

Structural Analysis of Bicycle Frame Using Composite Laminate

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Abstract—The frame of the bicycle is the main structure to support the external loads. Traditional materials of the bicycle frame are steel or aluminium alloy. For the purpose of reducing weight, the carbon/ epoxy composite materials are now widely used to make the bicycle frames. The structural analysis of the frame is a very important stage in the design process of the bicycle. Finite element method was adopted to analysis the structural behaviours of composite bicycle frame. Different stacking sequence and fiber direction have different impact on the failure index, i.e. the stress to strength ratio at different loading conditions. Hence an optimal ply design has to be done.

The strength values of T300 carbon / epoxy composite are used in this study. On the basis of Maximum stress criterion, an optimal ply design for different loading conditions has been suggested in this work. The most effective stacking sequence of the composite frame is suggested on the basis of Failure index of the above mentioned criteria. Individual Ply failure is considered and the ply failure will occur when failure index value is greater than one. Bicycle frame modelling was done in CATIA V5 software. Shell element is used to model the composite bicycle frame. Two testing methods for the bicycle frame, i.e. frontal and vertical loads are adopted in the analysis. From the finite element analysis results, weak regions, that is regions with higher stress concentration are identified on the bicycle frame.

In order to reduce this stress concentration, Structural changes are done on the frame work. Finite element analysis is again done on the frame work to validate the findings.

Keywords— Carbon/Epoxy composite, Laminate code, Quasi-isotropic Laminate, Maximum Stress Theory, Design Parameter R.

I. INTRODUCTION

A Composite is a structural material that consists of two or more different materials which are combined together to create a unique and superior third material. Composite materials which are composed of reinforced fibers and plastics matrix have superior properties like low density, high strength-to-weight, high stiffness-to-weight ratios, corrosion resistance, wear resistance, long fatigue life and environmental stability. Due to above properties, the laminated fiber-reinforced composite materials such as carbon/epoxy composites have wide applications. Some of the important areas that are applied are in aircraft, aerospace, military, automotive, marine, and sports structures. Now a days composite materials are used for the manufacture of high performance sports bicycles. The frame of the bicycle is the main structure that support the various external loads that are

acting on them. Steel or Aluminium alloy are the traditional materials that are used for the manufacture of bicycle frame. For the purpose of reducing weight, the carbon/epoxy composite materials are now widely used for the manufacture of bicycle frames.

In the design process of the bicycle, structural analysis of the bicycle frame is a very important stage. Before the manufacture of bicycle prototype and commercial products, the strength and stiffness of the bicycle structures can be predicted and modified to an optimal design with the aid of theoretical and numerical calculations.

The finite element method is one of the numerical methods applied in various physical problems. Using FEA methods we are able to calculate the stress and deformation of the structures.

Different stacking sequence and fiber direction have different impact on the design parameter, R, i.e. the strength to stress ratio at different loading conditions. Hence an optimal ply design common for different loading condition has to be done.

The strength values of T300 carbon / epoxy composite are used in this study. On the basis of Maximum Stress criterion, an optimal ply design for different loading conditions has been suggested in this work. The most effective stacking sequence of the composite frame is suggested on the basis of Failure index of the above mentioned criteria. Individual Ply failure is considered and the ply failure will occur when failure index value is greater than one. Bicycle frame modelling was done in CATIA V5 software. Finite element analysis was done using ANSYS 15 software. Shell element is used to model the composite bicycle frame. The bicycle frame consist of tubular structures made of carbon epoxy composite material. The composite structure consist of 8-ply laminate having an individual ply thickness of 0.3 mm. Two testing methods for the bicycle frame, i.e. frontal and vertical loads are adopted in the analysis. From the finite element analysis results, weak regions, ie; regions with higher stress concentration are identified on the bicycle frame.

In order to reduce this stress concentration, Structural changes are done on the frame work. Finite element analysis is again done on the frame work to validate the findings.

II. METHODOLOGY

For the purpose of reducing weight, the carbon/epoxy composite materials are now widely been widely used for the manufacture of bicycle frames. 'R' is defined as the design parameter. Different stacking sequence and fiber direction have different impact on the design parameter R, ie the strength to stress ratio. Larger value of Rmin implies higher factor of safety of the bicycle frame. Hence the thesis aim at

finding an optimal ply design for the composite bicycle frame at various loading conditions. Also structural changes are done on the bicycle frame so that the design parameter Rmin could be increased.

The whole work can be sub divided into the following sub-problems.

- a) To find the optimal 8 ply stacking sequence and fiber direction having the least failure index.
- b) To find out the weaker regions present in the structure, ie regions having higher stress concentration.
- c) To make some structural changes on the bicycle frame so that the design parameter R could be increased.
- d) To validate using Analytical Method, so that stress happening in each layer can be compared with the results obtained from Finite element analysis.

Different stacking sequence and fiber direction have different impact on the failure index, i.e. the strength to stress ratio at different loading conditions. For a body subjected to different types of loading as in bicycle frame, multi-directional laminates are more preferred over uni-directional laminates. From the multi-directional laminates quasi isotropic laminates are supposed to have better results. The laminate consisting of 0°, 90°, 45°, and - 45° plies is used for the bicycle frame design so that life can be increased by reducing stress concentration at their joints. After different loading conditions, weak regions ie, regions with higher stress concentration is expected to occur at the connecting regions or the joints in the frame work.

The stress concentration at the joints of a bicycle frame is the main reason for the failure of a bicycle frame after prolonged use. If structural changes are done near these connecting regions using structural features like stiffeners, deformation and stress concentration happening at these regions can be reduced significantly.

III. BICYCLE FRAME MODELLING

The Bicycle frame modelling was done in CATIA V5R18 software. The main dimensions of the bicycle frame are shown in the table given below. The bicycle frame consists of many tubes made of carbon/ epoxy composite laminates.



Fig.1: Bicycle model done in Catia software

Initially the CAD modelling was done in wire frame and surface design. This was done so that shell thickness of 2.4mm can be applied on the next stage. The main parts of the

bicycle frame can be divided into top tube, seat tube, front tube and rear tubes. The length of rear tubes are taken as 320mm.

Table 1; Main dimensions of Bicycle frame

Part	Length (mm)	Diameter (mm)
Top Tube	483	25
Seat tube	455	25
Front tube	169,200	25,13

IV. FINITE ELEMENT ANALYSIS

The finite element software ANSYS 15 is used in this thesis work. Advanced composite pre post, ACP is used for the analysis. All the composite structures in the bicycle frame are made of 8 ply carbon-epoxy composite laminates. Each ply thickness is 0.3mm. The direction of global coordinate system of the body is taken as the direction of principal material coordinate system of each ply. The density of carbon epoxy composite material is taken as 1500kg/m³. Orthotropic Elastic properties of carbon/epoxy composite are taken as shown below.

Table 2; Orthotropic Elastic properties of carbon/epoxy composite

Properties	Values
E ₁ (Young's Modulus)	162 GPa
E ₂	14.9 GPa
E ₃	14.9 GPa
ν ₁₂ (Poisson's Ratio)	0.283
ν ₁₃	0.283
ν ₂₃	0.283
G ₁₂ (Shear Modulus)	5.7 GPa
G ₁₃	5.7 GPa
G ₂₃	5.4 GPa

Strength values of T300 carbon/epoxy composite are specified as shown below.

Table 3. Strength values of T300 carbon/epoxy composite

Strength	Value (MPa)
S _{1t}	1760
S _{1c}	1570
S _{2t}	80
S _{2c}	80
S _{3t}	80
S _{3c}	80
S _{12, S_{23, S₃₁}}	98

The direction of global coordinate system is itself chosen as the direction of body coordinate system. After applying the engineering data's, the number of layers for the whole structure is applied. An 8 ply stacking sequence with 0.3 mm thickness and required stacking angle is specified.

Quadrilateral Meshing is being done on the structure. The element type used to simulate the carbon / epoxy composite laminate of the bicycle frame is SHELL91. SHELL91 is the 8-noded high-order shell element based on the thick shell theory. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes.

The below figure shows FE meshing that has been done. It contains 10417 number of nodes and 10364 number of elements. The minimum edge length is 2.483mm

A. Failure Criterion - Maximum stress Theory

Failure is predicted in a lamina, if any of the normal or shear stresses in the local axes of a lamina is equal to or exceeds the corresponding ultimate strengths of the unidirectional lamina. [6]

$$-(\sigma_1^c)_{ult} < \sigma_1 < (\sigma_1^t)_{ult}, \text{ or}$$

$$-(\sigma_2^c)_{ult} < \sigma_2 < (\sigma_2^t)_{ult}, \text{ or}$$

$$-(\tau_{12})_{ult} < \tau_{12} < (\tau_{12})_{ult}$$

Ply failure will occur when failure index value (stress to strength value) is greater than one.

B. Design Parameter

'R' is defined as the design parameter. Which is the strength to stress ratio and can be found out using the following.

$$R_{it} = |\sigma_i| / |\sigma_i| \text{ when } \sigma_i > 0, i=1,2,3$$

$$R_{ic} = |\sigma_i| / |\sigma_i| \text{ when } \sigma_i < 0, i=1,2,3$$

$$R_{ij} = |\tau_{ij}| / |\tau_{ij}|, i=1,2,3 (i \text{ not equal to } j) [6]$$

From finite element analysis all stress values $\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{31},$ and τ_{12} of each ply can be obtained.

$$R_{min} = \min [R_{it}, R_{ic}, R_{ij}]$$

Larger value of Rmin implies higher factor of safety of the bicycle frame.

C. Quasi-isotropic Laminate

Quasi-isotropic laminates are special type of orthotropic laminates. A laminate is called quasi-isotropic when its extensional stiffness matrix behaves like an isotropic material. This requires that

$$A_{11} = A_{22},$$

$$A_{16} = A_{26} = 0,$$

$$A_{66} = (A_{11} - A_{12}) / 2$$

Only Quasi isotropic laminates are taken for this work. No slippage is assumed between the element layers. Perfect bonding between plies is assumed in this analysis. Fibre direction is taken the same throughout the bicycle frame.

V. TESTING METHODS, BOUNDARY AND LOADING CONDITIONS

The bicycle frame is subjected to frontal loading test and vertical loading test. The boundary and loading conditions are taken from the past references. From the Finite element analysis the normal and shear stress of each ply under the frontal and vertical loading, is obtained. For the frontal loading test, static frontal loads of 490N, 750N and 1000N are applied on the each sides of the front tube. The frame is fixed

at the rear ends. For the vertical loading test, loads are applied on the head part, seat part, and bottom bracket part. Handle load of 58.8 N (6Kgf), Seat load of 656.6 N (67Kgf) and Peddle load of 132.3 N (13.5*2Kgf) are applied here. The total vertical load is 100 kgf. The frame is fixed at rear tube ends and front tube ends.

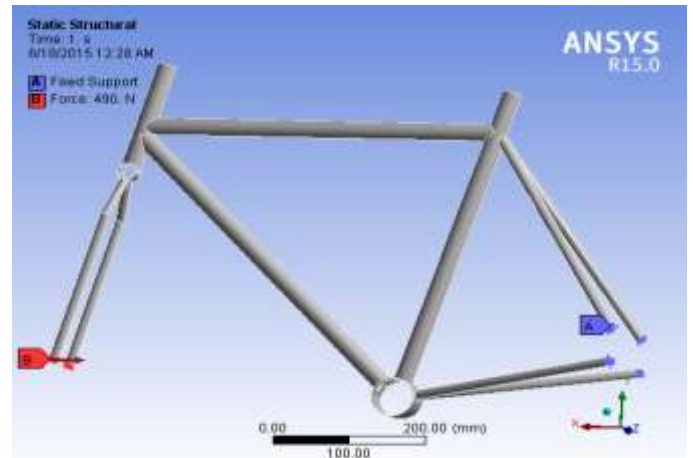


Fig 2. Static frontal loading with 490N

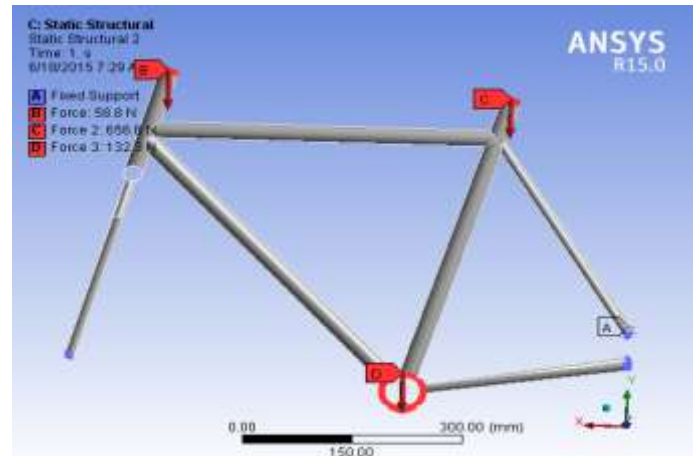


Fig 3. Static Vertical Loading

VI. RESULTS AND DISCUSSIONS

A. Frontal Loading Results

Normal stress acting on each layer, with respect to X, Y, Z direction and Shear stress acting on each layer, with respect to XY plane, YZ plane, XZ plane and total deformation happening on the bicycle frame are obtained from the FE analysis. Total deformation during frontal loading is found to be 50mm.

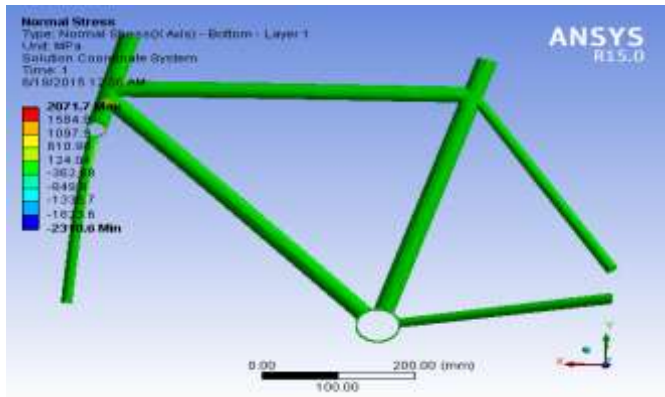


Fig 4. Normal stress in X direction, (σ_1) for layer 1

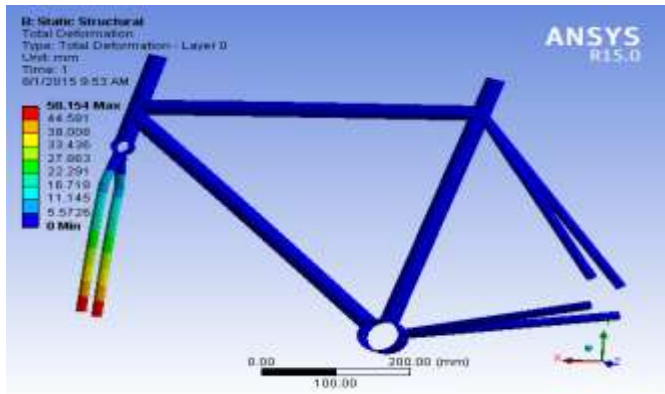


Fig 5. Total deformation during frontal loading

Table 4. Stress for [0/90/45/-45]_s laminate under frontal load

Ply	σ_1 (MPa)		σ_2 (MPa)		σ_3 (MPa)	
	Min	Max	Min	Max	Min	Max
1	-2310	2071	-198	182	0	0
2	-1568	1453	-183	162	0	0
3	-1221	1515	-120	110	0	0
4	-795	742	-84	89	0	0
5	-479	461	-50	46	0	0
6	-485	671	-52	39	0	0
7	-749	1005	-77	61	0	0
8	-1137	829.23	-94	140	0	0
R	0.6	0.84	0.4 (R_{min})	0.44	-	-

Ply	τ_{12} (MPa)		τ_{23} (MPa)		τ_{31} (MPa)	
	Min	Max	Min	Max	Min	Max
1	-114	97	0	0	0	0
2	-74	83	-128	121	-13.2	11
3	-56	52	-124	139	-153	125

4	-44	45	-169	137	-153	136
5	-36	33	-178	144	-161	143
6	-27	28	-136	154	-170	137
7	-64	37	-136	128	-117	104
8	-60	94	-13	11.6	-121	128
R	0.85	0.98	0.56	0.64	0.57	0.68

Table 5. Rmin Value for different laminate under frontal load.

Stacking sequence	R_{min} Value	Remark
[90/0/-45/45] _s	0.42	Very Good design
[0/90/-45/45] _s	0.41	Good design
[90/0/45/-45] _s	0.4	Good design
[0/90/45/-45] _s	0.4	Good design
[45/-45/90/0] _s	0.3	Poor design
[-45/45/90/0] _s	0.28	Poor design
[45/-45/0/90] _s	0.22	Poor design
[-45/-45/0/90] _s	0.2	Poor design

Ply failure will occur when failure index value (ie; stress to strength value) is greater than one. The larger value of Rmin (ie ; strength to stress value) implies the All quasi isotropic laminates show higher Rmin value when compared with unidirectional laminates. In the quasi isotropic composites laminates, the laminates having 0° ply and 90° ply located at the outer or inner layers of the bicycle frame shows relatively higher Rmin value than others. This is because 0° ply and 90° ply located at the outer or inner layers of the bicycle frame can effectively resist the higher stress at that areas.

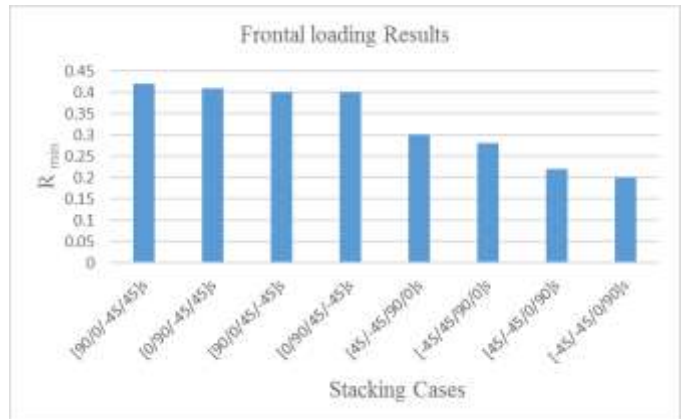


Fig 6. Rmin for different cases during frontal loading

From the Finite element result for frontal loading, the first or eighth layer was found to be the weak layer and the weak region was seen at the front joint which is the front tube-top tube connection region. Normal stress acting in Y direction, σ_2 is the failure stress. Total deformation during frontal loading is found to be 50mm

B. Vertical Loading Results

From the Finite element results normal stress acting on each layer, with respect to X, Y, Z direction and shear stress acting on each layer, with respect to XY plane, YZ plane, XZ plane and total deformation happening on the bicycle frame are obtained. Result images of the stacking sequence [0/90/45/-45]_s for vertical loading case is shown below. Total deformation during vertical loading is found to be 0.13mm

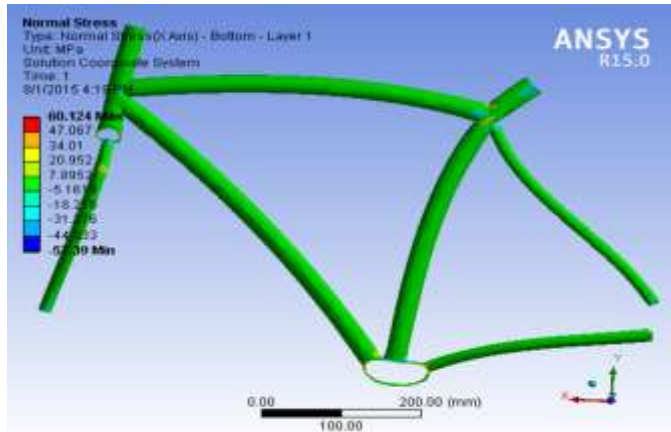


Fig 8. Normal stress along X direction, (σ_1) for layer 1

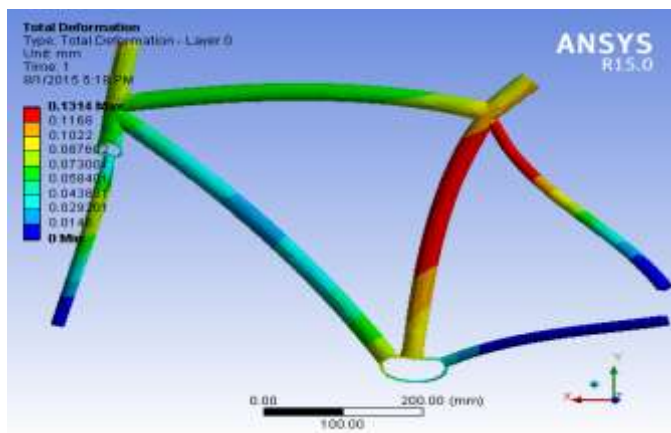


Fig 7.Total deformation for vertical loading

Table 6.Stress for [0/90/45/-45]_s laminate under vertical load

Ply	σ_1 (MPa)		σ_2 (MPa)		σ_3 (MPa)	
	Min	Max	Min	Max	Min	Max
1	-57	60	-6	4.7	0	0
2	-57	34	-5	4	0	0
3	-45	30	-4	3	0	0
4	-39.9	21	-3.9	2.6	0	0
5	-34	19	-3.2	2.06	0	0
6	-23	23	-3.3	2.2	0	0
7	-42	30	-2.3	2.2	0	0
8	-25	26	-4.1	3.2	0	0
R	27.54	29.3	13.3(R _{min})	20	-	-

Ply	τ_{12} (MPa)		τ_{23} (MPa)		τ_{31} (MPa)	
	Min	Max	Min	Max	Min	Max
1	-3.1	3.3	0	0	0	0
2	-2.7	2.5	-3.5	3.6	-0.4	0.3
3	-1.6	1.2	-3.7	3.9	-4.7	4.3
4	-1.6	1.2	-5.2	4.7	-4.3	4.2
5	-1.1	1.2	-5.4	5	-4.5	4.4
6	-1.3	1.14	-4.2	4.3	-5.2	4.7
7	-1.5	1.3	-3.8	3.8	-3.9	3.2
8	-1.7	1.9	-0.4	0.36	-3.6	3.5
R	31.6	29.6	18.14	20.8	18.84	20.85
1		96		5		

Table 7. R_{min} Value for different laminate under frontal load.

Stacking sequence	R _{min} Value	Remark
[0/90/45/-45] _s	13.3	Very good
[0/90/-45/45] _s	13	Good
[90/0/45/-45] _s	12.77	Good
[90/0/-45/45] _s	12.5	Good
[45/-45/90/0] _s	11.94	Poor design
[45/-45/0/90] _s	11.7	Poor design
[-45/45/0/90] _s	11.54	Poor design

All quasi isotropic laminates show higher R_{min} value when compared with unidirectional laminates. In the quasi isotropic composites laminates, the laminates having 0° ply and 90° ply located at the outer or inner layers of the bicycle frame shows relatively higher R_{min} value than others. This is because 0° ply and 90° ply located at the outer or inner layers of the bicycle frame can effectively resist the higher stress at that areas.

From the Finite element result for Vertical loading, the first or eighth layer was found to be the weak layer and the weak region was seen at the rear joint which is the seat tube-top tube joint region. Normal stress acting in Y direction, σ_2 is the failure stress.

After different loading conditions, [0/90/45/-45]_s laminate is found to be the optimal ply design. And weak regions ie, regions with higher stress concentration is found to occur at three connecting regions in the frame work. Structural changes are done near these connecting regions using structural features like stiffeners, so that deformation and stress concentration happening at these regions can be reduced significantly. Total deformation during vertical loading is found to be 0.13mm.

VII. ANALYSIS ON NEWLY SUGGESTED BICYCLE MODEL

The newly suggested bicycle frame is subjected to frontal loading test and vertical loading test. The boundary and loading conditions are taken just like the previous case itself. From the Finite element analysis the normal and shear stress of each ply under the frontal and vertical loading, is obtained.

Total deformation happening on the new bicycle frame are also obtained. Since $[0/90/45/-45]_s$ laminate is found to be the optimal ply design in the first model, the same stacking sequence was analysed here also. Result of the stacking sequence $[0/90/45/-45]_s$ for both vertical loading case and Frontal loading case is shown below.

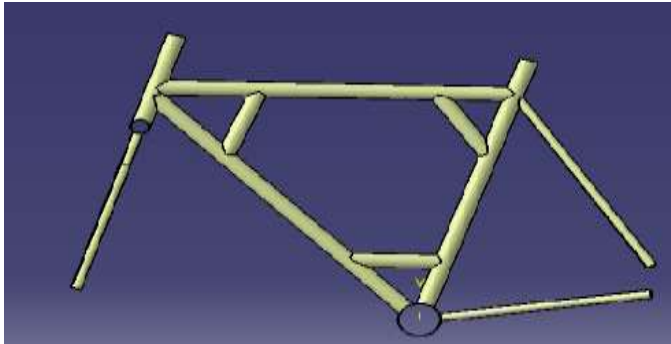


Fig 9. Newly suggested bicycle frame modelled in Catia V5 software

Quadrilateral Meshing is being done on the structure. The above figure shows FE meshing that has been done. It contains 11941 number of nodes and 11907 number of elements. The minimum edge length is 2.483mm. Since $[0/90/45/-45]_s$ laminate is found to be the optimal ply design in the first model, the same stacking sequence was analysed here also.

A. Testing Methods, Boundary and loading conditions

The new bicycle frame is subjected to frontal loading test and vertical loading test. The boundary and loading conditions are taken as same from previous case. From the Finite element analysis the normal and shear stress of each ply under the frontal and vertical loading, is obtained.

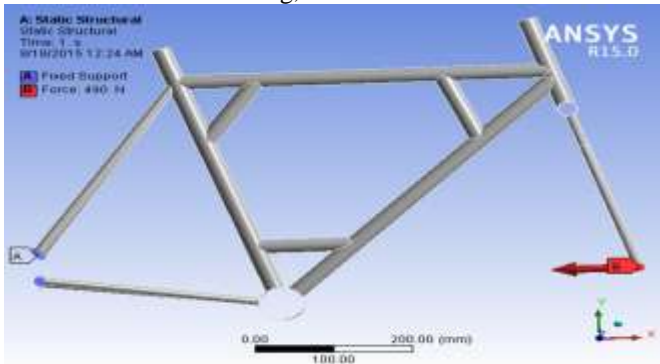


Fig 10. Static frontal loading with 490N

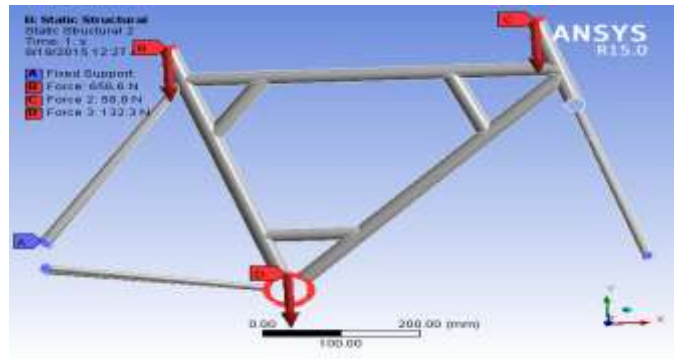


Fig 11. Static Vertical Loading

B. New Finite Element Results

From the Finite element analysis the normal and shear stress of each ply under the frontal and vertical loading, is obtained. Total deformation happening on the new bicycle frame are also obtained.

New Rmin value for frontal loading is 0.43 and vertical loading is 16 which are higher values compared with old Rmin values. Total deformation in case of frontal load is 43.28mm and 0.1314 in case of vertical loading. This shows lesser deformation from the first model.

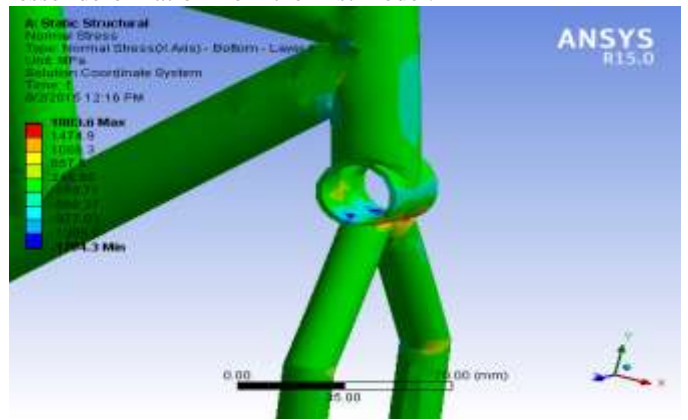


Fig 12. Normal stress along X direction, σ_1 for layer 1

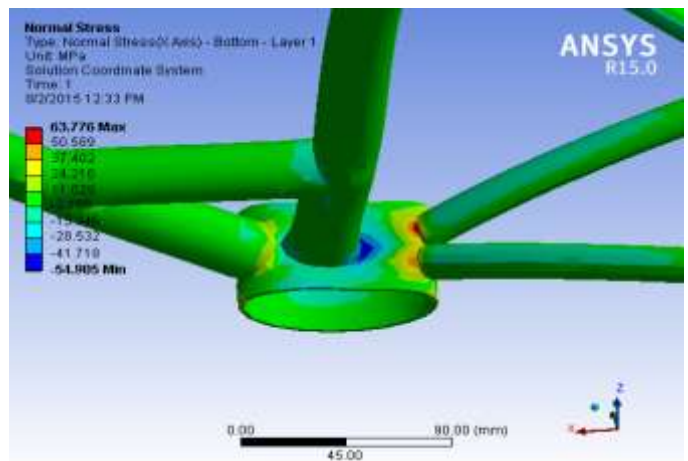


Fig 13. Normal stress along X direction, σ_1 for layer 1

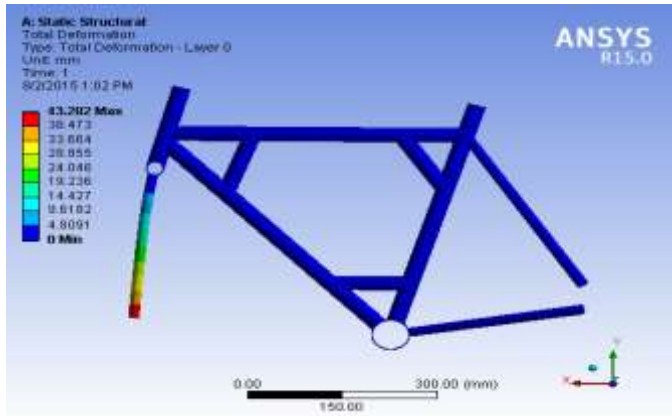


Fig 14. Total deflection for frontal loading

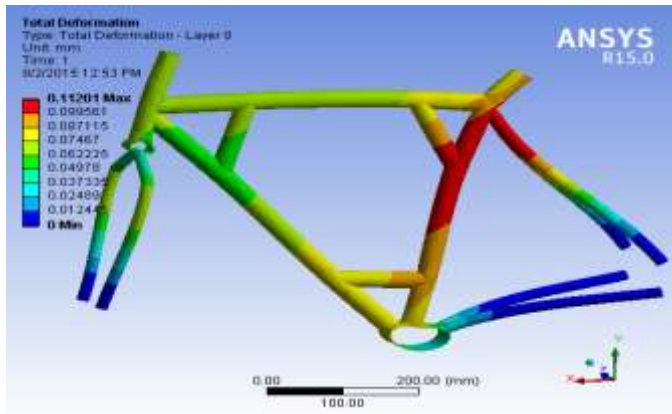


Fig 15. Total deflection for vertical loading

VIII. CONCLUSIONS

All quasi isotropic laminates show higher Rmin value when compared with unidirectional laminates. In the quasi isotropic composites laminates, the laminates having 0° ply and 90° ply located at the outer or inner layers of the bicycle frame shows relatively higher Rmin value than others. This is because 0° ply and 90° ply located at the outer or inner layers of the bicycle frame are able to effectively resist the higher stress at that areas.

Under the frontal loading, the first or eighth layer was found to be the weak layer and the weak region was seen at the front joint which is the front tube-top tube connection region. Normal stress acting in Y direction, σ_2 is the failure stress. But, under vertical loading, the weak region was shifted to the rear joint which is the seat tube-top tube joint region.

After different loading conditions, [0/90/45/-45]s laminate is found to be the optimal ply design. And weak regions ie, regions with higher stress concentration is found to occur at three connecting regions in the frame work. Structural changes are done near these connecting regions using structural features like stiffeners, so that deformation and stress concentration happening at these regions can be reduced significantly.

New Rmin value for frontal loading is 0.43 and vertical loading is 16 which are higher values compared with old Rmin values. Total deformation in case of frontal load is 43.28mm and 0.1314 in case of vertical loading. This shows lesser deformation from the first model

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