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Design, Analysis and Manufacturing of Front Sprocket of a Bicycle using Carbon Fiber Reinforced Plastics

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Abstract. Sprocket is an essential part of a bicycle which converts rotating motion of the sprocket to linear movement of the bicycle. During operation, teeth of the sprocket mesh with the chain. Ride of a bicycle is a labour intensive process. Use of light materials parts in a bicycle instead of conventional materials can reduce a significant amount of weight, and rider need to apply lower force to drive it. In geared cycles, different sized sprockets are employed which incorporated a substantial amount of weight to it. Composite materials are very strong and lightweight materials. The strength to weight ratio of the composite materials is very high, and they are able to replace traditional metals and alloys in several applications. Along with strength, durability and lightweight, the use of composite material also improves the aesthetic look of the component. Carbon fibre reinforced plastic (CFRP) is a high strength composite material that is used abundantly in various industries. In this work, virtual and experimental analysis of CFRP bicycle sprocket was carried out. The attributes showed by the CFRP sprocket were compared with the traditional sprocket. The problems faced by the CFRP sprocket fitted bicycle in real life conditions is also documented.

1. Introduction

The invention of a bicycle has played a crucial role in the development of human civilization as well as in the industrial progress. Some of the components firstly discovered for bicycles such as ball bearings, pneumatic tyres, chain-driven sprockets and tension-spoked wheels etc. have played a significant role in the evolution of automobiles especially two-wheelers. The form and format of the bicycle also changed over time [1]. Owing to many innovatively designed parts, its ride becomes safer, comfortable and less labor-intensive than ever before. Despite the development of luxury vehicles, the bicycle has not lost its usefulness yet. Even today, bicycles are the preferred means of transportation for a large section of society. A sprocket is a profiled wheel whose periphery consists of a number of teeth. The most basic form of sprocket is found in bicycles. In a bicycle, a large sprocket is connected with the small sprocket attached to the rear tyre through a chain. Sprocket attached with a pedal shaft is employed to convert the rotating speed into linear movement. Apart from bicycles, sprockets are used in motorcycles, cars, tracked vehicles and other machineries. As per the requirements, sprockets are manufactured from various materials and their designs, dimensions and teeth numbers are different. Mountain bicycles have gear changing mechanism therefore supplementary sprockets are attached to the drivetrain. These additional sprockets added extra weight to the bicycle. Thus, weight saving is accomplished by removing the material from low stressed areas. A bicycle rider has to do excessive physical labor to cover a long distance due to the weight of the cycle. The weight of the bicycle can be reduced in a significant amount by using design modification or using lightweight



materials. Lim et al. [2] designed and studied a lightweight bicycle cassette system made up of different sprockets and a spider. The purpose of their study was to develop a lightweight and efficient cassette system for a bicycle. They performed finite element analysis on a designed cassette to evaluate the safety of the system. They found adequate results on titanium alloy sprockets. Composite materials are nonmetallic lightweight and advanced materials that are successfully replacing conventional metallic materials used in many applications. Carbon fibre reinforced plastic (CFRP) is a very strong and lightweight fiber-reinforced plastic composite that incorporates carbon fibers as a reinforcement. CFRP is being used in all types of advanced engineering structures [3]. The properties of CFRP composite depend on its fabrication method, fibre types, fibre quantity, fibre orientation, type of resin and adhesion between fibre and resin [4]. Apart from many advantages, it is also true that CFRP composite is an orthotropic material and its strength strongly depends on the fiber orientation [5]. Therefore, to obtain the desired strength and stiffness from CFRP in a particular application, the layer orientation of the fibers are arranged accordingly during the composite fabrication process [6]. The production cost of metallic sprockets is high because of many machining operations involved. Apart from that, the maintenance cost, as well as the weight of the part, is also high. On the other hand, the CFRP composite sprocket is not only lightweight and maintenance free but also a suitable material for the economic point of view. The selection of CFRP composite would reduce the weight of the sprocket effectively with no compromise of its strength as well as aesthetic look. The operation of the bicycle would be smooth and low power consuming as the weight of the part would be sufficiently reduced. The noise generated during the relative motion of chain and CFRP sprocket would be very low.

In this study, virtual and experimental analysis of CFRP composite sprocket was performed. The properties of a newly developed CFRP composite sprocket was correlated with that of the commercial cold rolled carbon (CRC) steel sprocket, and the improved attributes and possible problems were discussed by testing it in real life conditions.

2. Experimental Procedure

2.1. Materials

The reference sprocket used in the present investigation was the front sprocket of a Neelam Bold cycle of 180 mm diameter, 3.2 mm thickness and consist of 48 teeth. The epoxy resin used for the fabrication of CFRP composite was procured from Huntsman Corporation Ltd. It was a blend of epoxy resin (Araldite LY1564) and hardener agent (Aradur 22962 (cycloaliphatic polyamine)) mixed in 4:1 (by weight). The reinforcement, i.e. plain carbon fiber woven fabric of 400 GSM was obtained from CF Composites. The physical and mechanical properties of matrix and reinforcement are listed in Table 1.

Table 1. Mechanical and physical properties of the composite constituents

Materials	Tensile Strength (MPa)	Young Modulus (GPa)	Density (g/cm ³)
Epoxy resin	75-80	2.8-3.3	1.1-1.2
Carbon Fiber	2500	240	1.9

2.2. Calculations for Sprocket Design

The parameters like chain pitch (P), number of teeth (N) and roller diameter (Dr) were obtained directly from reference sprocket (mentioned in section 2.1) which is required for solid modeling of the sprocket in CATIA. The sprocket tooth was designed as per the industry standard using the formulas listed in Table 2. The formulas were adopted from the reference [7]. Figure 1 exhibits the sketch of the sprocket tooth design. In this figure, the description of the dimensions necessary for the design of the teeth is also mentioned.

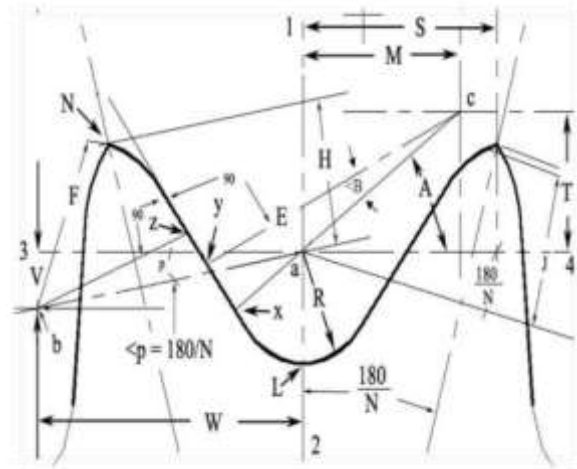


Figure 1. Sprocket tooth geometry [7]

Table 2. Formula for sprocket tooth design [7]

$P = \text{Chain pitch} = 0.5 \text{ inch}$	$E = 1.3025Dr + 0.0015$
$N = \text{Number of teeth} = 48$	Chordal length of arc xy $= (2.605Dr + 0.003) \sin\left(9^\circ - \frac{28^\circ}{N}\right)$ $= 0.11945 \text{ inch}$
$Dr = \text{Roller diameter} = 0.312 \text{ inch}$	$yz = Dr\left[1.4 \sin\left(17^\circ - \frac{64^\circ}{N}\right) - 0.8 \sin\left(18^\circ - \frac{56^\circ}{N}\right)\right]$ $= 0.8164 \text{ inch}$
$Ds = (\text{Seating curve diameter})$ $= 1.0005 Dr + 0.003$ $= 0.31656 \text{ inch}$	$ab = 1.4Dr = 0.4368 \text{ inch}$
$R = \frac{Ds}{2} = 0.5025Dr + 0.0015 = 0.15828 \text{ inch}$	$W = 1.4Dr \cos \frac{180^\circ}{N} = 0.4359 \text{ inch}$
$A = 35^\circ + \frac{60^\circ}{N} = 36.25^\circ$	$V = 1.4Dr \sin \frac{180^\circ}{N} = 0.4192 \text{ inch}$
$B = 18^\circ - \frac{56^\circ}{N} = 16.84^\circ$	$F = Dr\left[0.8 \cos\left(18^\circ - \frac{56^\circ}{N}\right) + 1.4 \cos\left(17^\circ - \frac{64^\circ}{N}\right) - 1.3025\right] - 0.0015 = 0.2502 \text{ inch}$
$ac = 0.8 \times Dr = 0.2496 \text{ inch}$	$H = \sqrt{F^2 - \left(1.4Dr - \frac{P}{2}\right)^2} = 0.1665 \text{ inch}$
$M = 0.8 \times Dr \cos\left(35^\circ + \frac{60^\circ}{N}\right) = 0.2012 \text{ inch}$	$S = \frac{P}{2} \cos \frac{180^\circ}{N} + H \sin \frac{180^\circ}{N} = 0.2604 \text{ inch}$
$T = 0.8 \times Dr \sin\left(35^\circ + \frac{60^\circ}{N}\right) = 0.14759 \text{ inch}$	$PD = \frac{P}{\sin[180^\circ/N]} = 7.6449 \text{ inch}$

2.3. Virtual Analysis of CRC Steel and CFRP Composite Sprocket

A virtual model of CRC and CFRP sprocket was created in CATIA V5R21 using the dimensions mentioned in section 2.2. This model was imported and analyzed in ANSYS R19.1 software. The reference sprocket was also modelled and analyzed for the specified loading conditions for comparison purpose. After analysis, the obtained results of CRC steel and CFRP sprockets was compared. The suitability and load bearing capacity of the composite material for the quoted application was tested.

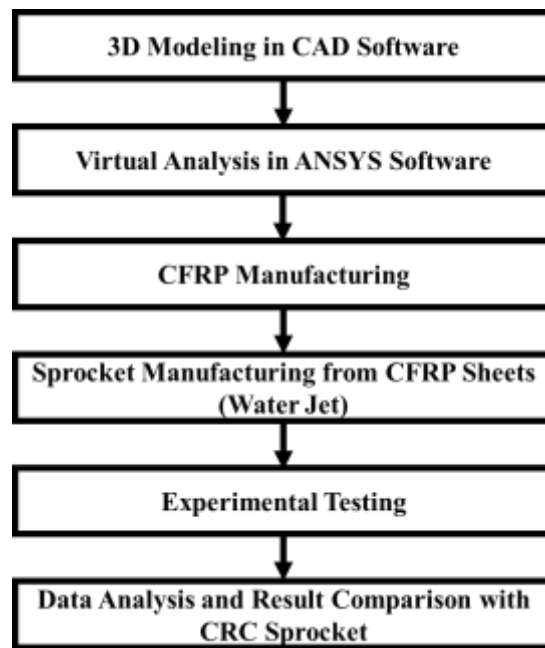


Figure 2: Schematic diagram of the work.



Figure 3. Sprocket manufacturing procedure (a) mould fabrication for sprocket (b) hand layup method of CFRP composite (c) finished composite (d) water jet machining for spline and teeth fabrication

2.4. Fabrication and Testing of CFRP Sprocket

The results obtained from the virtual analysis were also verified experimentally. For that purpose, the laminates of CFRP composite was prepared using hand layup method. The starting step of the process was to create a solid mould as per the required dimensions of the quoted component. A layer of epoxy resin was applied after the application of release agent (Waxpol) on the mould surface. The subsequent layers of carbon fiber and epoxy resin were applied concurrently. To minimize the orthotropic behaviour of carbon fiber, each layer of the carbon fiber mat is placed at a particular angle. The eight layers of carbon fiber mats were placed in the composite at 0° , 45° , 90° , 135° , 135° , 90° , 45° and 0° angles simultaneously. A proper care had taken to prevent the air entrapments among the layers because the presence of air bubble inside the material would significantly hamper the strength of the composite. Once the composite laminate was fabricated, the teeth on the periphery of the CFRP sprocket was machined out using water jet machining. The traditional sprocket was replaced by the CFRP sprocket in the Neelam Bold cycle and tested in real-life conditions. A step by step approach of the work is shown in Figure 2. The mould fabrication of sprocket and composite fabrication using hand layup method is shown in Figure 3.

3. Results and Discussion

All the necessary dimensions required for designing a sprocket in CATIA V5 was calculated and listed in Table 2. The isometric as well as 3D sprocket design made in CATIA V5 is shown in Figure 4 (a and b). Some commands like pad, pocket, fillet, and geometrical selections in part design module was frequently used for drawing. From the isometric drawing, all the necessary parameters required to calculate the applied forces on the sprocket teeth were deduced. The material properties used for virtual analysis are presented in Table 3.

The force required to drive a cycle is 120 N, and out of 48 teeth, maximum 26 teeth remain in contact with the chain at a time. Therefore, the force applied to run the bicycle is distributed in these 26 teeth. If it is assumed that all 26 teeth experienced an equal tangential force, then the amount of force is 4.61 N per teeth. As the forces on teeth are applied at a different angle, the resolved force components on the teeth were different. The x and y components were calculated and listed in Table 4.

Table 3: Materials properties [8]

S. No.	Property	CFRP Composite	CRC Steel
1	Tensile Strength (GPa)	3.5	1.3
2	Tensile Modulus (GPa)	230	210
3	Density (g/cm^3)	1.75	7.87

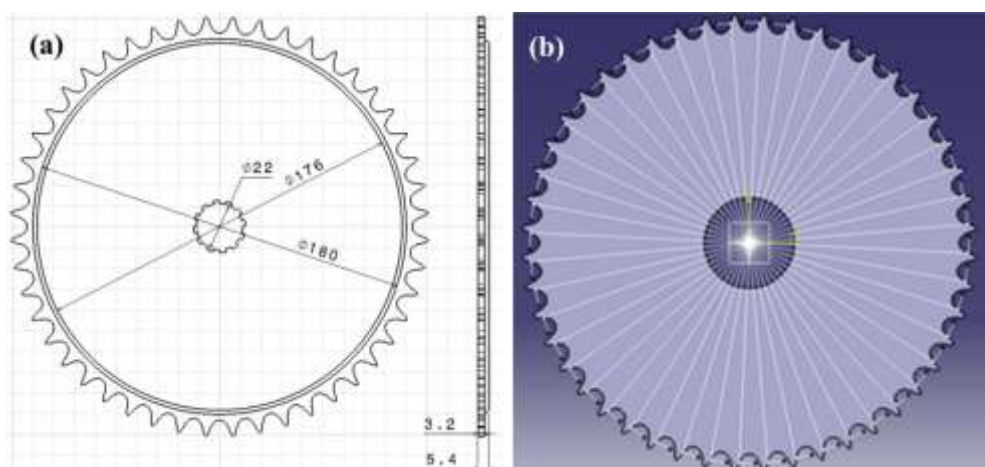


Figure 4. (a) Draft of Sprocket (b) CAD model of Sprocket

Table 4: Resolved force components applied on the teeth of sprocket

Teeth Number	X-component of force	Y-component of force	Teeth Number	X-component of force	Y-component of force
1	4.593	0.3892	14	-0.985	4.503
2	4.5034	0.98	15	-1.56	4.336
3	4.336	1.564	16	-2.117	4.094
4	4.944	2.117	17	-2.633	3.783
5	3.78	2.633	18	-3.105	3.407
6	3.407	3.105	19	-3.523	2.972
7	2.972	3.523	20	-3.88	2.48
8	2.48	3.331	21	-4.17	1.95
9	1.959	4.172	22	-4.39	1.398
10	1.207	4.392	23	-4.537	0.81
11	0.8129	4.537	24	-4.605	0.21
12	0.2137	4.605	25	-4597	-0.369
13	-0.3092	4.5935	26	4.605	-0.213

The 3D model developed in CATIA was imported for analysis in the design modeler of the ANSYS. This analysis was done in static loading condition. The imported 3D model of the sprocket was discretized into a finite number of elements to divide the applied force uniformly on the whole body. This process is called meshing, and the accuracy of the results highly dependent on an appropriate meshing operation. A fine mesh on CFRP sprocket model consists of 25504 elements and 30582 nodes were prepared. To deal with orthotropic behavior of carbon fibers, eight layers of carbon fibers (0.4 mm thickness each) were considered at predetermined angles in the composite. Each layer had meshed with 3188 number of elements. Likewise, the meshing and analysis of CRC sprocket were carried out (nodes 14302 and elements 7032). In the case of CRC sprocket, there was no need of creating layers because of the isotropic nature of the material. After meshing it properly, important constraints were imposed in the form of boundary conditions on the specimen. In the present study, the specimen was restricted to move radially in a fixed plane as shown in Figure 5. Besides, tangential forces were implemented to the 26 teeth of the sprocket in a clockwise direction. After properly establishing all the boundary and load conditions, the virtual analysis of the sprocket was conducted.

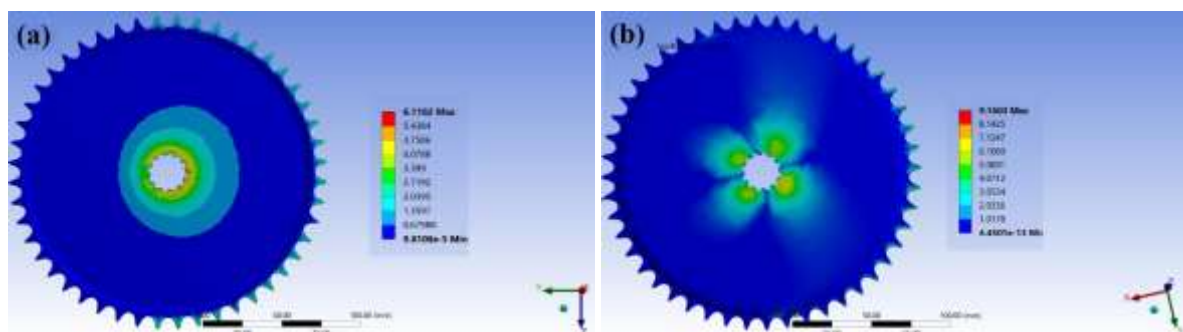


Figure 5. von-Mises stress profile for (a) CRC steel (b) CFRP composite sprocket

Figure 5 (a and b) displayed equivalent stress (von-Mises stress) profile at previously described loading conditions for CRC and CFRP sprockets. The probability of material failure by various types of stresses is explained by the von-Mises theory. If the von-Mises stress is lower than the yield strength of the material, then the possibility of material failure is extremely low. In the present investigation, the observed stress on the various sections of CRC and CFRP material is well below the yield strength of the respective material. However, on comparing the stress profile of both the

materials, it was found that the stress concentration is intensive on CFRP material than CRC steel. In the case of CRC steel sprocket, the stress concentration is maximum around the spline section, and its intensity reduced towards the radial direction uniformly. On the other hand, the stress distribution around the spline section of CFRP sprocket is nonuniform and concentrated at some points. The prime reason of this nonuniformly distributed stress profile around spline section of the composite sprocket is the orthotropic nature of carbon fibers. On inspection of the sprocket teeth, it was observed that the top surface of the teeth is also sensitive to stress concentration. This was true for both the materials but the stress intensity was different.

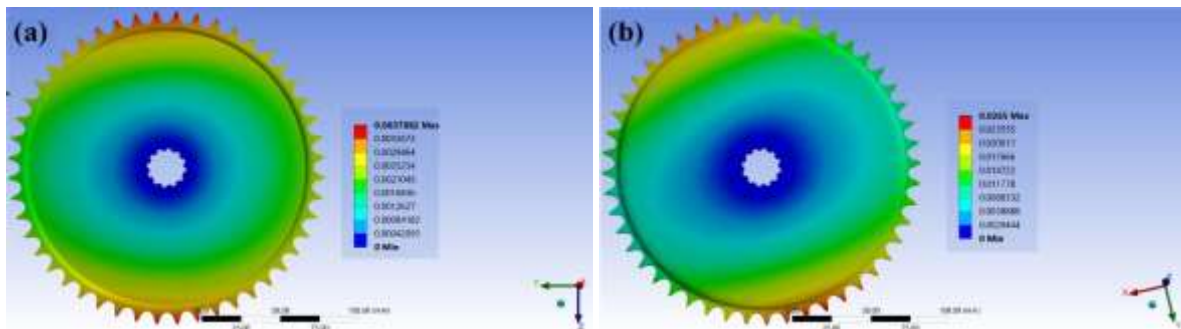


Figure 6. Deformation profile of (a) CRC steel (b) CFRP composite sprocket

Figure 6 revealed the deformation behaviour of CRC steel and CFRP composite sprocket at similar loading conditions. The maximum deformation occurred at the tip of the peripheral teeth of the sprocket at both the cases. The deformation profile changed in descending order from the periphery to centre. Again, the deformation was more or less uniform in CRC steel sprocket than in CFRP composite sprocket owing to the uniform microstructure of CRC steel. The possibility of maximum deformation was observed at the upper and lower contact point of the sprocket with chain.

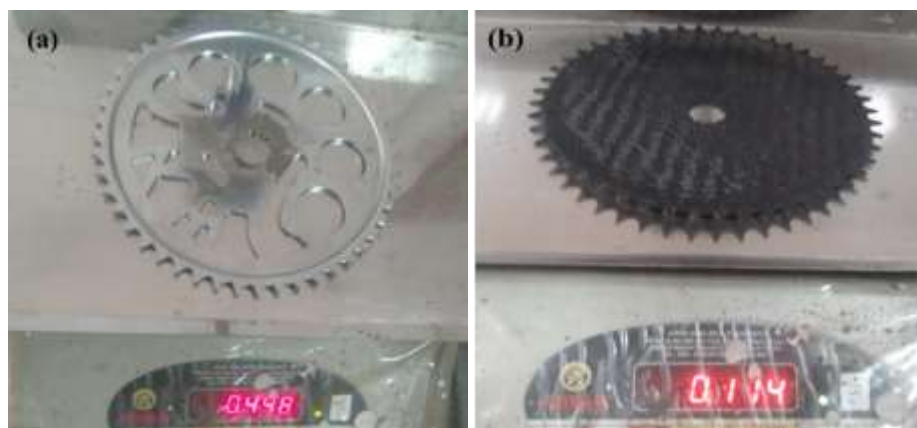


Figure 7. Variation of weight in (a) CRC and (b) CFRP composite

To verify the results of a virtual analysis, the sprocket of the CFRP material was manufactured by the method described in the previous section (section 2.4). There was a significant difference in the weight of the sprockets of both the materials. The weight of the CFRP composite sprocket was 114 g which is much lower than the CRC steel sprocket (i.e. 448 g) (shown in Figure 7). The difference in weight is approximately 75%, which is a huge difference. To check the utility of CFRP sprocket in real life conditions, CRC steel sprocket was replaced by CFRP sprocket in the bicycle as shown in Figure 8 (a and b). The bicycle fitted with newly developed sprocket was driven for few kilometres,

and after that, the sprocket was inspected thoroughly. The inspection revealed some defects like delamination of composite layers at the tooth tip and wear in spline region of the sprocket. The pictures of the delamination and spline wear are shown in Figure 9 (a) and Figure 9 (b) respectively. Despite possessing high strength, composite materials are highly sensitive to localized mechanical damage. Delamination is also a type of mechanical damage that is mainly occurred in the composite due to the low-velocity localized force. This damage appears mostly on the interface of laminated layers of composites. There is also a high possibility of delamination in composite materials from a relatively lesser impact [9,10]. As the virtual analysis revealed that the upper part of the teeth were high stress concentrated areas along with high deformation probability, due to this, delamination damage was found in this part. The reason of worn surface around spline of the sprocket is also due to the presence of stress-centric areas around it as predicted in the virtual analysis. It was observed that the virtual analysis and experimental analysis are complementing each other in this study. The orthotropic nature of carbon fibers played a significant role in the damage occurrence at certain places in the CFRP composite sprocket.



Figure 8. (a) CFRP sprocket attached with pedal shaft (b) CFRP sprocket fitted cycle

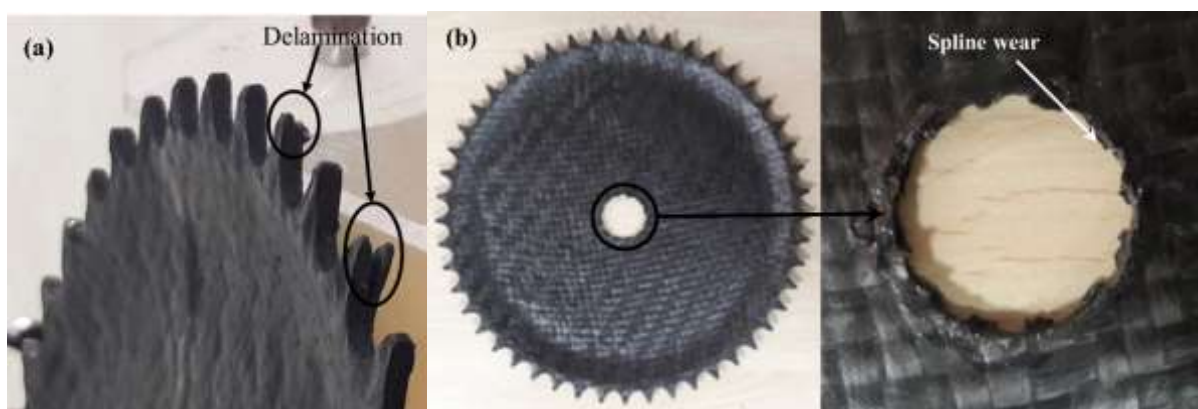


Figure 9. The problem encountered when CFRP sprocket was fitted in a cycle and travelled 4 km (a) Delamination (b) Spline wear

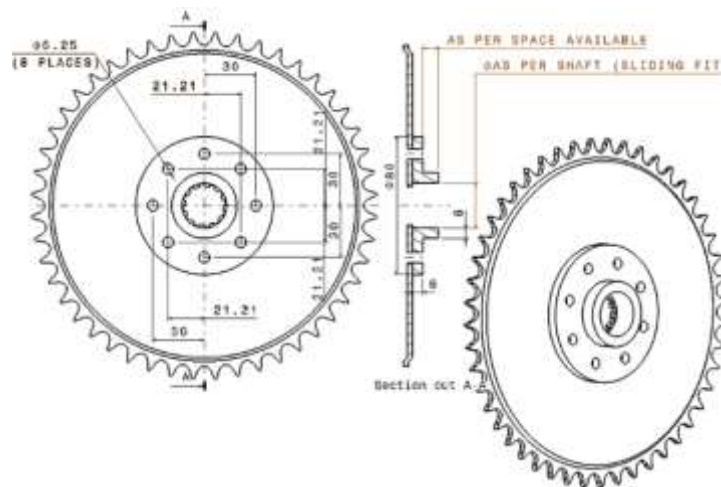


Figure 10. Isometric and 2D drawing of updated CFRP sprocket



Figure 11. (a) Modified CFRP sprocket (b) fitted in cycle

To solve the worn spline problem, a little change was made in the sprocket design whose isometric drawing is shown in Figure 10. As discussed in the previous section, the spline portion was damaged due to friction imposed by the pedal shaft on it, and the sprocket was nearly unusable. To reuse the damaged sprocket, a circular mild steel plate was welded to pedal shaft, and the modified pedal shaft was fastened to the sprocket with the help of nut and bolt (shown in Figure 11 (a)). The delamination problem appeared at the teeth was fixed using cyanoacrylate adhesive. The repaired sprocket was reassembled in the bicycle (shown in Figure 11 (b)) and tested in real life conditions again. Even after 132 km of the run in different terrains there is no sign of delamination and wear. Although the revised design of the sprocket increased the weight of the part slightly, but the CFRP composite sprocket has become more durable and sturdy now. Another advantage of CFRP composite sprocket is that the noise produced due to the friction of chain and sprocket is almost negligible. Therefore, CFRP sprocket can be a suitable alternative to CRC sprocket in the bicycle. However, further research is needed to use it commercially.

4. Conclusions

In this work, the virtual and experimental analysis of CFRP bicycle sprocket was carried out. CFRP composite sprocket was designed based on the dimensions of a CRC steel sprocket obtained from Neelam Bold bicycle. The virtual analysis on original CRC sprocket was also performed for the comparative study. On the basis of the virtual analysis, it was noticed that the maximum stress was

concentrated around the spline region and on the teeth tips. In the CRC steel sprocket, the distribution of stress around the spline region was more or less uniform than the CFRP composite sprocket. The deformation sensitive zones in both the sprockets were tooth tips. During the testing of CFRP sprocket in real life conditions, delamination at tooth tip and wear at spline region was observed. The obtained experimental results were in good agreement with the predicted results by virtual analysis. A design modification was performed on CFRP composite sprocket to circumvent the delamination and worn spline problem. A circular mild steel plate was welded to pedal shaft and fastened on the spline region of sprocket using nuts and bolts. The delamination problem was fixed using cyanoacrylate adhesive. The modified design of the sprocket performed well in real life testing conditions. There was no sign of degradation on sprocket even after 132 km run in different terrains. Apart from the lightweight and robustness of CFRP composite sprocket, the noise generated due to the friction of chain and sprocket was also found less.

Acknowledgment

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