COMPARISON OF MECHANICAL BEHAVIOUR OF METALLIC AND COMPOSITE FRONT DOOR OF A STANDARD AUTOMOBILE CAR BY FEA

by

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Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
Spring 2017

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Andrey Beyle for his inspiring guidance, encouragement and for investing his valuable time. His patience, understanding and humaneness have been a tremendous value to me. I sincerely wish him peace and happiness for his entire life.

Also, my sincere thanks to Dr. Wen Chan and Dr. Kent Lawrence for agreeing to serve on my thesis defense committee by giving their valuable time and opinions whenever I needed them.

I am indebted to my colleagues and friends for being there whenever I needed any help.

Lastly, I'd like to thank my family for supporting me all these years and offer my regards to all those who supported me through this period.

April 21,2017

ABSTRACT

COMPARISON OF MECHANICAL BEHAVIOUR OF METALLIC AND COMPOSITE FRONT DOOR OF A STANDARD AUTOMOBILE CAR BY FEA

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With the advent of technology, materials have advanced many folds; one such technical revelation has been Fiber-reinforced Composite Materials. Composite materials have two major advantages, among many others: improved strength and stiffness, especially compared to other materials on a unit weight basis and low density with ease of manufacturing. These advantages have led to new aeronautical, automobile and marine designs that are radical departures from past efforts based on conventional materials.

This paper focusses on a comparative study between Aluminum Alloys, Manganese alloys, structural steel, Composite materials and investigates the static and dynamic behaviors for a composite front door of vehicle. There were successful attempts to use composite doors in automotive industry but the analysis was done by traditional methods ignoring many details of the design. Now many firms are investigating replacement of traditional door by composite ones.

The objective of this study was to find the cause of failure of the unidirectional composite layers in varying cross sections of the door. Finite element method is used to calculate Static and dynamic behavior under possible impact using ANSYS software to simulate real time operating conditions (speed, etc.). Anisotropic material properties and fiber architecture are adjusted to the acting stresses. The car door is modeled using

SOLIDWORKS for the various materials like reinforced fiberglass epoxy, Kevlar epoxy and Carbon epoxy which are of great interest to the transportation industry. It is observed that compared to conventional materials, composites show lower stresses in all for the same boundary and loading conditions and much higher safety factor.

Thus, retaining stiffness of the door like existing one but increasing strength significantly compared to persisting design increasing car safety. Composite doors are lighter achieving higher fuel efficiency and energy conservation. It will lead to higher survivability of humans in the case of collision. All these effects can be achieved, when the cost of the door will be bigger less than 2 times or total car cost increase less than 10%.

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Chapter 1

Introduction and Background

Lightweight structures will drive the future of automobile industry. Due to unprecedented climatic change issues, automobile industry is moving towards low-emission vehicles with development in areas of advanced materials, low carbon manufacturing technologies depending upon consumer requirements [22]. There is a constant demand to decrease the cost of operation as the cost of fossil fuels keep on increasing day by day [22]. Composite doors have higher strength compared to conventional material doors thus proven better than them. Composite doors also have a reduced weight as composites have very low density as compared to steel and other alloys used in manufacturing of doors. They pose a better elastic strain, energy storage and lower fatigue. The only challenge faced is the complexity of composite structure. The door used here is a conventional design door. This research focusses on a comparative study between Aluminum Alloys, Manganese alloys, Structural steel, Composite materials and investigates the static and dynamic behaviors for a composite front door of vehicle.

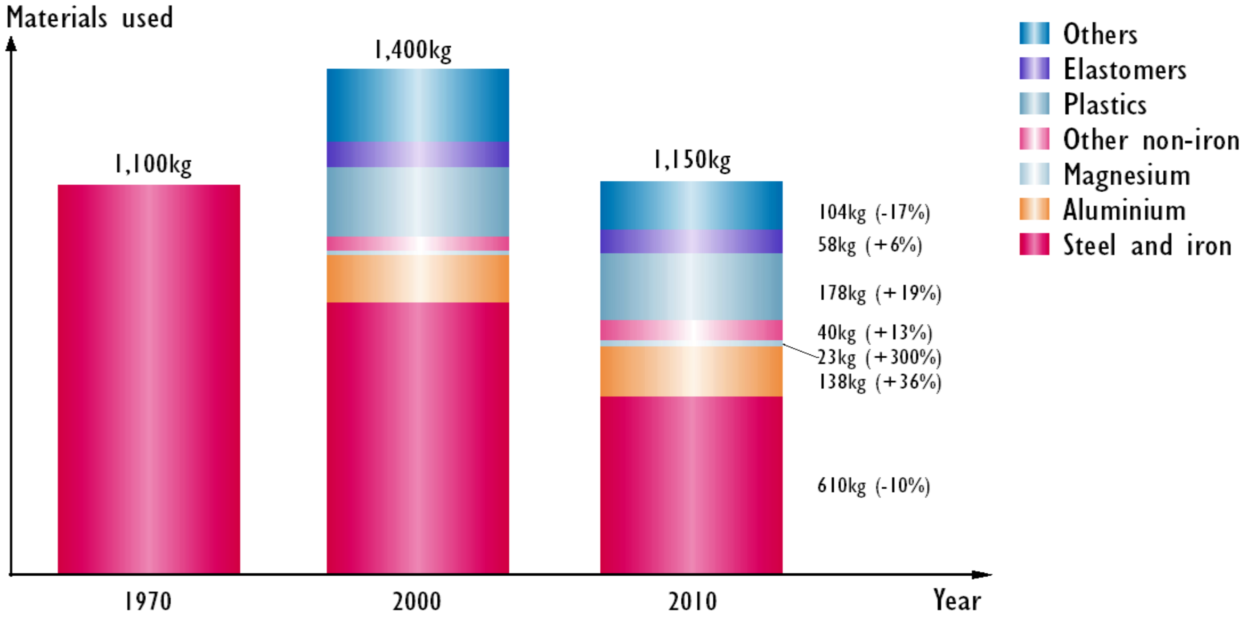


Fig 1.1 Percentage of materials used in industry

1.1 Car Door

A car door is basically a panel which is typically hinged to a car frame and located in front of an opening to enter or exit a vehicle. They are mainly made of steel. It consists of two panels, outer and inner panel welded together. Ribs in between them to provide strength and high impact resistance. Conventional doors have many parts like door handle, door switch, glass window and various storage compartments.

- Types of vehicle doors:
    1. Conventional doors
    2. Suicide doors
    3. Scissor doors
    4. Butterfly doors
    5. Gull-wing doors
    6. Sliding doors
    7. Canopy doors

Conventional door

Suicide door

Scissor door

Canopy door

Sliding door

Gull-wing door

Butterfly door

Fig 1.2 Types of doors

1.2 Composites

A material containing two or more distinct constituents is called a composite material. One of the constituents is used to reinforce the other constituent(s). Major constituent is the fiber which is the major load carrying component and occupies the largest volume fraction. Another constituent is the matrix which helps the fiber to keep in place and transfer the stresses between the fibers. Matrix binds the fiber together somewhat like an adhesive and makes them more resistant to external damage. Whereas fibers make the matrix stronger, stiffer and help it to resist cracks and fractures. The major advantages of composites are high specific stiffness, high specific strength and low density. They also provide design flexibility thus counting for parts reduction and easy fabrication of parts.

The present research will concentrate on Carbon fiber fabric, E-glass fiber fabric and Kevlar honeycomb. Carbon fibers have very high specific stiffness and are of two types - high modulus and high strength. High modulus carbon fiber has a factor 4 times higher than modulus of steel, whereas the density is lower by the same factor. Modern high strength fiber being as twice as strong compared to the strength of best glass fibers, whereas 30% lighter. Carbon fibers are the most widely used composites in automobile industries. Glass fibers have high strength and relatively low stiffness about 40% of steel. They have high chemical and biological resistance. This material offer low cost than any other composites being used in this research. Glass fibers of are of various types mainly E-glass where E stands for electric purposes, S-glass- S stands for structural and C glass mainly which stands for corrosion resistance glass. Honeycombs are basically named such due to their structure being as honeycombs. They are light weight and strong enough to resist the impact damage. Kevlar honeycomb is being used here which has high toughness with great structural strength [24]. Because of their anti-shock properties, honeycomb structures are used as shock absorbent layers in various parts of automobile construction [24]. They are ideally suited for this purposes because of their optimal ratio of weight to load-bearing capacity and bending strength. Fig 1.3 shows how a honeycomb structure is being built. Fig 1.4 shows how the stiffness increases by increasing the thickness of material at the cost of negligible weight increase. Fig 1.5 shows the toughness of various materials. Toughness is the area under the stress strain curve of the material.

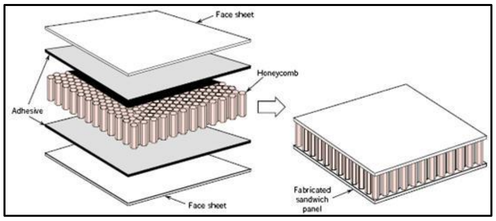
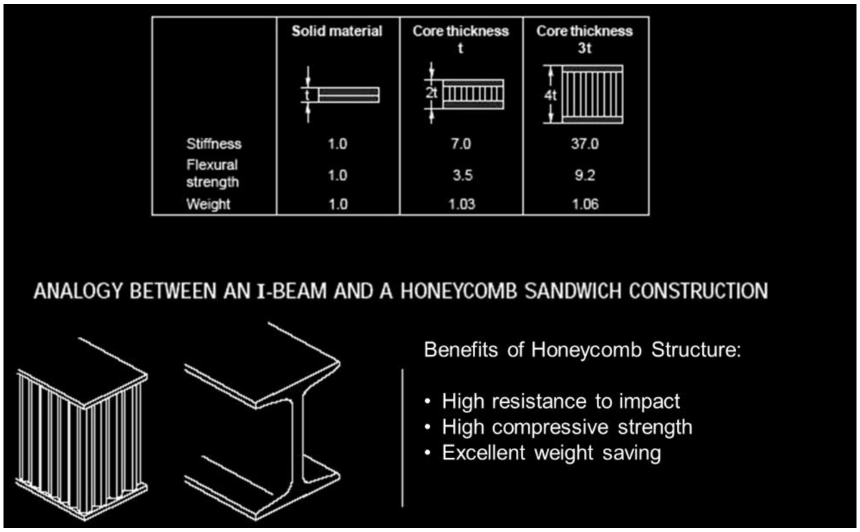


Fig 1.3 Honeycomb structure



	Solid material	Core thickness t	Core thickness 3t
Stiffness	1.0	7.0	37.0
Flexural strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

ANALOGY BETWEEN AN I-BEAM AND A HONEYCOMB SANDWICH CONSTRUCTION

Benefits of Honeycomb Structure:

- High resistance to impact
- High compressive strength
- Excellent weight saving

Fig 1.4 Properties of Sandwich construction

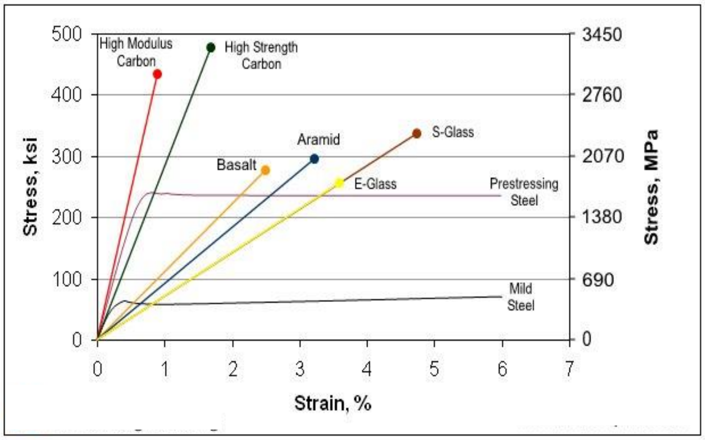


Fig 1.5 Stress-Strain plot for various materials

1.3 Motivation and Objective

During a side impact, door is the most important component which takes the load and ensures the safety of occupants. The most important factor in automotive industry is the crashworthiness of the structure in vehicle. It’s the ability to absorb impact energy and be survivable for passengers. Composites absorb more impact energy than conventional materials. Higher toughness compared to steels thus higher energy conservation.

Thus, retaining stiffness of the door like existing one but increasing strength significantly compared to persisting design increasing car safety. Higher survivability of humans in the case of collision as higher factor of safety. Thus, door is the most critical part of a car and should be considered for better design out of better material. As conventional doors are made from steel and alloys which weigh from 22-25kgs and thus must be replaced by a material which has less density and higher strength. Composite materials have stiffness 15 times less or twice greater to the stiffness of steel but with a strength decimal order higher and more than 4-5 times lighter (example: carbon fiber depending on fiber concentration and fiber architectures). The objective of this study was to find the cause of failure of the unidirectional composite layers.

Chapter 2

Literature Review

Information from various papers and patents was referred for the completion of this thesis. Some of the papers that made a valuable contribution are: Design optimization of vehicle structures for crashworthiness improvement, Hesham Ibrahim, Concordia University, Quebec, Canada; National Highway Traffic Safety Administration, Washington, DC 20590; Finite element analysis of internal door panel of a car by using bamboo fiber reinforced epoxy composite, Eniyew Tiguh, Addis Ababa University; Design of light weight mixed material door through structural optimization, Anand Ramani, Anshul Kaushik, Bangalore, India. All these various studies were referred and studied for better understanding of this topic.

Chapter 3

Geometry and Boundary Conditions

3.1 CAD Model

Door consists of 2 panels. The outer panel is attached to inner panel by means of welding in case of steel and using adhesives in composites. Here front door is considered for analysis purpose. Contact type is kept bonded for panels in this case simply for simulation process. A standard thickness of 3 mm was used for panels in case of steel, Aluminium and manganese alloys. For composite by having surface model from Solidworks 2016, thickness of 5.4 mm was calculated using stacking process of composite plies. The packaging dimensions of door are 1050*950 mm length*breadth. Different views of door are being depicted as follows:

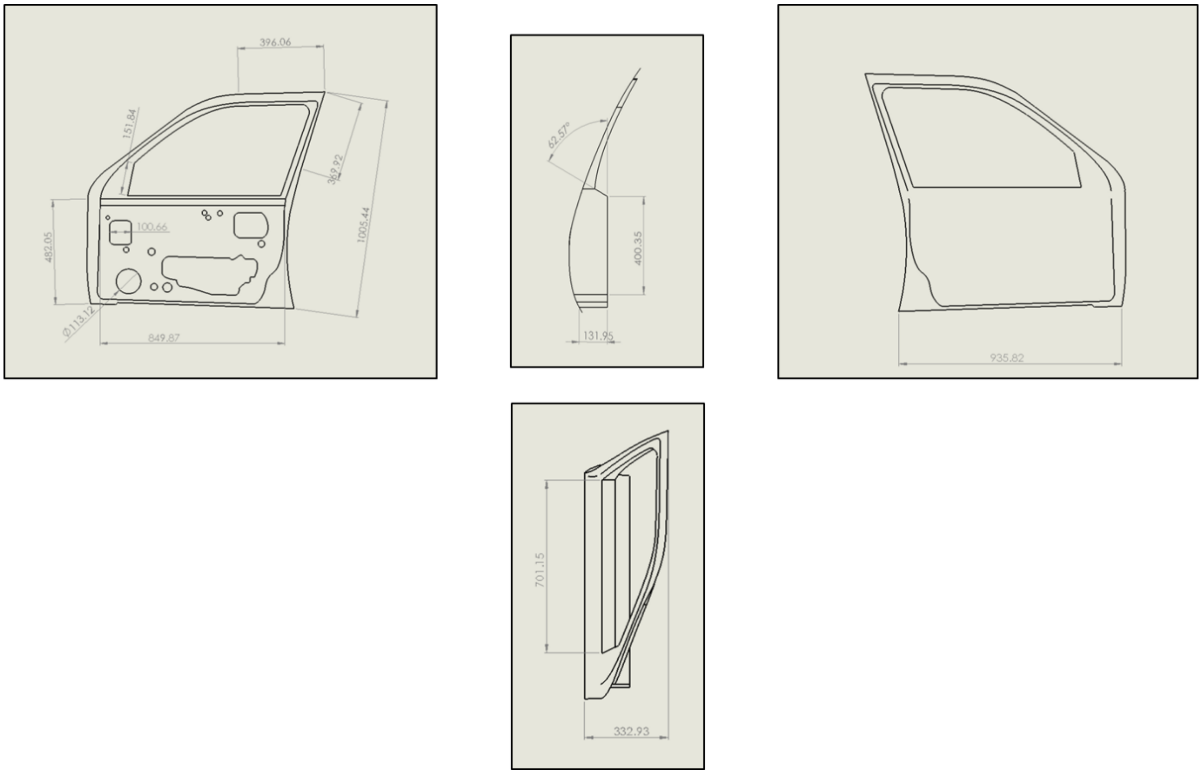


Fig 3.1 Different views of Front door (all dimensions are in mm)

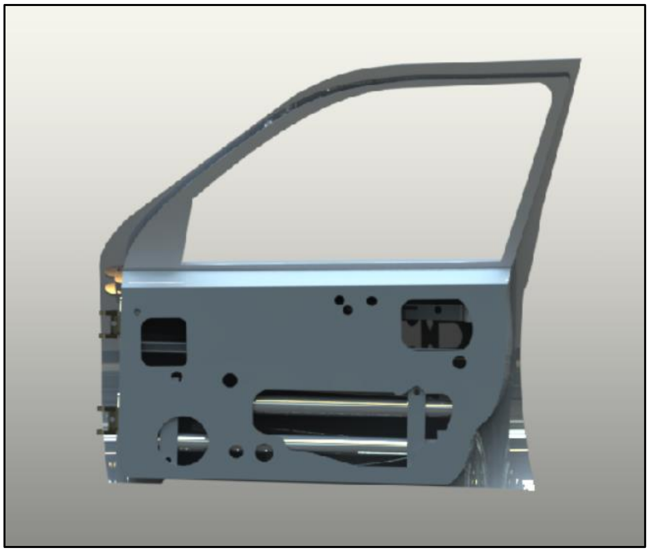


Fig 3.2 Rendered 3D Model (back view)

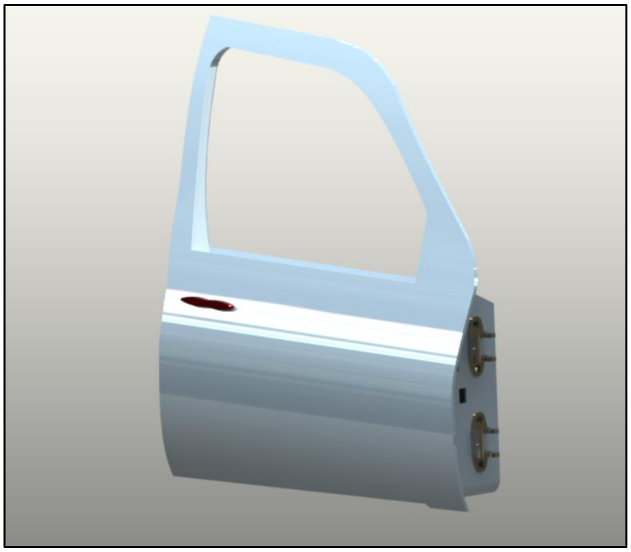


Fig 3.3 Rendered 3D Model (Isometric view)

Door consists of 2 hinges typically bolted to door and thus pivoted on another end and thus connected to chassis. Door is used to enter and exit the vehicle. It consists of handle which mechanically or electronically opens the door. The holes and various cut-outs on the back side are given for compartments on the inner side of door which provide multipurpose uses. They are conventionally produced out of steel sheets. Ribs are welded in between two panels for better impact strength and rigidity as shown in fig 1.7.

3.2 Meshing

The CAD model was meshed using Solid brick elements. Solid 186 is a higher-order 3-D 20 nodes solid element that exhibits quadratic displacement behavior. 20 nodes having three degrees of freedom per node define the element [16]: translations in the nodal x, y, and z directions. The element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities [16]. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperplastic materials [16].

Meshing was done by using body sizing and by use of hex dominant method with element type as all quad. Thus generating a mesh with brick elements particularly SOLID 186. Mesh sizing was selected based on mesh sensitivity analysis. As shown in fig 1.9 the curve converges after 2mm. So, the mesh size was kept 2mm which is optimum size.

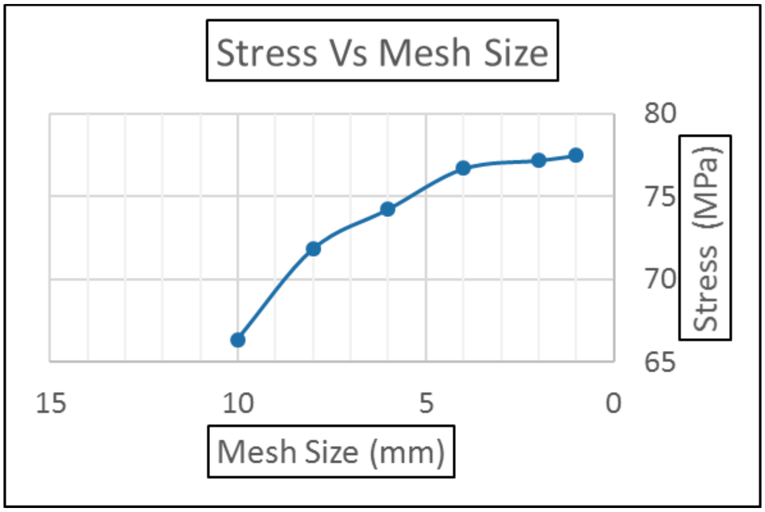
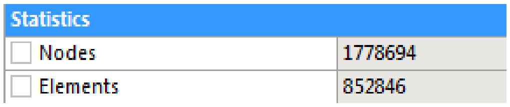


Fig 3.4 Mesh sensitivity analysis

The meshed CAD model for static and dynamic analysis and mesh data is given below



Statistics	
☐ Nodes	1778694
☐ Elements	852846

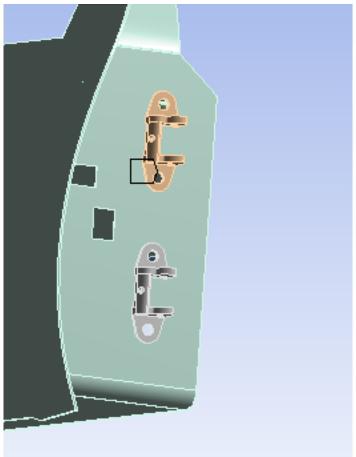
Fig 3.5 Mesh Data

Fig 3.6 Meshed CAD model

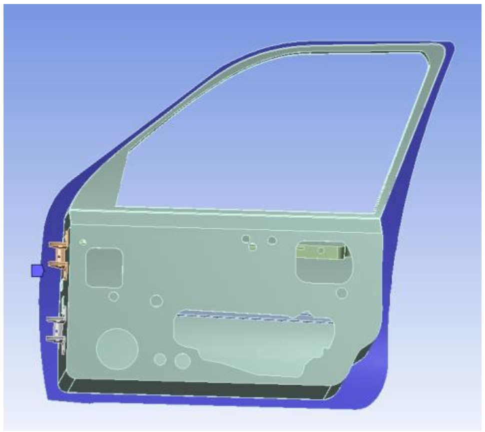
This CAD model was saved as IGES file in *.igs format so that they can be transferred to ANSYS V17 Education Edition for analysis.

3.3 Boundary Conditions

Here we consider the various loads acting on the door, supports to be provided for analysis. Two fixed supports are being considered. One is the holes where hinges are going to be bolted onto car frame. Two is the outer periphery of door which is supported by vehicle chassis i.e. vehicle door frame.



(a)

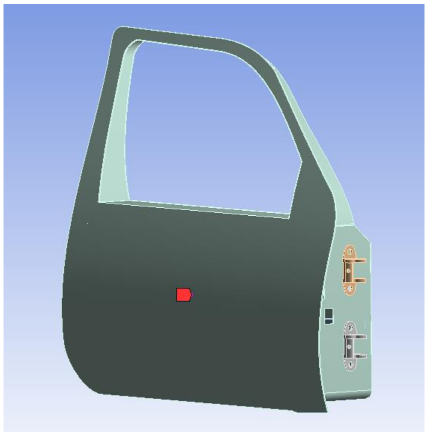


(b)

Fig 3.7 (a)Fixed support at hinges, (b) Fixed support at outer periphery of door

Two loading conditions are being considered here. One distributed load and another point load. Both the loads are applied to the outer panel. Distributed load is distributed evenly on the outer surface of the door. Point load is applied at a point at the center of the door on the outer surface. The force was calculated using information from National Highway Traffic Safety Administration. The force calculated was 8336 N. This was calculated by assuming a vehicle of 1600 kg approaching this car at a speed of 40 MPH. Speed was 18m/s.

(a)



(b)

Fig 3.8 (a) Distributed load, (b) Point load

Chapter 4

Material Properties

Materials used are Carbon fiber (fabric), E-glass fiber (fabric) and honeycomb Kevlar as discussed earlier. Conventional materials to be compared with composite materials are Steel ASTM a36, Aluminium 6061-T6, Magnesium alloy Am60B. The material properties required here for analysis are mainly:

- Young's Modulus, E (GPa)
- Shear Modulus, G (GPa)
- Poisson's Ratio, v

4.1 Steel ASTM a36

Conventional material used for manufacturing of doors in automobile industry.

Physical Properties:

Ultimate Tensile Strength	400 MPa
Tensile Yield Strength	250 MPa
Modulus of Elasticity	200 GPa
Poisson's Ratio	0.260
Shear Modulus	79.3 GPa
Density	7.85 g/cc

4.2 Aluminium 6061- T6

Material is used in high-end applications instead of steel where weight is critical criteria without compromising strength of structure.

Physical Properties:

Ultimate Tensile Strength	310 MPa
Tensile Yield Strength	276 MPa
Modulus of Elasticity	68.9 GPa
Poisson's Ratio	0.33

Shear Modulus	26 GPa
Density	2.7 g/cc

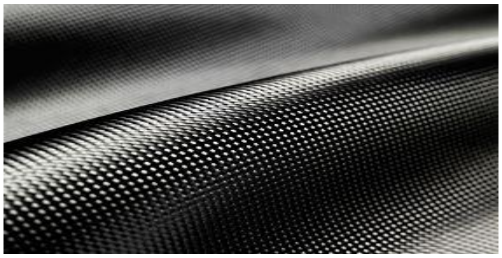
4.3 Magnesium alloy Am60B

Physical Properties:

Ultimate Tensile Strength	240 MPa
Tensile Yield Strength	130 MPa
Modulus of Elasticity	45 GPa
Poisson’s Ratio	0.35
Shear Modulus	17 GPa
Density	1.85 g/cc

4.4 Carbon Fiber (Fabric)

Unidirectional prepreg Carbon fiber with 60% fiber volume concentration is used. Carbon fibers are 3 to 10 times stronger than the E-glass fibers. These fibers take a longer time to prepare as compared to other fibers. They also need an extended time of temperature processing. These are the reasons why they are comparatively more expensive than others are. Carbon fibers are very strong and stiff when compared to any other fiber. They are usually black in color.



(a)

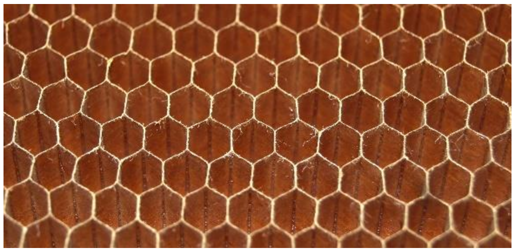
4.5 E-Glass Fiber (Fiber)

Unidirectional prepreg E-glass fiber with 60% fiber volume concentration is used. Glass Fibers have high strength which is maintained even in a humid environment. Compared to other composites they have low stiffness but also are comparatively cheaper. They have high chemical and biological resistance. They are usually white in color.

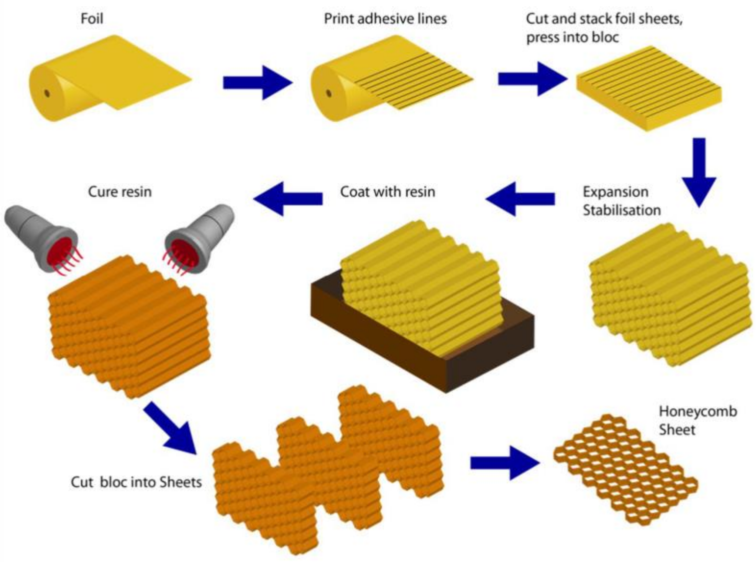
(b)

4.6 Kevlar Honeycomb

Known as Aramid fibers. Kevlar is registered trademark for aramid honeycomb. Extremely light weight, high impact strength, nonmetallic honeycomb impregnated with heat resistant phenolic resin. This core material exhibits improved performance characteristics over Nomex and Korex in the areas of weight, strength, stiffness and fatigue. Kevlar 49 is being used as it has high stiffness as compared to Kevlar 29. These fibers have a yellow color.



(c)



(d)

Fig 4.1 (a) Carbon fiber, (b) E-glass fiber, (c) Kevlar Honeycomb, (d) manufacturing process for honeycomb structures

4.7 Epoxy resin

Mixtures of Organic compounds which are highly viscous. Mainly of two types thermoset and thermoplastic. Thermoset are mainly used in industry due to their better properties over thermoplastic. They are widely used as resins and structural adhesives. They have high strength and modulus, brilliant adhesive properties, great chemical resistance and low shrinkage.

Properties	Glass Fiber	Kevlar Fiber	Carbon Fiber	Epoxy Matrix
E1 (GPa)	74	151.17	440	3
E2 (GPa)	74	4.1	14	3
v12	0.21	0.35	0.3	0.3
v23	0.21	0.15	0.15	0.3
G12 (GPa)	4	2.9	8	1.11
G23 (GPa)	2.85	1.782	6.087	1.11

Table 4.1 Fiber and Matrix Properties

Chapter 5

Simulations

5.1 Static Analysis

Static and Dynamic analysis are being carried out using ANSYS V17. Static analysis of door modelled in Solidworks with materials like steel, aluminum, magnesium alloy, carbon fiber, E-glass fiber and Kevlar honeycomb is carried out in ANSYS. Dynamic Analysis is being done using explicit dynamics module in ANSYS. For composite material analysis, door is being modelled in ANSYS PrePost. ANSYS PrePost procedure can be divided into three steps mainly:

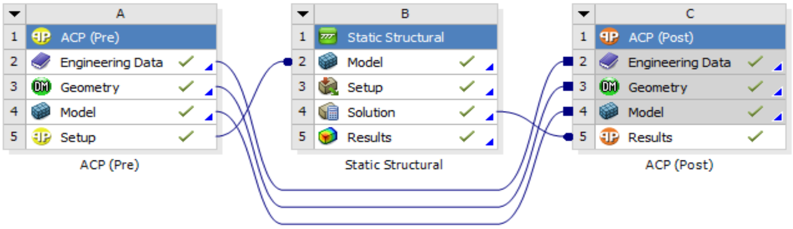
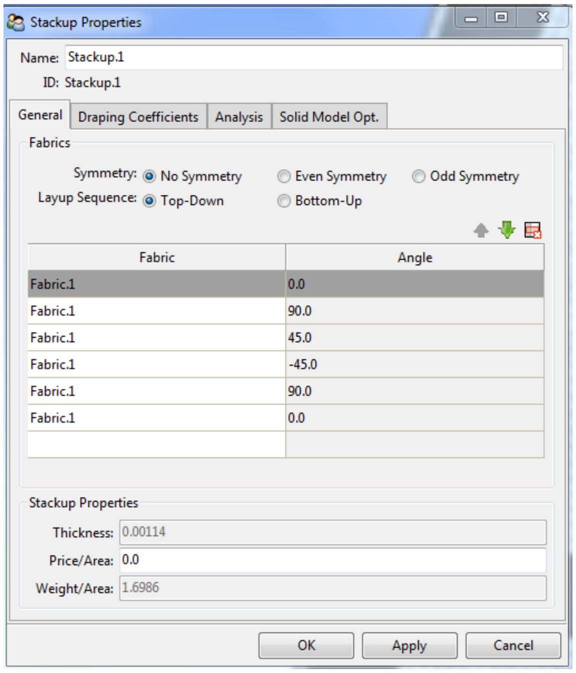


Fig 5.1 ANSYS PrePost

As we can see in the above figure ACP Pre is being used for stacking process of door. A surface model is being imported to ACP Pre. Material properties are being assigned. In ply stacking 3 types of stacking sequence are being analyzed. Firstly, Carbon fiber-honeycomb-E-glass fiber. Secondly E-glass fiber-honeycomb-carbon fiber. Thirdly carbon fiber -honeycomb-carbon fiber. In all cases honeycomb is being used as core material. This structure is called as sandwich structure. Ply angles are being determined using the performance analysis of angles. 0-degree ply is being kept at surface for better resistance to bending in horizontal direction as the door is rectangular as length being greater than breadth. 90-degree ply follows the 0-degree ply to provide better impact strength. +45 and -45 are being used in center of stacking sequence to cancel out shear forces generated due to one another. To keep the sequence balanced +45 -45 are being followed by +90 and 0 deg. Thus, the stacking sequence is balanced but asymmetric. Carbon fiber plies are of 0.19mm thickness and E-glass fiber ply's is 0.25mm thick. Stacking is being done in the following manner. Six plies of carbon fiber are being used and six plies of E-glass fiber are used. Fabric properties are given. Ply direction is kept normal to surface as shown in figure below.



Name: Stackup.1
ID: Stackup.1

Fabrics

Symmetry: ● No Symmetry ○ Even Symmetry ○ Odd Symmetry
Layup Sequence: ● Top-Down ○ Bottom-Up

Fabric	Angle
Fabric.1	0.0
Fabric.1	90.0
Fabric.1	45.0
Fabric.1	-45.0
Fabric.1	90.0
Fabric.1	0.0

Stackup Properties

Thickness: 0.00114
Price/Area: 0.0
Weight/Area: 1.6986

Fig 5.2 Stacking sequence Ply angles

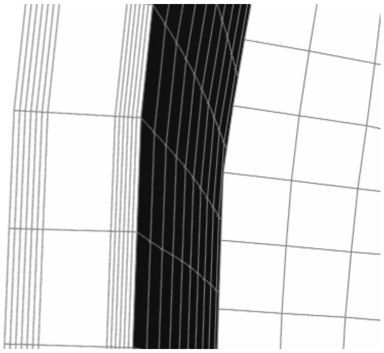
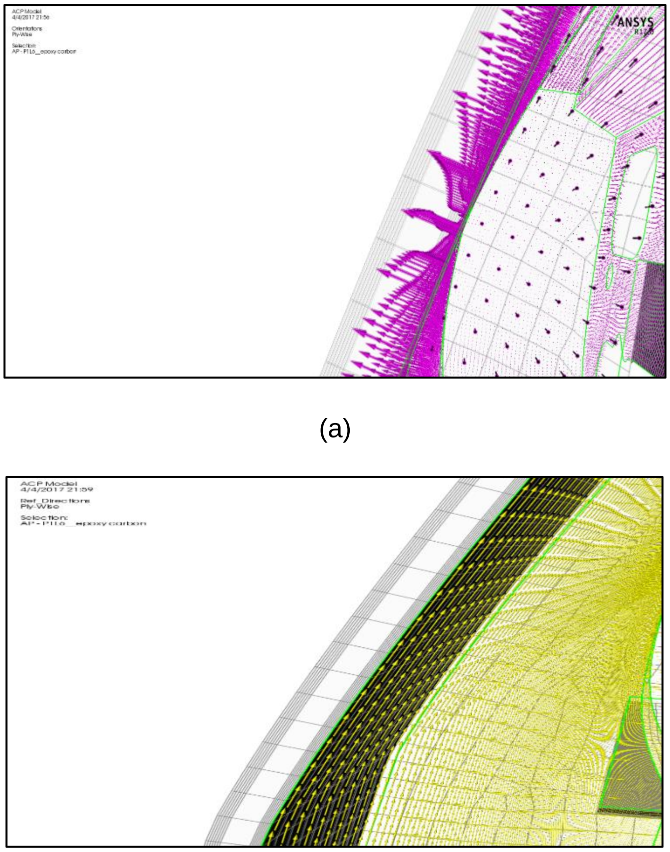


Fig 5.3 Ply stacking on door



(a)

(b)

Fig 5.4 (a) Ply Layup direction, (b) Fiber direction

Loading and Boundary conditions are being applied in static structural. Meshing is done in static structural. Post analysis is being used for solution of analysis. Ply wise Normal stress, strain, total deformation, interlaminar stresses, interlaminar shears stresses and interlaminar shear strains are being calculated from post solution.

5.2 Dynamic Analysis

Explicit dynamics module is being used from ANSYS for carrying out dynamic analysis. In this the mesh size is reduced to 5mm from 2mm because of the time required for analysis in dynamics is very large in case of 2mm mesh size as compared to 5mm. Fine mesh is used. Here a ball of 600kg is modelled and considered to impact this door at the speed of 40 mph on the outer surface of door as shown in figure. Ball is spherical in shape and material is steel. The process followed in ANSYS for carrying out explicit dynamics is being shown below.

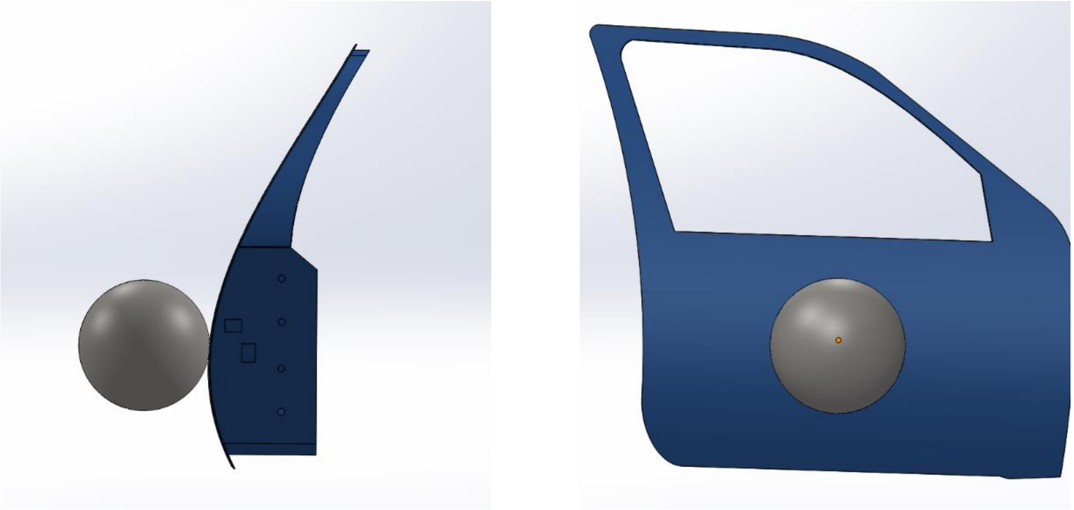


Fig 5.5 Explicit Dynamics setup

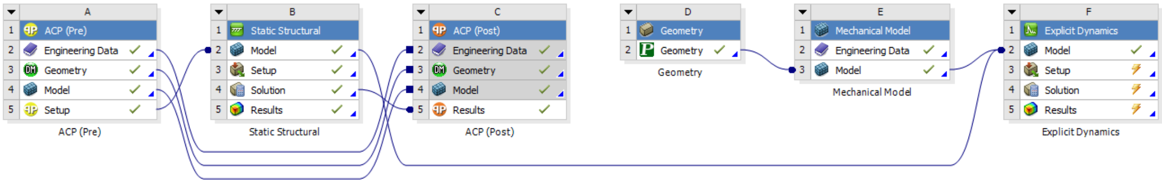


Fig 5.6 Process for Explicit Dynamics

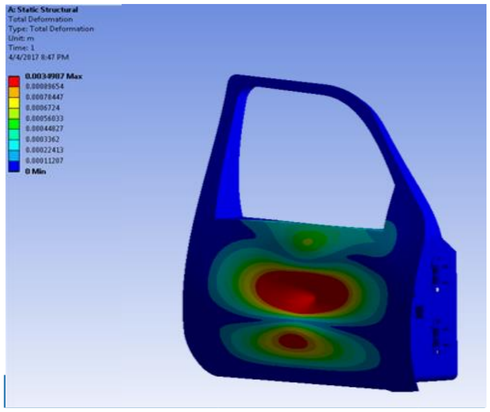
Chapter 6

Results

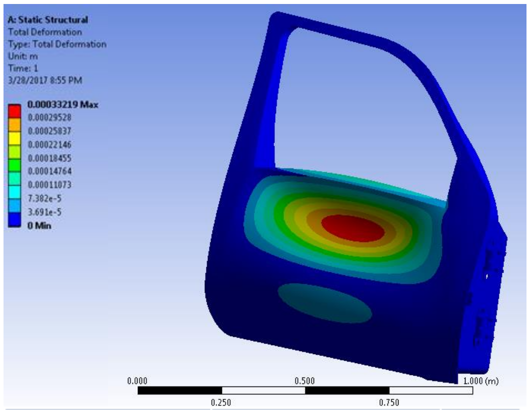
6.1 Static Analysis Results

Simulations are run for all described materials above with the pre-defined conditions earlier. Results obtained are as follows:

- Steel



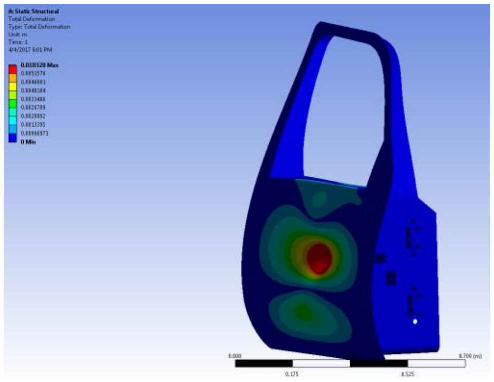
Maximum deflection	Maximum stress	FOS
3.49 mm	165 MPa	1.2



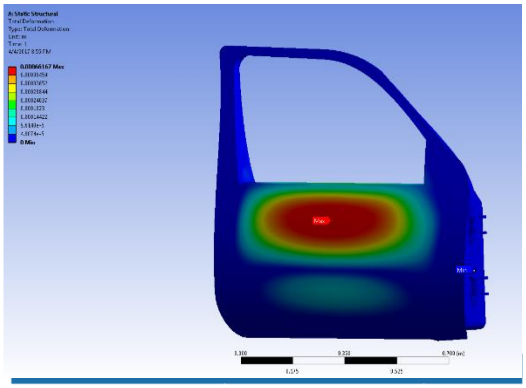
Maximum deflection	Maximum stress	FOS
0.3 mm	76.1 MPa	1.72

(a)

- Aluminum



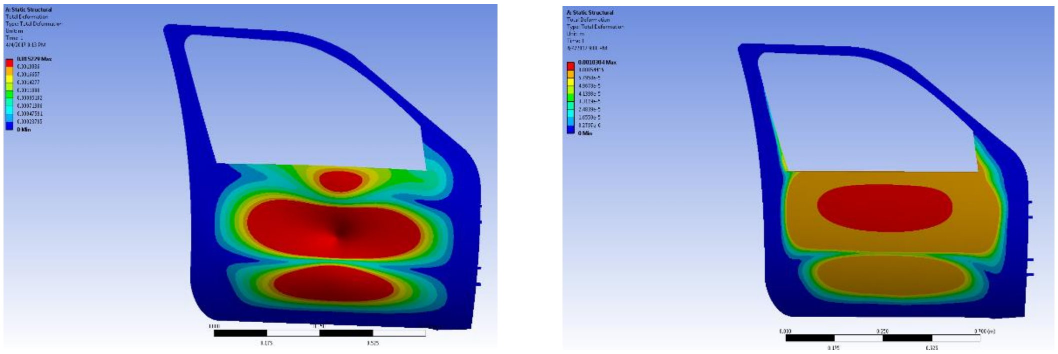
Point load		
Maximum deflection	Maximum stress	FOS
10.3 mm	206.3 MPa	1.3



Maximum deflection	Maximum stress	FOS
0.6 mm	18.4 MPa	8.62

(b)

- Magnesium



Point load

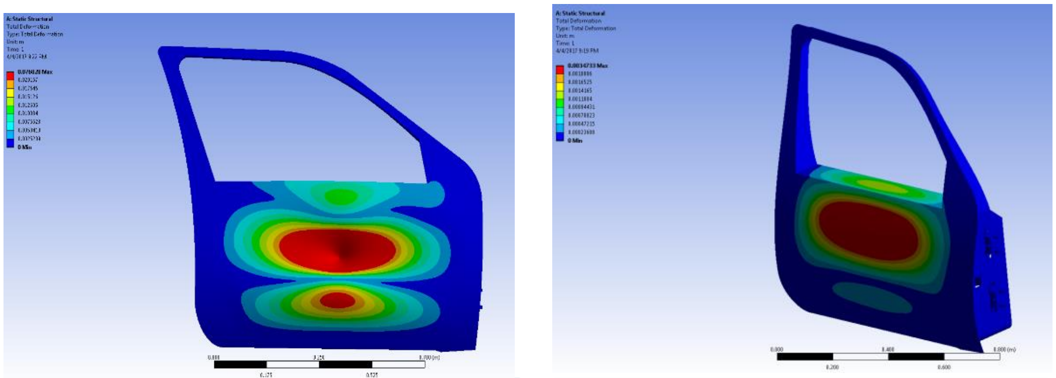
Maximum deflection	Maximum stress	FOS
15.23 mm	176 MPa	1

Distributed load

Maximum deflection	Maximum stress	FOS
1 mm	19.2 MPa	6

(c)

- Epoxy Carbon



Point load

Maximum deflection	Maximum stress	FOS
76.8 mm	63.4 MPa	9.05

Distributed load

Maximum deflection	Maximum stress	FOS
3.47 mm	80.64 MPa	7.12

(d)

Fig 6.1 Static analysis results (a), (b), (c), (d)

- Carbon fiber – Honeycomb - E-glass fiber

Ply order 1	Ply Angles	PLY NO.	FOS	Ply Wise stress (MPa)	Deformation mm
Carbon	0	Ply 1	12.68	64.36	2.71
	90	Ply 2	6.77	120.48	
	45	Ply 3	16.54	49.35	
	-45	Ply 4	9.74	83.81	
	90	Ply 5	6.20	131.68	
	0	Ply 6	7.60	107.39	
Honeycomb		Ply 7	2.31	1617	
Glass	0	Ply 8	28.03	20.48	
	90	Ply 9	41.57	13.81	
	45	Ply 10	13.89	41.33	
	-45	Ply 11	33.63	17.07	
	90	Ply 12	12.71	45.16	
	0	Ply 13	7.77	73.84	

Table 6.1 Distributed load results

Ply order 1	Ply Angles	PLY NO.	FOS	Ply Wise stress (MPa)	Deformation mm
Carbon	0	Ply 1	5.57	146.6	17.829
	90	Ply 2	5.50	148.3	
	45	Ply 3	5.62	145.15	
	-45	Ply 4	1.49	545.8	
	90	Ply 5	0.27	2928.4	
	0	Ply 6	0.31	2623.6	
Honeycomb		Ply 7	0.36	10323	
Glass	0	Ply 8	2.67	214.8	
	90	Ply 9	2.75	208.09	
	45	Ply 10	1.57	381.36	
	-45	Ply 11	0.76	753.89	
	90	Ply 12	0.42	1338.8	
	0	Ply 13	0.34	1680.9	

Table 6.2 Point load results

- E-glass fiber – Honeycomb – Carbon fiber

Ply order 2	Ply Angles	PLY NO.	FOS	Ply Wise stress(MPa)	Deformation mm
Glass	0	Ply 1	21.54	26.65	2.88
	90	Ply 2	11.33	50.67	
	45	Ply 3	22.24	25.81	
	-45	Ply 4	16.99	33.79	
	90	Ply 5	20.60	27.86	
	0	Ply 6	16.04	35.78	
Honeycomb		Ply 7	2.03	1841.6	
Carbon	0	Ply 8	19.62	41.61	
	90	Ply 9	27.81	29.36	
	45	Ply 10	8.86	92.16	
	-45	Ply 11	14.42	56.63	
	90	Ply 12	8.22	99.24	
	0	Ply 13	5.03	162.05	

Table 6.3 Distributed load results

Ply order 2	Ply Angles	PLY NO.	FOS	Ply Wise stress(MPa)	Deformation mm
Glass	0	Ply 1	5.80	98.93	16.815
	90	Ply 2	7.48	76.7	
	45	Ply 3	7.13	80.43	
	-45	Ply 4	1.98	288.87	
	90	Ply 5	0.42	1347.3	
	0	Ply 6	0.42	1364.7	
Honeycomb		Ply 7	0.75	4937	
Carbon	0	Ply 8	3.72	219.39	
	90	Ply 9	2.53	322.23	
	45	Ply 10	1.34	605.4	
	-45	Ply 11	0.75	1085.2	
	90	Ply 12	0.34	2401.8	
	0	Ply 13	0.29	2755.4	

Table 6.4 Point load results

- Carbon Honeycomb Carbon

Ply order 3	Ply Angles	PLY NO.	FOS	Ply Wise stress(MPa)	Deformation mm
Carbon	0	Ply 1	15.20	53.74	2.551
	90	Ply 2	7.43	109.86	
	45	Ply 3	18.95	43.1	
	-45	Ply 4	12.39	65.89	
	90	Ply 5	7.68	106.31	
	0	Ply 6	8.43	96.87	
Honeycomb		Ply 7	2.16	1735.1	
Carbon	0	Ply 8	21.55	37.89	
	90	Ply 9	32.06	25.47	
	45	Ply 10	10.10	80.82	
	-45	Ply 11	16.80	48.61	
	90	Ply 12	9.06	90.188	
	0	Ply 13	6.47	126.28	

Table 6.5 Distributed load results

Ply order 3	Ply Angles	PLY NO.	FOS	Ply Wise stress(MPa)	Deformation mm
Carbon	0	Ply 1	6.16	132.6	14.03
	90	Ply 2	3.99	204.46	
	45	Ply 3	5.59	146.1	
	-45	Ply 4	1.46	560.48	
	90	Ply 5	0.28	2911.8	
	0	Ply 6	0.31	2606.3	
Honeycomb		Ply 7	0.26	14325	
Carbon	0	Ply 8	3.63	224.78	
	90	Ply 9	3.61	226.34	
	45	Ply 10	1.61	506.33	
	-45	Ply 11	0.89	917.58	
	90	Ply 12	0.36	2264.9	
	0	Ply 13	0.33	2441.1	

Table 6.6 Point load results

In above tables Factor of safety (FOS) is calculated using allowable stress upon stress induced. Allowable stress regarding composites is Ultimate Tensile strength. Here total deformation is being calculated. In Tables 1.2 and 1.4 factor of safety is low for ply no. 6 and ply no. 15 respectively. For increasing factor of safety an extra ply is being added after each 90-degree ply. Thus, a total of 15 plies. Following tables show the improved stresses and factor of safety on addition of plies.

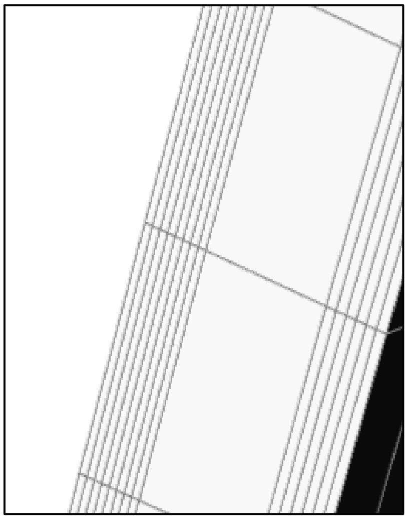


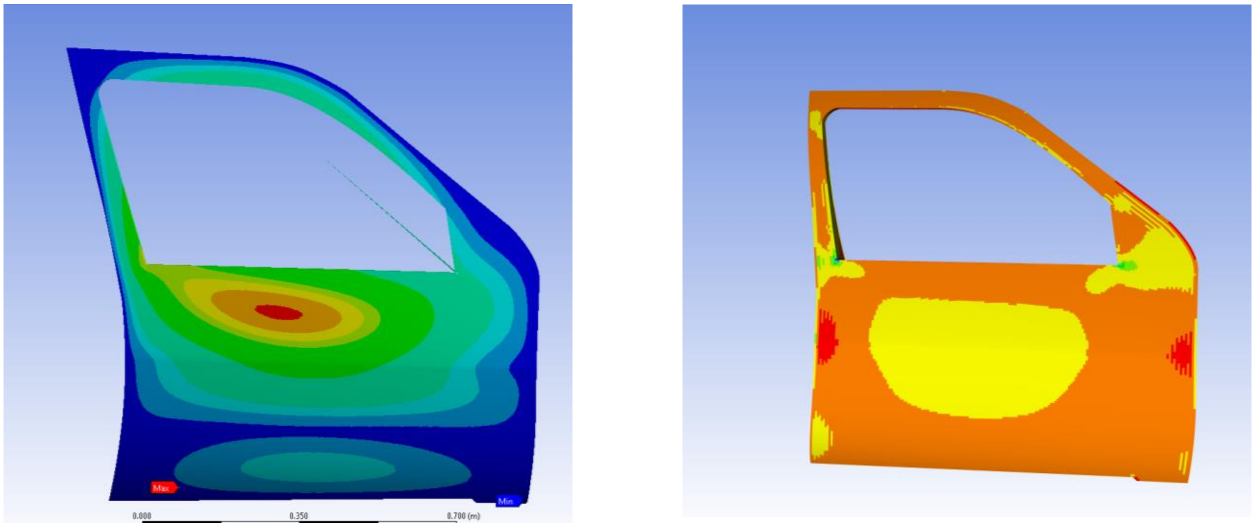
Fig 6.2 Improved ply stacking (8 plies)

Ply order 1	**Ply Angles**	**PLY NO.**	**FOS**	**Improved FOS**	**Ply Wise stress (MPa)**			**Deformation mm**	**New Deformation mm**
					Improved stress	Max	Min		
Carbon	0	Ply 1	12.68	14.69	55.58	64.36	-131.4	2.71	2.25
	90	Ply 2		9.45	86.4				
	90	Ply 3	6.77	12.30	66.35	120.48	-132.92		
	45	Ply 4	16.54	17.12	47.7	49.35	-101.79		
	-45	Ply 5	9.74	13.27	61.54	83.81	-157.28		
	90	Ply 6	6.20	10.16	80.35	131.68	-94.89		
	90	Ply 7		8.39	97.25				
	0	Ply 8	7.60	7.68	106.28	107.39	-146.04		
Honeycomb		Ply 9	2.31	2.54	1474.7	1617	-2563.4		
Glass	0	Ply 10	28.03	29.85	19.23	20.48	-55.78		
	90	Ply 11	41.57	52.24	10.99	13.81	-29.77		
	45	Ply 12	13.89	15.06	38.11	41.33	-50.55		
	-45	Ply 13	33.63	38.24	15.01	17.07	-41.86		
	90	Ply 14	12.71	14.85	38.65	45.16	-49.01		
	0	Ply 15	7.77	8.65	66.31	73.84	-59.63		

Table 6.7 Improved FOS (Carbon fiber – Honeycomb - E-glass fiber)

Ply order 2	**Ply Angles**	**PLY NO.**	**FOS**	**Improved FOS**	**Ply Wise stress(MPa)**			**Deformation mm**	**New Deformation mm**
					Improved stress	Max	Min		
Glass	0	Ply 1	21.54	24.38	23.54	26.65	-62.17	2.88	2.85
	90	Ply 2	11.33	11.79	48.69	50.67	-66.49		
	45	Ply 3	22.24	25.95	22.12	25.81	-43.82		
	-45	Ply 4	16.99	17.46	32.87	33.79	-74.24		
	90	Ply 5	20.60	22.86	25.11	27.86	-43.29		
	0	Ply 6	16.04	17.04	33.68	35.78	-59.35		
Honeycomb		Ply 7	2.03	2.41	1554	1841.6	-1894.2		
Carbon	0	Ply 8	19.62	20.71	39.43	41.61	-135.87		
	90	Ply 9		23.11	35.33				
	90	Ply 10	27.81	29.25	27.92	29.36	-59.72		
	45	Ply 11	8.86	9.69	84.25	92.16	-140.82		
	-45	Ply 12	14.42	14.98	54.5	56.63	-123.16		
	90	Ply 13		7.52	108.5				
	90	Ply 14	8.22	8.54	95.61	99.24	-105.23		
	0	Ply 15	5.03	6.66	122.58	162.05	-127.65		

Table 6.8 Improved FOS (E-glass fiber – Honeycomb – Carbon fiber)

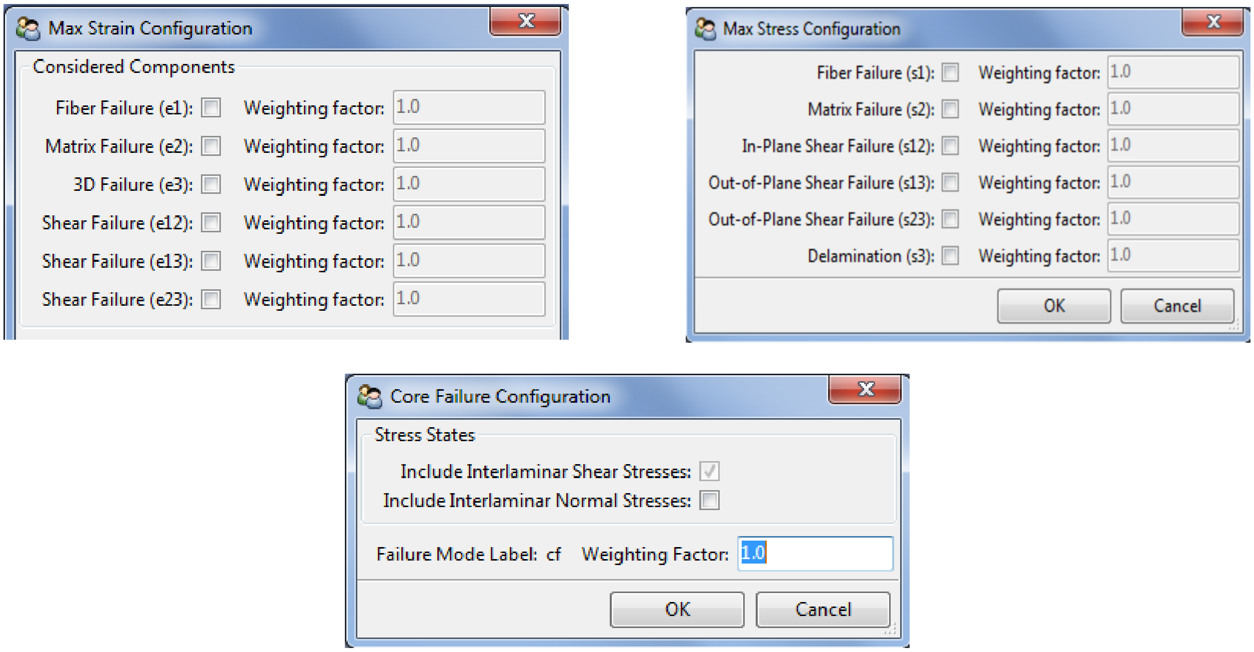


Distributed load	
Maximum deflection	Maximum stress
2.88 mm	26.65 MPa

Fig 6.3 Maximum Deflection and Maximum Stress in Composites

6.2 Failure Criteria

Failure criteria's are being defined. Box type criteria is being used. Maximum stress and maximum strain are the criteria's considered for failure of various plies. In maximum stress criteria fiber and matrix failure is being considered. In-plane shear stresses and in-plane shear strains are being calculated. Shear failures in-plane and out of plane are being considered. Interlaminar stresses are calculated. Delamination is also considered here for de-bonding. Core failure criteria is being considered for Honeycomb failure. Various failure criteria's, their values and their plots are shown below.



Max Strain Configuration

Considered Components

Fiber Failure (e1): ☐ Weighting factor: 1.0
Matrix Failure (e2): ☐ Weighting factor: 1.0
3D Failure (e3): ☐ Weighting factor: 1.0
Shear Failure (e12): ☐ Weighting factor: 1.0
Shear Failure (e13): ☐ Weighting factor: 1.0
Shear Failure (e23): ☐ Weighting factor: 1.0

Max Stress Configuration

Fiber Failure (s1): ☐ Weighting factor: 1.0
Matrix Failure (s2): ☐ Weighting factor: 1.0
In-Plane Shear Failure (s12): ☐ Weighting factor: 1.0
Out-of-Plane Shear Failure (s13): ☐ Weighting factor: 1.0
Out-of-Plane Shear Failure (s23): ☐ Weighting factor: 1.0
Delamination (s3): ☐ Weighting factor: 1.0

Core Failure Configuration

Stress States

Include Interlaminar Shear Stresses: ☑
Include Interlaminar Normal Stresses: ☐

Failure Mode Label: cf Weighting Factor: 1.0

Fig 6.4 Failure Criteria's

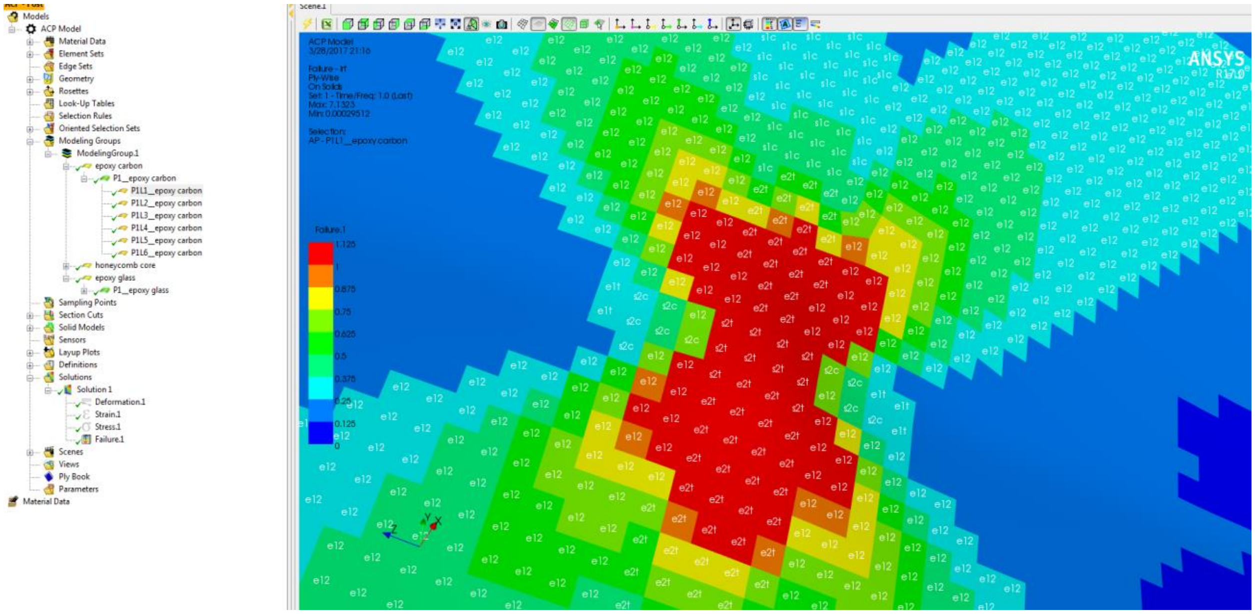


Fig 6.5 Failure plot depicting maximum stress and maximum strain failure in a ply

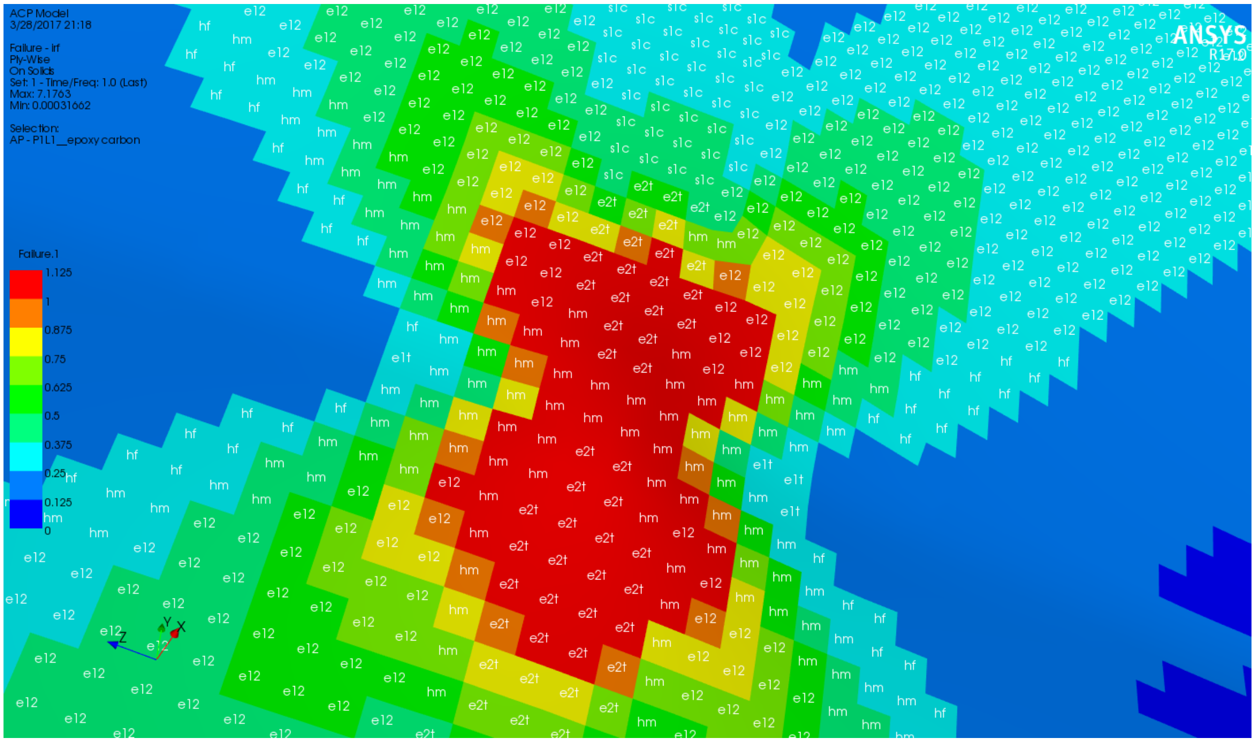
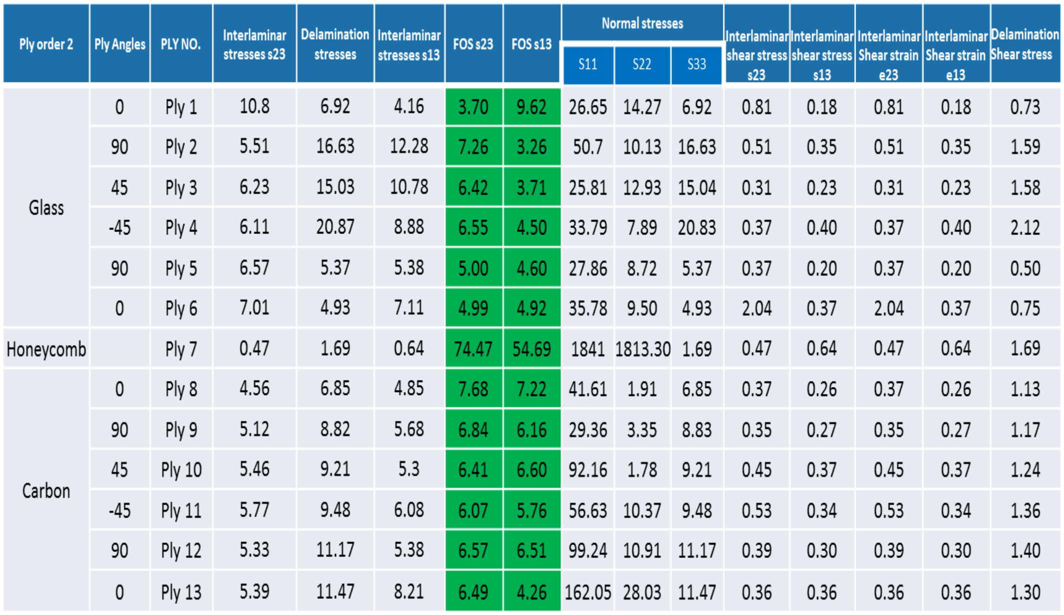


Fig 6.6 Failure plot depicting matrix and fiber failure.

In above plots the terms mentioned stand for

s – stress
c – compression
t – tension
hm – matrix failure

e – strain
1 – fiber direction
2 – matrix direction
hf – fiber failure



Ply order 2	Ply Angles	PLY NO.	Interlaminar stresses s23	Delamination stresses	Interlaminar stresses s13	FOS s23	FOS s13	Normal stresses			Interlaminar shear stress s23	Interlaminar shear stress s13	Interlaminar Shear strain e23	Interlaminar Shear strain e13	Delamination Shear stress
								S11	S22	S33					
Glass	0	Ply 1	10.8	6.92	4.16	3.70	9.62	26.65	14.27	6.92	0.81	0.18	0.81	0.18	0.73
	90	Ply 2	5.51	16.63	12.28	7.26	3.26	50.7	10.13	16.63	0.51	0.35	0.51	0.35	1.59
	45	Ply 3	6.23	15.03	10.78	6.42	3.71	25.81	12.93	15.04	0.31	0.23	0.31	0.23	1.58
	-45	Ply 4	6.11	20.87	8.88	6.55	4.50	33.79	7.89	20.83	0.37	0.40	0.37	0.40	2.12
	90	Ply 5	6.57	5.37	5.38	5.00	4.60	27.86	8.72	5.37	0.37	0.20	0.37	0.20	0.50
	0	Ply 6	7.01	4.93	7.11	4.99	4.92	35.78	9.50	4.93	2.04	0.37	2.04	0.37	0.75
Honeycomb		Ply 7	0.47	1.69	0.64	74.47	54.69	1841	1813.30	1.69	0.47	0.64	0.47	0.64	1.69
Carbon	0	Ply 8	4.56	6.85	4.85	7.68	7.22	41.61	1.91	6.85	0.37	0.26	0.37	0.26	1.13
	90	Ply 9	5.12	8.82	5.68	6.84	6.16	29.36	3.35	8.83	0.35	0.27	0.35	0.27	1.17
	45	Ply 10	5.46	9.21	5.3	6.41	6.60	92.16	1.78	9.21	0.45	0.37	0.45	0.37	1.24
	-45	Ply 11	5.77	9.48	6.08	6.07	5.76	56.63	10.37	9.48	0.53	0.34	0.53	0.34	1.36
	90	Ply 12	5.33	11.17	5.38	6.57	6.51	99.24	10.91	11.17	0.39	0.30	0.39	0.30	1.40
	0	Ply 13	5.39	11.47	8.21	6.49	4.26	162.05	28.03	11.47	0.36	0.36	0.36	0.36	1.30

	Ultimate shear strength (MPa)	Ultimate shear strain (%)	Shear modulus (MPa)	
Carbon	35	0.7	4700	3100
E-glass	40	1	3846.2	5000
Honeycomb	50	1	37	70

Table 6.9 Composite properties

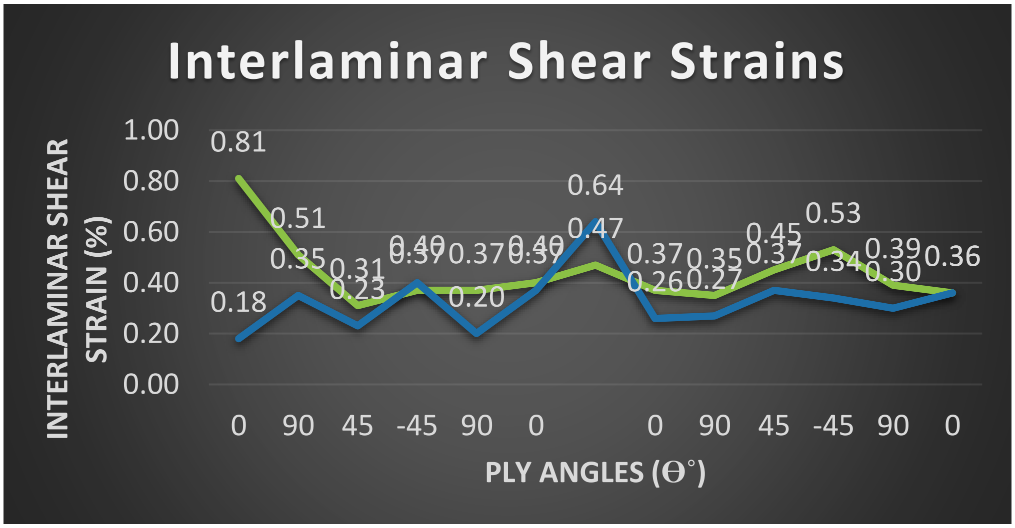


Fig 6.7 Interlaminar Shear strain graph

6.3 Dynamic Analysis Results

In dynamic analysis, component deformation and deceleration are being calculated. It's difficult to calculate the deceleration of car as many factors vary as car speed, direction, mass, etc. Deceleration of passenger also can't be calculated. Thus, deceleration of sphere that impacts on door is being calculated. Composite door absorbs more energy of impact and thus less energy is transferred to car and passengers. In composite, stacking Glass – Honeycomb – Carbon absorbs the most of the energy. Thus, it has the highest deceleration and the design is safe. Passengers are thus safe and there is high survivability.

Materials	**Deceleration (m/s^2)**
Steel	4.89e+6
Composites GHC	5.98e+8
Composites CHG	1.09e+8

Table 6.10 Deceleration

Chapter 7

Analytical Calculations

Theoretical calculations are being carried out to ensure that the results obtained from ANSYS are right and there's no error. Here a rectangular plate of the length and breadth of door is being considered neglecting the part of window. This plate is simply supported and load is applied to upper surface using uniformly distributed load as shown in figure below. Deflection is being calculated for steel and composite stack-up to cross check the values obtained from ANSYS.

Calculations for Steel:

Thickness of one ply (h) =1.14 mm

Total thickness of laminate (H) = 5.64 mm

Uniformly Distributed Load (P_0) = 8336 N

Plate (length*breadth) (b*a) = (850*450) mm

Young's Modulus Steel (E) = 200 GPa

Deflection (w_{max})

Moment of Inertia (I)

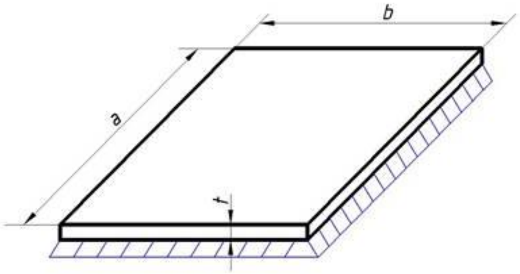


Fig 7.1 Simply supported Steel plate

$$w_{max} = 0.00946\frac{P_0a^4}{D}$$

D= E*I

I= $\frac{hH}{2}$ $[H - 2h + \frac{4h2}{3H}]$

Deflection = 1.12 mm

Here plasticity of steel is not considered.

Calculations for Composite: Carbon fiber – Honeycomb - Carbon fiber

Fiber volume concentration (C) = 60%

Carbon Fiber Young's modulus (E_f) = 300 GPa

Deflection (w_{max})

Composite Young's Modulus (E)

$$w_{max} = 0.00946\frac{P_0a^4}{D}$$

D= E*I

E= $\frac{3}{8}$*C*E_f

I= $\frac{hH}{2}$ $[H - 2h + \frac{4h2}{3H}]$

Deflection = 3.31 mm

Here symmetric stack-up is considered i.e. carbon fiber is used on either side of honeycomb core. Also, here honeycomb core is acting as a load transferring unit and not load carrying unit. Thus, we can see that deflection in case of steel is approximately equal to the deflection obtained from ANSYS. There's slight percentage error. In case of composite stack-up of symmetric stacking Carbon – Honeycomb – Carbon the deflection obtained from ANSYS is higher to that obtained from analytical calculations. There's a difference of 1 mm as this is because Honeycomb is considered as load transferring unit and not load carrying unit for simplification. Thus, deflection obtained in case of analytical is higher than that of ANSYS. Formulas are taken from reference no. [8]. The formula [$E= \frac{3}{8}*C*E_f$] is calculated by using formula of mixture i.e. [$E= \frac{3}{8}*C_f*E_f + \frac{5}{8}*C_m*E_m$]. Where the second term is negligible as compared to first term as young's modulus of matrix is very small as compared to that of fiber. Cm stands for matrix volume concentration. This formula is mainly derived from Rule of Mixtures.

Chapter 8

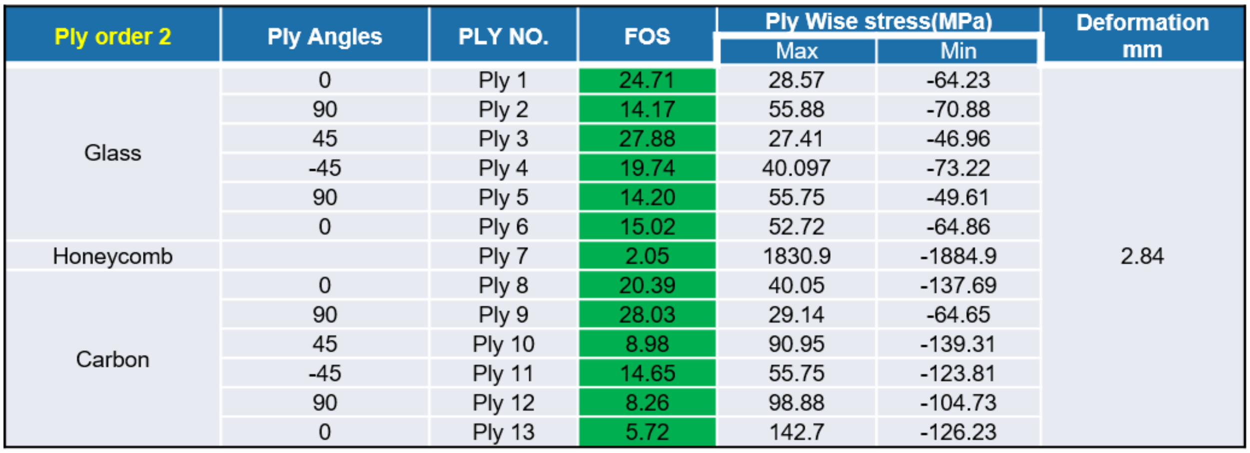
Comparisons

8.1 Comparison between E-glass and S-glass

As E-glass stands for electrical purpose and S stands for structural, S-glass fiber fabric should be used instead of E-glass Fiber fabric but when compared and analyzed E-glass was proved better than S-glass. Following tables show the Factor of Safety, stresses and deformation for E-glass and S-glass. The factor of safety was not so effective or reasonably high as compared to E-glass fiber, also S-glass is 4 to 5 times costly than E-glass fiber, thus E-glass is considered here for analysis. Also, the decrease in deformation is not so reasonable.

Ply order 2	**Ply Angles**	**PLY NO.**	**FOS**	**Ply Wise stress(MPa)**		**Deformation mm**
				Max	Min	
Glass	0	Ply 1	21.54	26.65	-62.17	2.88
	90	Ply 2	11.33	50.67	-66.49	
	45	Ply 3	22.24	25.81	-43.82	
	-45	Ply 4	16.99	33.79	-74.24	
	90	Ply 5	20.60	27.86	-43.29	
	0	Ply 6	16.04	35.78	-59.35	
Honeycomb		Ply 7	2.03	1841.6	-1894.2	
Carbon	0	Ply 8	19.62	41.61	-135.87	
	90	Ply 9	27.81	29.36	-59.72	
	45	Ply 10	8.86	92.16	-140.82	
	-45	Ply 11	14.42	56.63	-123.16	
	90	Ply 12	8.22	99.24	-105.23	
	0	Ply 13	5.03	162.05	-127.65	

Table 8.1 E-glass Fiber



Ply order 2	**Ply Angles**	**PLY NO.**	**FOS**	**Ply Wise stress(MPa)**		**Deformation mm**
				Max	Min	
Glass	0	Ply 1	24.71	28.57	-64.23	2.84
	90	Ply 2	14.17	55.88	-70.88	
	45	Ply 3	27.88	27.41	-46.96	
	-45	Ply 4	19.74	40.097	-73.22	
	90	Ply 5	14.20	55.75	-49.61	
	0	Ply 6	15.02	52.72	-64.86	
Honeycomb		Ply 7	2.05	1830.9	-1884.9	
Carbon	0	Ply 8	20.39	40.05	-137.69	
	90	Ply 9	28.03	29.14	-64.65	
	45	Ply 10	8.98	90.95	-139.31	
	-45	Ply 11	14.65	55.75	-123.81	
	90	Ply 12	8.26	98.88	-104.73	
	0	Ply 13	5.72	142.7	-126.23	

Table 8.2 S-glass Fiber

8.2 Comparison of materials

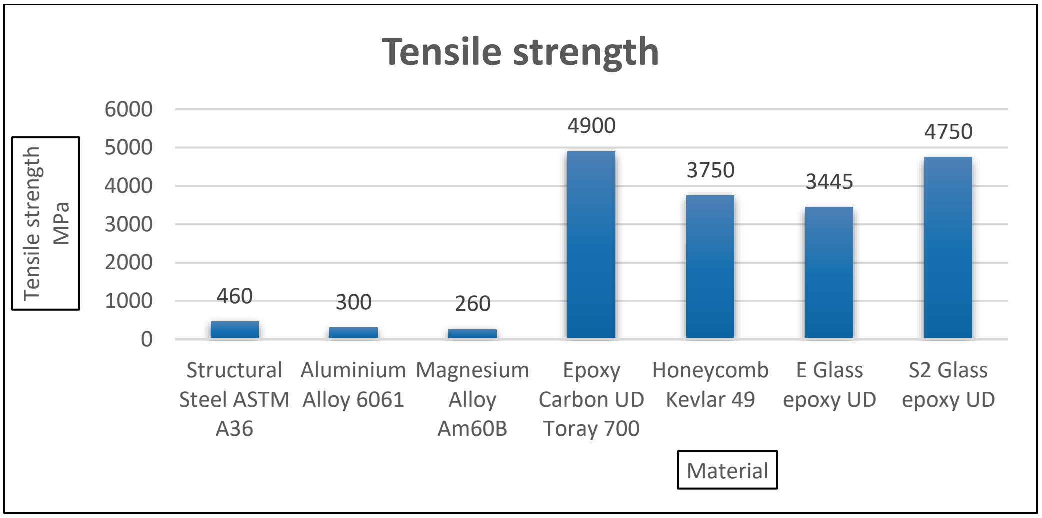


Fig 8.1 Tensile strengths of materials being used

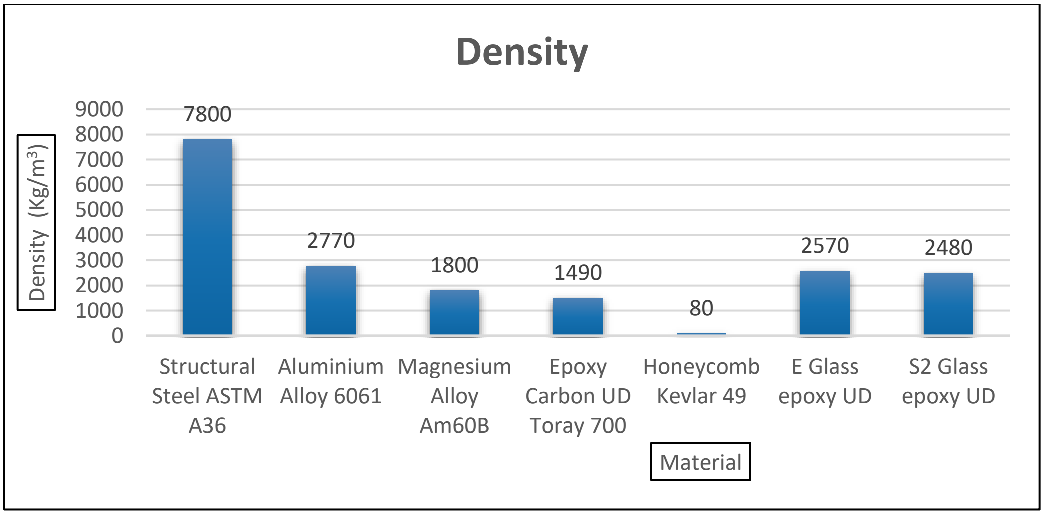


Fig 8.2 Densities of materials being used

From the above graphs, it’s observed that composite materials have high specific strength as compared to steel and alloys. Densities of composite materials being 3-4 times less, whereas strengths being ten times higher than that of conventional materials. Thus, composite materials are being used. The only drawback is high manufacturing cost which can be brought to reasonable values once mass production of this materials is being manufactured in industries.

Following table shows the cost of each material per kg, total weight of the door if being modeled with that material and total cost of that door being manufactured out of that respective material neglecting labor and production cost just considering material procurement cost. As we can see in below table the weight of steel door is around 26kgs as compared to 16kgs in case of composite materials. Also, cost of S-glass is four times more than E-glass thus E-glass is used. Total weight was being calculated from Solidworks. The total cost of door in case of composites is being calculated using fiber matrix volume concentration and the multiplying by no. of plies. As we can see composite doors are costlier than steel and alloys.

Material	**Cost $/kg**	**Total Weight Kg**	**Total Cost $**
Structural Steel ASTM A36	0.5	25.66	15
Aluminium Alloy 6061	2.5	9.76	25
Magnesium Alloy Am60B	2.2	7.87	18
Carbon Fiber	3	2.5	7.5
Honeycomb Kevlar 49	15	0.25	4
E-glass Fiber	0.5	4	2
S2 Glass Fiber	2	4	8
Epoxy Resin	8.5	4.5	38
Carbon-Honeycomb-Glass		15.78	50
Carbon-Honeycomb-Carbon		13.64	65
Glass-Honeycomb-Glass		16.81	44

Table 8.3 Material cost

8.3 Comparisons of Honeycomb materials

Different possible materials of Honeycomb structure are being compared in this chapter. In the following table its seen that the compressive strength of Kevlar is highest as compared to others but the cost is high. But even the density is low in case of Kevlar as compared to others. As honeycomb is being used as a core material, its compressive strength is of utmost importance and that's the property which defines its impact resistance. Craft paper is being used in wooden household doors, where it is being placed between 2 panels for strength. Aluminum is used in lightweight and materials which undergo less impact force. The only competition for Kevlar was Nomex but compressive strength being approximately half then Kevlar and density being higher it sets a drawback in selection. Thus, Kevlar Honeycomb is being considered in this thesis work.

Honeycombs	**Cost $/m^2$**	**Compressive strength (MPa)**	**Density Kg/m^3**
Kevlar	15	3.8	36
Nomex	10	1.86	48
Craft paper	1	0.68	40
Aluminium	5	1.08	83

Table 8.4 Comparison of Honeycomb materials

Chapter 9

Conclusion

- From the results obtained, it can be concluded that from all the materials being used in analysis, composite materials proved to perform better than the conventional materials.
- In composite stacking, the E-glass fiber – Honeycomb – carbon fiber proved to be more stiff, strong and highly energy absorbing. Less deflections proved the passengers were safe.
- High Factor of safety ensured greater survivability of occupants in case of collusion. Interlaminar shear stresses and strains calculated were compared and thus were less than ultimate shear strength and ultimate shear strains, which thus concludes that there was no debonding thus no delamination induced in the plies. S3 stresses i.e. the delamination stresses are below ultimate shear strength of material in 3rd direction, thus safe.
- A composite door is thus lighter than conventional steel doors. Thus, achieving higher fuel efficiency. When compared, there was a difference of 10kgs between the composite and steel doors. Thus, a weight reduction of around 40% was achieved. As a standard vehicle weighs 1600kgs, when all four doors are being considered there can be a reduction of 40kgs i.e. 10kg per door. Experiments show 10% of weight reduction can lead to 6-8% improvement in fuel usage thus reducing the Greenhouse gas reductions. (0.3-0.4 lit/ 100 km per 100 kg reduction)

Future Work

- Fiber matrix concentration can be varied and results can be observed. As here 60% fiber volume concentration was used.
- Optimum door designs can be made to find the structurally best fit design. Good aerodynamic and ergonomic design can be selected having better structure that transfers most of the load due to its structural design.
- Door panels can be filled with crash absorbing and rigid foam in addition to honeycomb core.
- Whole car body and internal parts can be made of composites to reduce the overall weight of the vehicle. As shown in figures below car sub frame, chassis, wheels, car floor and outer body panels can be made from composites.

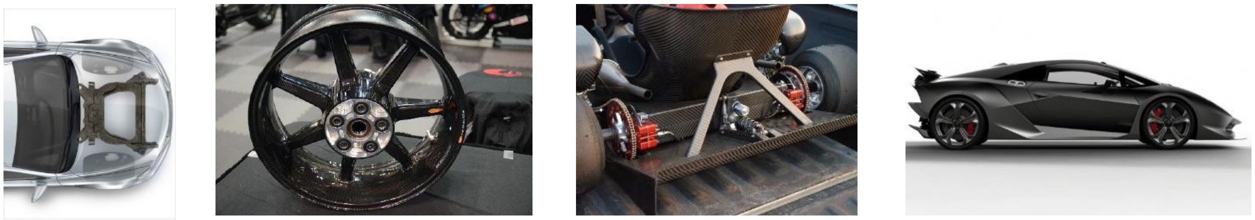


Fig 9.1 various components of vehicle made from composites

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BIOGRAPHICAL STATEMENT

Aniket Chandu Thosar was born on 11th of August 1992. He received his Bachelor of Engineering in Mechanical Engineering from the University of Pune, India in 2014. He worked as Graduate Trainee in FIAT India Automobiles LTD from August 2014 to February 2015. He enrolled into Master of Science in Mechanical and Aerospace Engineering program at the University of Texas at Arlington in Fall 2015. From November 2016, he started working under Dr. Andrey Beyle, on composites. He is proficient in Solidworks, ANSYS workbench, ANSYS Composite PrepPost and Auto-Cad. He has a certification CSWA in Solidworks. He also trained and motivated new members in field. He served as a Graduate Teaching Assistant for Senior Design Capstone Projects under one of the renowned professors, Dr. Woods and Dr. Fernandez at University of Texas from August 2016 to May 2017 i.e. for one academic year. He graduated in May 2017.