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Modelling and structural analysis of bicycle frame using FEA for different materials

In the latest years, because of the immoderate exploitation and growing use of petroleum for energy, present day industries and transportations are contributing to the direction of emission of exhaust gases including CO_2 *and inflicting international warming. Bicycle is very environmentally friendly, safe, and efficient way of conveyance among the man powered vehicles and are a form of exercise with many other applications and advantages, the bicycle industries are promoting them as green products. The frame is the main component in a bicycle to support the external loads acting on it. As all the important accessories are mounted on the frame, different kinds of masses along with weight of rider, braking force, and the response from floor are immediately transferred to it. The frame needs to be strong, stiff, and lighter in weight, that is acquired through combining extraordinary substances and optimizing its structures. In this paper, the static, dynamic and fatigue evaluation of a bicycle frame is achieved to decide the life of frame, deformation, stresses, and von-misses stress appearing at the frame under loading circumstances for different materials. The frame modelling carried using CATIA V5R20 and simulation performed by ANSYS 19.0 Workbench software. From the analysis it is found that for all the cases the maximum stress is less than yield strength of selected materials, so the design is safe.*

Keywords: (Finite element analysis) FEA, bicycle frame, CATIA, ANSYS.

1.0 Introduction

The bicycle frame is a central system to assist and locate the various components of the bicycle, which includes a chain drive device, a handlebar and a steering device, a set of pedals and a seat. To achieve a very good performance of the bicycle it is necessary to meet various conditions such as stability, ride quality, ergonomics for the cyclist and so on. Bicycles are regarded as excellent in view of increasing environmental pollution and fuel price. This will be maintained at a low cost. Since, their inception bicycles have supplied society with a source of transportation, exercise, recreation, and sport. Modern bicycle frames are typically influenced through stiffness and weight concerns and frequently contain the usage of excessive overall performance engineering substances. Competitive cycling has encouraged the use of a variety of improved structural materials, including non-ferrous metals (e.g., aluminum and titanium) and reinforced plastics (such as carbon and graphite reinforced epoxies).

The research M.A. Maleque et.al [1] of covers the creation of a material selection technique as well as deciding on the suitable material for the use of a folding bicycle frame. For material selection, two approaches are presented: one cost per unit of property and second digital logic methods. Only strength is evaluated in a cost per unit technique, but in a digital logic method, various characteristics such as yield strength, tensile strength, and Young's modulus are considered for material selection. Aparna Deshpande et.al [2] have discussed that structural design of frame and the weight optimization are the very important aspects for the optimization of bicycle performance. In this study modal analysis is done for composite material for the optimization of design of frame structure using FEA. Nikhil Y Patil et.al [3] have dealt with structural analysis of folding frame using FEM, the stress analysis is done for 3 different loading conditions like horizontal, vertical, and impact loading for aluminium, titanium, and carbon fiber. Result shows that the maximum stress occurs at front and rear fork part of frame structure which is finalized as failure location for further design optimization. Xiang zhongxia et al. [4] have taken into account the examination of bikes in various riding situations. The stress distributions based on simulation outcomes for various riding conditions differ from the stress distribution based on testing standards. As a result, the development of a cycle testing standard is required. M.S. Sani et al. [5] used FEM analysis and experimental analysis, the dynamic characteristics and modal analysis for a bicycle frame determination. The study finds that experimental modal

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analysis or finite element analysis may be used to compute modal characteristics. Chien-cheng et al. [6] in their work structural analysis and optimization of design for various frame types are mentioned. The diamond-shaped frame was the stiffest. The construction has great stiffness because the centerlines of the bottom and top tubes connect with the head tube. Derek covill et al. [7] performed FEA on the behaviour of the bicycle frame under various loads, such as bumps in the road at front wheel, bumps in the road at the rear wheel, climbing into the saddle, and climbing out of the saddle. More load scenarios were investigated as a result of this research to better understand the relationship between tube shapes and frame toughness. Alexandre callens et al. [8] in their research carried out fatigue experiments on tubular T joint specimens used to develop the S-N curve. Multiaxial stresses in crucial regions of bicycle frames might be investigated more readily this way. Derek Covill et.al [9] have discussed bicycle frame finite element analysis. They has done the finite element model as using beam type element for characterizing a typical road frame and carry out FEA of frame. This finite element model was exposed to two typical loading situations in order to better understand the vertical conformity and lateral stiffness characteristics of the provided bicycle frame construction and to assess these characteristics under these conditions. Nair Ajit et.al [10], “Design and analysis of mountain bike frame” studied a bicycle frame was modelled and perform FEA, structural static and dynamic analysis under different loading conditions such as a bump on road at front and rear wheel and climb whilst seated and not seated in saddle for road and off road for magnesium alloy. Horizontal loading test and vertical loading test are made, and they concluded that the model is suited for off road conditions and best in on road conditions. Rajeev Gupta et.al [11] have discussed a mountain bicycle frame analysis which was done by using FEM for Al 6061- T6 and Al 7005 T-6 are materials and the load cases applied were five times individually. Comparative study was made, FOS for Al 6061<Al 7005, increasing frequency Al 6061<Al 7005, and increasing deformation Al 7005<Al 6061 for all load cases. V. Kausalyah et.al [12], in their study on dynamic analysis of a cross country mountain bike frame was done with different rider loading and different materials such as aluminum, titanium, and carbon fiber and various stresses and frequencies were recorded. The load was distributed in several point age on seat, paddle, and handle. A load of 150kg was considered to study the extreme rider weight. The study indicated the highest stress values with 2.32% improvement in stresses with the aluminum frame and 0.65% for the carbon fiber frame. Arun Sam Varghese et.al [13], discussed the strength values of the T300 carbon/epoxy composite used in their study. This study proposes an optimized ply design for various loading conditions based on maximum stress criteria. Individual ply failure is considered, and ply failure is identified when a failure index value is greater than one. Bharati et.al [14], has discussed the FEA of various designs of bicycle frame. In this paper they talked about, the analysis of avon falcon size bicycle frame which was done under start up, pedaling, and vertical impact conditions using steel as material and concluded the stress induced in frame of avon falcon is least and FOS is also well above the limit and equivalent stress is less than ultimate stress of the material, so that the design is sturdy. Devaiah B.B et.al [15], in their paper, a cycle frame model was designed, and static structural analysis is done using steel as material under various loads and analyzed stress induced in each tube of the frame. All stresses were obtained to be far below material’s yield stress, and outcomes were found to match well with the theoretical results. In earlier work, Venkatesha B K et al. [16-17] studied the numerical analysis of damage tolerance design. Fatigue crack growth rate and stress intensity factor range was estimated with Paris law of damage crack growth.

2.0 Materials and methods

The methodology section shows a flowchart that shows how the frame was designed and analyzed depending on the requirements. The methodology used here consists of modelling of frame is done in CATIA V5R20 software and finite element analysis using ANSYS 19.0 software. CATIA is designed software that allows to create and modify things as shown in Fig.1. The process of designing a new object or changing an existing one is known as design. The depiction or idea of an object is referred to as drafting. Modelling is the process of converting a two-dimensional model into a three-dimensional model.

2.1 Material Selection

The material used in design is determined by several criteria, including load, function, climatic conditions, lifespan, and estimated cost. Material selection was done with the above aspects kept in mind in order to build a frame that was both efficient and affordable. During the selection process, steel, aluminum 6061 T6 and T700s carbon fiber were preferred.

2.2 CAD Modelling

All tubes are given a consistent thickness of 1mm; with a radius of 4mm maintained at all tube junctions [15]. The single and collective drawings of the bicycle frame are made using the CATIA V5 software. The model was created in CATIA software as shown in Fig.2. Table 2 describes the dimensions of cycle frame.

Table 1: Material properties

Materials	Density (kg/m^3)	Poisson’s ratio	Young’s modulus (N/m^2)
Steel	7850	0.3	$2*10^{11}$
Aluminium 6061 T6	2600	0.33	$6.89*10^{10}$
T700s carbon fiber	1800	0.2	$2.3*10^{11}$

TABLE 2: DIMENSIONS OF CYCLE FRAME

Geometry	Dimensions
Top tube length	567 mm
Top tube OD	32 mm
Head tube length	125 mm
Head tube OD	38 mm
Seat tube length	540 mm
Seat tube OD	33 mm
Down tube length	620 mm
Down tube OD	33 mm
Seat stays length	494 mm
Seat stays OD	19 mm
Chain stays length	417 mm
Chain stays OD	19 mm
Head tube angle	69°
Seat tube angle	73°

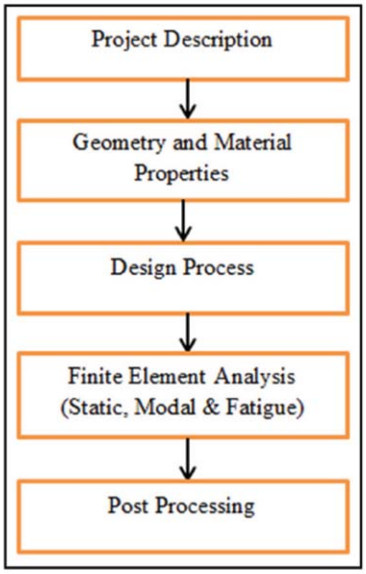


Fig.1: Product design methodology

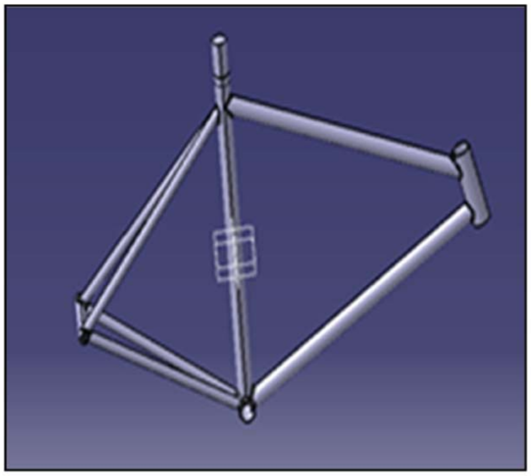


Fig.2: CAD model

2.3 LOAD CALCULATIONS

The following calculations are performed by considering the gravitational force (g) acts [16],

- Rider weight : 100 Kg
- Impact load : (m*g) = 100*9.81= 981 N

2.4 FINITE ELEMENT ANALYSIS

2.4.1 Meshing and boundary conditions

The finite element model consists of 97797 nodes and 51640 triangular elements. A force of 981 N was applied on the saddle post so that the force was axially downward direction to the seat tube. The boundary conditions applied to the head tube, rare wheel fork and pedal stay as fixed support conditions.

2.4.2 Static analysis

It is the most basic and widely used type of analysis. It only shows a single unbroken element with a red colour zone at the failure location. By comparing the maximum stress value with the yield or ultimate strength, the component can be considered as safe or not.

2.4.3 Modal analysis

The dynamic characteristics of a structure under vibrational excitation are studied using modal analysis. Model analysis helps to determine a natural frequencies and mode shapes and mode deformations.

2.4.4 Fatigue analysis

When structural components are subjected to external loads fluctuating in time, the inner stresses induced in the component can cause fatigue failure. This analysis assists to recognize the life of design, damage, and safety factor.

3.0 Results and discussion

This section describes the results of weight of the bicycle frames, static structural analysis, model analysis, and fatigue analysis.

3.1 WEIGHT OF BICYCLE FRAMES

The bicycle frame designed with different material properties were used to check the different weight for the same frame. Table 3 describes the weight of frame for different alloys used. The frame with T700s carbon fiber having low weight compared to other two materials.

3.2 STATIC ANALYSIS

The static analysis was carried out for the steel, aluminum 6061 T6 and T700s carbon fiber in order to check the different

TABLE 3: WEIGHT OF FRAME FOR DIFFERENT ALLOYS

Materials	Weight of frame (kg)
Steel	28.088
Aluminium 6061 T6	9.3032
T700s carbon fiber	6.4407

changes in the equivalent stress and total deformation. Figs.3, 4 and 5 represents the stress plot for steel, aluminum 6061 T6, and T700s carbon fiber, respectively. Similarly Figs.6, 7 and 8 represents the displacement plot for steel, aluminum 6061 T6, and T700s carbon fiber, respectively.

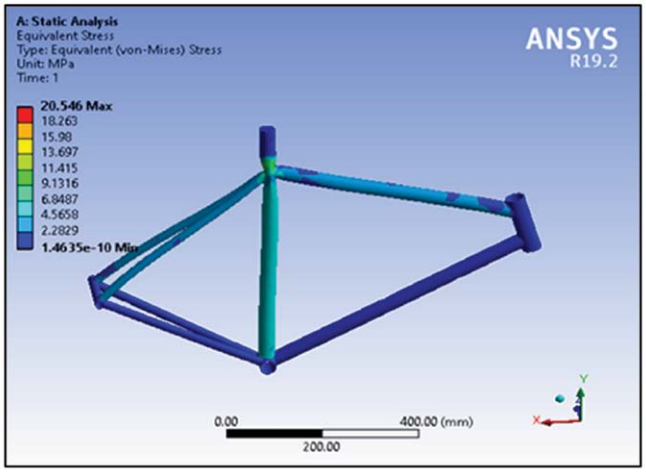


Fig.3: Stress plot for steel

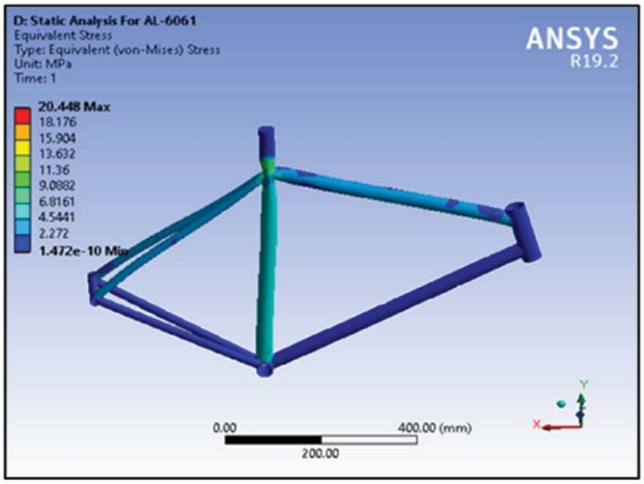


Fig.4: Stress plot for aluminum 6061 T6

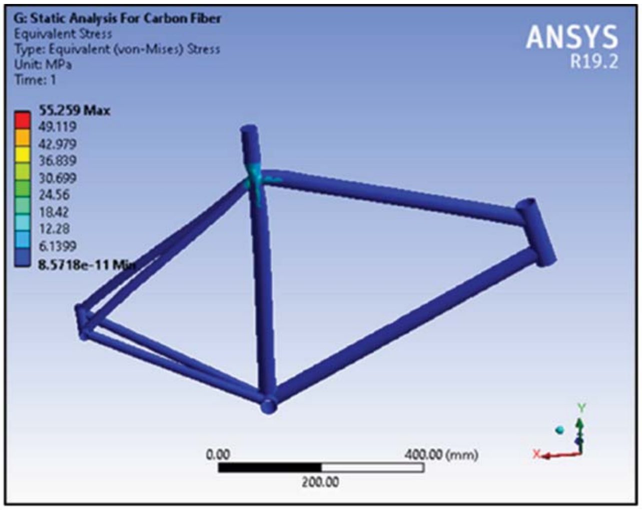


Fig.5: Stress plot for T700s carbon fiber

TABLE 4: RESULTS OF STATIC ANALYSIS FOR DIFFERENT MATERIALS

Materials	Total deformation (mm)	Equivalent Stress (MPa)
Steel	0.017543	20.546
Aluminum 6061 T6	0.050837	20.448
T700s Carbon fiber	0.13185	55.259

The results of static analysis are shown in the Table 4. We can observe from Table 4, carbon fiber has better equivalent stress when compared to other materials.

3.3 MODAL ANALYSIS

Based on the equivalent stress obtained from static analysis, further model analysis was carried out in order to determine different modal deformation for different frequencies for the results of natural frequencies and deformations of model analysis. Different dodes of 1, 2, 3, 4, 5 and 6 for steel, aluminum 6061 T6, and T700s carbon fiber, respectively are shown from Figs.9 to 26.

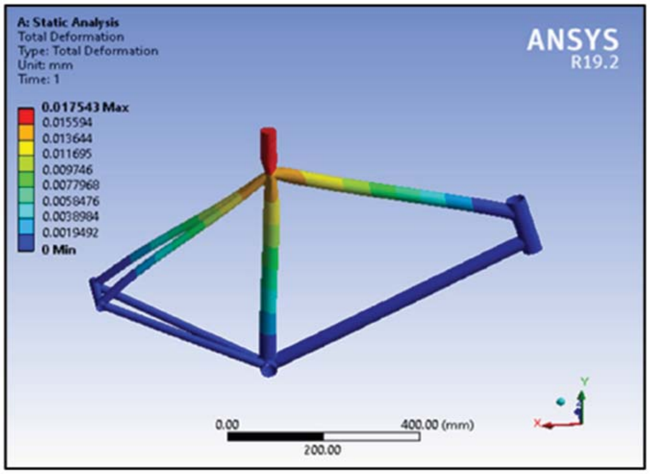


Fig.6: Displacement plot for steel

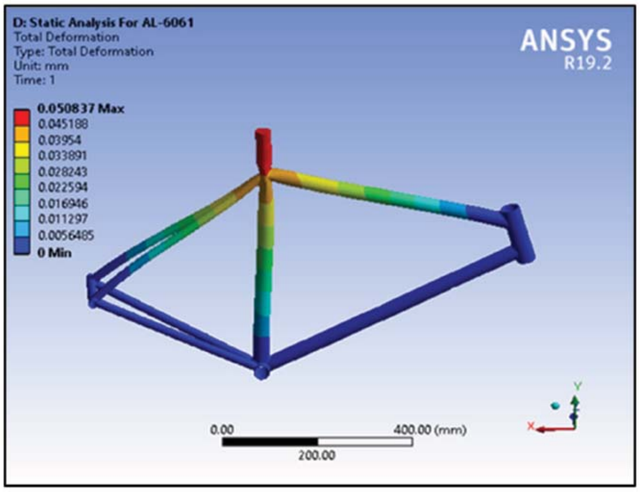


Fig.7: Displacement plot for aluminum 6061 T6

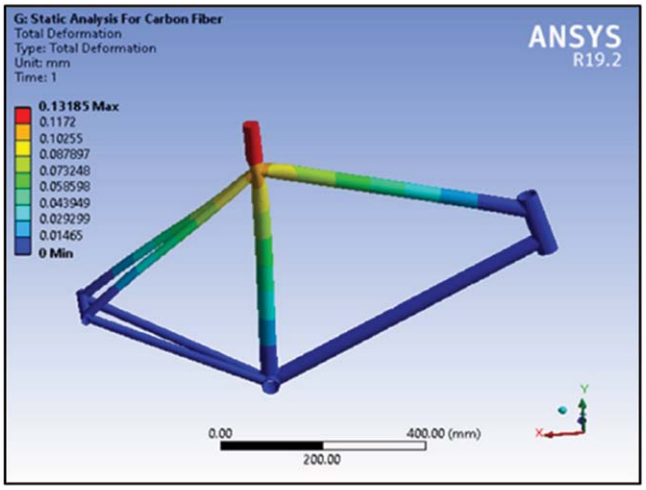


Fig.8: Displacement plot for T700s carbon fiber

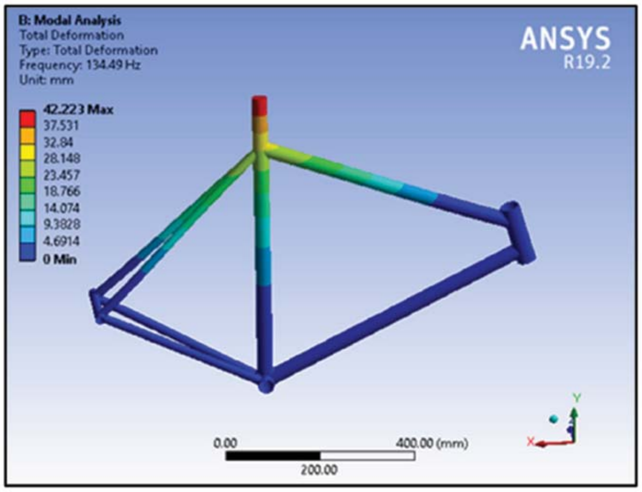


Fig.9: Mode 1 for steel

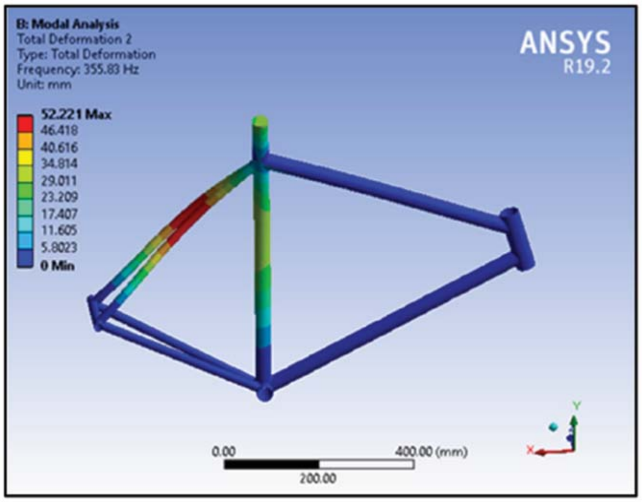


Fig.10: Mode 2 for steel

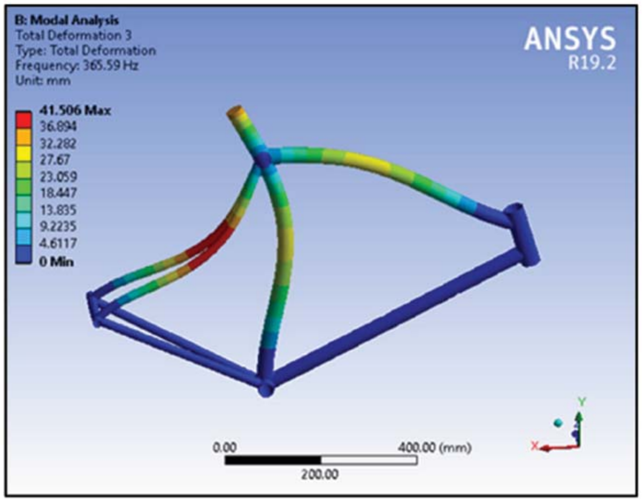


Fig.11: Mode 3 for steel

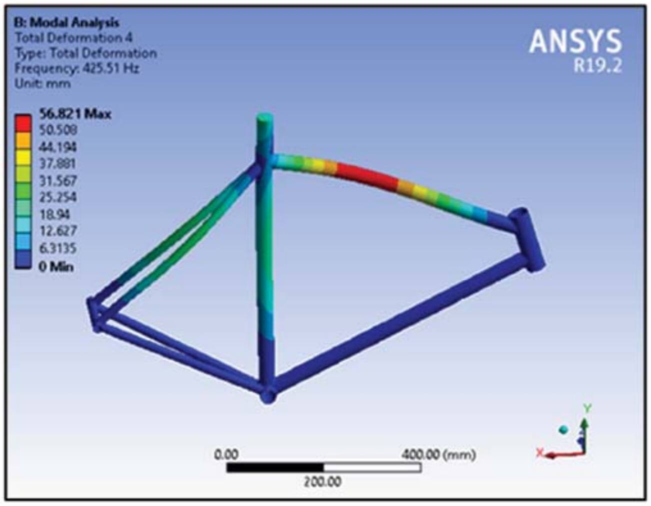


Fig.12: Mode 4 for steel

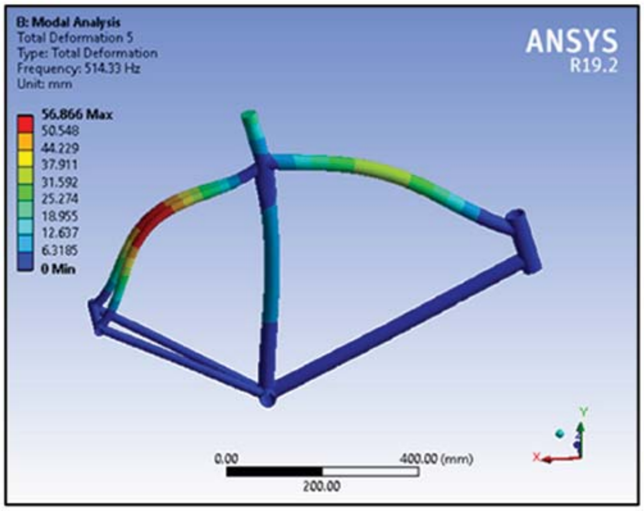
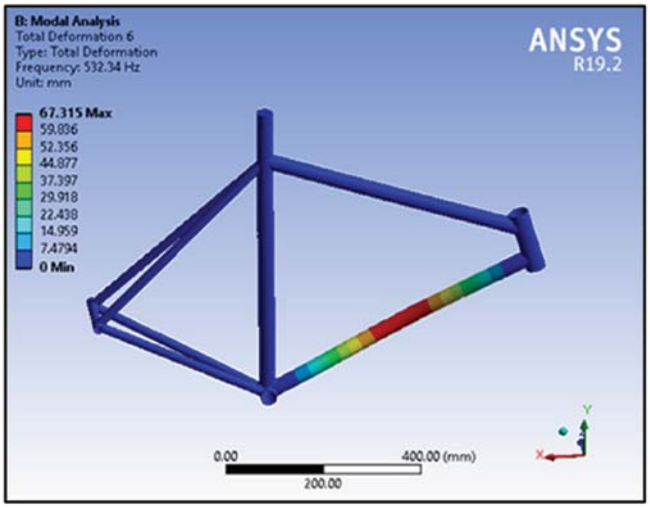
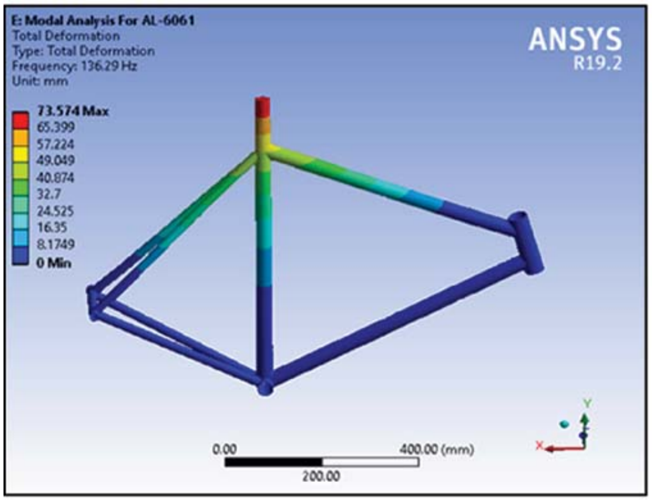


Fig.13: Mode 5 for steel



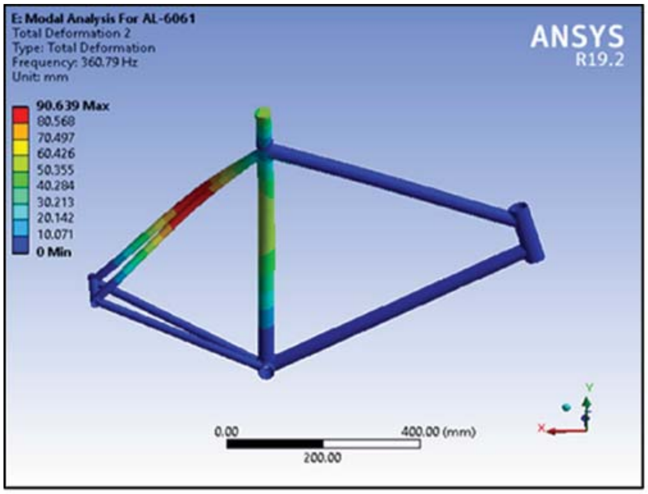
B: Modal Analysis
Total Deformation 6
Type: Total Deformation
Frequency: 532.34 Hz
Unit: mm

Fig.14: Mode 6 for steel



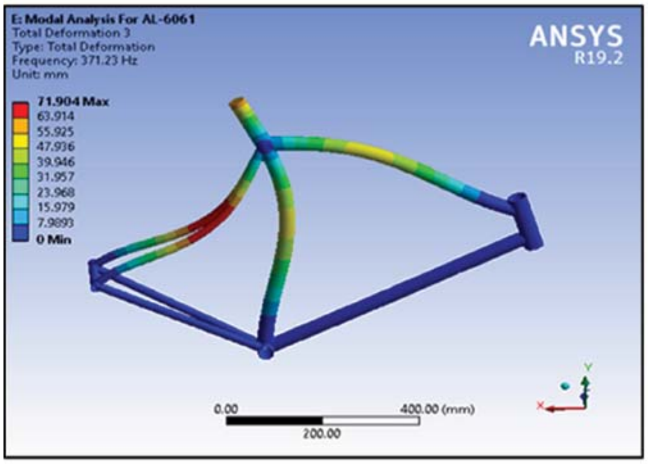
E: Modal Analysis For AL-6061
Total Deformation
Type: Total Deformation
Frequency: 136.29 Hz
Unit: mm

Fig.15: Mode 1 for aluminum 6061 T6



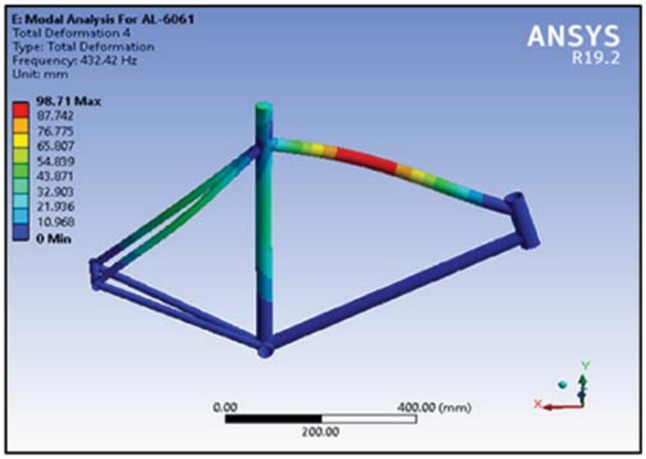
E: Modal Analysis For AL-6061
Total Deformation 2
Type: Total Deformation
Frequency: 360.79 Hz
Unit: mm

Fig.16: Mode 2 for aluminum 6061 T6



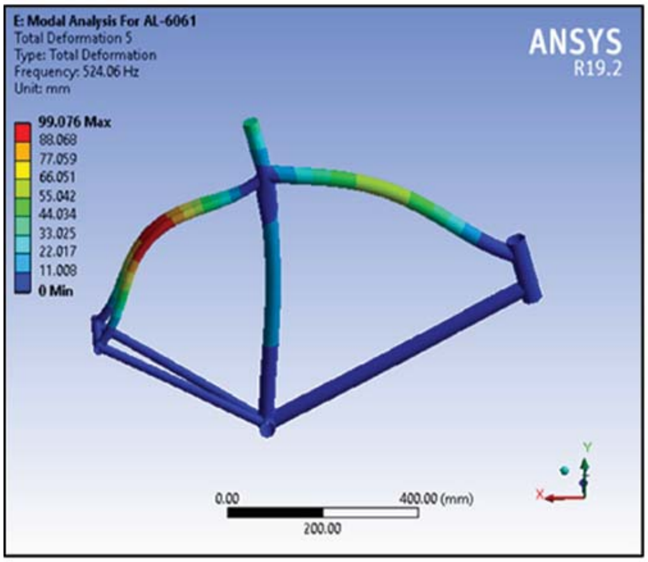
E: Modal Analysis For AL-6061
Total Deformation 3
Type: Total Deformation
Frequency: 371.23 Hz
Unit: mm

Fig.17: Mode 3 for aluminum 6061 T6



E: Modal Analysis For AL-6061
Total Deformation 4
Type: Total Deformation
Frequency: 432.42 Hz
Unit: mm

Fig.18: Mode 4 for aluminum 6061 T6



E: Modal Analysis For AL-6061
Total Deformation 5
Type: Total Deformation
Frequency: 524.06 Hz
Unit: mm

Fig.19: Mode 5 for aluminum 6061 T6

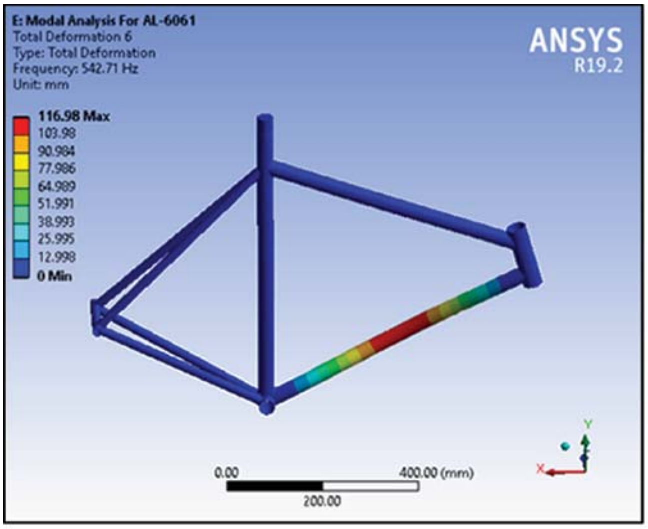


Fig.20: Mode 6 for aluminum 6061 T6

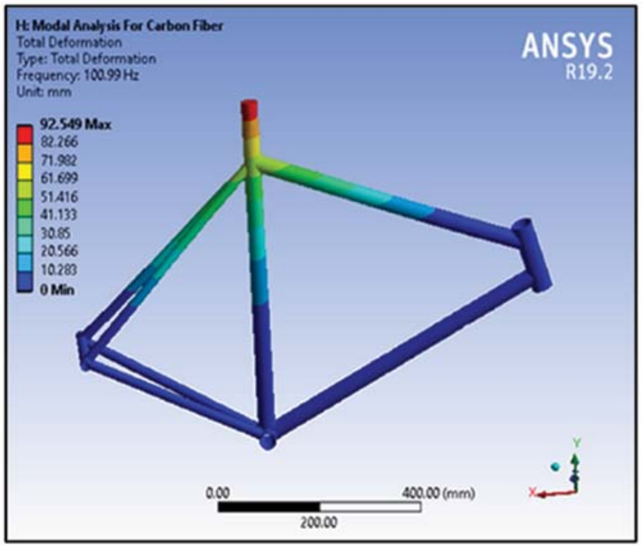


Fig.21: Mode 1 for T700s carbon fiber

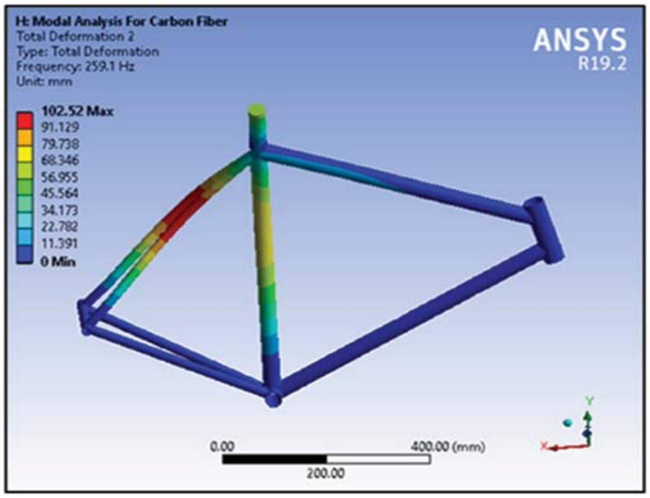


Fig.22: Mode 2 for T700s carbon fiber

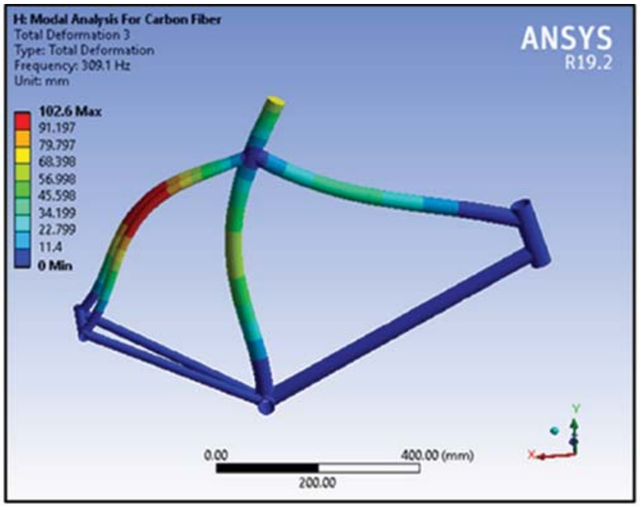


Fig.23: Mode 3 for T700s carbon fiber

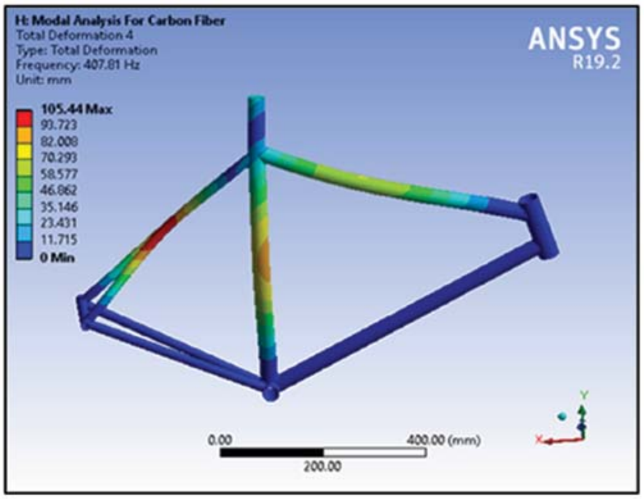


Fig.24: Mode 4 for T700s carbon fiber

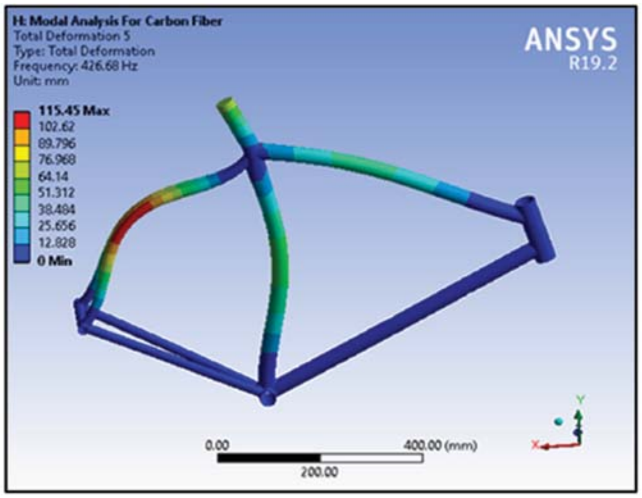


Fig.25: Mode 5 for T700s carbon fiber

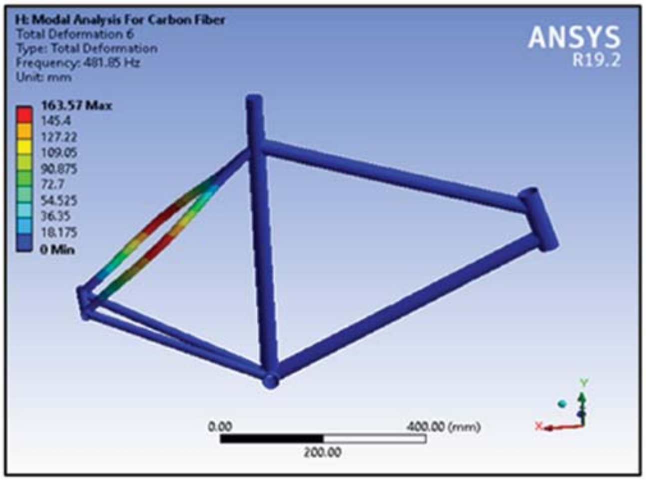


Fig.26: Mode 6 for T700s carbon fiber

The results of modal analysis are shown in the Table 5 for steel, aluminium 6061 T6 and T700s carbon fiber, respectively. From Table 5, the maximum natural frequency, and deformation was observed in 6th mode of T700s carbon fiber and the minimum natural frequency, and deformation was observed in 1st mode of steel.

3.4 FATIGUE ANALYSIS

Based on equivalent stresses and deformation, further fatigue analysis was conducted to determine the life of model and the safety factor.

TABLE 5: NATURAL FREQUENCY AND DEFORMATIONS FOR STEEL

Modes	Natural frequency (Hz)	Deformations (mm)
	Steel	
Mode 1	134.49	42.223
Mode 2	355.83	52.221
Mode 3	365.59	41.506
Mode 4	425.51	56.821
Mode 5	514.33	58.886
Mode 6	532.34	67.315
	Aluminum 6061 T6	
Mode 1	136.29	73.574
Mode 2	360.79	90.639
Mode 3	371.23	71.904
Mode 4	432.42	98.71
Mode 5	524.06	99.076
Mode 6	542.71	116.98
	T700s carbon fiber	
Mode 1	100.99	92.549
Mode 2	259.1	102.52
Mode 3	309.1	102.6
Mode 4	407.81	105.44
Mode 5	426.68	115.45
Mode 6	481.85	163.57

Figs.27, 28 and 29 represent the fatigue life for steel, aluminum 6061 T6, and T700s carbon fiber, respectively. Similarly Figs.30, 31 and 32 represents the safety factor for steel, aluminum 6061 T6, and T700s carbon fiber, respectively.

The results of fatigue analysis for steel, aluminum 6061 T6, and T700s carbon fiber are shown in Table 6. From the Table 6, the material T700s carbon fiber has a better life and safety factor as compared with steel and aluminium 6061 T-6 for the bicycle frame.

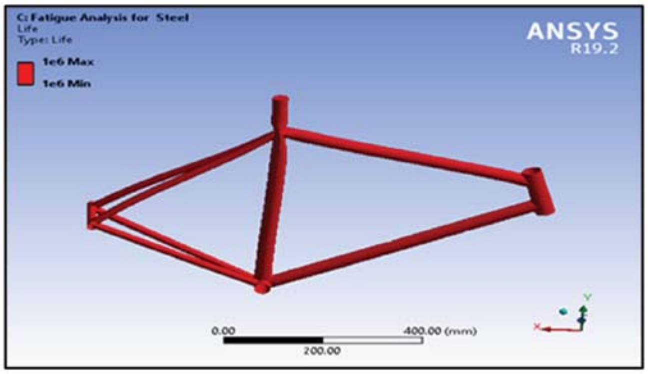


Fig.27: Fatigue life for steel

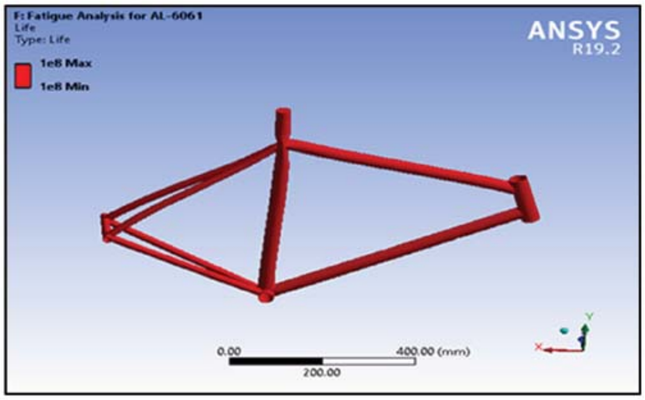


Fig.28: Fatigue life for aluminum 6061 T6

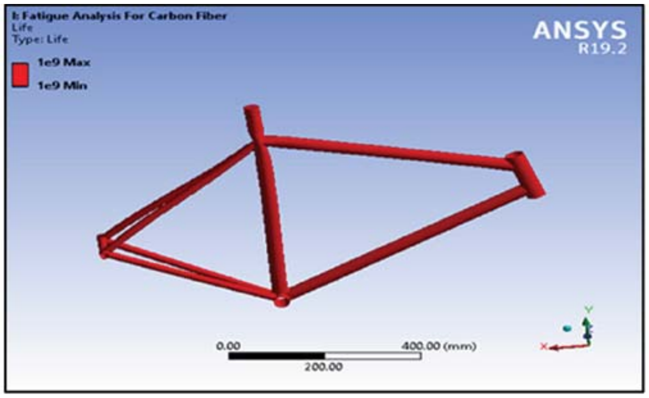


Fig.29: Fatigue life for T700s carbon fiber

TABLE 6: FATIGUE LIFE AND SAFETY FACTORS

Materials	Life	Safety factor
Steel	$1* 10^6$	4.1954
Aluminium 6061 T6	$1* 10^8$	4.0463
T700s carbon fiber	$1* 10^9$	15

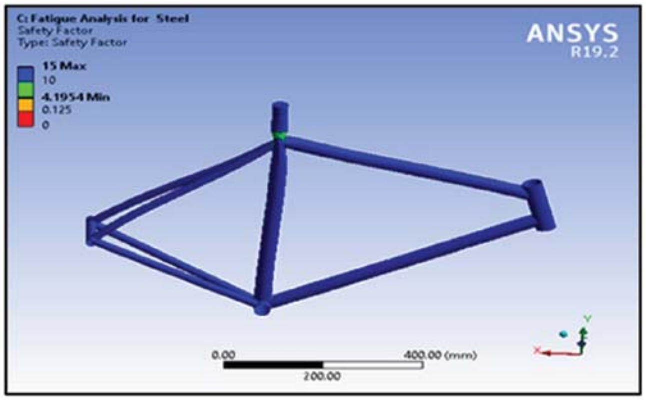


Fig.30: Safety factor for steel

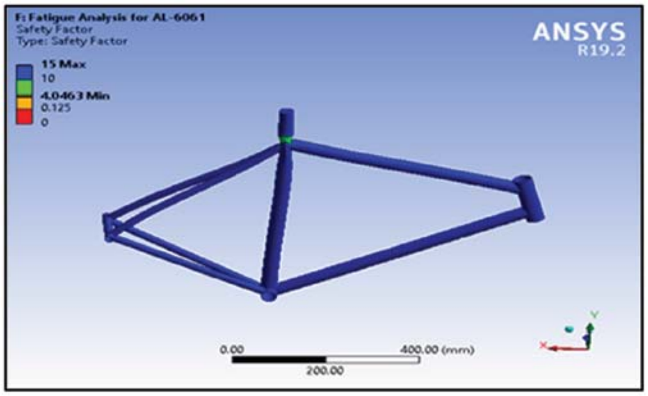


Fig.31: Safety factor for aluminum 6061 T6

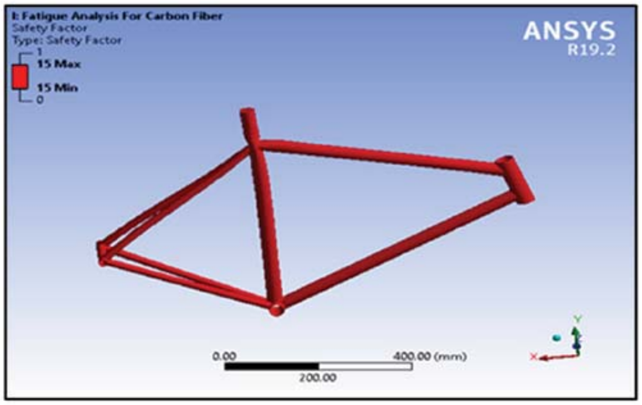


Fig.32: Safety factor for T700s carbon fiber

4.0 Conclusions

In actual existence scenario the important concern was safety and making bicycle frame sturdy sufficient to withstand to heavy load, additionally the weight reduction and fatigue life was also a main challenge from transferring traditional bicycle frame to a modified carbon fiber frame. The following conclusions can be made as follows,

- The work discusses about the entire procedure of static, dynamic and fatigue investigation of bicycle frame for 3 materials such as steel, aluminium 6061 T6 and T700s carbon fiber. The static analysis for all the material was carried out in ANSYS 19.0 to make comparative study.
- The results for all three instances reveal that the maximum stress in all the members of bicycle frames is less than yield strength of the selected materials. Using all the results demonstrates that the overall design is safe, effective, lightweight and reliable for the needs.
- By enhancing materials properties, the bicycle frame design has considerably increased its strength and durability with decrease in its weight.
- Dynamic characteristic can be truly essential to predict behaviour of the frame.
- Among all three materials, T700s carbon fiber has greater deformation and equivalent stress and also has greater strength and stiffer than other two bicycle frames.
- The fatigue analysis was done for all the 3 selected materials, the life was better for the T700s carbon fiber among the 3 materials.
- In consideration of price, T700s carbon fiber bicycle frame is expensive but overall comparative study illustrates that the T700s carbon fiber bicycle frame is best among 3 selected materials.

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