ID 1665

Design of a Lightweight Composite Bicycle Fork

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SUMMARY: This research concerns the design, analysis and manufacturing method used in the making of a lightweight composite bicycle fork. This type of composite fork would be used on high end racing bicycles, where stiffness, strength and light weight are all critical design parameters. Work on the design of a composite fork begins with the definition of geometry that must be a combination of stiffness, strength, light weight, functionality and aesthetics. In the world of high end bicycles, all of the above parameters are essential. The functionality and aesthetics are achieved through the use of CAD software tools. Based on the geometry and suitable stiffness and strength must be achieved through the use of carbon fiber materials. However, metallic inserts are used as interfaces to the rest of the bicycle structure and are desirable for safety reasons. Both woven and unidirectional carbon fiber are used in the design and titanium is used at the extremities. The choice of titanium is logical in this application since it is a lightweight metal that is compatible with carbon fiber. The next step is to analyze the proposed structure using finite element analysis techniques. FEA is essential, since the complex geometry makes it difficult for any meaningful hand calculations. Finally, the fork is manufactured and tested. Development of a Resin Transfer Molding (RTM) technique is demonstrated and proven to be successful in this application. Difficulties in perfecting the manufacturing technique require some back-and-forth iterations between the theoretical design and a design that can be manufactured. Early prototypes are tested in the laboratory in order to compare fork stiffness and strength with theoretical predictions. Thus the three main aspects involved in the design of a complex composite structure are presented here. There is no priority given to any of the three aspects (design, analysis and manufacturing) because each plays an important role in the success of the finished structure.

KEYWORDS: Design, Finite Element Analysis, Resin Transfer Molding, Manufacturing.

INTRODUCTION

The use of composite materials in the bicycle industry has increased considerably in the last 10 years. Prototypes of composite frames and bicycles have made their way into production and now many can be seen on the market. The market competition has seemingly increased and now composite parts are asked to meet high standards of performance and be extremely lightweight while remaining at a competitive price with metallic components [1, 2].

The fork is a critical component of a bicycle. It is connected to the frame through bearings. The fork is a major component in the ride quality of the bicycle. The response of the bicycle to the road and during turning depends greatly on the stiffness and damping of the fork. Furthermore, the fork undergoes many types of load during use. Failure of the fork would be catastrophic, so extreme caution has to be put into testing to assure high impact resistance and long fatigue life. It is also preferable that the mode of failure of the fork be slow and shows signs of failure before breaking.

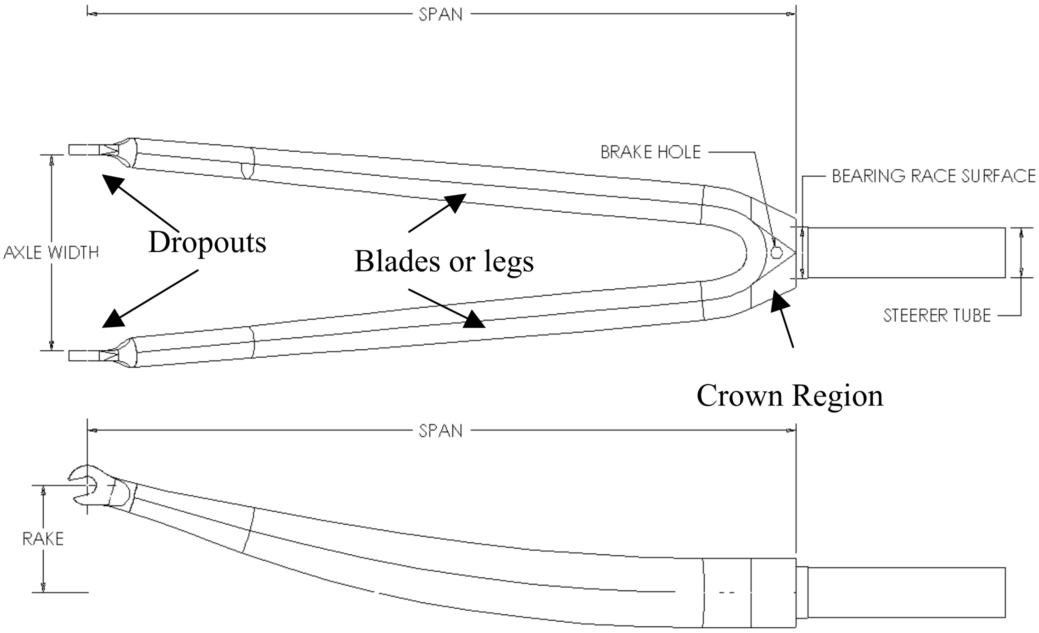

Figure 1 Fork dimensions and nomenclature.

The objectives for this research are to develop a new structure for a carbon fibre fork with manufacturing in mind. The new design is oriented in order to reduce the fork weight and increase its performance. The design also has to be easily produced at minimum cost with high quality and repeatability. The performance of the fork and the consistency of the manufacturing method will be validated with static and fatigue loading experiments.

DESIGN

The design of the new carbon fiber fork begins with a look at the limitations of previous forks. Commonly, carbon fiber forks are designed using carbon fiber in the blades or legs (see Figure 1) and using metallic materials for the steerer tube and dropouts. Metals are useful in these regions because they are bearing surfaces for the wheel axle and the steerer tube bearing races. Some carbon fiber forks have reduced the amount of metal in the steerer tube region by adopting a design with a carbon fiber tube with some metal sleeves. However, many of the design choices take place in the crown region of the fork and the performance of a design will greatly depend on how much carbon fiber is used in this region. A conservative (heavy) design will use metal in the entire crown region extending well into the blades. An optimized design is to keep the amount of metal to a minimum and to use mostly carbon fiber in the crown region. The design here focuses on what can be done in this region of the fork.

A previous design was used as a starting point which consisted of a metallic steerer tube possessing metallic extensions that embedded themselves into the carbon fiber of the crown region (see figure 2(a)). These extensions contributed greatly to the weight of the fork, not only because of the extra metal due to the extensions, but from the fact that steel was the material chosen for the steerer tube. Both these facts limited the design. In figure 2(b), a new steerer tube, made from titanium, is shown.

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(a) (b)

Figure 2 Old and new steerer tube insert designs.

However, removing the metal extensions also meant removing the main contribution to stiffness and stability of the crown region of the fork. The transmission of loads from the steerer tube to the carbon blades of the fork takes place in this region. The stiffness loss left by removing the metal extensions is compensated by a suitable carbon fiber structure that will not only maintain the stiffness, but should provide a better design overall. Essentially, the material now used in the carbon fiber blades extends over the entire crown region and attaches to the titanium steerer tube by having carbon material that extends inside the titanium tube. A stress analysis, presented in the following, will provide confidence that the new design is beneficial.

ANALYSIS

A finite element analysis was performed to evaluate the new design of the carbon fiber fork. Changes in the crown region of the design equate to more carbon fiber in this region, several changes in the fiber direction, and a different interface region between carbon fiber and the metallic steerer tube insert. These phenonona take place mostly in the thickness direction in the crown region. Thus, the use of three-dimensional finite element analysis is essential for proper modeling of the stress problems in the crown region.

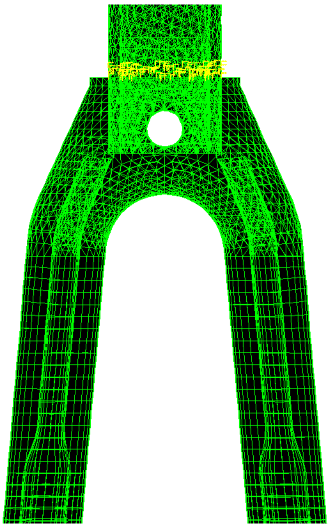
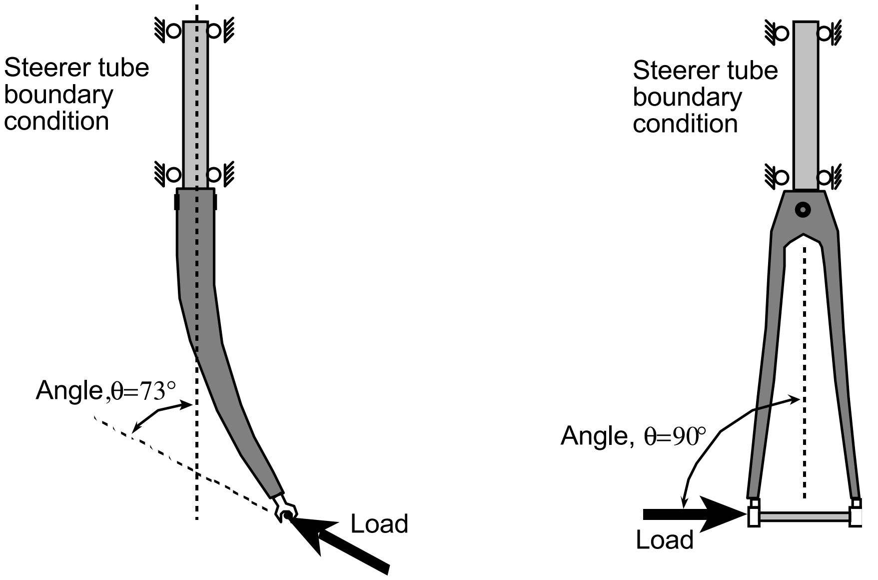


Figure 3 Finite element meshing of the crown region of the fork.

Three-dimensional orthotropic brick and tetrahedral elements were used in the finite element analysis. Essentially elliptical regions were easy to mesh using brick elements, such as the majority of the blade regions of the fork. However, because of the complex geometry in the crown region, a free-meshing option was used to fill the crown region with tetrahedral elements. Care was taken to partition titanium regions from carbon fiber regions. A view of the finite element model of the key part of the crown region is shown in Figure 3.

Two types of loading were applied to the fork in order to simulate two real situations. Figure 4 shows the front and side load cases. The front load case corresponds to forces due to a frontal impact. The head angle of the frame geometry at which the fork is mounted is taken into account in the definition of the load direction. The boundary conditions simulate the fixation imposed by the bearing attachments to the fork. The lateral load case represents forces induced when the bicycle and rider are turning, with similar fixation boundary conditions as in the first load case.



(a) Front Load (b) Lateral Load

Figure 4. Load cases and boundary conditions.

Material properties for the actual material used in the manufacturing process were not available (see section on manufacturing). However, material properties from a carbon fiber pre-preg system with similar fibers was used in the analysis. The ply layup varied depending on the region of the fork under consideration, with a range a layers varying from four to eight. The lower areas of the blades are not under high stress, therefore four layers are used in those regions. Since the blades transmit loads mainly along the axis of the blades, then two unidirectional layers are used, with woven layers on the inside and outside of the ply layup. In regions of high stress, such as in the crown region, the layup reaches eight layers, with five layers of unidirectional material and three layers of woven material. Details about the ply arrangements can be found in [3].

A few of the results of the stress analysis can be seen in figures 5 and 6. Figure 5 shows the displaced geometry and magnitude of displacements for the frontal load case. The displacements are as expected, with the largest displacements at the dropouts where the load is applied (it is basically a cantilevered beam situation). The magnitude of displacement under a 1000 N load is less than 2 cm. Figure 6 shows a close-up view of the crown region, where the highest stresses are expected. Previous analytical studies, performed on a fork having a steerer tube configuration as shown in Figure 2(a), revealed that there were several stress concentration problems in the design [4]. The stresses from this analysis are much lower and indicate no major stress concentration problems. Figure 6 shows the most critical stress region, where the titanium steerer tube meets with the composite laminate. Reduction in the stress concentrations are mainly attrributed to a better steerer tube design and the fact that Titanium has a lower modulus than steel, making it more compatible with carbon fiber composites.

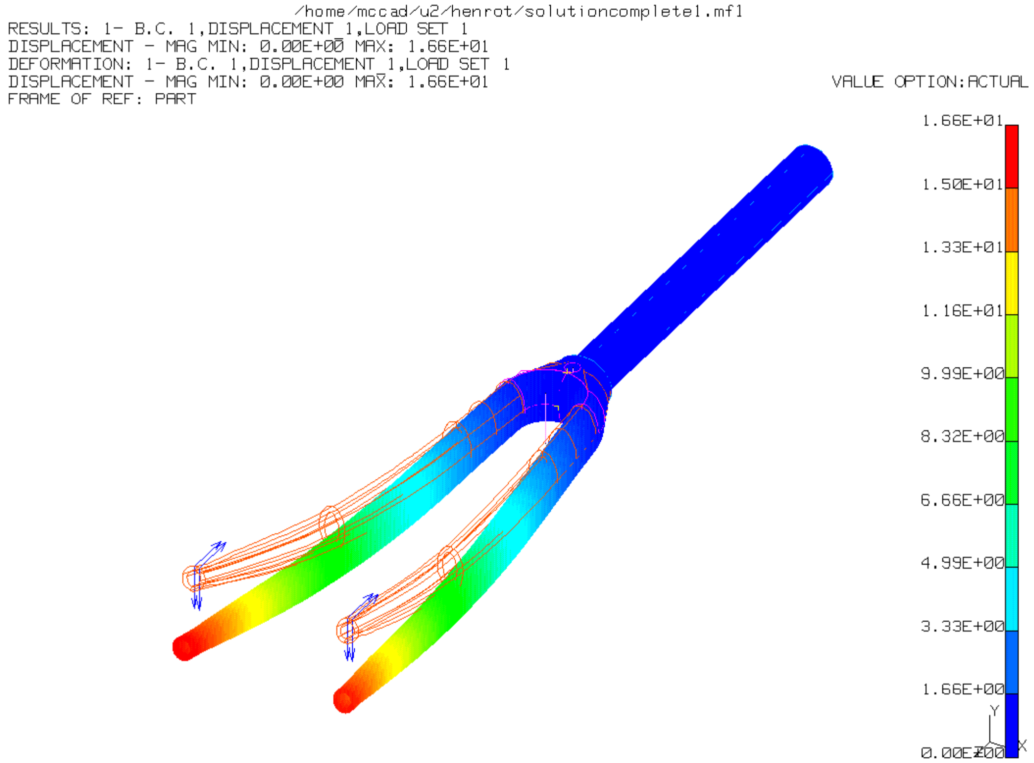


Figure 5. Magnitude of displacement (colors) and undisplaced geometry (red outline) due to the frontal load case using 1000N of load.

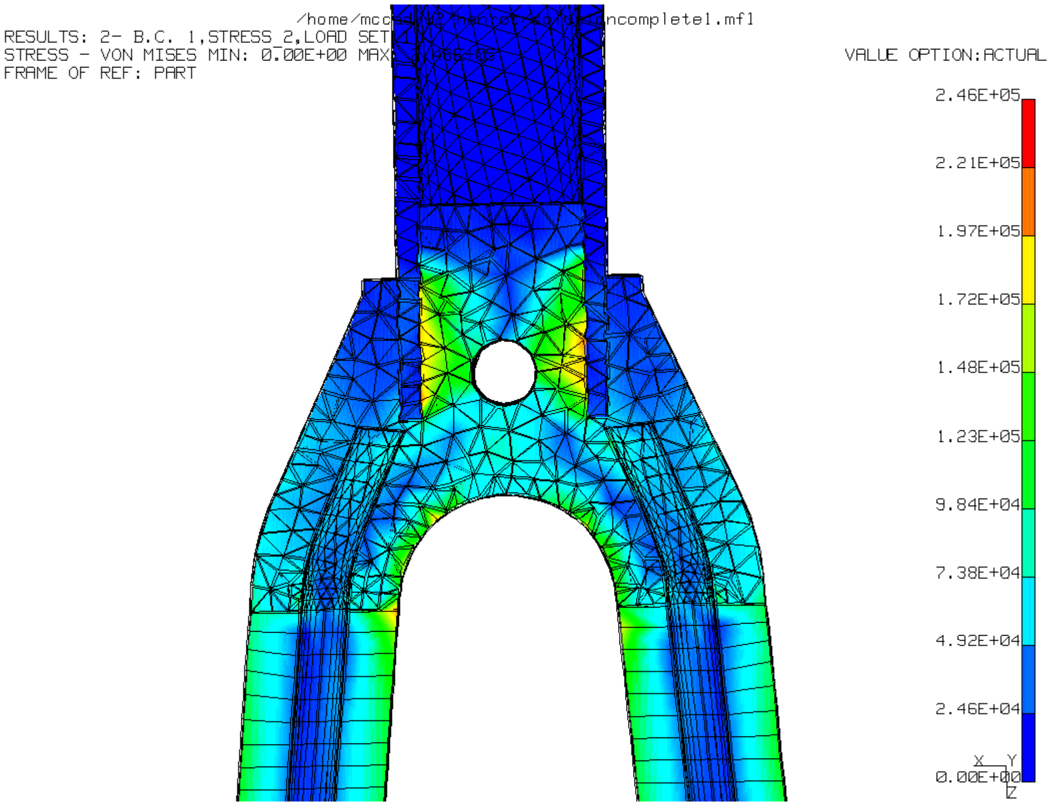


Figure 6. Stresses in the crown region due to the lateral load case using 500 N of load.

MANUFACTURING

The manufacturing of the fork presented some challenges. The fork is designed with a fairly complex layup which must conform to a changing geometry and must be put into production in a repeatable and efficient fashion. The manufacturing method of choice was Vacuum Assisted Resin Transfer Moulding (VARTM), which is a variation of the RTM process whereby a vacuum pressure is used to help the injected resin flow through the narrow passages of the process.

The material most suited to this part is braided tubular carbon fiber material. The braided tubes, otherwise known as "socks", can easily conform to the elliptical cross-sections of the fork blades and can also conform to gradually changing dimensions, such as is the case here. The blades have an elliptical cross section which starts off small at the dropout regions and gets larger as one gets closer to the crown. The braided sock material is available in both woven and unidirectional form, so it is possible to obtain the layups that were chosen analytically (combinations of woven and unidirectional layers). In the crown region, the layup becomes more complicated as the two blades blend into the crown.

The blade regions are meant to be mostly hollow, with the composite layup on the outer circumference. In order to keep this space empty during the injection process, two methods were attempted: inner bladder moulding and a foam core insert. Inner bladder molding was abandoned when it became difficult to produce a suitable bladder for the process. The retained solution was that of foam core inserts inside each of the two blades of the fork. The foam used is a high density polyurethane foam which has a closed cell structure (that resist injection pressure and resin absorption). The foam core "legs" are numerically machined in order to take into account the thickness of the laminate that surrounds them and obtain a precise fiber volume fraction in the finished product. The foam core has abrupt thickness changes whenever a change in layup occurs along the fork (i.e., when layers are added).

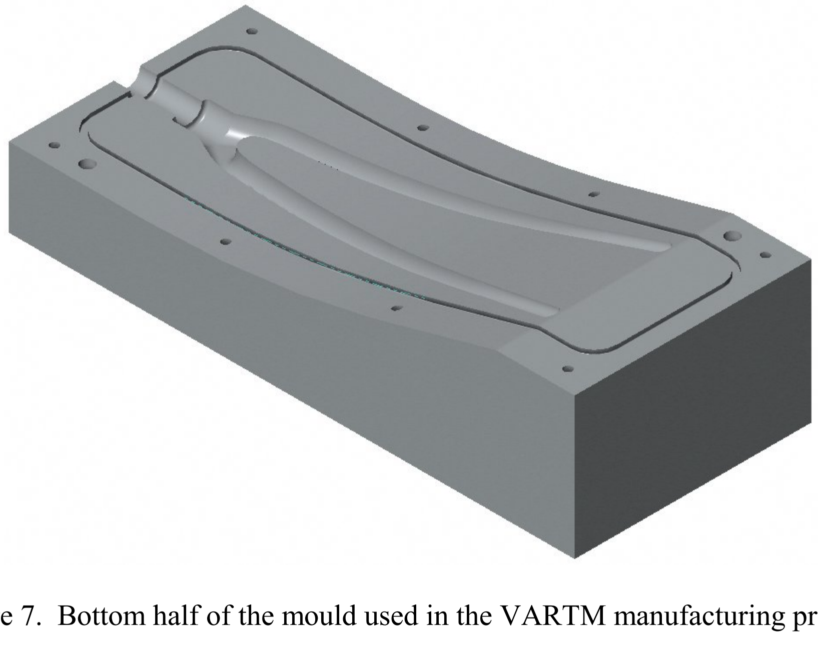
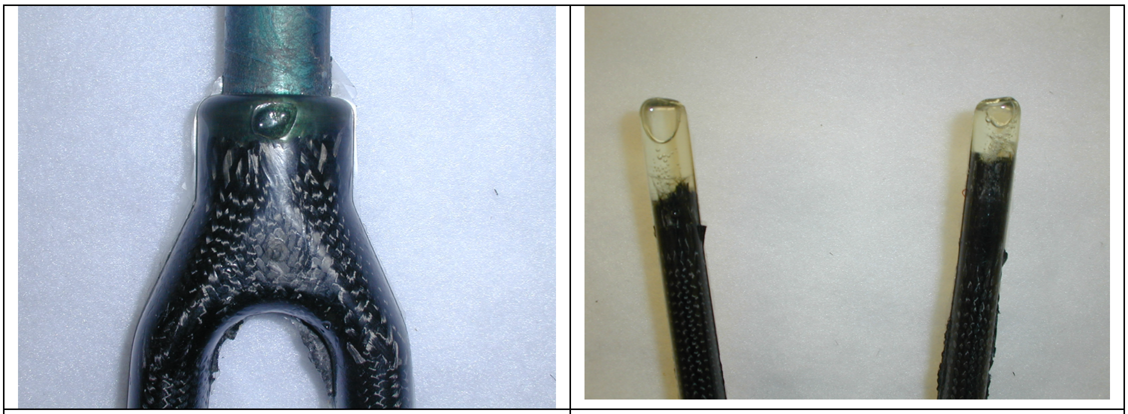


Figure 7. Bottom half of the mould used in the VARTM manufacturing process.

The VARTM manufacturing process requires a suitable mould, which in this case is a two part mould (bottom half shown in Figure 7). All of the essential elements are placed inside the mold: the Titanium steerer tube, carbon fiber pre-form and two foam core legs. The mould has ports for injection and vacuum. The mould is essentially the final outer shape of the part with two exceptions: the crown bearing race region and the dropout region. Because these regions are sharp corners, they are impractical to mould or to place fibers. Extra space is provided in these regions, which will be corrected with post-machining operations. Figure 8 shows the two extra resin rich regions. The crown area has extra material so that the crown race can be machine to exact dimensions (in order to press fit a bearing). The fork dropouts are cut off squarely in order to bond two titanium dropouts.

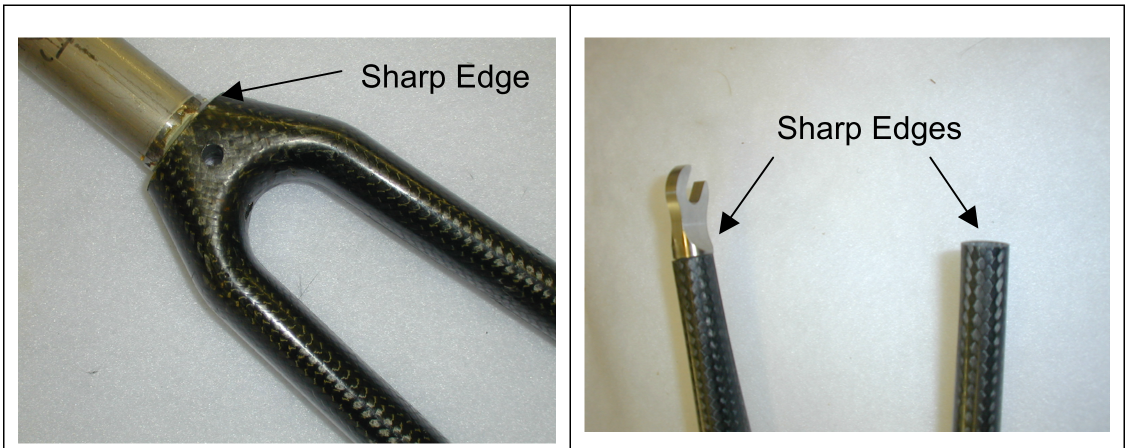


Fork Crown extra material

Fork dropout extra material

Figure 8 Extra material resulting from the moulding process.

Figure 9 shows the results of the post-machining processes and the bonding of one of the dropouts. The dropout was bonded into the blade using a precise bonding fixture (not shown).



Crown edge

Dropout edges

Figure 9 Result of post-machining and finishing processes.

After finishing the two post-machining processes, the fork is essentially ready to use. Aesthetic additions are required such as paint or a clear coat in order to enhance the look of the carbon fiber fork.

TESTING

After developing the manufacturing process, prototypes were fabricated to verify the validity of the design and manufacturability of the fork. The prototypes were tested statically and in fatigue to determine the structural properties and examine the mode of failure. Early injections were performed using fiberglass rather than carbon fiber in order to adjust the process parameters and to analyze problem regions. Since fiberglass is transparent after curing with epoxy, the early prototypes were ideal for identifying pre-form and foam core misalignment, as well as air bubbles and void problems resulting from non-optimized injection of the resin. After adjusting temperature and pressure and vacuum parameters, several successful prototypes were produced and tested.

Description	**Steerer**	**Weight (g)**	**Stiffness N/mm**
New Fork 1	Titanium	515	98
New Fork 2	Titanium	474	102
Old Fork 1	Steel	685	116
Old Fork 2	Steel	690	112
Old Fork 3	Steel	780	128

Table 1 Results of Selected Tests

In Table 1, results are shown for two different versions of the new fork as well as three from the older design. Two objectives were met: reduction in fork weight and a more efficient design. From Table 1, the new design called New Fork 2 represents an optimized design which reduces the weight by at least 31% (when compared to the lightest of the old designs). Although the new forks are not as stiff, it should be noted that the old fork was considered "too stiff", therefore even the reduction in actual stiffness is not a drawback in the new design.

CONCLUSIONS

In this research, the design of a new light and efficient composite fork has been successfully performed. Tests verify that the design meets the objectives. A manufacturing method was also developed to bring the fork up to the prototype production stage. Future work on this analysis of this design will be simplified if a study is made to measure the actual material properties of the material used in the RTM process, rather than use assumed values. Further work on the development of the manufacturing process should also be performed in order to optimize the process and reduce the cycle time for manufacturing.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the cooperation of Serotta Competition Bicycles in the development of this research.

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