COMPOSITE ATTACHMENTS

THE TREK BOTTOM BRACKET

A Senior Thesis
By
David Mallard

1997-98 University Undergraduate Research Fellow
Texas A&M University

Group: Engineering III

COMPOSITE ATTACHMENTS

THE TREK BOTTOM BRACKET

A Senior Thesis

By

David Mallard

1997-98 University Undergraduate Research Fellow

Texas A&M University

Group: ENGINEERING III

COMPOSITE ATTACHMENTS

The Trek Bottom Bracket

by

David Edwards Mallard

Submitted to the
Office of Honors Programs and Academic Scholarships
Texas A&M
University in partial fulfillment of the requirements for

1997-98 UNIVERSITY UNDERGRADUATE RESEARCH FELLOWS PROGRAM

April 16, 1998

Approved as to style and content by:

Ozden O. Ochoa

Dr. Ozden O. Ochoa
Department of Mechanical Engineering

Susanna Finnell

Susanna Finnell, Executive Director
Honors Programs and Academic Scholarships

Fellows Group: Engineering III

Abstract

Bottom bracket failures have been one of the most common failures in the composite bicycle frames produced by the Trek Bicycle Corporation. The bottom bracket is the portion of the frame that supports the crank and pedals. An aluminum insert is chemically adhered to the composite shell of the Trek frames with an epoxy. This insert is the attachment point for the crank assembly, so it is exposed to cyclical and often relatively large loads. The most common failure is a disbond in the epoxy. This research analyzed a composite bicycle frame using finite element analysis software to help determine the stresses in the frame about the point of failure. A model of the entire frame and a more detailed model of the bottom bracket region were constructed to perform the analysis. The model of the frame was analyzed using a static analysis and loads specified by Trek. Results from the frame model were then applied to the bottom bracket model for analysis. Stresses as high as 320 MPa (46,500 psi) resulted. The stresses and the resultant strains cause the failure. A different epoxy resin or a different manufacturing process will be required to remedy this problem.

Background and Introduction

The bicycle is the primary mode of transportation for more than half of the world's population. Over 100 million bicycles are sold each year in the global market.[1] The bicycle allow riders to efficiently and economically attain fairly high speeds and long distances of travel. While most bicycle components are presently made from metals, including chrome-molybdenum-manganese (cro-moly) steels, aluminum, and even titanium, composite components are becoming more prevalent. In 1996 alone, 195.3 million pounds of composite material were used in the bicycle industry.[2] Presently, the carbon fiber reinforced epoxy matrix composites are the most common type used for bicycle components. These have generally been reserved for high end racing bikes and mountain bikes due to their high cost.

Composite Materials

Composites achieve unique mechanical properties by combining more than one material—the fiber and the matrix. In addition to a high strength to weight ratio, composites can be designed for high stiffness and toughness, proper dampening behavior, and good fatigue and torsional resistance.[3] Because of their unique characteristics, they have been applied in many industries and products. Aircraft and automobile bodies, skis, golf club shafts, fishing rods and many other products are now made from composites.

Structural durability, lightweight construction, and the ability to withstand various environmental conditions are all concerns facing bicycle designers. Composite materials have been used to produce lightweight, high performance parts for bicycles. While they allow for a new freedom in the design of products, their mechanical properties also impose limitations. The attachment of components like the bottom bracket is one challenging issue for engineers.

The Bicycle Frame

Most bicycles use the diamond-truss frame configuration. An example of this frame is shown in Figure 1. This frame consists of a top tube, a seat tube, a down tube, a head tube, two chainstays, and two seatstays. The seat tube, the down tube and the chainstays converge at the bottom bracket housing. An epoxy is used to adhere the bottom bracket insert to the housing. The crank and pedals are threaded into to the insert.

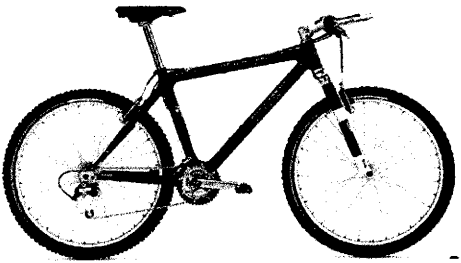

Figure 1- The Diamond Truss Frame (Trek 9800 Shown)

The Problem

The carbon/epoxy composites used in the bicycle industry are known to be very strong yet brittle. In the past, many composite frames have failed when exposed to the high and unpredictable loads associated with a crash or even extreme use. Many of these failures occur at the attachment points for various components. Bolted joints and special polymer adhesives have been two general attachment methods.[4] Actually forming the composite around the attachment by winding the fibers or molding the part around the attachment are other solutions. These processes are difficult and expensive, though.

The rear quick release axle, the rear derailleur hanger, the headset, and the bottom bracket are all examples of components that need to be attached to the frame. According to Trek, the bottom bracket attachment fails the most often.

Due to its function and position, the bottom bracket region of the frame experiences large cyclical loads. Each variation in the force applied to the pedals loads the composite housing/insert assembly differently. Fatigue becomes a major issue in this region of the frame. The fit between the composite shell and the bottom bracket usually becomes loose. In many cases, the epoxy actually disbonds. Solving this problem is a main area of research in the industry. Figure 2 shows the placement of the bottom bracket insert relative to the housing.

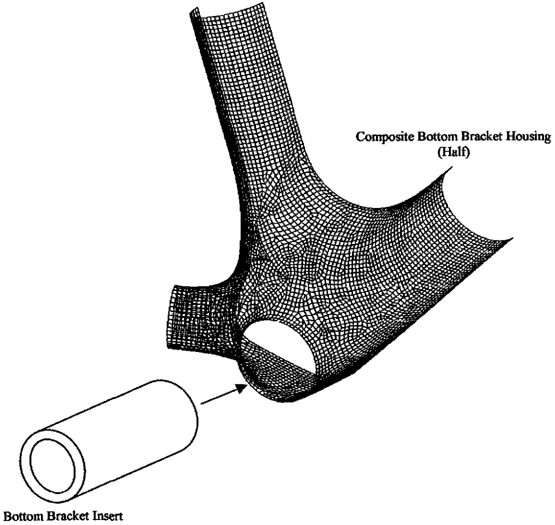

Figure 2—Exploded View Schematic of Bottom Bracket Insert and Composite Frame Half

Finite Element Analysis

Finite element analysis is a method of numerically analyzing the mechanical, thermal, or even electrical condition of a system. The system model is broken into small parts, or elements. Each of these elements is connected to the elements around it with nodes. A system of nodes and elements is called a mesh. Boundary conditions, loads, and mechanical properties are applied to the model, and global results are found by analyzing the individual elements.[5]

Initial Work

During the summer of 1997, some initial work was conducted during the Summer Undergraduate Engineering Research Program. A simplified two-dimensional model of the frame was created and analyzed. For simplicity, only one chainstay and one seatstay were used, and they were generated in the plane of the other four beam members of the frame.

The geometry was defined using scaled two-dimensional drawings and additional data from Trek. An International Graphics Exchange System (IGES) file of a frame drawing was scaled to actual size using Pro/ENGINEER®. Intersection coordinate points for the six beam members of the frame were found. The coordinates of these points were entered into the MARC/MENTAT® finite element package and used to generate line curves. Each curve represented the axis of a beam member of the frame. The curves were converted to nodes and elements for use in the finite element analysis.

The axis of the bottom bracket (axis of pedal rotation) was the origin for the coordinate system.

MARC Element 14 was used to complete the analysis. This element is a thin-walled beam with no warping. A closed circular section was used, and the thicknesses and radii were specified. This element allows six degrees of freedom, which include three global displacements and three global rotations. The strains include axial stretch, two curvatures, and twist per unit length. Axial and shear stresses are given at each of the 16 numerical integration points.[6]

Each element was assigned the proper parameters for the analysis. These included the material properties, the geometric properties, and the boundary conditions.

Orthotropic material properties were assigned to each element, and the tube dimensions were set to represent an actual composite frame. The material properties were determined using CLASS 3.50, Composite Laminate Analysis Systems. This software determines the properties using the stacking sequence and layer properties of the composite. The orientation of the material properties was specified for each element.

Three boundary conditions were applied to the model. The rear axle displacement was set to zero and rotation was constrained to the plane of the frame. The head tube was constrained to only horizontal displacement and rotation in the plane of the frame, and a load of 1000-lb (4448.2 N) was applied to the node representing the bottom bracket axis (see Figure 3).

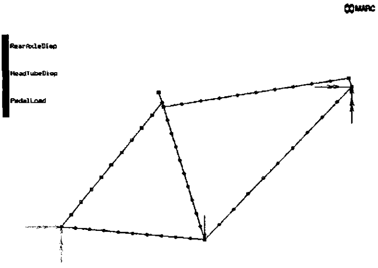

Figure3—Mentat Model Showing Boundary Conditions

MARC was used to analyze the model shown in Figure 3. Figure 4 shows the magnified deformation of the composite frame due to the loading and boundary conditions and labels the beam members of the frame. These results were used to verify the accuracy of the three-dimensional model of the frame (see *Methods*).

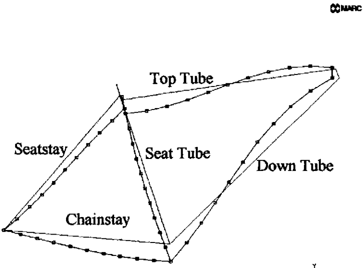

Figure 4-Deformed Frame
(130x Magnification of Deformation)

Methods

For the current research, two models were created. A global model of the frame was analyzed first. The results from that analysis were applied to the more detailed local model of the bottom bracket. The coordinate system for each model was located on the axis of the bottom bracket. The x-axis was horizontal, the y-axis was vertical, and the z-axis was parallel to the axis of the bottom bracket. The x and y axes defined the "plane of the frame."

The Global Model—The Frame

The first model created was a three-dimensional model of the entire frame. The model was split at the plane of the frame, and only the right half was used for the analysis. This reduced the size of the model and simplified the modeling procedure.

First, a solid model of the frame was constructed using Pro/ENGINEER®. The surfaces created by the solid model were exported to Patran®, a graphical FEA software package, using an IGES file. Each of the surfaces was then converted into a mesh of four side/four node thin shell elements.

It is very important that the elements represent the actual geometry of the model. To accomplish this, the elements were constructed using a curvature check. The height of the curved section of the frame could not exceed one-tenth the edge length of the element.

After the meshes were created, the boundaries of all the elements did not perfectly align. To "knit" the elements together, many of the elements were modified and their adjacent nodes were equivalenced. Several three side/three node elements were used to repair the mesh. The final model consisted of 8292 elements and 8805 nodes. Figure 5 shows the finite element (FE) model.

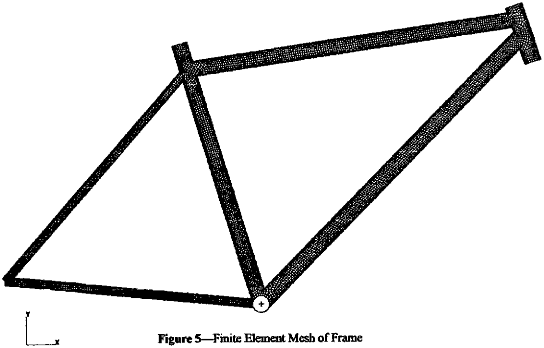

Figure 5—Finite Element Mesh of Frame

After the meshing was complete, each element was assigned material properties. The same orthotropic material properties used in the initial work were applied to these elements. Since directional material properties were applied to each element, an orientation of the material was also assigned. A local coordinate system was created for each beam in the model. The local x-axis corresponded to the axis of the beam. The material properties for each surface mesh were aligned to the appropriate coordinate system.

Boundary conditions were then applied to the model. These conditions were the same as those used to analyze the preliminary two-dimensional model. The rear axle displacement was set to zero and rotation was constrained to the plane of the frame, and the head tube was constrained to only horizontal displacement and rotation in the plane of the frame. A vertical load of 500-lb (2224 N), which is half the actual load, since the model is only half the actual model, was applied. The load was distributed equally (93 N per node) among 24 nodes on the bottom surface of the bottom bracket mesh.

An additional boundary condition was applied to the frame model. The nodes on the x-y plane were constrained to remain in the x-y plane (zero displacement in the z-direction). This constraint is the one that allows only half of the frame to be used for the analysis. Since all the loads are parallel to the plane of the frame, and since the frame is symmetric about its plane, there is displacement along the center plane of the frame.

The model was analyzed using Abaqus®. The element type was a four node, thin shell element—S4R5. It is a doubly curved, reduced integration element with hourglass control. There are five integration points per element and five degrees of freedom at each node. These include three displacements (u_x, u_y, and u_z) and two surface rotations.[7]

The deformation of the frame was observed and compared with that of the previous model for accuracy. Three displacement measurements were then taken. One measurement was taken from each of the beams that converge into the bottom bracket region. The measurement was taken at the position of the beam corresponding to the correct application region of the bottom bracket model.

The Local Model—The Bottom Bracket

Trek provided an IGES file of one of their composite mountain bike bottom brackets. This model was imported into Pro/ENGINEER® and modified for this analysis. It is shown in Figure 6.

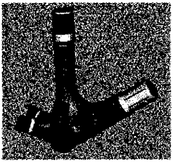

Figure 6—Bottom Bracket Model as Provided by Trek

The imported surfaces used to produce this model were copied. This allowed them to be modified individually. Some extraneous surfaces were deleted—only the actual shell was kept. One of the shell surfaces was damaged however, so it could not be merged with the others. After the surfaces composing the right hand side of the model were repaired as much as possible in Pro/ENGINEER®, they were exported to Patran®. There, the rest of the damaged surfaces were repaired or replaced using the geometry tools. The final surfaces were all meshed using the same criteria as the surfaces of the frame. The mesh contained 5471 elements (S4R5) and 5681 nodes. Figure 7 shows the finite element model of the bottom bracket.

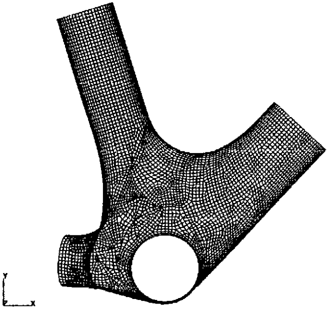

Figure 7—Finite Element Model of Bottom Bracket

Material properties were applied to each element of the bottom bracket model. The material was defined as a layered composite. The lamina (layer) properties were defined using the data provided by Trek. The layered composite material (laminate) was created by stacking the lamina according to the specifications. The laminate properties were applied to each element. The laminate orientation was aligned to the default coordinate system of each element.

The boundary conditions applied to the local model were the three displacements found using the global model and the symmetry condition. The displacements were applied to the elements at the edge of each of the three tubes—the chainstay, the down tube, and the seat tube. The displacements of each of the ends with respect to one other were the important ones. For the analysis, the top of the seat tube was held in place. The chainstay and down tube were displaced relative to the seat tube.

Discussion of Results

The results of the two-dimensional frame (*Initial Work*) matched values obtained using classical mechanical calculations. The three-dimensional model of the frame deformed in a manner consistent with that of the two-dimensional model. This is evident both visually (see Figures 4 and 8) and analytically. For example, the bottom bracket node deflected 0.50 inches vertically in the two-dimensional model and 0.47 inches at one of the corresponding nodes of the three dimensional model.

The lower portion of the bottom bracket is where the load was applied to the three-dimensional frame model. In Figure 8, it can be observed that this small region deformed much more than the rest of the frame. It should be noted that the deformations in Figures 4, 8, and 9 are magnified by 130, 50, and 20 times respectively.

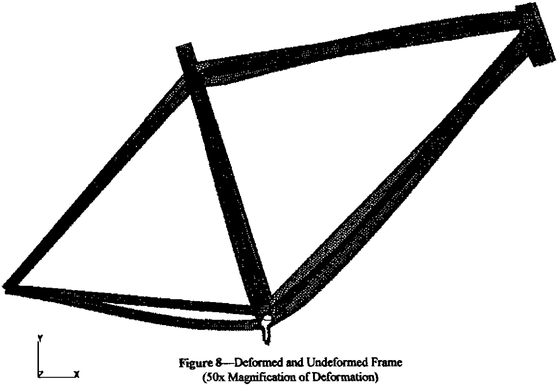

Figure 8—Deformed and Undeformed Frame
(50x Magnification of Deformation)

The resultant displacements, when applied to the bottom bracket, deformed the bracket as expected (see Figure 9). The circular region used to attach the bottom bracket deflected downward and deformed. According to the model, the lower portion of the circular region deformed the most.

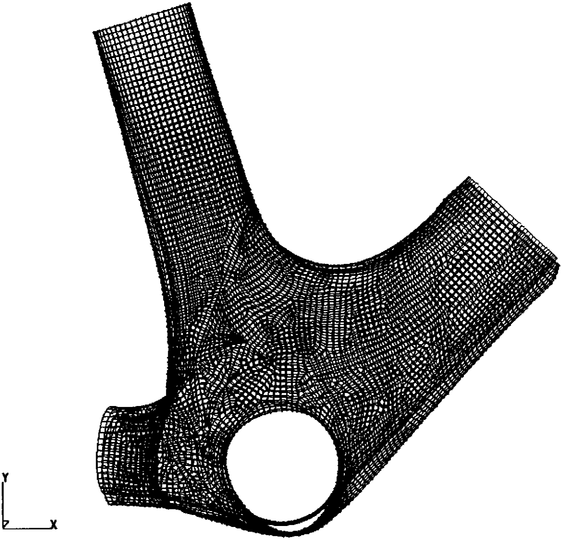

Figure 9—Deformed and Undeformed Bottom Bracket
(20x Magnification of Deformation)

Stresses in the bottom bracket laminae were found to be as high as 320 MPa (46,400 psi). At the edge of the housing, also the edge of the region where the epoxy is applied, stresses as high as 70 MPa (10,000 psi) were recorded. A resultant strain of about 0.001 was found also. The stress contour plot for the first layer of the laminate is shown in Figure 10.

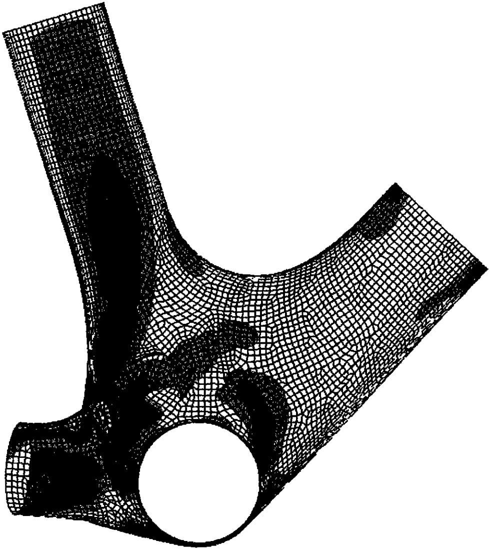

Figure 10—Stress Contour Plot for First Layer of Composite

Conclusions

The composite housing deforms while the bicycle is in use. This cyclical deformation induces various loads in the epoxy bond and causes it to fail. According to the models used in this research, the hole in the housing that accepts the bottom bracket insert tends to become elliptical. The stresses and strains that result from the loads cause the epoxy to fail over time.

Recommendations

With the current design, the epoxy used to attach the bottom bracket insert into the housing will inevitably be cyclically loaded. Redesigning the housing/insert interface to increase the surface area of the epoxy bond will decrease the stresses. Also, if it is available, a higher strengh resin system could be used.

Other options also exist that might reduce the chance of failure. The bottom bracket insert could be molded directly into the housing. This option would shorten the load path between the insert and the housing and decrease the chance of failure by eliminating the weak portion of the design—the adhesive. The very strong composite material and the insert would bear the entire load.

More refined models and physical testing could be used to further this research. The current models used all used a constant wall thickness. The actual Trek bottom bracket uses doublers to thicken the cross section in high stress areas. If information about the location of the doublers was available, it could be incorporated into the model. In addition, symmetric loading is not always applied to bicycles. The loadcases applied to the models could be varied to include different (and non-symmetric) loads. Finally, dynamic analyses and physical testing would be useful in analyzing the frame.

References

1. Lindsay, Karen. "Composites cycle into use on both exotic and every-day bikes." Composites Design & Application. Composites Institute of the Society of the Plastics Industry, Inc. Fall 1996 pp. 24-25.

2. Lindsay, Karen. Composites Design & Application.

3. Easterling, K. E. Advanced Materials for Composites. Chapman and Hall, London. 1993. p. 16.

4. Easterling, K. E. Advanced Materials for Composites. pp. 72-73.

5. Cook, Robert D. *Concepts and Applications of Finite Element Analysis.* John Wiley & Sons. New York. 1974. pp. iii, 3.

6. MARC Analysis Research Corporation, Volume B Element Library, 1994. p. B 3.14-1.

7. Abaqus Version 5.2 Manual. Volume 1. Hibbitt, Karlsson & Sorrenson Inc. 1992. P. 3.6.4-1.

Acknowledgements

I would like to thank Ray Blotteaux of the Trek Bicycle Corporation for his cooperation and support. Also, Brian McNichols, Sherif Shushawi, Tom Eason, and David Judice, graduate students of Dr. Ochoa, gave helpful guidance and support through the course of the summer. Magda Lagoudas of the Department of Mechanical Engineering and Mike at the Super Computer Help Desk also offered valuable advice.

Biography

David Mallard is a senior mechanical engineering major at Texas A&M University. He is from San Marcos, Texas and currently resides in College Station. David has worked for Rollerblade, Inc. as a concept engineer in the research, design, and development department. He will attend graduate school in California to study mechanical engineering and pursue a career in the design of sports products.

COMPOSITE ATTACHMENTS

The Trek Bottom Bracket

by

David Edwards Mallard

Submitted to the
Office of Honors Programs and Academic Scholarships
Texas A&M
University in partial fulfillment of the requirements for

1997-98 UNIVERSITY UNDERGRADUATE RESEARCH FELLOWS PROGRAM

April 16, 1998

Approved as to style and content by:

Dr. Ozden O. Ochoa
Department of Mechanical Engineering

Susanna Finnell, Executive Director
Honors Programs and Academic Scholarships

Bottom bracket failures have been one of the most common failures in the composite bicycle frames produced by the Trek Bicycle Corporation. The bottom bracket is the portion of the frame that supports the crank and pedals. An aluminum insert is chemically adhered to the composite shell of the Trek frames with an epoxy. This insert is the attachment point for the crank assembly, so it is exposed to cyclical and often relatively large loads. The most common failure is a disbond in the epoxy. This research analyzed a composite bicycle frame using finite element analysis software to help determine the method of failure. A model of the entire frame and a more detailed model of the bottom bracket region were constructed to perform the analysis. The model of the frame was analyzed using a static analysis and loads specified by Trek. Results from the global (entire frame) model were then applied to the local (bottom bracket) model for analysis.

Background and Introduction

The bicycle is the primary mode of transportation for more than half of the world's population. Over 100 million bicycles are sold each year in the global market.[1] The bicycle allow riders to efficiently and economically attain fairly high speeds and long distances of travel. While most bicycle components are presently made from various metals, including chrome-molybdenum-manganese (cro-moly) steels, aluminum, and even titanium, composite components are becoming more prevalent. At present the carbon fiber reinforced epoxy matrix composites dominate the bicycle market. 195.3

These composite components generally have been reserved for the high end racing bikes and off road mountain bikes due to their high cost.

Structural durability, lightweight construction, and the ability to withstand various environmental conditions are all concerns facing bicycle designers. Composite materials are used to produce lighter weight, high performance parts for bicycles. The combination of more than one material (fiber and matrix) allows the material designer to incorporate the desired characteristics of each component into the composite material. Because of their unique characteristics, composite materials have been applied in many industries for the production of a wide variety of products. In addition to lightness and strength, composites can be designed for high stiffness and toughness, proper dampening behavior, and good fatigue and torsional resistance.[3] Aircraft and automobile bodies, skis, golf club shafts, fishing rods and many other products are now made from composites.

While composites allow for a new freedom in the design of products, they also impose many limitations. The attachment of components like the bottom bracket is a challenging issue for engineers.

The Bicycle Frame

Most bicycles use the diamond-truss frame configuration (see Figure 1). This frame consists of a top tube, a seat tube, a down tube, a head tube, two chainstays, and two seatstays.

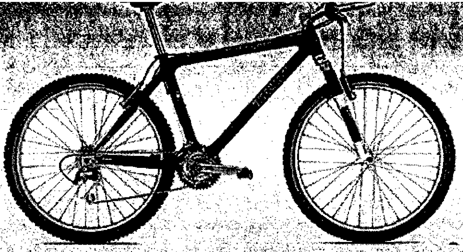

Figure 1- The Diamond Truss Frame (Trek 9800 Shown)

The Problem

The carbon/epoxy composites used in the bicycle industry are known to be very strong yet brittle. In the past, many composite frames have fractured when exposed to the high and unpredictable loads associated with a crash or even extreme use. Another concern for the composite frame designer is the ability to attach components to the frame. Bolted points and special polymer adhesives have been two general solutions to the attachment problem.[4] Actually forming the composite around the attachment by winding the fibers or molding the part around the attachment has been another solution. These processes are difficult and expensive, though.

The rear quick release axle, the rear derailleur hanger, the headset, and the bottom bracket are all examples of components that need to be attached to the frame. The bottom bracket attachment fails the most often.

Due to its function and position (see Figure 2), the bottom bracket region of the frame experiences large cyclical loads. Each variation in the force applied to the pedals loads the composite shell/insert assembly differently. Fatigue becomes a major issue in this region of the frame. The fit between the composite shell and the bottom bracket usually becomes loose and the performance is hindered. In many cases, the epoxy actually disbonds. Solving this problem is a main area of research in the industry.

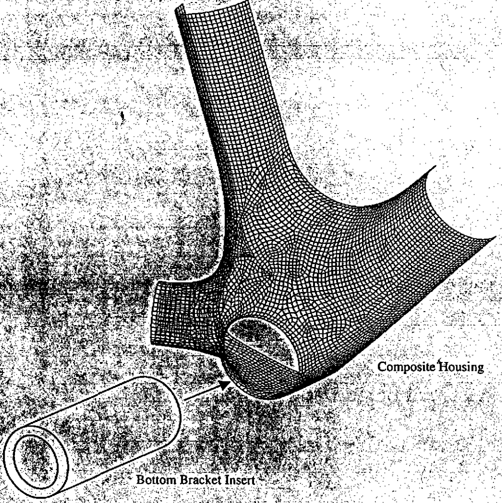

Figure 2—Exploded View Schematic of Bottom Bracket Insert and Composite Frame Half

Finite Element Analysis

Finite element analysis is a method of analytically analyzing the mechanical, thermal, or even electrical condition of a system. The system model is broken into small parts, or elements. Each of these elements is connected to the elements around it with nodes. A system of nodes and elements is called a mesh. Boundary conditions, loads, and mechanical properties are applied to the model, and global results are found by analyzing the individual elements.[5]

Preliminary Research

During the summer of 1997, some preliminary research was conducted during the Summer Undergraduate Engineering Research Program. A simplified two-dimensional model of the frame was created and analyzed. For simplicity, only one chainstay and one seatstay were used, and they were generated in the plane of the other four beam members of the frame.

The frame geometry was defined using scaled two-dimensional drawings and additional dimensional data from Trek. An International Graphics Exchange System (IGES) file of a frame drawing was scaled to actual size using Pro/ENGINEER®. Intersection coordinate points for the six beam members of the frame were found. The coordinates of these points were entered into the MARC/MENTAT® finite element package and used to generate line curves. Each curve represented the axis of a beam member of the frame. The curves were converted to nodes and elements for use in the finite element analysis. The axis of the bottom bracket (axis of pedal rotation) was the origin for the coordinate system.

closed circular section was used, and the thicknesses and radii were specified. This element allows six degrees of freedom, which include three global displacements and three global rotations. The strains include axial stretch, two curvatures, and twist per unit length. Axial and shear stresses are given at each point of the cross section. 16 numerical integration points are used in the section.[6]

Each element was given the proper parameters and constraints for the analysis. These parameters included the material properties, the geometric properties, and the boundary conditions.

The material was defined with orthotropic properties and the tube dimensions were altered to represent an actual composite frame. The orthotropic material properties were determined using CLASS 3.50, Composite Laminate Analysis Systems. This software determines the laminate properties using the stacking sequence and lamina properties of the composite. The orientation of the material properties was specified for each element.

Three boundary conditions were applied to the model. The rear axle displacement was set to zero and rotation was constrained to the plane of the frame. The head tube was constrained to only horizontal displacement and rotation in the plane of the frame, and a load of 1000-lb (4448.2 N) was applied to the node representing the bottom bracket axis (see Figure 3).

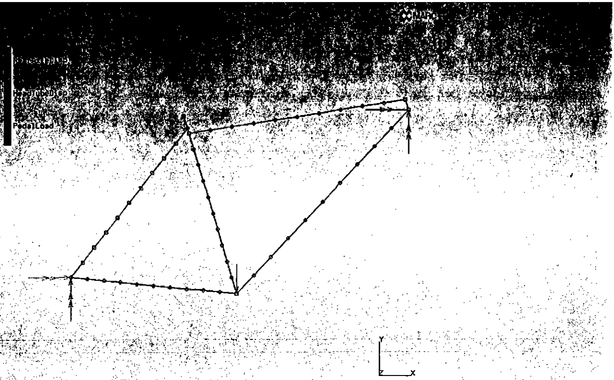

Figure3—Mentat Model Showing Boundary Conditions

MARC was used to analyze the model shown in Figure 3. Figure 4 shows the magnified deformation of the composite frame due to the loading and boundary conditions and labels the beam members of the frame.

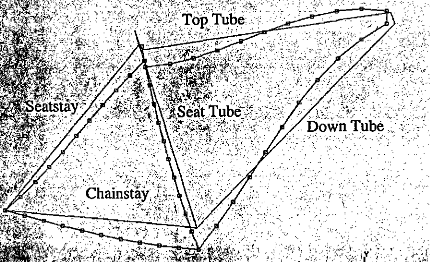

Figure 4-Deformed Frame
(130x Magnification of Deformation)

Methods

For the current research, two models were created. The global model (the frame), was analyzed, and the results from that analysis were applied to the local model (the bottom bracket). The coordinate system for each model was located on the axis of the bottom bracket. The x-axis was horizontal, the y-axis was vertical, and the z-axis was parallel to the axis of the bottom bracket. The x and y axes defined the "plane of the frame."

The Global Model—The Frame

The first model to be created was a three-dimensional model of the entire frame. The model was split at the plane of the frame, and only the right half the model was used for the analysis. This reduced the size of the model and simplified the modeling procedure.

First, a solid model of the frame was constructed using Pro/ENGINEER®. The surfaces created by the solid model were exported to Patran®, a graphical FEA software package, using an IGES file. Each of the surfaces was then converted into a mesh of four side/four node thin shell elements.

It is very important that the elements represent the actual geometry. The elements were constructed using a curvature check. The height of the curved section of the frame could not exceed one tenth the edge length of the element.

After the meshes were created, the boundaries of all the elements did not perfectly align.

To "knit" the elements together, many of the elements were modified and their nodes were equivalenced. Several three side/three node elements were used in the mesh. The final model consisted of 8292 elements and 8805 nodes. Figure 5 shows the finite element (FE) model.

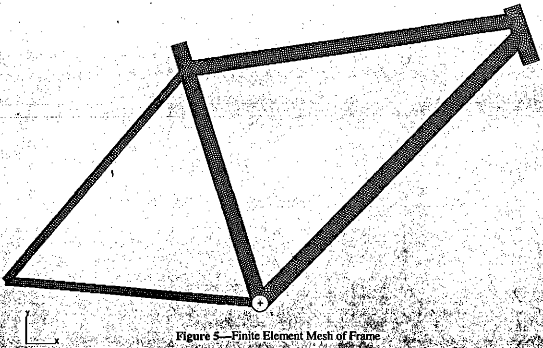

Figure 5—Finite Element Mesh of Frame

After the meshing was complete, each element was assigned material properties. The same orthotropic material properties found using the CLASS 3.50 system were applied to these elements. Since directional material properties were applied to each element, an orientation of the material was assigned. A coordinate system was created for each beam in the model. The local x-axis corresponded to the axis of the beam. The material properties for each surface mesh were aligned to the appropriate coordinate system.

Boundary conditions were then applied to the model. These conditions were the same as those used to analyze the preliminary two-dimensional model. The rear axle displacement was set to zero and rotation was constrained to the plane of the frame. The head tube was constrained to only horizontal displacement and rotation in the plane of the frame. A vertical load of 500-lb (2224 N), which is half the actual load since the model is only half the actual model, was applied. The load was distributed equally (93 N per node) among 24 nodes on the bottom surface of the bottom bracket mesh.

An additional boundary condition was applied to the frame model. The nodes on the x-y plane were constrained to remain in the x-y plane (zero displacement in the z-direction). This constraint is the one that allows only half of the frame to be used for the analysis. Since all the loads are parallel to the plane of the frame, and since the frame is symmetric about its plane, there is displacement along the center plane of the frame.

The model was analyzed using Abaqus®. The element type was a four node, thin shell element—S4R5. S4R5 is a doubly curved, reduced integration element with hourglass control. There are five integration points per element and five degrees of freedom at each node. These include three displacements (u_x, u_y, and u_z) and two surface rotations.[7]

The deformation of the frame was observed and compared with that of the previous model for accuracy. Three displacement measurements were then taken. One measurement was taken from each of the beams that converge into the bottom bracket region. The measurement was taken at the position of the beam corresponding to the correct application region of the bottom bracket model (explained below).

The Local Model—The Bottom Bracket

Trek provided an IGES file of one of their composite mountain bike bottom brackets. This model was imported into Pro/ENGINEER® and modified for this analysis. The entire model is shown in Figure 6.

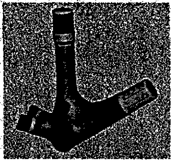

Figure 6—Bottom Bracket Model

The imported surfaces used to produce this model were copied. This allowed them to be modified individually. Many surfaces were deleted—only the actual shell was kept. Some of the shell surfaces were damaged however. These could not be merged with the others. After the model was repaired as much as possible, the surfaces composing the right hand side of the model were exported to Patran®.In Patran®, the rest of the damaged surfaces were repaired or replaced using the geometry tools. The resultant surfaces were all meshed using the same criteria as the surfaces of the frame. 5471 S4R5 elements and 5681 nodes were used to create the mesh. Figure 7 shows the FE model of the bottom bracket.

Material properties were applied to each element of the model. The material was defined as a layered composite. A lamina (layer) property was defined, and then the composite material was created by stacking the lamina according to the specifications provided by Trek. This layered composite is called the laminate. The laminate properties were applied to each element. The laminate orientation was aligned with the individual coordinate system of each element.

The boundary conditions applied to the local model were the three displacements found using the global model. A displacement was applied to the elements at the edge of each of the three tubes—the chainstay, the down tube, and the seat tube. The displacements of each of the ends with respect to one other were the important ones. For the analysis, the top of the seat tube was held in place. The chainstay and down tube were displaced relative to the seat tube.

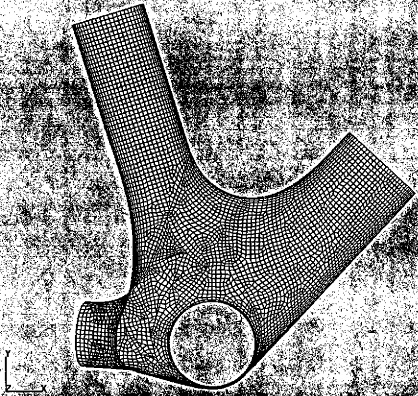

Figure 7—Finite Element Model of Bottom Bracket

Discussion of Results

The results of the 2-dimensional frame (previous research) matched values obtained using classical mechanical calculations. The 3-dimensional model of the frame deformed in a manner consistent with that of the preliminary 2-dimensional model. This is evident both visually (Figures 3 and 5) and analytically.

The lower portion of the bottom bracket is where the load was applied to the frame model. In Figure 8, it can be observed that this region deformed much more than the rest. It should be noted that the deformations in Figures 4, 8, and 9 are magnified by 130, 50, and 20 times respectively.

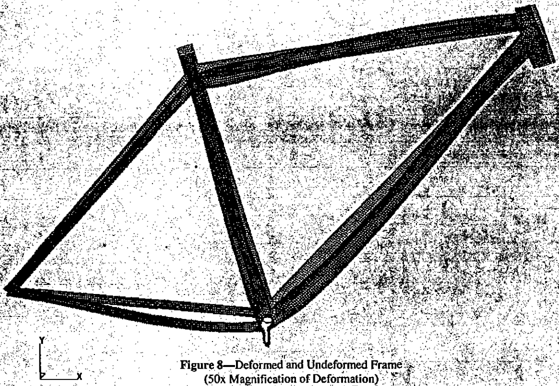

Figure 8—Deformed and Undeformed Frame
(50x Magnification of Deformation)

The resultant displacements, when applied to the bottom bracket, deformed the bracket as expected (see Figure 9). The circular region used to attach the bottom bracket deflected downward and deformed. According to the model, the lower portion of the circular region deformed the most. This deformation would tend to peal the composite housing away from the aluminum insert. A tensile stress in the epoxy would result and after many cycles of loading, failure could result.

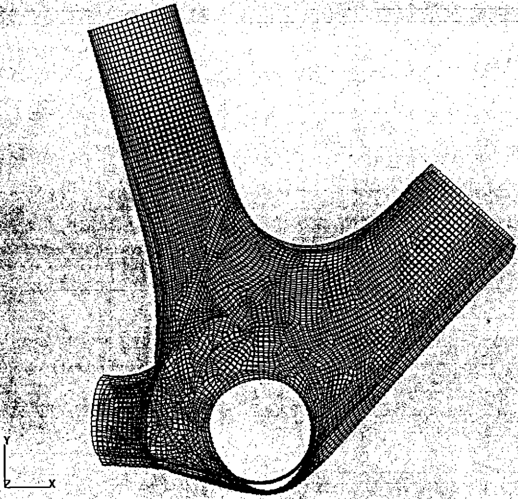

Figure 9—Deformed and Undeformed Bottom Bracket
(20x Magnification of Deformation)

Conclusions

The composite housing deforms while the bicycle is in use. This cyclical deformation induces various loads in the epoxy bond and causes it to fail. According to the models used in this research, the hole in the housing that accepts the bottom bracket insert tends to elongate vertically. The induced tensile loads in the top and bottom are most likely the most damaging, but shear stresses on the sides could also damage the epoxy.

Recommendations

With the current design, the epoxy used to attach the bottom bracket insert into the housing will inevitably be cyclically loaded. Redesigning the housing/insert interface to increase the surface area of the epoxy bond will decrease the stresses. Other options exist that might reduce the chance of failure. The bottom bracket insert could be molded directly into the housing. This option would shorten the load path between the insert and the housing and decrease the chance of failure by eliminating the weak portion of the design. The very strong composite material and the insert would bear the entire load.

More refined models and physical testing could be used to further this research. The models used all had a constant thickness. The actual Trek bottom bracket uses doublers to thicken the cross section in high stress areas. If information about the location of the doublers was available, it could be incorporated into the model. In addition, symmetric loading is not always applied to bicycles. The loadcases applied to the models could be varied to include different (and non-symmetric) loads. Finally, dynamic analyses could be performed to simulate riding conditions.

Actual physical testing is always the best type. Physical experimentation on these parts would be very beneficial.

References

1. Lindsay, Karen. "Composites cycle into use on both exotic and every-day bikes." Composites Design & Application. Composites Institute of the Society of the Plastics Industry, Inc. Fall 1996 pp. 24-25.
2. Lindsay, Karen. Composites Design & Application.
3. Easterling, K. E. Advanced Materials for Composites. Chapman and Hall, London. 1993. p. 16.
4. Easterling, K. E. Advanced Materials for Composites. pp. 72-73.
5. Cook, Robert D. *Concepts and Applications of Finite Element Analysis.* John Wiley & Sons. New York. 1974. pp. iii, 3.
6. MARC Analysis Research Corporation, Volume B Element Library, 1994. p. B 3.14-1.
7. Abaqus Manual. Volume 1. Element Library.

Acknowledgements

I would like to thank Ray Blotteaux of the Trek Bicycle Corporation for his cooperation and support. Also, Brian McNichols, Sherif Shushawi, Tom Eason, and David Judice, graduate students of Dr. Ochoa, gave helpful guidance and support through the course of the summer. Magda Lagoudas of the Department of Mechanical Engineering and Mike at the Super Computer Help Desk also gave valuable advice.

Biography

David Mallard is a senior mechanical engineering major at Texas A&M University. He is from San Marcos, Texas and currently resides in College Station. David has worked for Rollerblade, Inc. as a concept engineer in the research, design, and development department. He will attend graduate school at the University of California, Davis in mechanical engineering and pursue a career in the design of sports products.