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Static analysis of flax epoxy composite and flax-glass epoxy composite automotive bumper beam under low-speed frontal impact condition

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ABSTRACT

This work studies flax fiber-reinforced epoxy resin composite as an alternative material for an automotive bumper beam. Various parameters such as fiber volume fraction, fiber orientation, and stack-up sequence that affect the performance of the natural fiber composite material are considered. From the literature, it is found that flax fibers are one of the strongest natural fibers that have found their way in a number of day-to-day applications, and hence they are taken under consideration in this study. A suitable geometry of the bumper beam is selected and static analysis with help of the ANSYS static analysis module is performed. Results are obtained from the software and analyzed on the basis of factor of safety, deflection of the beam, and the energy absorbed by the beam during the low-velocity frontal impact. Finally, the conclusion is formulated with the help of the weighted average method.

From this work, it has been observed that the $[0_F45_F90_F\text{-}45_F]_1[0_F]_1[\text{-}45_F90_F45_F0_F]_1$ configuration for flax epoxy composite and $[0_G45_F90_G]_1[0_F]_1[90_G\text{-}45_F0_G]_1$ configuration for flax glass hybrid epoxy composite with flax:matrix ratio as 53:46 and flax:glass:matrix ratio as 17.67:35.33:46 respectively are best suitable for an automotive bumper beam.

Keyword: -Natural fiber composites, Static analysis, Bumper beam, Hand layup method, Fiber orientations, fiber fractions, stacking sequences.

I. INTRODUCTION

Natural fibers have found their application in human life since ancient times. Recently, natural fibers reinforced in polymer matrix material, generally known as natural fiber composites (NFC) are popular in the automotive and aerospace sectors. The directional properties of NFCs have proven to be superior to conventional materials such as steel and aluminum. Hence, the use of such NFCs is profitable in certain specific applications. Over the years automobile companies have developed various parts of their vehicles by using NFCs. Mostly NFC material is used for manufacturing nonstructural members such as dashboards, internal door panels, etc. However, the potential superior directional properties of NFCs can be exploited as a material for structural members such as the bumper beam.

A bumper beam is a structural member of a vehicle that forms a basic component of the bumper system. It is a safety member and protects the car and passengers in low to medium speed collisions by absorbing the impact energy and elastic deformation. Bumpers are designed to prevent or reduce physical damage in the front end as well as the rear end of the vehicle. There is a limit to the deformation of the bumper. Such limits are specific to the geometry and overall design of the beam and the car. The deformation is constrained in such a way that the bumper should protect the hood, fuel, exhaust, and cooling system, parking lights, headlamps, and taillights that are not damaged during low-speed collisions. Various impact regulations to check the performance of the beam are used in different countries. United Nations Economic Commission for Europe regulation no. 42 (UN ECE R42) is the most widely used regulation.

II. EFFECT OF MATERIAL PROPERTIES ON MECHANICAL PROPERTIES OF THE BUMPER BEAM

For impact on the bumper beam, the maximum deflection and the remained plastic deflection after the impact decrease with the increasing yield strength. Also, maximum deflection time and separation point occur early. The bumper system collides inelastically with the coefficient of restitution of lower than one and consequently plastic strain energy dissipated during an impact [1]. An increase in beam thickness decreases δmax, increases impact force, increases SEA (specific energy absorption), increases the weight of the beam, and decreases the time of the collision. So it has a positive effect on a few performance parameters whereas a negative effect on others. So it is essential to find an optimal value that will maintain the deflection limit and weight limit. There are many factors that affecting energy absorption. Some factors that have been found are cross-section, rib, thickness, material, shape, and also impact condition [2].

Use of materials with low young module cause low rigidity and use of high-strength materials lead to good impact behavior. Increasing bumper thickness causes a rise in bumper rigidity and impact force. The addition of ribs causes an increase in rigidity of the bumper beam center and consequently increases the impact force [2].

In aluminum bumper due to the low stiffness, the impact area of the beam is wide. It means a wider area of the bumper is involved. So plastic deformation and consequently, dissipated energy is small since the coefficient of restitution is bigger than other metals. Another observation is the difference in impact velocities. With comparison clearly shows that there is a difference in impact velocities among magnesium, steel, and aluminum bumper. In aluminum bumper, the difference between Impactor velocity and vehicle velocity after impact is higher than steel and magnesium bumper. In other words, in an aluminum bumper more kinetic energy from Impactor transfers to the vehicle. It means that in steel and magnesium bumpers, reduction of Impactor velocity and increasing of vehicle velocity is lower than an aluminum bumper. It can be proved by the above-mentioned impact laws [1].

III. IMPACT MECHANICS OF BUMPER BEAM

For designing a bumper beam the impacts are categorized into two categories: Low-Speed Impact and Low-Speed Full Crash Impact. In the case of a low-speed impact, the stress developed is within the elastic limit. Since the stresses don't rise to the plastic region there is no permanent deformation. Energy transfer, in this case, is reversible, i.e. after separation, the entire energy stored as internal energy in the bumper beam gets distributed among the Impactor and the vehicle in the form of kinetic energy based upon the stiffness of the beam and coefficient of restitution. In the case of Low-Speed Full Crash impact, the stress developed in the beam goes beyond the elastic limit. This results in the permanent deformation of the beam. Energy transfer, in this case, is irreversible, i.e. some amount of impact energy is lost in the form of permanent deformation of the bumper beam [3]. The impacting phenomenon between an Impactor and the front bumper in a low-speed full crash could be very complicated hence, automobile manufacturers insist that the bumper system should not have any material crash or failure. Thus for design purposes which is an iterative process, the bumper beam is subjected to low-speed impact tests [1].

The impacting phenomenon between an Impactor and the front bumper in a low-speed full is complicated since transient and nonlinear analyses are involved. But, in designing the front bumper, automobile manufacturers insist that the bumper system should not have any material crash or failure. Therefore, up to that point, the total energy is conserved throughout the impact duration. Since the Impactor is assumed to be rigid and the bumper beam was made of metallic and composite material and the shock absorber is a relatively low stiffness material, the distribution of the impact load is irregular along the contact area and over the contact region of the bumper, the bumper beam subjected to the impact load undergoes a constant deformation d-max [1].

Structural crashworthiness is very important in the design of automotive parts. It refers to the response of a vehicle when it is involved in or undergoes an impact. Crashworthiness performance is good when less damage to the vehicle and passengers after the crash. Crashworthiness for structural members is required to be analyzed before implementing it in the actual field. Specific energy absorption, mean crushing load, and crash load efficiency are the indicators of crashworthiness.

FEA analysis can predict energy absorption even there is a small percent of error FEA simulation, but the result obtained is reasonable as it's within the standard requirement. There are many factors affecting energy absorption. Some factors that have been found are cross-section, rib, thickness, material and shape, and impact condition [2].

IV. MODELING AND ANALYSIS

The geometry of the beam was taken from [04] where the material used for the beam is steel and static, as well as dynamic analysis, are performed on the beam. Detailed drawing of the beam is as shown in figure no. 01.

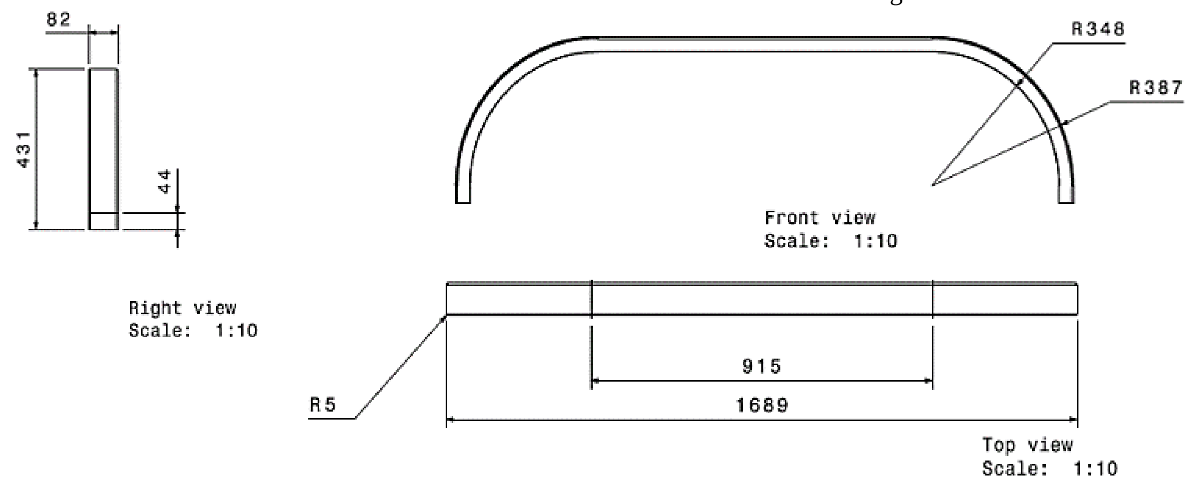

Fig. -1: Dimensions of the bumper beam

A shell model of the given dimensions was modeled using Catia V5 software. The part file was converted to a standard format and then imported into the ANSYS Composite Preprocessor (ANSYS ACP pre). Here the composite beam was modeled by creating a fabric of flax fiber and glass fiber respectively. The properties of glass epoxy lamina are preloaded in the ANSYS library whereas the properties of Flax epoxy lamina are manually fade in the software. The values of the flax epoxy lamina are taken from [05]. These are mentioned in table no. 01. Total eight stacking configurations with 1mm thickness per lamina of fiber epoxy composite are considered in this study. These configurations are mentioned in table no. 02.

Parameter	Units	Value
Density	Kg/m^3	1250
Longitudinal elastic modulus	MPa	31420
Transverse elastic modulus	MPa	5580
Poisson's ratio		0.353
In-plane shear modulus	MPa	2070
Tensile strength in the longitudinal direction	MPa	287.7
Tensile strength in the transverse direction	MPa	127.1
compressive strength in the longitudinal direction	MPa	33.86
Compressive strength in the transverse direction	MPa	79.94
In-plane shear strength	MPa	37.35
Maximum strain for matrix failure	mm/mm	0.006
Maximum in-plane shear strain	mm/mm	0.018
Maximum strain for fiber tension	mm/mm	0.009
Maximum strain for fiber compression	mm/mm	-0.004

Table -1: Properties of flax epoxy composite ply 1 mm thickness

Layup No.	Configuration	Weight of beam in kg
1	$[0_F]_9$	3.1136
2	$[0_F90_F]_4[0_F]_1$	3.1136
3	$[0_F45_F90_F\text{-}45_F]_1[0_F]_1[\text{-}45_F90_F45_F0_F]_1$	3.1136
4	$[0_G0_F]_3[0_G]_1$	3.2699

5	$[0_G]_2[0_F]_3[0_G]_2$	3.2699
6	$[0_G90_G]_1[0_F90_F0_F]_1[90_G0_G]_1$	3.2699
7	$[0_G45_F90_G]_1[0_F]_1[90_G\text{-}45_F0_G]_1$	3.2699
8	$[0_G90_F]_1[0_G0_F0_G]_1[90_F0_G]_1$	3.2699

Table -2: Laminate layup configurations

A suitable crash can of 4 mm thickness is designed in Catia V5 and a solid model of the crash can is imported in ANSYS mechanical model module. The bumper and the crash cans are meshed in the respective ANSYS modules. A fine mesh is automatically generated by the software. According to the geometry of the part, a combination of triangular and quadrilateral elements is generated in the mesh. The Setup component of ANSYS ACP pre consists of the modeled bumper beam and the model component of the ANSYS mechanical module consists of the crash can. Both these components are then connected to the setup component of the ANSYS static structural module. In this setup component, the type of contact between the crash cans and the bumper beam is defined. The type of contact between these two parts is bonded type contact. The force is applied at two distinct vertical lines in the front face of the beam. The location of these two lines was selected in such a way that the static analysis will approximately replicate the real-time collision conditions. Fixed support is defined at the open end surface of both the crash cans. The value of force applied is 38756 N. This value of the force is the value corresponding to the maximum value of load experienced by an aluminum beam of the same geometry under low-speed frontal impact condition and Impactor velocity equal to 4 km/hr (1111 mm/sec).

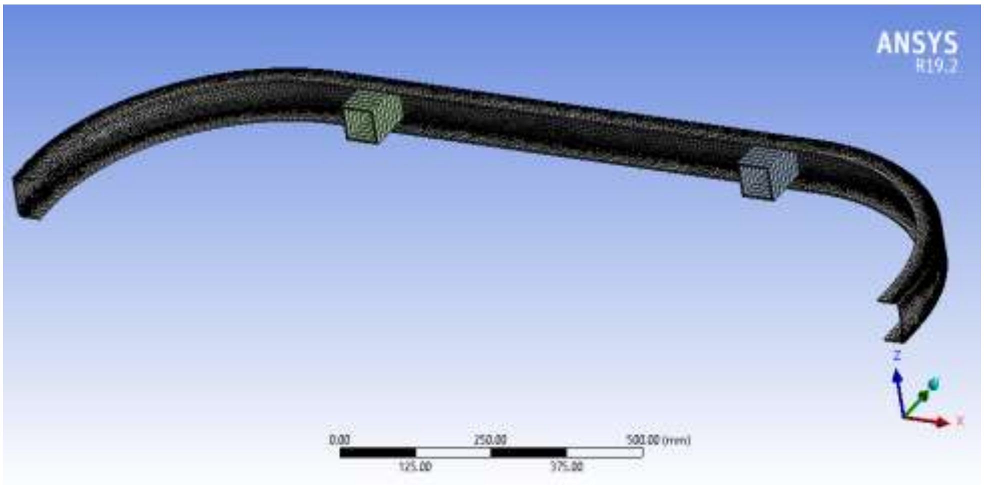

Fig. -2: Meshed assembly in ANSYS Mechanical Model module – static analysis

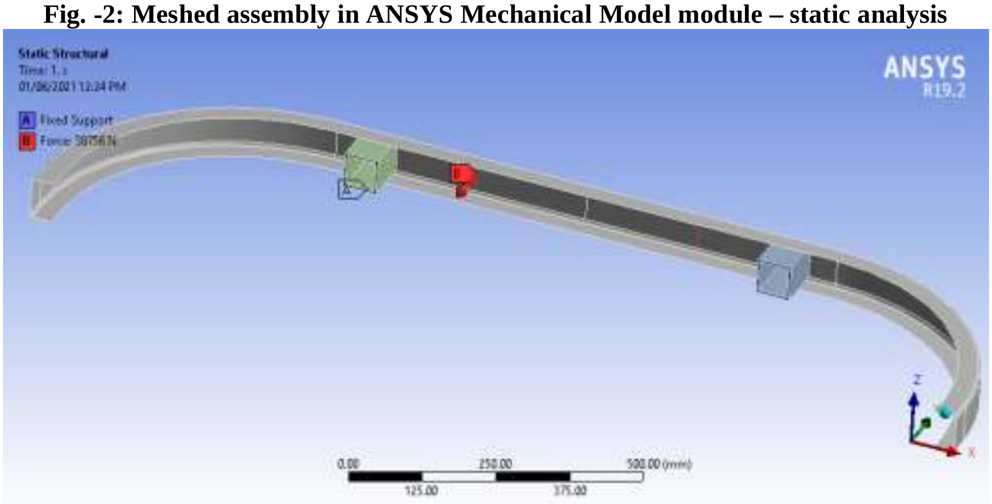

Fig. -3: Simulation condition in ANSYS Static Structural module

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Stress and energy induced in the beam and the maximum deformation of the beam are found out with the help of results generated by the software. These results are presented in table no. 03 and 04. In the case of stresses induced in the beam, individual ply stresses were obtained by using ANSYS ACP post-processor. Out of these, the maximum value of stress generated in both the flax fiber ply and the glass fiber ply are noted in the table for each configuration.

Lay Up no.	Layup Configuration	Thick -ness	Weight	Difference in Weight	Equivalent Max. Stress	Total Strain Energy	Max. Displacement
		Mm	kg	%	MPa	mJ	mm
Aluminum		4	3.09	0	1200.7	123	9.025
1	$[0F]_9$	9	3.11	0.72	377.53	297	24.507
2	$[0F90F]_4[0F]_1$	9	3.11	0.72	508.28	461	32.11
3	$[0F45F90F\text{-}45F]_1[0F]_1[\text{-}45F90F45F0F]_1$	9	3.11	0.72	546.64	495	35.29
4	$[0G0F]_3[0G]_1$	7	3.26	5.77	565.9	396	25.502
5	$[0G]2[0F]_3[0G]_2$	7	3.26	5.77	553.3	310	25.394
6	$[0G90G]_1[0F90F0F]_1[90G0G]_1$	7	3.26	5.77	572.48	360	33.049
7	$[0G45F90G]_1[0F]_1[90G\text{-}45F0G]_1$	7	3.26	5.77	765.5	373	34.853
8	$[0G90F]_1[0G0F0G]_1[90F0G]_1$	7	3.26	5.77	651.9	332	28.886

Table -3: Static analysis results for Aluminium and Flax composite beams

Lay-up no.	Individual maximum Ply Stress MPa								
	1	2	3	4	5	6	7	8	9
1	277.1	272.3	267.5	264.2	271.6	284.9	299.2	313.5	328.3
2	389.0	167.8	379.6	83.58	387.5	117.6	412.4	215.2	444.0
3	437.3	219.6	184.6	160.1	434.0	169.9	192.8	231.3	471.
4	417.5	286.7	401.5	287.9	436.7	325.2	494.8	--	--
5	413.8	406.6	280.5	286.6	302.4	456.4	482.9	--	--
6	572.4	236.8	390.6	83.6	413.2	309.1	643.6	--	--
7	604.2	199.5	198.3	419.9	271.0	227.5	666.7	--	--
8	491.06	189.48	474.64	340.54	511.75	238.3	573.36	--	--

Table -4: Static analysis results for individual ply stresses

V. ANALYSIS OF SIMULATION DATA

For selecting the best configuration, the performance of each configuration is to be evaluated through simulation data. The three main parameters to evaluate performance are: "strain energy absorbed (EA), Factor of Safety (FOS) and Maximum displacement (δ)". FOS value for a configuration is taken as the minimum among the FOS for each fabric of that configuration. (The FOS is minimum in Flax fabric for all the configurations because of its lower yield strength.)

The ideal material would be the one with maximum Strain Energy Absorption, maximum FOS, and minimum displacement. However, it is observed in simulation data that not a single configuration has all three values better than any other configuration. That is to say, no ideal material configuration as such exists. Hence the weighted average method is followed to select the optimum configuration.

VI. RESULTS – DISCUSSION, WEIGHTED AVERAGE METHOD

The weighted average is a calculation that takes into account the varying degrees of importance of the numbers in a data set. In calculating a weighted average, each number in the data set is multiplied by a predetermined weight before the final calculation is made. A weighted average can be more accurate than a simple average in which all numbers in a data set are assigned an identical weight.

The procedure is as follows:

1. Mark the best value for all three parameters. The best value for 'Strain Energy Absorption' would be the maximum value (495 Joule). The best value for 'FOS' would also be the maximum value (0.95).The best value for 'Max displacement' (δ) would be the minimum value (24.507 mm).
2. Evaluate percentage deviation from the best value for all three parameters in all of the eight configurations using the following relation:
   % deviation= $[(V_{best}\text{-}Vi)/Vbest]\times 100$

Percentage deviation in EA, FOS and δ calculated using the above relation are mentioned in Table no. 05.

3. A weighing factor (Weight) is assigned to each of the three parameters, by taking into consideration the functional requirement of the bumper and the effect on the bumper if that parameter assumes a poor value.
   i. The main function of the bumper is to absorb the impact energy and protect the car chassis from fatal damage. Thus Energy Absorption appears to be the most important parameter. It is given a weighting factor of '5'.
   ii. One important criterion to be satisfied by the bumper is that there shouldn't be any permanent deformation after the impact. This implies that stress developed in each layer must not exceed its yield strength. That is to say, the value of FOS should not be less than 1. Hence FOS is an equally important parameter in the performance evaluation. It is given a weighing Factor of '5'.
   iii. As long as the maximum displacement is within the specified limit of 50 mm, it doesn't matters how large or small the value is. From simulation data, it is evident that a material configuration with high Energy Absorption will have high displacement. Hence percentage deviation in displacement is very high for High Energy Absorbing material. This makes high-energy absorbing material look like a poor choice. To avoid this 'Maximum Displacement" is given a weighting factor of '3'.
   iv. Calculate weighted average percentage deviation in three parameters for all the 8 configurations using the following relation:
   v. Weighted avg % Dev = [(%Dev in EA)*5+(% Dev in FOS)*5+(% Dev in δ)*3]/13

   vi. The weighted average percentage deviation for all 8 configurations is shown in Table no. 05.
   vii. The configuration with the lowest value of weighted average percentage deviation is selected as the optimum material.

VII. CONCLUSIONS

1. When compared to an Aluminium beam of 4 mm thickness, Flax composite beams of equivalent weight will fail in low-speed frontal impact conditions by undergoing permanent deformation. Hence, a reduction in the weight of the beam by using flax composite material is not possible. Although, among the different fiber layup configurations; $[0_F45_F90_F\text{-}45_F]_1[0_F]_1[\text{-}45_F90_F45_F0_F]_1$ for Flax epoxy composite & $[0_F45_F90_F]_1[0_F]_1[90_F\text{-}45_F0_F]_1$ for Flax-Glass epoxy composite are best suitable for an automobile bumper beam.

2. Even though the cost of flax cultivation can be less than the cost involved in manufacturing Aluminium, the cost of Flax composite beams will be more than the Aluminium beam. This is because of the preprocessing required on flax fibers before they can be used as a reinforcement in the matrix material. Also, the cultivation and processing industry for flax fibers is not well established as compared to the Aluminium manufacturing industry. Hence, the auxiliary costs associated with flax production remain uncertain.

3. According to the static analysis results, it can be concluded that during the real-time low-velocity impact, the natural fiber beam will absorb most of the impact energy and will transfer the very little load to the car body at the cost of permanent deformation of the beam itself. Hence, the natural fiber beam will have to be replaced every time after the impact; which is not the case for the Aluminium beam.

VII.FUTURE SCOPE

Based on static analysis, an optimal stacking sequence and fiber orientation are identified. It is concluded that weight reduction won't be possible even by using the best material configuration because of the permanent deformation experienced by the bumper beam of equivalent weight (Since FOS < 1).

However, simulation data shows that the energy absorbed by the composite beam was much higher as compared to that absorbed by the aluminum beam. Hence it seems possible that a composite beam of higher thickness capable of limiting the maximum deflection within 50mm and avoiding plastic deformation will give better protection to car chassis in impact conditions than that of an Aluminum beam. However to conclude this, Dynamic Simulation and experimental analysis of impact tests will be required. It will involve multiple simulations performed on the beam by progressively increasing the thickness of the beam in steps until the above-stated requirements are fulfilled.

This further study can be carried out by increasing the thickness of configuration no. 3 in case of pure flax epoxy composites and configuration no. 7 in case of flax-glass epoxy composite materials, which is suggested to be the best configuration by our study.

Also, further research on the addition of binding materials into the matrix, which will felicitate better adhesion between fibers and matrix material will significantly improve the mechanical properties of the composites.

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