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# Structural Optimization of Bicycle Frame to Avoid Weld Failure and Fatigue Life Prediction of Failing Weldment

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**ABSTRACT**

**This research presents a procedure and a software application to optimize the topology, size and shape optimization of a cycle frame structure for its weld failure through FEA analysis. The root cause analysis of the failure will be determined and the structural optimization will be carried out to eliminate the failure. The objective of the optimization is the size of the structure subjected to stress and displacement constraints. The fatigue life of the weld will also be predicted. The CAD model of the frame will be prepared using CAD software package and then it will be analyzed through FEA software code. Weld fatigue life prediction will be done through calculations.**

***Keywords*—bicycle frame, Fatigue, FEA, Structural optimization,**

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## I INTRODUCTION

There is an evidence of increasing participation and interest in cycling and a large body of literature exist relating to bicycle technology. Most modern bicycle frames have the simple form. This shape emerged in about 1895 following several decades of vigorous development and evolution and has remained basically unchanged since that time. The need for low weight coupled with high strength and stiffness has lead to continuing trail and development of high performance material for bicycles. A promising solution is to turn a proven tool of structural engineering; the Finite Element Analysis method.Performing Finite Element Analysis on bicycle frames has become a common activity for designer and engineers in the hope of improving the performance of frames. This is achieved by balancing priorities for key requirement. FEA has been used to analyse composite, aluminium and steel bicycle frame with the aim of understanding physical behaviour and improving performance relating, however a comprehensive study on the influence of key geometric parameters on frame stiffness has not been conducted. Bicycle frame is usually made up of composite, aluminium and steel material. Historically the most common material for the tubes of bicycle frame has been steel. Steel frame can be very inexpensive, strong and easy to work but denser than many other structural materials. The aim of the study is to evaluate maximum stress occurred at weld region and finds an optimal solution to that weld failure. The structural optimization of modern steel frame is carried out for its weld failure with the help of the most recent tools available for optimization.In practical application frame is failing at weld shown in fig 1.

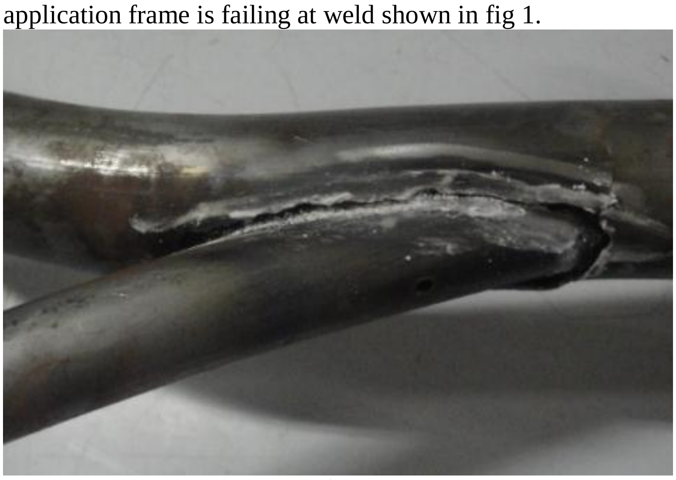

Fig 1. Crack Initiation of Weld in Bicycle Frame

The Gas Tungsten Welding (GTAW) also known as tungsten inert gas (TIG) is a welding process used for welding of bicycle frame. It is observed that cycle frame is failed at weld. Welding process is already modified so as to have uniform stress distribution. Aim of this work is to redesign the frame so as to avoid weld failure. Design modifications in bicycle frame are also suggested if required. Fatigue life prediction of failing weld is also done by analysis software.

A. BICYCLE FRAME:

Since their inception, bicycles have provided society with a source of transportation, exercise, recreation and sports. But with the advent of motorized vehicles and various alternative forms of entertainment, the bicycle suffered a temporary decline in appeal. Within recent years a revival in the interest of bicycles has occurred, fuelled by technological developments in advanced materials and innovative frame designs.New bicycle frame designs are generally motivated by weight and/or stiffness considerations and often incorporate the use of high performance engineering materials. Indeed competitive bicycling has promoted the use of various advanced structural materials including non ferrous alloys (e.g. carbon and graphite reinforced epoxies). Both the frame design and material contribute to the rider's energy consumption.

B. MATERIAL PROPERTIES:

The materials used for building a bicycle frame are steel, aluminium, carbon fibre, magnesium and titanium. The material is selected upon their physical properties, their characteristics and how they behave under certain conditions. Listed below are some of the properties bicycle designers looks at the time of building a bicycle.

1.Density:
Density is how much a material weighs for a given volume. Titanium isabout one-half the density of steel, and aluminum is about one-third the density of steel.

2.Stiffness:
The measurement for stiffness is called the modulus of elasticity; it is the degree to which a material that undergoes stress can deform, and then recover and return to its original shape after the stress ceases. A steel bicycle tube is generally stiffer than a titanium or aluminum tube, although tube diameter and wall thickness also affect stiffness.

3. Elongations:
Elongation is a measure of how far a material will stretch before it breaks. It is very sensitive to the type of alloy used and how the metal is processed. The smaller the elongation number, which is expressed as a percentage, the more brittle the bicycle frame. Elongation numbers for titanium bicycle tubes are highest—from 20% to 30%; for steel tubes, from about 10% to 15%; and for aluminum, from 6% to 12%
.

4. Tensile Strength:
Tensile strength is a measure of the greatest longitudinal stress a substance can bear without tearing apart; it is expressed as a ratio of maximum load to cross-sectional area. The tensile strength of a bicycle tube varies with the type of alloy used and how the tube is made. The tensile strength of a typical titanium alloy bicycle tube ranges from approximately 700 to 910 MPa; of a steel tube, from 630 to 1190 MPa; and of an aluminum tube, from 210 to 350 MPa

5. Fatigue Strength:
Fatigue strength is a measure of the stress at which a material fails after a number of cycles. Steel and titanium alloys have a specific fatigue strength below which a load (force) may be applied an infinite number of times without causing the metal to bend or break. Aluminum alloys will, however, fail after enough load cycles even with a very small load. This is why aluminum tubes are generally much thicker than steel or titanium tubes.

6. Toughness:
Toughness is the ability of a metal to absorb energy and deform before fracturing (breaking). A tough metal is more ductile and deforms rather than breaks. A very important requirement of bicycle tubes is their ability to flex. Toughness is, however, a complex property to measure and analyze.

## IIFEA ANALYSIS OF EXISTING FRAME

A.CAD Model of Bicycle Frame

The CAD model of bicycle frame is prepared by using modeling software which is shown in the following fig.2

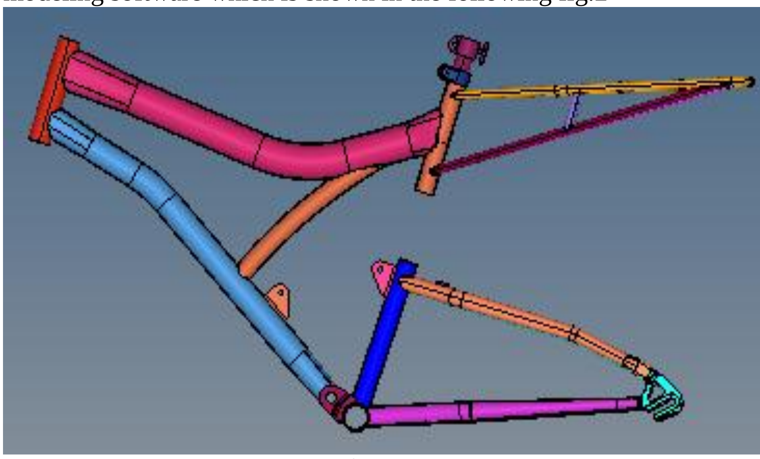

Fig 2. CAD Model of Bicycle Frame

B. Meshed Model of Bicycle Frame

The bicycle frame is meshed in hypermesh11 using shell elements which are 2D elements. The weld regions (joints) in the bicycle frame are meshed with Penta elements which are a type of 3D element.
The element size for the mesh is 1mm- 5mm. The critical region where the crack is occurred is fine meshed with element size 1 mm to have uniform stress distribution
No of Elements- 55989
No of Nodes- 56002

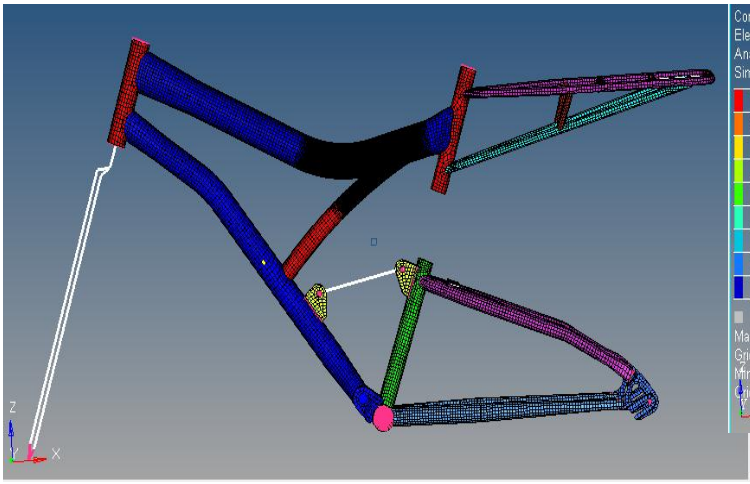


Fig 3. Meshed Model of Bicycle Frame

C. Loading and Boundary Conditions:

The loads and boundary conditions are shown in the fig4. Three loads of 100 N, 1000N and 400N are applied on the bicycle frame. A load of 100N is applied along central axis of head tube. A load of 1000N is applied along central axis of seat tube. And a load of 400N is applied on carriage.

The boundary conditions are constraint in all degrees of freedom at chain stays and at hub.

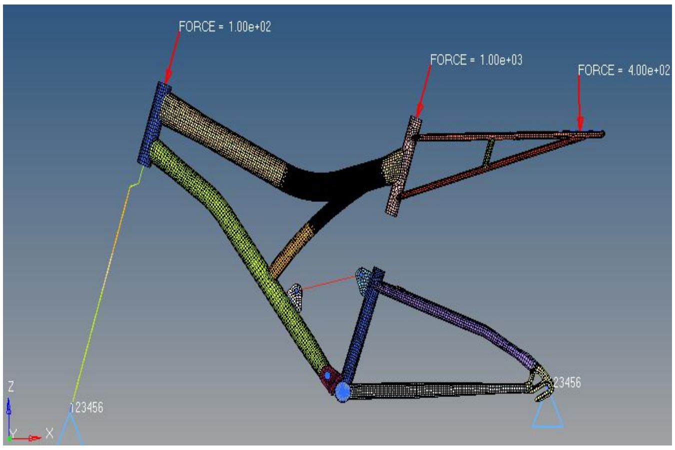


Fig 4 Loading and Boundary Conditions of Frame

D. Analysis of Bicycle Frame

The solution algorithms for linear and nonlinear problems are very efficient compared to conventional solvers. OptiStruct easily simulates structures with millions of degrees of freedom (DOFs) without any model size restrictions.FEA analysis of bicycle frame is carried out in OptiStruct software. The material details are as follows,

Name: IS 2039 ERW steel ERW C1
Tensile Modulus E= 210 GPa
Yield Strength = 206 MPa
Ultimate Strength = 306 MPa
Max. Elongation = 10%

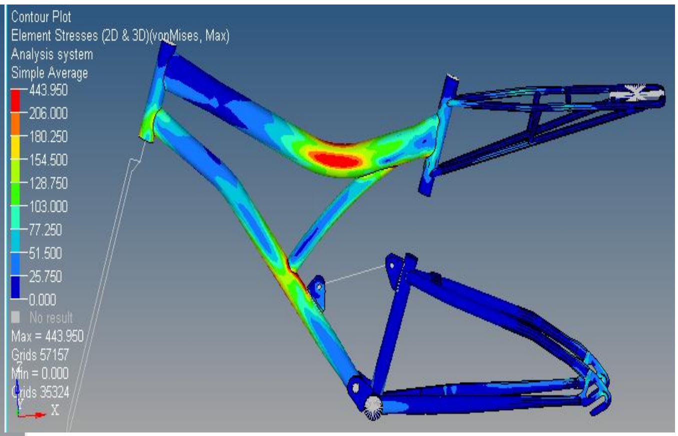


Fig 5.Stresses induced in Bicycle Frame.

The top tube of bicycle frame is having thickness of 1.1mm.The von Mises stress found which exceeds the ultimate strength of the material. The maximum stress of 440MPa (approx.) is induced at weld region.

## III STRUCTURAL OPTIMIZATION

A structure in mechanics is defined as "any assemblage of materials which is intended to sustain loads." *Optimization* means making things the best. Thus, *structural optimization* is the subjects of making an assemblage of materials sustain loads in the best way.

The structural optimization is further divided into three categories that are,

1. Size Optimization:

In size optimization thickness or cross sectional area will be changed to find the optimal solution.

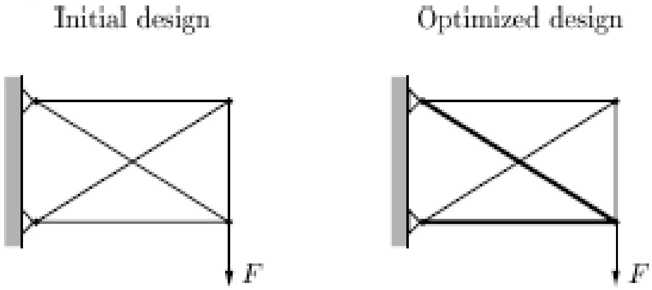


Fig.6 Size Optimization of Truss Member

2. Shape Optimization:

In order to optimize the shape of the structure, one naturally has to be able to control the shape of its boundary using some design variables. Following figure shows the function η(x) describing the shape of the beam like structure.

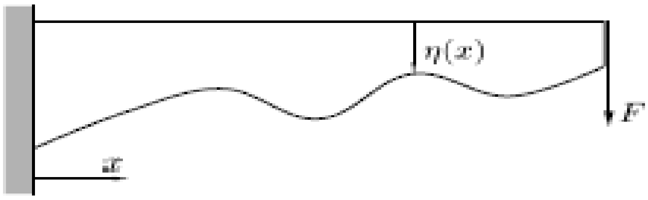


Fig. 7 Shape Optimization Problem

 

3. Topology Optimization:

This is the most general form of structural optimization. It is achieved by taking cross-sectional areas of truss members as design variables and then allowing three variables to take the value zero i.e. bars are removed from the truss. The connectivity of nodes is variable so that the topology of truss changes. Following fig shows the topology of the truss.

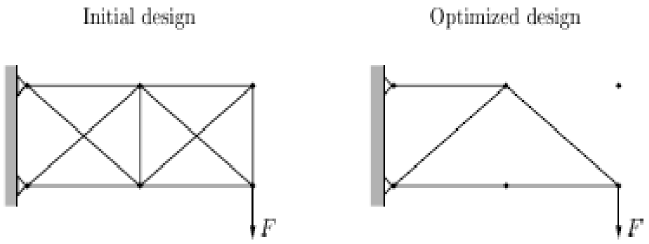


Fig. 8 Topology Optimization of a Truss.

## IV FEA ANALYSIS OF MODIFIED FRAME

For this analysis size optimization is used to avoid the weld failure of bicycle frame. The thickness of top tube of failed frame is 1.1 mm and the maximum stress induced at weld region is 440 MPa. In the optimization process step by step iterations are taken to minimize the stress within limit. The analysis is done for the thicknesses 1.2mm, 1.25mm, 1.3mm, 1.35mm and 1.4 mm of top tube. From this it is found that at 1.4 mm thickness, the stress induced is within limit. The loading and boundary conditions are same as shown in Fig.4. The results of analysis of modified frame is shown in the fig 9

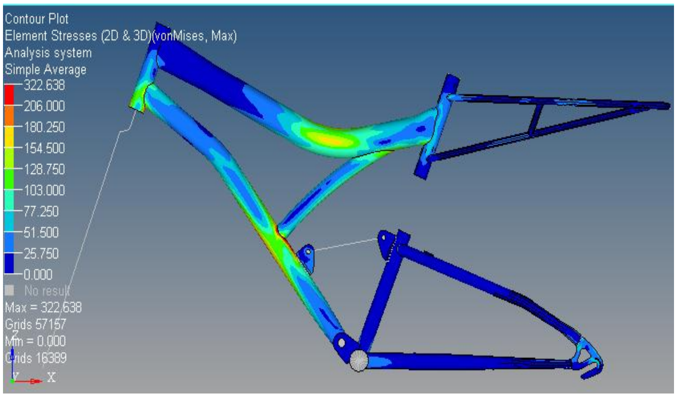


Fig 9. Stresses induced in modified Frame.

The stress induced in the critical region is shown in the fig no. 10 the yellowish region shows, the stress induced is within a limit.

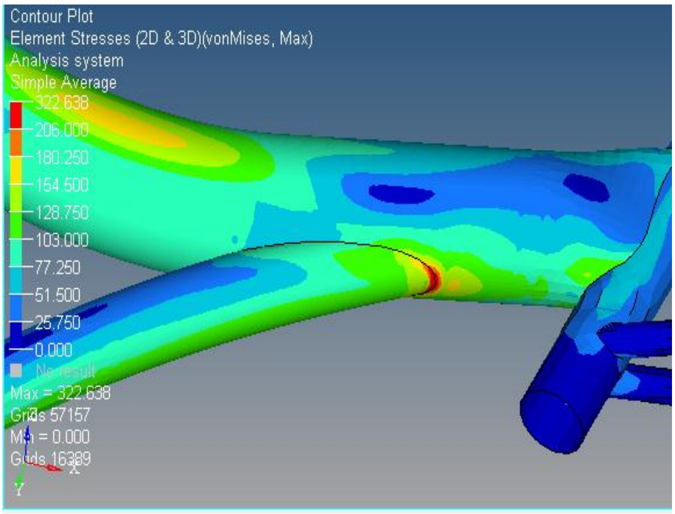


Fig 10. Stresses induced in Critical region of Modified Frame.

## V. EXPERIMENTAL VALIDATION

Experimental stress measurement was performed on a specially built testing jig which is developed. The jig consists of a box structure to restrict the deflections of the bicycle frame. Different points of the frame were fixed to the structure using attachments, thus creating fixed boundary conditions for the test. Three pneumatic cylinders are attached to the testing jig to apply loads to the bicycle frame. The applied load was measured by calibrated load cells placed in between the hydraulic cylinders and the load application points.

Test was performed on modified steel frame experimentally using testing jig and compared with the FEA results. The motivation behind this testing was to validate the finite element models. The results of FEA and Experimental are shown in Table1. The experimental set up for the stress analysis is as shown in following fig 11.

Fig 11. Experimental Set Up.

## VI FATIGUE LIFE PREDICTION

Many structures do not operate under a constant load and stresses. In fact, these loads and stresses are constantly changing. These constant changes in stress can cause fatigue failure in which the material suddenly fractures. The process that leads to fatigue failure is the initiation and growth of cracks in the material. Fracture occurs when the crack grows so large that the remaining uncracked material can no longer supports the applied loads. The fatigue life of bicycle frame is done in analysis software. The analysis is shown in Fig 12.

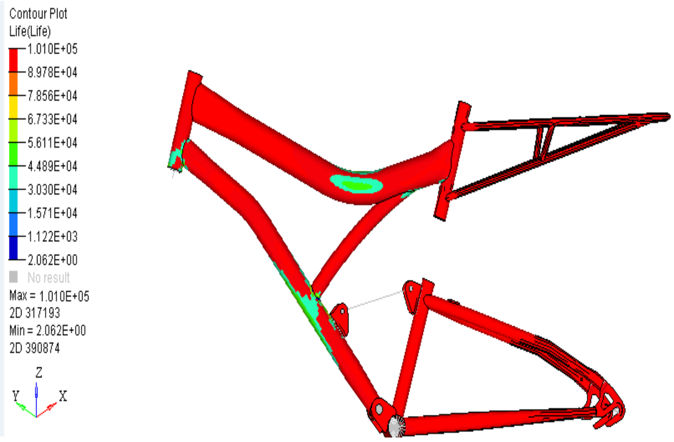


Fig 12 .Fatigue Life of Bicycle Frame

The above fig. 12 shows that crack initiation starts in the frame after 44890 cycles. And will fail after 101000 cycles.

## VII CONCLUSION

The importance of using finite element analysis as a way of minimizing cost and time required for designing frame concept. Analysis can also be used to redesign highly stressed areas of the frame, in which the stress distribution is more balanced. In test, the difference between the FEA and experimental is less than 6%. The main advantage that experimental results match the FEA gives confidence in other FEA results. As the goal was to compare frames without actually building them, experimental testing on frames confirms the idea that FEA testing can replace experimental testing to some extent.

Table 1. Comparison of Stresses in FEA and Experimental

| | **Max Stress MPa (Frame)** | **Max Stress MPa (Critical Region)** |
|---|---|---|
| **FEA** | **322.628** | **315(approx)** |
| **Experimental** | **341.339** | **332.475** |
| **Percentage Difference** | **5.79%** | **5.54%** |

The fatigue life 44890 cycles which is predicted in analysis shows that crack initiation will start after these cycles.

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