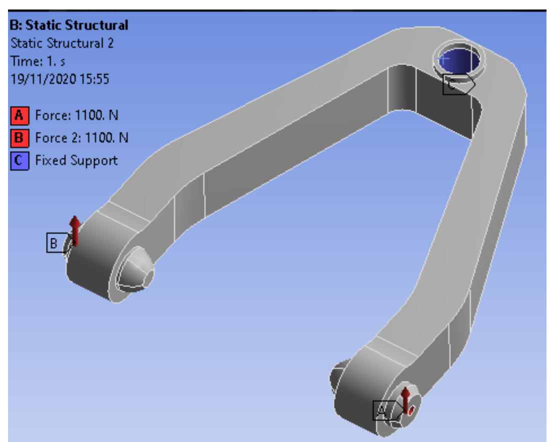


Simulation and Analysis:

The model was created using SOLIDWORKS software and imported into ANSYS. The mesh type used as unstructured as the shape of the geometry is quite complex. The mesh sizing was manually decided to obtain a fine meshing. Different mesh sizes were checked out of which a 4mm mesh size was found to be appropriate with minimal skewed cells.

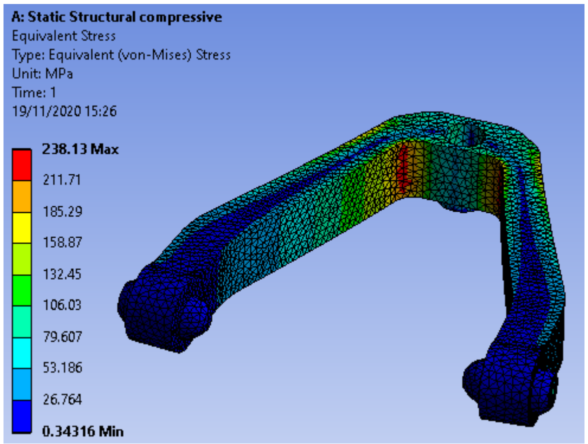
Two separate static structural analyses were set-up in order to test for bending loads and compressive loads. Below is the set-up of the wishbone under the compressive forces. As aforementioned, 9000N was taken as the compressive load. Similarly, for bending loads, the forces act perpendicular to the horizontal plane as shown in the figure. As determined before, the magnitude of the bending forces was 1100N.

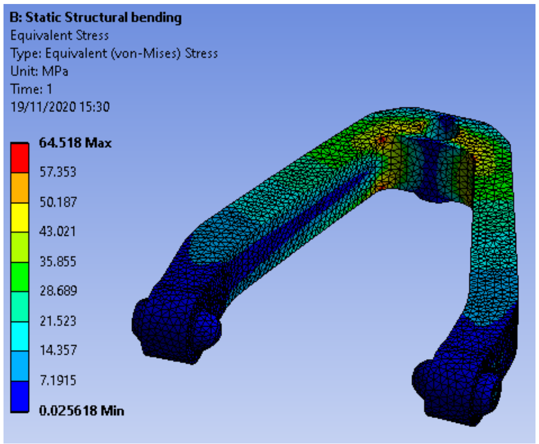




To find the maximum equivalent stresses due to the forces, the maximum equivalent stress solver, provided by ANSYS, was employed. To find the safety factor involved due to these forces, the built-in ANSYS stress tool was employed. Lastly, for fatigue analysis the ANSYS built-in fatigue tool was used which was able to provide the life and the fatigue-based safety factor for the component. For the fatigue analysis, the zero-based model was used as it is appropriate to this design problem.

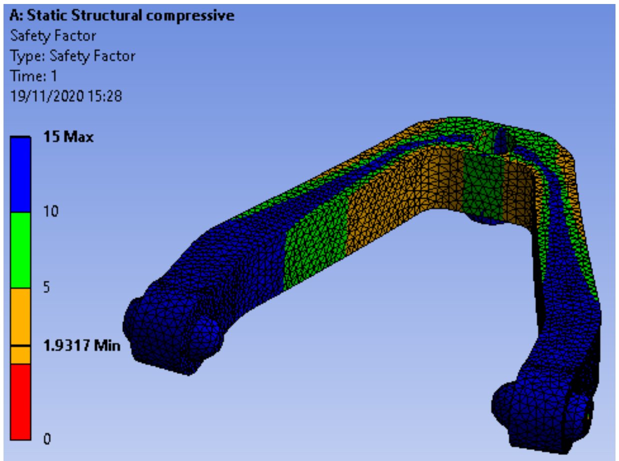
Stress Concentration

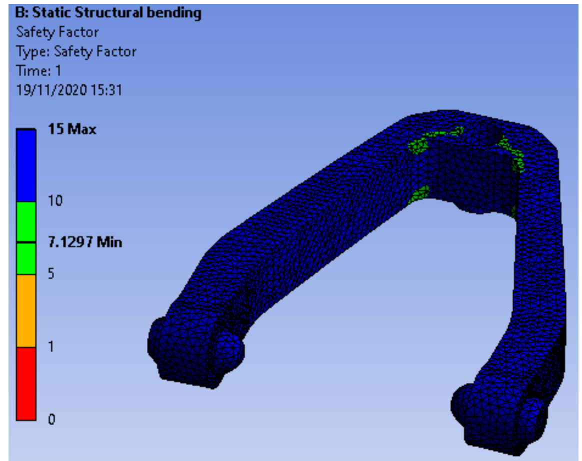




The figures above show the equivalent stress under the compressive (left) and bending forces (right). As visible, the maximum forces occur at the bent sections only. Furthermore, the maximum stress reached is 238.13 MPa under compressive loads. The same stress concentration is seen for Aluminium due to the similar behavior of metallic compounds. Similarly, under bending loads, the maximum equivalent stress is 64.518MPa for steel, and a similar value is noticed for Aluminium. However, further analysis to differentiate the two metals can be done using a safety factor analysis of stress and fatigue components under the same forces.

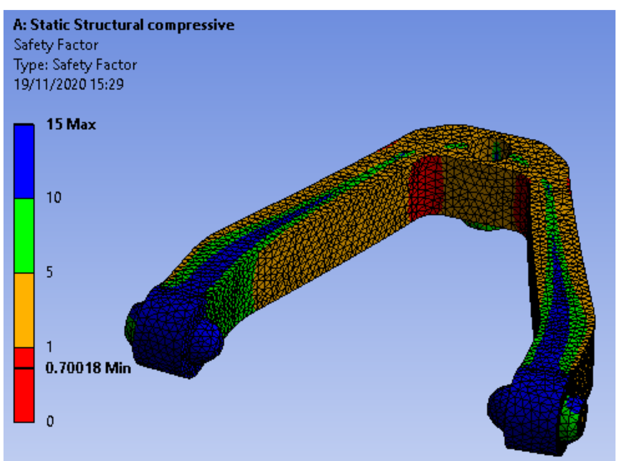
Steel

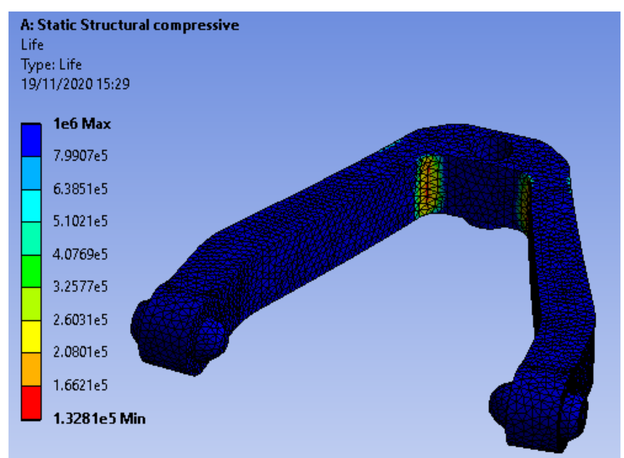




The safety factor can be mathematically defined as the ratio between the ultimate yield stress and the maximum equivalent stress. As shown by the figure above; the minimum safety factor is 1.9317 under compressive loads. Alternatively, for bending stresses, the safety factor is consistent and relatively higher which suggests that the effect of bending stresses under this magnitude of force does not have a major effect on steel wishbone structures.

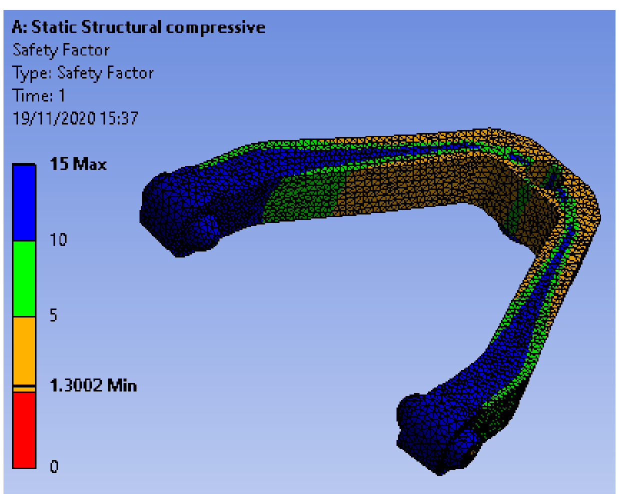
Further analysis was performed on the fatigue behavior of the component as shown below.

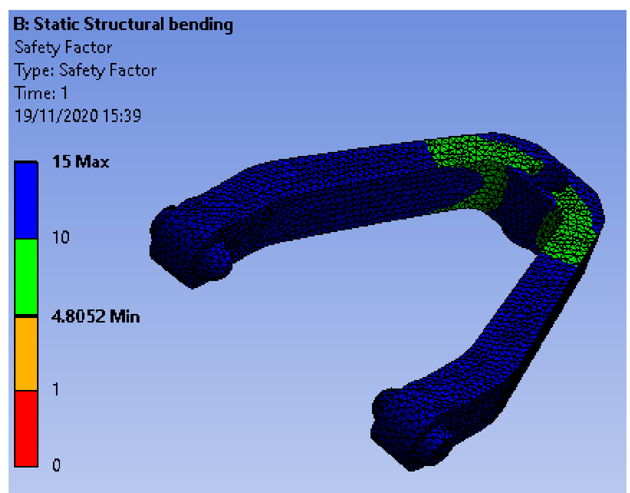




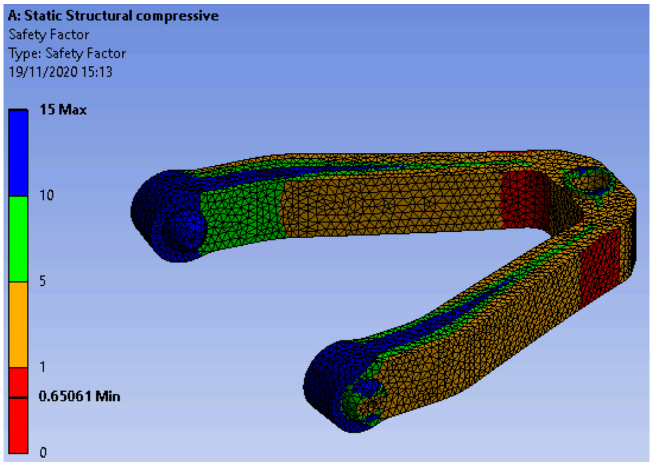
The figures above show the fatigue safety factor under the specified compressing and bending loads respectively. As seen the compressive loads have a greater effect on the fatigue safety factor where the value drops to 0.70018 on the bent section and a further low value can be seen throughout most of the part. However, the safety factor of the bending load is relatively higher and more concentrated in the bending section. This figure shows the fatigue life of steel wishbone. As visible, a steel wishbone under these specified conditions can go for 1.328E+5 cycles before fatigue failure occurs. In the figure depicting the fatigue life, most of the part is highlighted blue signifying a very high fatigue life, this is due to the endurance limit present in ferrous alloys (Steel). Endurance limit is present in ferrous alloys and unlike other metals, as the S/N curve reaches this value it tends to infinity, signifying that the part can operate for an infinite number of cycles. Many formula students team, work under a tight budget and have to perform in consequent races, therefore a high fatigue life of their component is extremely important. Steel and its alloys are able to provide that at an affordable price.

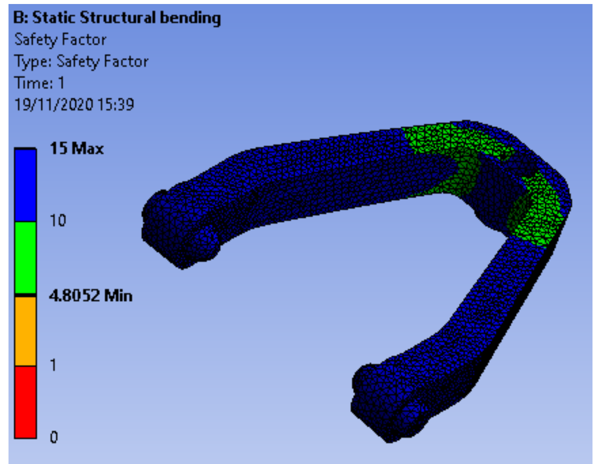
Aluminum





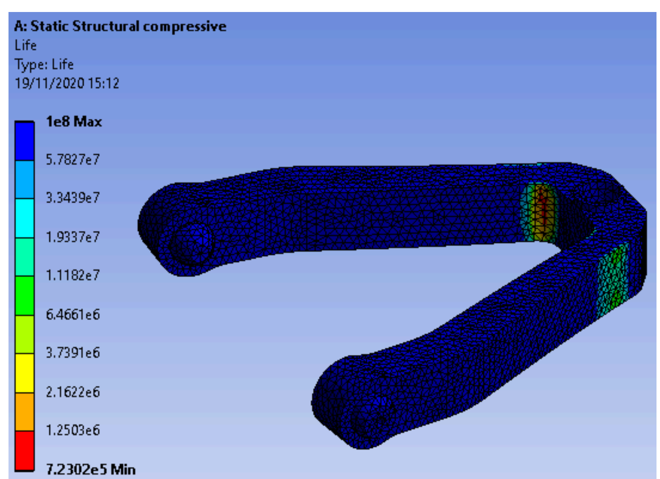
Above is the compressive and bending stress safety factor analysis results from ANSYS. It is evident that the compressive load has a much larger impact on the structure than the bending load. The compressive load causes the safety factor to drop to a value of 1.3002 whilst under bending forces the safety factor only drops to 4.8052.



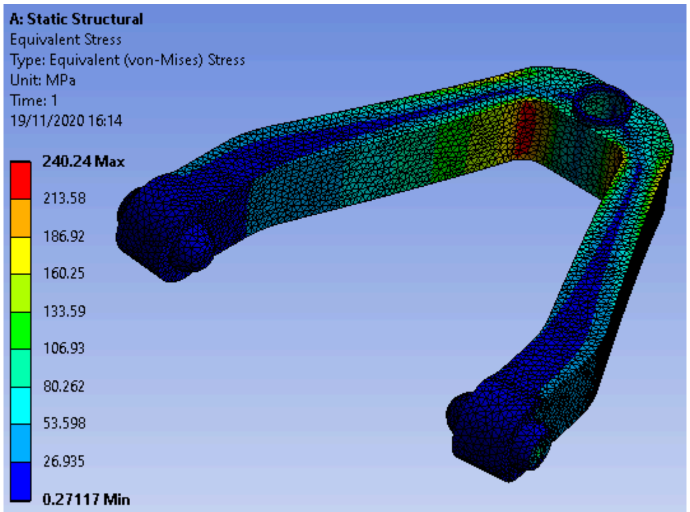


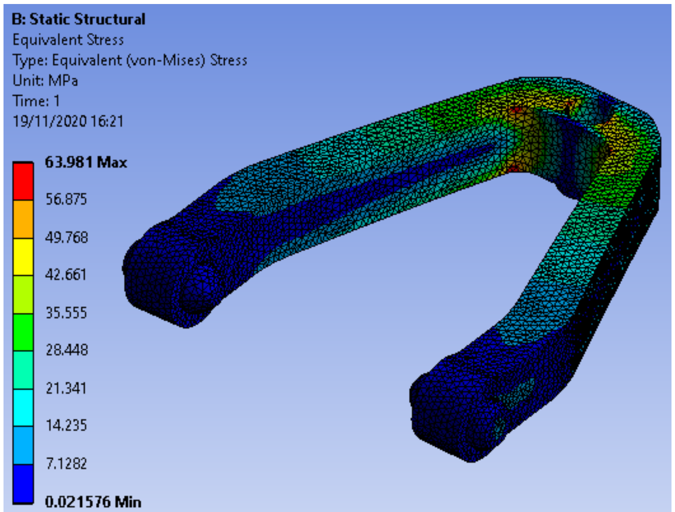
The figures above show the safety factor under compressive loads(left) and under bending loads(right) of the aluminium wishbone. The safety factor of the aluminum model is very low under compressive loads. As visible, a relatively low safety factor is present on the majority of the cross-section. Alternatively, bending loads of this magnitude do not have a great effect on the wishbone. As visible, the safety factor is quite high due to the mechanical properties of this aluminium-6 alloy.

The fatigue life of the aluminum model has a very high fatigue life of 7.2302E+5 cycles. As visible, most of the part does not exhibit much degradation due to fatigue and this may be due to the extreme strength and hardness of the aluminium-6 alloy. Majorly, the effect of the loads concentrates in the bent section and yet the metal is able to provide a relatively high fatigue life. This is very ideal for a Formula Student team, furthermore with such a high fatigue life, further topological optimizations are also possible.

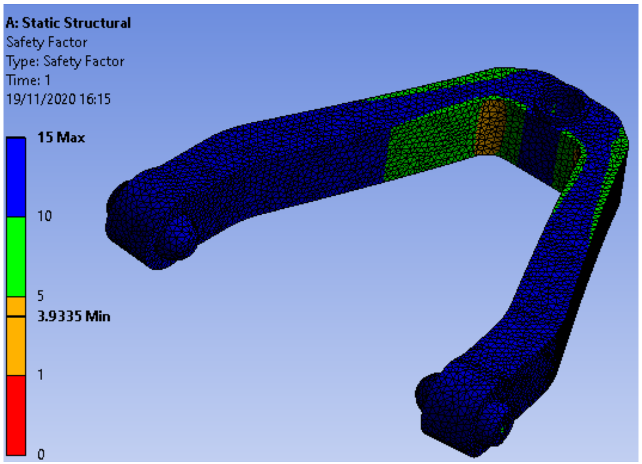


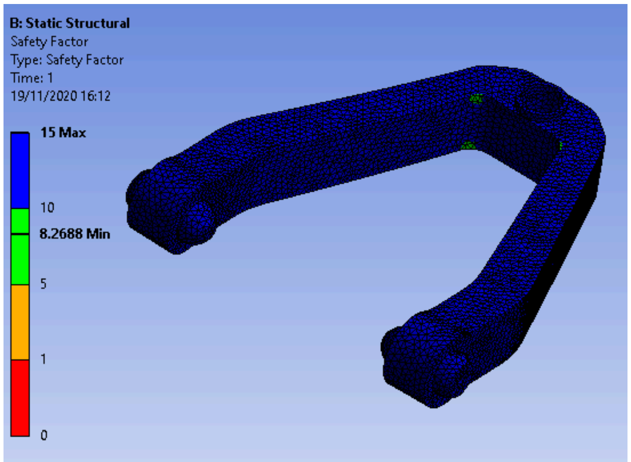
Carbon Fiber Epoxy (230gm):



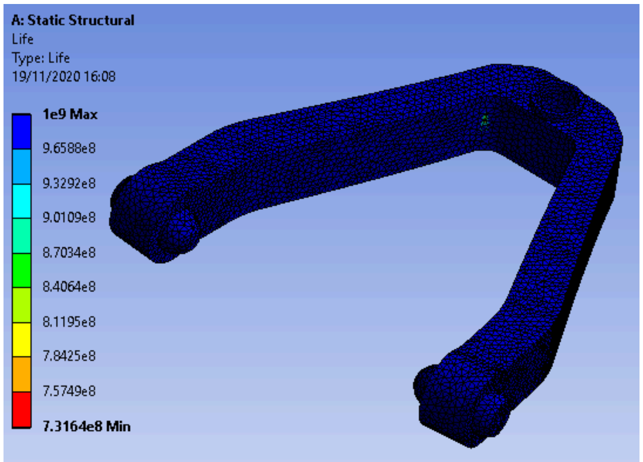


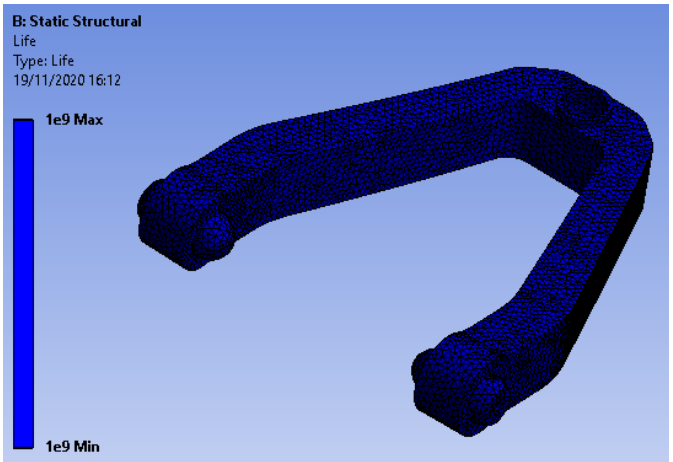
Static structural analysis of Carbon Fiber Epoxy wishbone upper arm, yields similar equivalent stresses compared to Aluminum alloy and steel wishbone arm. The maximum stress was 240.42Mpa for the compressive load (during acceleration/braking) and 63.9Mpa for bending load (During turning). Moreover, the stress concentration remains at the same area for all Wishbone Arm (CFRP, Aluminium, and steel).





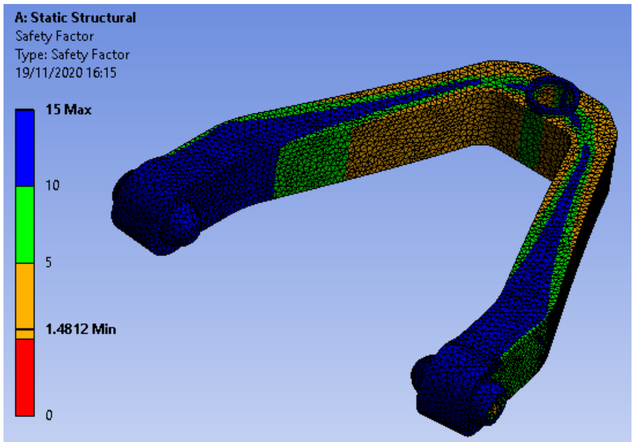
The safety factor can be mathematically defined as the ratio between the ultimate yield stress and the maximum equivalent stress. Using the ANSYS stress tool for static analysis of Carbon Fiber Epoxy - composite wishbone arm suggested a considerable improvement in the wishbone arm's structural strength. The safety factor for a wishbone arm of carbon fiber epoxy fiber was about 3.93 for compressive load and 8.26 for the bending load, which provides higher safety of margins. A wishbone made up of carbon fiber epoxy composite can withstand higher loading conditions and survive in a crash where the load on the wishbone arm may exceed 9000N.





The component's fatigue life has dramatically improved, observed through the simulation of Carbon fiber Epoxy- wishbone arm under fluting load (zero-based)—the minimum fatigue life of the wishbone arm when under compressive load is 7.3E+8. The wishbone arm will not fail under fluctuating load; hence the team can reliably use it for a long time, saving valuable cost. Like other materials, the fatigue life of the component under bending load is unresponsive, however, it may exhibit fatigue failure at an extremely high number of cycles.

By analyzing the factor of safety for carbon fiber epoxy - wishbone arm under fluctuating load using the fatigue tool, we observed that no area of the component is racing under one, providing the team margin to decrease and optimize the design further. The minimum safety of the factor obtained was 1.48.



Result and Discussion:

All results and data including the safety of factor, equivalent stress, and fatigue life, obtained from the simulation of the upper wishbone arm made up of Aluminium alloy, steel, and Carbon fiber Epoxy composite have been presented in a tabulated form. It also includes an estimate for the mass for each component and its manufacturing cost.

Material	Mode of Force	Max Equivalent Stress (MPa)	Stress Tool Safety Factor	Fatigue Safety Factor	Fatigue life (Min.)	Mass (kg)	Estimated Cost (Including manufacturing cost)
Steel	Compressive	238.13	1.9317	0.7002	1.3281E+5	5.25 kg	400+1440
	Bending	64.518	7.1297	2.5843	1E+9		
Al-6061 T6	Compressive	238.43	1.3002	0.6506	7.2303E+5	1.85 kg	620+1800
	Bending	64.513	4.8052	2.4045	1E+9		
Carbon Fiber	Compressive	240.24	2.760	0.940	7.316E+8	1.29 kg	1500+3000
	Bending	63.981	8.268	7.230	1E+9		

From the simulations of the wishbone using different materials, several comparisons can be made for analysis. All three materials used for the analysis of the wishbone proved to be operational under the specified loads. Static loading of the wishbone can be compared using the stress safety factor. A higher stress safety factor allows for further optimization and a greater margin of safety is available. It was evident that the compressive stresses had a larger impact on the wishbone. Overall, aluminium showed the lowest safety factor values both under bending and compressive loads of 4.8052 and 1.3002 respectively. Whereas, the highest values were noticed in the Carbon Fibre wishbone with a stress safety factor of 2.760 under compressive forces and 8.268 under bending forces. The steel wishbone also showed similar results to the carbon fiber counterpart.

Another aspect that was analyzed was the effect of fluctuating load. The fluctuating load on the different wishbones can be analyzed using the fatigue safety factor and the overall fatigue life. From the simulations, it was evident that the Steel and Aluminium wishbones performed at a similar level, with steel providing a slightly better fatigue safety factor and aluminium providing a moderately higher fatigue life under compressive loads. A fractionally better fatigue factor of safety of 0.940 under compressive load was noticed with the Carbon Fibre wishbone. However, under bending loads, the carbon fiber wishbone had a massive advantage as the calculated fatigue safety factor of 7.230 was nearly three times that of steel and aluminum. Under the given bending load of 1.1kN, the fatigue life of all three components was not majorly affected. Under compressive loads, however, it was noticed that steel had the lowest fatigue life and carbon fiber had the highest fatigue life of 7.316E+8 cycles.

Furthermore, another perspective to compare the three materials can be done by looking at the difference in the overall weight of the wishbone. Carbon Fiber is known for having extremely high strength as well as being very light. ANSYS was used to determine the weight of the wishbone using each material. It was noticed that Steel had the highest value of 5.25kg, then aluminum of 1.85kg, and the lightest of all carbon fiber which had a weight of 1.29kg. From this data, an overall weight reduction of 65% is calculated when aluminum is used instead of steel and a weight reduction of over 70% was noticed with the carbon fiber wishbone. Lastly, between aluminum and carbon fiber a weight reduction of 30% is calculated.

Conclusion

The analysis of the wishbone upper arm of Steel, Aluminium alloy, and Carbon fiber Epoxy (230gm) using ANSYS indicated that all the aforementioned materials are safe to use under static and fluctuating loads. Each material has its advantages and limitations. However, the strength under a compressive and fluctuating load of the wishbone made up of Carbon Fiber Epoxy was greatest among other materials. Moreover, it experiences no fatigue fracture up to a high number of loading cycles. Furthermore, using carbon fiber epoxy as material also leads to a 65% reduction of the wishbone arm's weight compared to aluminum and steel. However, the manufacturing cost for the wishbone arm of composite material is considerably larger than other materials.

Future Improvements in Study

There are aspects of this study that can be improved upon with the use of more professional software. The fatigue analysis of a carbon fiber component is extremely complex as there are multiple variables involved. The singular fiber strains can get damaged which can cause slow degradation of the whole component. With further probabilistic analysis, the individual strain rupture may be simulated allowing for a more accurate result. Another major challenge that can be overcome is the inclusion of the properties of the epoxy used to manufacture the component.

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