

Evaluation of Finite Element Modeling Methodology for Composite Materials

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***Abstract---** Over past few decades, tremendous innovations have occurred in the aerospace/marine industry because of environmental regulations, rising fuel costs, increase in airline traffic etc. These reasons lead to more usage of composite materials in the primary structural components. These materials are known for their high strength and stiffness to weight ratio and hence used in structural applications where there are stringent weight requirements as in aerospace and marine applications.*

Because of recent advancements in manufacturing techniques, there is increase in trend of using composite materials in many complex aerospace and marine structures. Since design and analysis of these structures becomes extremely difficult, Finite Element method is used extensively in most of the applications to reduce time and effort.

Marine propellers are generally doubly curved and tapered with solid cross sections due to acoustic requirements and hence modelling of these kind of propeller blades becomes extremely difficult in Finite Element Method. In this thesis, different FE modelling strategies for a complex shaped 3D composite structure is discussed and compared. By selecting a more appropriate methodology, a typical marine propeller blade is analysed and results are compared with metal blade.

***Keywords---** Solid Elements, Composite Structures, FEA and Nastran, Ansys ACP.*

I. INTRODUCTION

The unrelenting passion for the aerospace industry is to enhance the performance of commercial and military aircraft which is constantly driving the development of improved high performance structural materials. One such type of materials are composite materials that has superior strength to weight and strength to stiffness ratios than metals and are playing a significant role in the aerospace industry.

A composite material consists of relatively strong, stiff fibres in a tough resin matrix. A material with most of the benefits or few of the weaknesses can be obtained by combining materials with complementary properties. Carbon and glass fibres are the better known man made composite materials which are stiff and st

Fibre layup has a major role in attaining the desired strength and stiffness to the structure. The stiffness obtained should be able to withstand the loads applied on it. Ply tailoring helps in obtaining the required stiffness. There are different ways in which a fibres can be laid. They are:

1. Uni-directional layup

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2. Bi-directional layup
3. Multi-directional layup

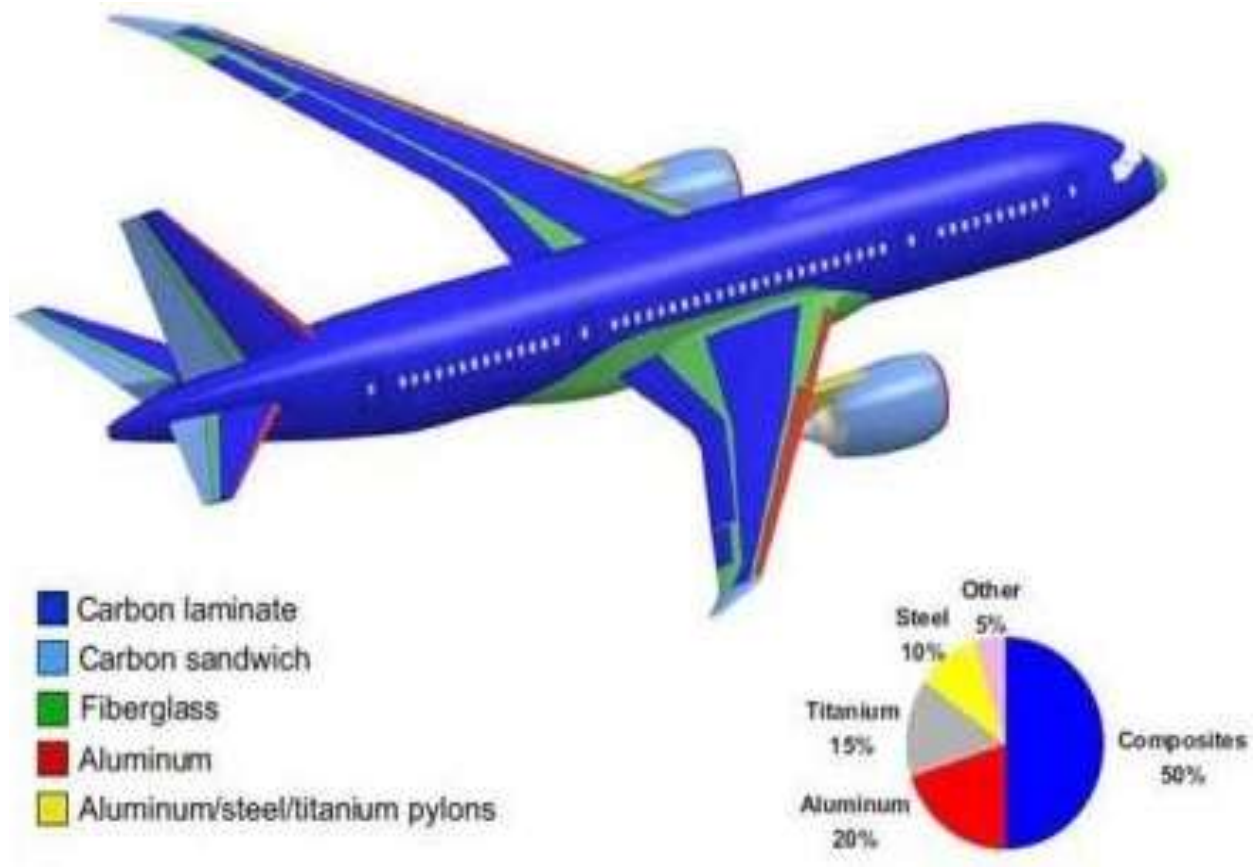
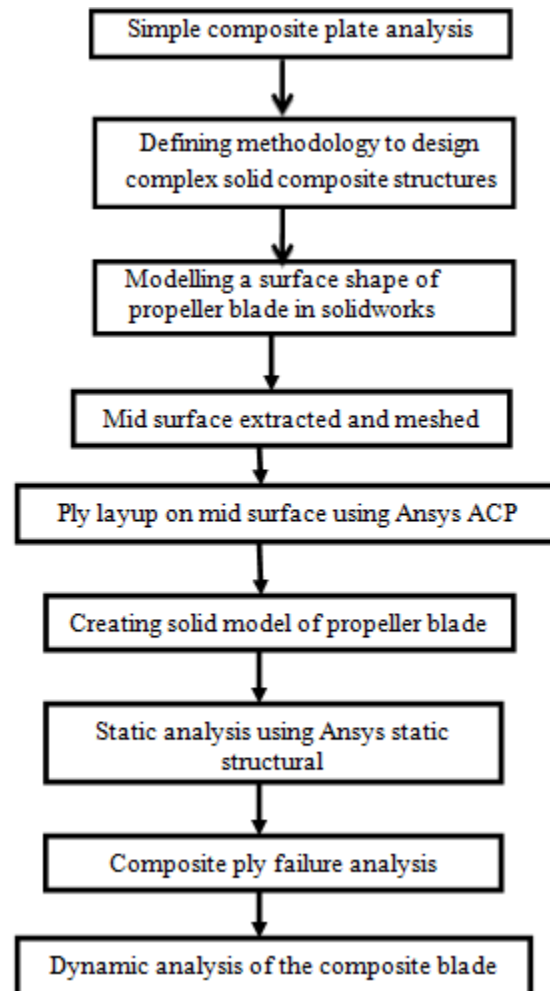


Fig. 1.1: Composites Usage in Modern Aircraft

II. CHAPTER-2 METHODOLOGY

- Analyze a simple rectangular composite plate using shell and solid elements and comparing the results in Nastran and Ansys.
- Analyze a tapered plate in Nastran, Ansys and Ansys ACP to evolve the modelling strategies.
- Selection of FE tool/methodology to be used in the modelling of doubly curved and tapered solid composite blade.
- Design a propeller blade in solidworks whose co-ordinates has to be matched with the co-ordinates of the pressure data that is to be mapped.
- Model and analyze the composite propeller blade using solid elements in Ansys ACP.
- Results comparison with the metallic blade and tailor the ply layup for strength and stiffness requirements.



III. CHAPTER-3 SIMPLE PLATE DESIGN

A simple composite plate is modelled with both shell and solid elements in different modelling package and the results obtained are compared. Based on the strategies followed to develop a simple composite plate a methodology for designing complex composite structures with solid elements is developed.

The different types of plates modelled are:

- Simple rectangular plate.
- Stepped plate.
- Taper plate.

Shell and solid elements are considered in FE modelling of these plates in different softwares and the variations obtained in the deformation are compared.

The modelling packages used to model the composite plate are:

- Hypermesh □ pre and post processor .
- Nastran ▽ solver.

- Ansys .
- Ansys ACP (Advance Composite Prepost).

The whole simple plate design and analysis is done in two phases:

- In the first phase all the three types of plates are modelled using both shell and solid elements in hyper mesh and analyzed using nastran and the results obtained between shell and solid element modelling are compared.
- In the second phase these plates are modelled in Ansys ACP and results obtained from Ansys are compared with the results obtained from Nastran.

Certain guidelines are extracted from the above procedure to model solid composite structures and are applied in modelling of composite propeller blade.

3.1 Material Properties

The Plate is modelled with Epoxy Carbon UD and Resin Epoxy and the various material properties are given below:

Fibre Material: Epoxy Carbon UD (230 GPa) Prepreg.

- Properties:
 - EX = 121000 MPa
 - EY = 8600 MPa
 - EZ = 8600 MPa

$$ov_{12} = 0.27$$

$$ov_{23} = 0.4$$

$$ov_{31} = 0.019$$

$$oG_{12} = 4700 \text{ MPa}$$

$$oG_{23} = 3100 \text{ MPa}$$

$$oG_{31} = 4700 \text{ MPa}$$

Matrix Material: Resin Epoxy.

- $E_1 = 3780 \text{ MPa}$

$$ov = 0.3$$

$$oG = 1400$$

Different cards are used in hyper mesh to define the material, property of the elements. Some of the cards used in this analysis are defined below:

- **MATORT** card is used to define orthotropic material properties.
- **MAT1** card is used to define isotropic material properties.
- **PCOMP** card is used to define composite material for shell elements.
- **PCOMPLS** card is used to define composite material for solid elements.
- **PSHELL** card is used to define shell elements

3.2 Modelling in Hypermesh

1. Simple Rectangular Plate

A simple rectangular plate with 70 x 50 x 5mm geometry is modelled with shell elements having a thickness of 5mm constant throughout the plate. Maintaining the constant plate thickness and varying the ply thickness a plate with 2, 4, 6,8,10 plies is modelled. With decrease in ply thickness there is an increase in number of plies.

Modelling is carried out in Hypermesh and Nastran is used as a solver. The plate is considered as cantilever and one end of the plate is fully constrained and the other end is loaded with 10 N/mm². The results obtained demonstrated that with the decrease in thickness of plies the deformation of the plate decreases.. Maintaining the ply thickness as less as possible is suggested which has many other advantages such as crack resistance in plies in addition to the deflection.

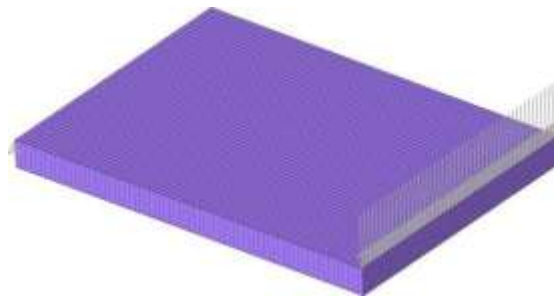


Fig. 3.1: Simple rectangular plate with Shell elements and loads applied

Table 3.1: variation with varying no of plies in a simple rectangular plate

Plate Type	Material Used	Thickness (mm)	Type of Element	Load applied (N/mm ²)	No of Layers	Deflection (mm)
Simple rectangular plate	Epoxy Carbon	5	2d shell	10	2	3.36
					4	1.936
					6	1.798
					8	1.752
					10	1.732

3.2.1 Stepped Plate

A stepped plate is modelled in which the ply doesn't extend up to the end and drop in between which creates a step like structure. Results obtained between both shell and solid elements have been compared. Carbon Epoxy is used with 5 plies with ply orientation of (0⁰/45⁰/90⁰/-45⁰/0⁰) and thickness of ply set to 1mm each. Hypermesh is used for modelling of elements and Nastran is used as solver.

The plate with shell elements is modelled in two methods:

3.2.1.1 Continuity of elements along the thickness of the plate

A plate of 70 x 50 x 5mm is modelled using shell elements. Based on the ply drop the length of the plate is divide into five sections which makes each section with 14mm and each represented in different colour as shown in Fig 3.2. The first section represented in grey colour in fig 3.2 and 3.3 has shell elements with more thickness when compared with other sections because of presence of all 5 plies. Therefore the thickness of shell elements at this

section is 5mm.

In the second section which is blue in colour in fig 3.2 where one ply has been dropped the thickness of shell elements is reduced to 4mm. In the third section, one more ply drops and the thickness of shell elements is reduced to 3mm. In the fourth and fifth sections there is only one ply drop and the thickness of these two sections is the same i.e., 2mm. Load is applied at the thinner section which resembles a cantilever beam with other end completely constrained.

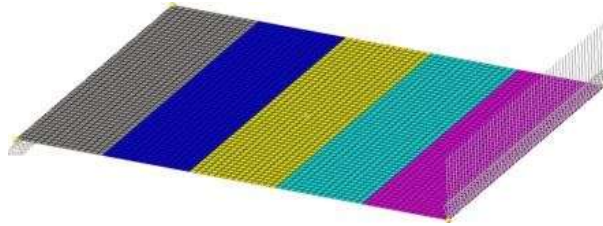


Fig 3.2: Traditional representation of 2-d shell elements along thickness continuity

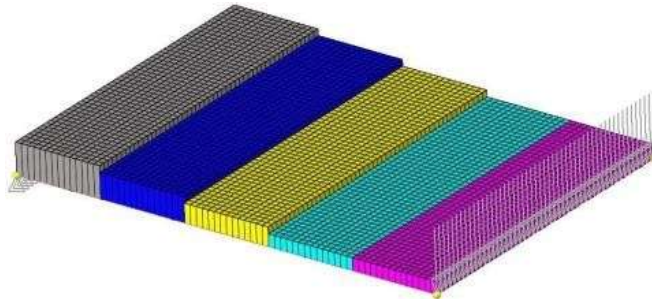


Fig 3.3: Detailed element representation along thickness continuity

3.2.1.2 Continuity of elements along the length of the plate

In this method a plate with similar dimensions is modelled using shell elements. But the way of modelling differs because of the element continuity. In this method modelling of elements depends upon the length of each ply. Length of first and second layers from the base of the plate extends up to the end. First layer is modelled with all elements and for the second layer all elements in the first layer are duplicated and translated above the first ply with 1mm. Third ply doesn't extend up to the end of the plate, where the elements with the respective length are selected, duplicated and translated above the second ply with 2mm. The same procedure is followed for fourth and fifth plies with an offset of 3mm and 4mm respectively.



Fig. 3.4: Traditional representation of 2-d shell elements in length continuity

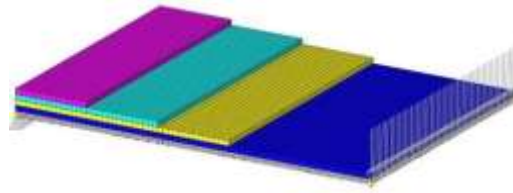


Fig. 3.5: Detailed element representation along length continuity

Results defined that the deflection of the plate whose elements continuity is along the length has less deflection when compared with the other model.

Table 3.2: Deflection comparison in stepped plate with shell elements by different element continuity

Plate type	Element Used	Continuity	Deflection (mm)
Stepped	Shell	Thickness	9.24
		Length	9.02

3.2.1.3 Comparison of stepped plate between shell and solid elements

A stepped plate with solid elements is created in hypermesh. Property with PCOMPLS card is defined for each of the layer where its orientations and thickness are specified in it and is assigned to the respective elements. Same load as applied to the shell model is applied to the solid model. Deflection analysis is performed on the solid model and the results are compared with the shell model.



Fig. 3.6: Stepped plate with solid elements

Table 3.3: Deflection comparison in stepped plate among shell and solid elements

Plate type	Element used	Load applied (N/mm ²)	Deflection (mm)
Stepped	Shell	10	9.02
	Solid	3.33	9.35

3.2.2 Taper Plate

A taper plate is similar to a stepped but has drop-offs filled with matrix material after the ply drop. These drop-offs prevent the structure from delamination. This is considered as a cantilever and the loads are applied at one end and the other end is completely constrained.

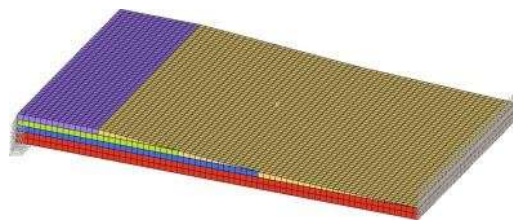


Fig. 3.7: Taper plate filled with matrix material after ply drop

With the addition of matrix material the plate undergoes less deformation when compared to the stepped plate which has no matrix material and is also less prone to delamination.

Table 3.4: Comparison between stepped and taper plate

Plate type	Element used	Load applied (N/mm ²)	Deformation (mm)
Stepped	Solid	3.333	9.35
Taper	Solid	3.333	5.63

3.1 Modelling in Ansys Acp

Ansys is a complete FEA tool to model and analyse structures. ACP (Advance Composite Prepost) is a component system used only to develop composite structures which makes the modelling simple with its unique features such as selection rules, ply drop-offs, edge sets, extrusion guidelines, etc. Simple plates like rectangular plate, stepped plate, taper plate are developed in ACP using both shell and solid elements and the results obtained are compared with the results obtained by nastran.

3.3.1 Simple Rectangular Plate

A simple rectangular composite plate with 70 x 50 x 5mm is modelled in ansys ACP using both solid and shell elements. This blade is composed of 5 plies with each ply thickness as 1mm and carbon epoxy material is applied to the blade. The results obtained are compared with the results obtained in nastran.

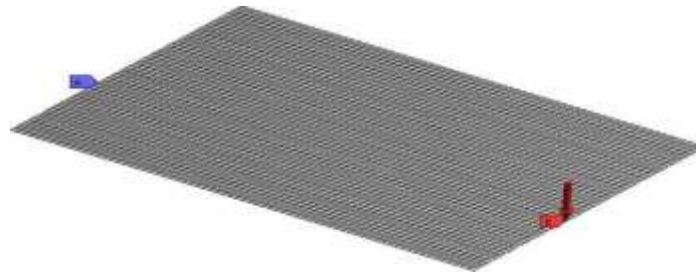


Fig. 3.8: Shell model of the plate with loading

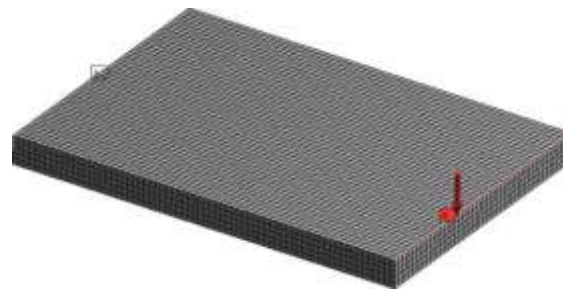


Fig. 3.9: Solid model of the plate with loading

Table 3.4: Deflection comparison of rectangular plate in Nastran and ACP

Plate type	Type of element	Load applied (N/mm ²)	Deflection (mm)	
			Nastran	ACP
Simple rectangular plate	Shell	10	1.136	1.167
	Solid	10	1.182	1.161

The results compared shows that the deflection is almost the same in both the softwares.

3.3.2 Stepped Plate

A stepped plate with ply drops in the top three plies is modelled in ACP using the Parallel selection rule, a feature in ACP which selects the elements within a specified region. This selection rule helps in saving designing time and makes the designing comfortable.



Fig 3.10: Stepped plate with solid elements

Deformation analysis is performed on the plate and the results obtained are compared with the results obtained from nastran.

Table 3.5: Deflection comparison of stepped plate in nastran and ACP

Plate type	Elements used	Load applied (N/mm ²)	Deflection (mm)	
			Nastran	ACP
Stepped plate	Shell	10	9.24	9.022
	Solid	10	9.715	9.412

3.3.3 Taper Plate

A taper plate has matrix elements filled from the end of the ply drop. This ply dropoff is modelled using cut off geometry feature from ACP which considers the surface shape and the material out of this surface is removed automatically. This feature is mostly used in modelling of complex composite structures.



Fig. 3.11: Taper plate with Matrix elements after the ply dropoff.

Table 3.6: Deflection comparison of taper plate in nastran and ACP.

Plate type	Elements Used	Load applied (N/mm ²)	Deflection(mm)	
			Nastran	ACP
Taper	Solid	10	5.63	5.9

The overall comparison of the results are tabulated and based on the modelling methodology in both the softwares Ansys ACP is preferred for modelling complex solid composite FEA model.

Table 3.7: Overall comparison of results between different plates using nastran and ACP..

Plate type	Material used	No. of layers	Thickness (mm)	Type of element	Load applied	Deflection	
						Nastran	ACP
Simple rectangular	Carbon epoxy	5	5	Shell	10	1.136	1.167
				Solid	10	1.18	1.161
Stepped plate	Carbon epoxy	5	5	Shell	10	9.24	9.022
				Solid	10	9.715	9.412
Taper plate	Carbon epoxy	5	5	Solid	10	5.63	5.9

CHAPTER-4

IV. PRESSURE DISTRIBUTION ON PROPELLER BLADE

A propeller has a hub which is the centre piece and strongly holds the blades in place. These blades are curved so that when they rotate they slice the water and produce lift to move the ship. The higher pressure is on the blade's face section that can be seen from the shaft and the lower pressure on the blade's back section.

Propellers usually comprise of 2 to 6 blades which are long and thin and upon the section cut resemble an airfoil shape. As the blade rotates the tip moves faster than the root. In order to make the propeller more efficient, the blades are usually twisted. All these design aspects makes the analyzing of flow around a propeller a difficult task.

Propeller propulsion is a very complex concept because the propeller is like a rotating wing. From airfoil theory, the pressure on the top of the lifting wing is less than the pressure below the wing. Hence a spinning propeller sets up a pressure lower than the free stream at the front and higher than the free stream at the back.

Pressure magnitude on the propeller blade differs at every unit area. Considering the pressure loading on the propeller surface, the back surface involves suction and the face surface is the pressurized surface. Overall pressure distribution on the face section is found to be more uniform compared to the back section because of the interaction of hydrofoil geometry profile and flow stream.

The hydrofoil stagnation point or the leading edge is exposed to higher pressure when compared to the trailing edge. This is because the leading edge cuts the flow stream and as a reaction, high pressure is developed at that point and subsequently distributed to the whole blade surrounding. Propeller rotation speed also has a great influence on the blade pressure distribution i.e., higher the speed higher is the pressure surrounding.



Fig. 4.1: Pressure distribution on suction side

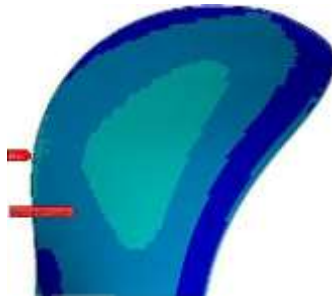


Fig. 4.2: Pressure distribution on face si

CHAPTER-5

V. COMPOSITE DESIGN GUIDELINES

The properties of composite materials such as light, strong and versatile attracts the designers for many types of manufacturing. Aerospace and automotive sectors, typically use composite materials like carbon fiber (CFRP) and are rapidly increasing in other applications, such as bicycle frames, musical instruments, etc.

Composite materials give scope for designing the material as well as a structure through judicious placement of ply orientation. The strength and stiffness of the layers is more in the fibre direction and less in the transverse direction. This ability of composites gives designers a huge potential in tailoring the layup orientations.

Before these design guidelines there are certain fundamentals of composites to be known:

5.1 *Fundamentals of Composites Design Decisions*

- Equal fibre and load directions

Fibres carry load in the same direction in which they are laid. Woven fabrics which has fibres in other direction serve other purposes.

- Parallel laid fibres vs. Woven fibres

These woven fibres has a crimp in which fibres are laid up and down in which stress concentration at the crimp is more. Hence this results in the strength reduction of fibres at least 5-10%.

- Voids decrease strength of the composite structure

Voids (air bubbles) that are trapped in the laminates which do not carry any load degrade the strength of the laminate drastically. 2-3% of voids can cause strength reduction up to 10-20%.

- Resin weak and soft vs. Fibres

Resin is used to bind the fibres is weaker than the fibres when compared with stiffness and tensile strength. Hence excess resin can result in less strength to weight ratio.

- **A load carried in sandwich structures is along its facing direction** Sandwich facings carry loads only in the direction that lies within the facing plane. Core carries load in any direction except in the facing direction even though the load has to go through the facing to reach the core.

CHAPTER-6

VI. COMPOSITE PROPELLER BLADE DESIGN

Following all these guidelines a composite propeller blade with solid elements has been modelled in ansys workbench using ACP (Ansys composite Prepost).

Accurate simulation is a challenge because of their composite nature. Traditionally, shell elements are used in modelling of layered composite structures. This approach is said to be valid in designing of thin parts, such as panels for airframes, hollow tubes for bikes, and wind turbine blades. But when the parts are more massive, such as stringers for pressure vessels or gas turbine blades, usage shell elements is not recommended. In such cases, both shear stresses out of plane and stresses in the direction of the thickness are significant, and hence solid models are required. Solid models approach is also appropriate when the structure is subject to large deformations and when loads applied are in the direction of the thickness.

This entire simulation process is performed in ANSYS Workbench using ANSYS Composite PrepPost (ACP). The workflow begins by,

1. Defining the shape of geometry.
2. Extraction of mid surface.
3. Meshing the mid surface.
4. Importing the meshed mid surface into Ansys ACP.
5. Creating the composite layup.

The investigation of composites failure occurs as the last step.

6.1 Defining the Shape of Geometry

6.1.1 Selecting the Airfoil

National Advisory Committee for Aeronautics (NACA) developed the airfoil shapes for aircraft wings. The shape of the NACA airfoils is described using a series of digits following the word NACA. The parameters in the numerical can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

These airfoils are categorized into 6 families basing on the applications. They are

1. 4-digit
2. 5-digit
3. 6-series
4. 7-series
5. 8-series
6. 16-series

16-series airfoils are used in aircraft propellers and ship propellers because of their low pressure peaks and low drag at high speed. They relatively have low lift.

NACA 16-021 airfoil has been used in modelling of composite propeller blade.

The selected NACA airfoil is used at the root of the blade. The airfoil shape as well as the pitch varies along the length of the blade. But airfoil shapes at different sections has to be in such a way that pressure side has lower surface area and the suction side has higher surface area. Along with the change in airfoil shape, blade is also doubly curved and tapered along the length. Hence the area of the airfoil sections decreases with increase in radius.

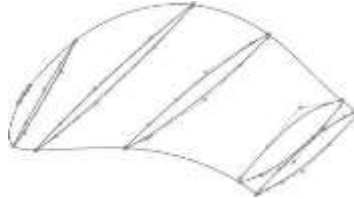


Fig. 6.1: Airfoil sections with varying pitch in a propeller blade

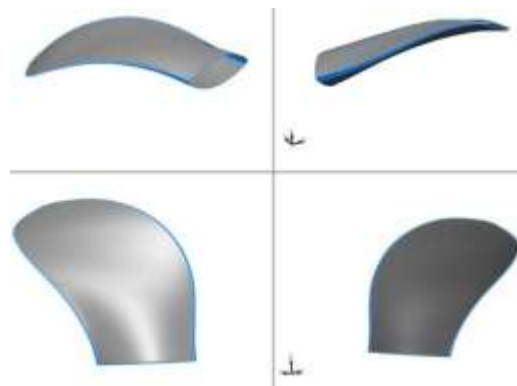


Fig. 6.2: Propeller blade showing curves on leading and trailing edge

A surface model is first created instead of solid model as it has to be used in ACP in defining the layup and surface shape of the composite model. Later a solid model has been created with aluminum metal applied to the blade.

6.2 Extraction of MID surface from the Profile and Meshing

A mid surface from the profile is extracted and is meshed in HYPERMESH. This meshing is done basing on the composite layup. At the edge of the surface element size of 0.5mm is maintained. This is because the layup is based on the elements of the mid surface and the mid plies are not extended up to the edge of the mid surface. These will be dropped before the end element of the mid surface and upon this end element a matrix material is applied.



Fig. 6.3: Mid Surface meshed

After the extraction of mid surface the surface areas on which the plies has to be laid has to be extracted. Each ply thickness is maintained at 0.3mm and hence surface areas with 0.3mm interval along the thickness of the blades is extracted and these surface areas are used in ACP in layup of the plies.

6.3 Material Properties of Propeller Blade

The propeller blade is modelled with Epoxy Carbon Woven and Resin Epoxy and the various material properties are given below:

Fibre Material: Epoxy Carbon Woven (230 GPa) Prepreg.

- Properties:

- $E_X = 61340 \text{ MPa}$
- $E_Y = 61340 \text{ MPa}$
- $E_Z = 6900 \text{ MPa}$
- $\nu_{xy} = 0.04$
- $\nu_{yz} = 0.3$
- $\nu_{xz} = 0.3$
- $G_{xy} = 19500 \text{ MPa}$
- $G_{yz} = 2700 \text{ MPa}$
- $G_{xz} = 2700 \text{ MPa}$
- $\rho = 1420 \text{ kg/m}^3$

Matrix Material: Resin Epoxy.

- Properties:

- $E_1 = 3780 \text{ MPa}$
- $\nu = 0.35$
- $G = 1400 \text{ MPa}$
- $\rho = 1160 \text{ kg/m}^3$

6.4 Importing the Required Cad Geometries

The required CAD geometries are imported in the IGES format. The imported mid surface will be used in defining the layup of the composite model. The following sequence is followed in defining the layup i.e., Defining the material and fabric along with the thickness of each layer. Rosettes are created to define the ply orientation. Selection rules are created using the imported CAD geometries. Most important selection rule is the CAD selection rule in which all the surface areas required to define the plies are added. This selection rule selects the elements of the mid surface that comes within the surface area and the ply is laid on them.

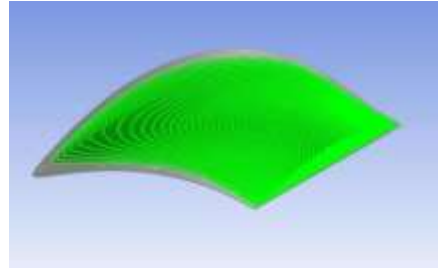


Fig. 6.4: Ply surface areas

Oriented selection set which defines the direction of layup and the rosette to be used is created. Then modelling groups are created which consists of ply layup data such as ply material, orientation, area in which the ply has been laid, ply terminating point. This approach is very much similar to the actual manufacturing process. This layup is performed on the extracted middle surface from the blade profile.

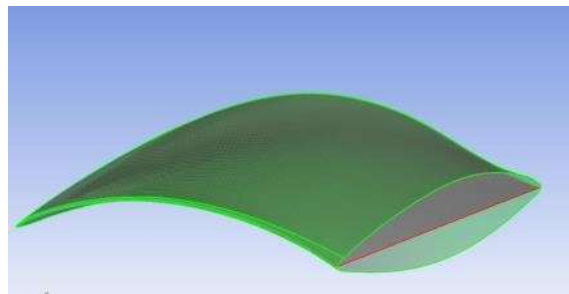


Fig. 6.5: Mid surface with blade profile

The most critical area in designing the solid composites is creating the solid model using the above definitions. The ACP tool offers much advanced capabilities such as ply tapering, extrusion guidelines to deal with the complex shapes. Ply tapering can be obtained by using the cut-off rules. Snap-to-geometry is used in surface smoothing and to fit the solid model in the imported CAD geometry.

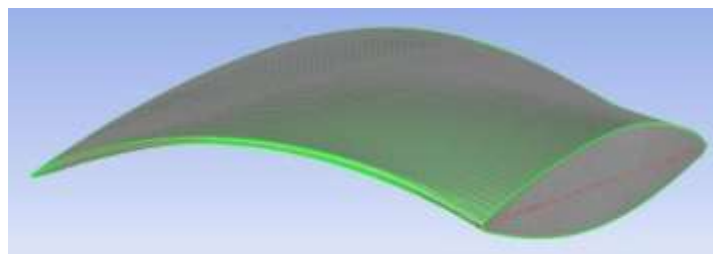


Fig. 6.6: Composite blade with carbon plies

6.5 PLY DROP-OFFS

Another important aspect in modelling of solid composites is handling of drop-offs. If these ply drop-offs are not maintained properly they can cause severe damage and delamination in composite. Degenerated brick elements are used for representation of ply drop-off elements which are usually made of homogeneous material such as resin.



Fig 6.7: Composite blade differentiating fibres and matrix material

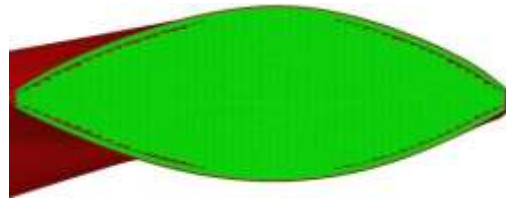


Fig 6.8: Composite blade showing the ply drop-offs

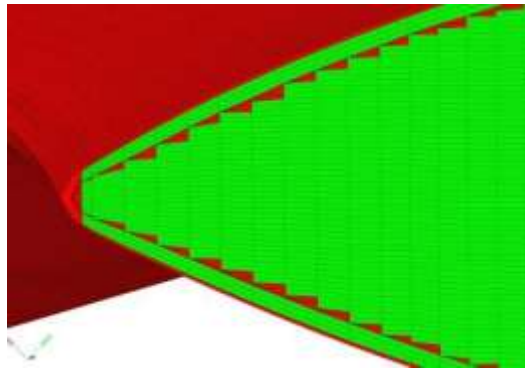


Fig 6.9: Composite blade the layup of the fibres and resin after the ply drops and outer surface covered plies.

The created solid composite model is transferred to static structural analysis system where the loads are applied and solved. Standard results such as deformations, stresses can be obtained. In the presence of any non composite parts in the assembly, they have to be transferred to the same static structural analysis system where the composite model is transferred and the contact detection between parts has to be specified.

6.6 Ply Orientation Defined in Propeller Blade

Ply orientation is the most important aspect of the composites design. A blade with all 0^0 plies is first analyzed and results obtained such as deformations, stress variations are observed. Based on the results and the guidelines provided layup has been defined. The total number of layers formed for designing the propeller blade is:

Total number of layers: 82 plies + 2 matrix layers = 84 layers

Top section about mid surface: 44 plies + 1 matrix layer = 45 layers Bottom section about mid surface: 38 plies + 1 matrix layer = 38 layers

6.6.1 Top Section about Mid Surface Ply Orientation

Upon considering the above guidelines ply orientation for the top section about the mid surface has been defined. Considering the top down approach the ply orientation is:

$$[45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/(0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ})/90^{\circ}/45^{\circ}/0^{\circ}/-45^{\circ}]$$

Outer plies load carrying plies

6.6.2 Bottom Section about Mid Surface Ply Orientation

Same as top section ply orientation, bottom section about the mid surface has also been defined using the guidelines provided. Considering the bottom up approach the ply orientation is:

$$[45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/(0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ})/0^{\circ}/45^{\circ}/90^{\circ}]$$

Outer plies load carrying plies

6.7 Complete Ply Orientation of the Propeller Blade

Considering the top down approach the complete ply orientation of the propeller blade is defined as:

$$[45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/(0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ})/90^{\circ}/45^{\circ}/0^{\circ}/-45^{\circ}/90^{\circ}/45^{\circ}/0^{\circ}/(-45^{\circ}/90^{\circ}/45^{\circ}/0^{\circ})/-45^{\circ}/90^{\circ}/45^{\circ}]$$

6.8 Boundary Conditions of Propeller Blade

A propeller is a rotating component in which blades are attached to the hub. This design shows that one end of the propeller blade is fixed to the hub which is the root and the other end of the blade is free which is the tip.

The hub is connected to a rotating shaft which supplies torque and thus helps in rotating of the propeller blade. The rotating velocity of the propeller depends upon the application of the propeller and its respective design. If the diameter of the propeller is more then lesser rotational speeds is recommended because of its structural loading. But for the vessels with high speed (35+ knots) a propeller with less diameter and higher rotational speed is recommended propeller the operating speed is 1500-2000 rpm.

CHAPTER-7

VII. RESULTS AND DISCUSSIONS

Structural and dynamic analysis has been performed on both aluminum and composite blade of same design and the results are compared. It is found that composite blade exhibit better properties than the metallic blade.

The blade undergoes bending, twisting, strain along length under working conditions. These deformations lead to different stresses in the blade which are discussed.

7.1 Mass Comparison

As known composites exhibit less weight when compared to the metals for the same structure under same working conditions. Hence there is almost 50% mass reduction in the composite blade.

Table 7.1: Mass comparison in aluminum and composite blade.

	Aluminum blade	Composite blade	% decrease
Mass (kg)	0.33801	0.14126	58.2

7.2 Deflection Comparison

The blade can be considered as cantilever beam with one end fixed and the other end free, the free end exhibits more deflection for the load applied. Similarly for the loads applied on the blade, the maximum deformation in the blade is at the tip. But the deflection in the metallic blade is less compared to the composite blade.

With all 0^0 plies the deflection of the composite blade obtained is 0.32861mm. But after tailoring the ply stack up the deflection of the composite blade is reduced by 27%.

Table 7.2: Deflection comparison in aluminum and composite blade before ply tailoring.

	Aluminum blade	Composite blade	% increase
Deflection (mm)	0.16899	0.32861	94.4

Table 7.3: Deflection comparison in aluminum and composite blade after ply tailoring.

	Aluminum blade	Composite blade	% increase
Deflection (mm)	0.16899	0.28247	67.1

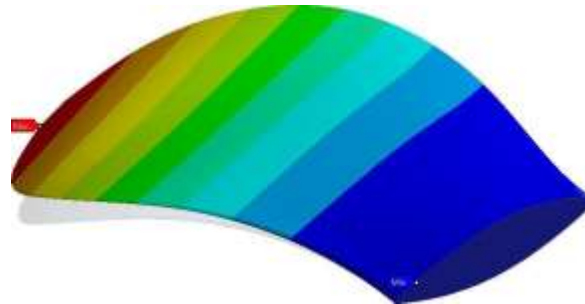


Fig. 7.1: Undeformed and deformed shape of propeller blade.

Modal Analysis

Natural frequencies for the propeller blade have been defined and the frequencies obtained are more than the aluminum blade. As we know higher the natural frequency, higher is the stiffness of the structure. Hence the stiffness of the composite blade is found to almost 10% more than the aluminum blade.

Table 7.4: Natural frequencies at 0 RPM.

Modes	Aluminum blade	Composite blade	% increase
I	993.56	1091.5	9.85
II	2291.5	2537.5	10.73
III	3258.4	3595.4	10.34
IV	4002.6	4313.9	7.77
V	5221.4	5590.2	7.06
VI	7595.8	7694	1.29

Table 7.5: Natural frequencies at 2000 RPM.

Modes	Aluminum blade	Composite blade	% increase
I	991.4	1043.9	5.29
II	2290.9	2437.9	6.41
III	3262.1	3557.2	9.04
IV	4003.9	4331.5	8.12
V	5221.8	5700.2	9.16
VI	7599.6	7714.2	1.50

From the above frequencies at stationary and at 2000RPM it can be seen that frequencies are almost 10% more in composite blade. Hence the stiffness will also be almost 10% higher in case of composite blade.

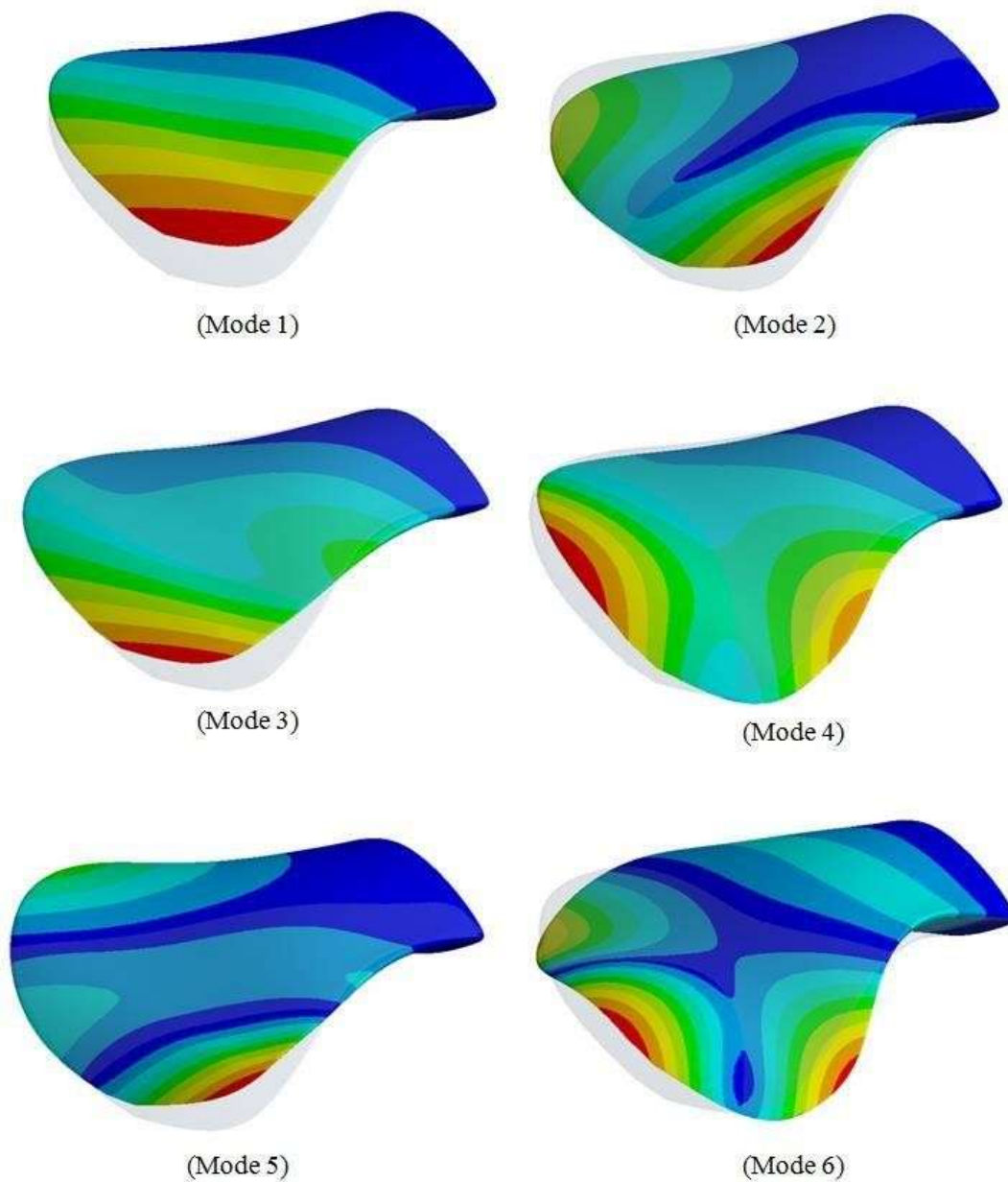


Fig. 7.2: Different mode shapes of a propeller

Campbell Diagram

Campbell diagram is the graph between RPM and the natural frequencies and is the most important part in analyzing the rotating structures. This diagram gives the critical speed of the rotating structure. Operating at these critical speeds can cause vibrations of dangerous character and leads to failure of the structure.

Based on this Campbell diagram, the optimum operating speed range is defined or the structure is modified by adding dampers or stiffeners which avoids critical speeds in the required operating speeds.

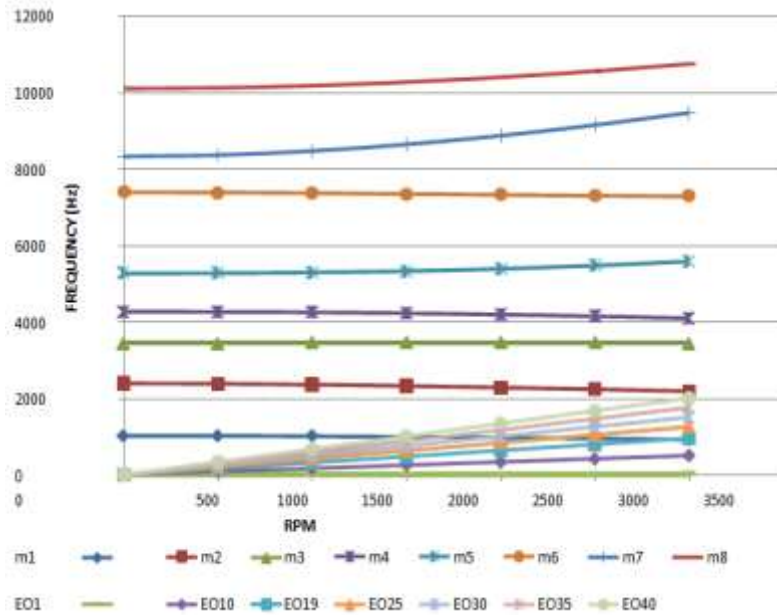


Fig 7.3: Campbell diagram for a composite propeller.

From the above graph critical speeds can be determined. The 'M' lines are the different modes in modal analysis and the 'EO' (Engine Order) lines are ratio between frequency and speed. The speed corresponding to the point at which the EO and M line intersect is the critical speed (resonance).

This propeller has 5 blades and hence there will be 5 EOs. The optimum operating speed for torpedo propeller is considered as 1500-2000rpm. Hence it has to be made sure that these 5 EO lines do not intersect at any M line in between 1500- 2000rpm. A margin of 10% of natural frequency is provided for avoiding a resonance situation.

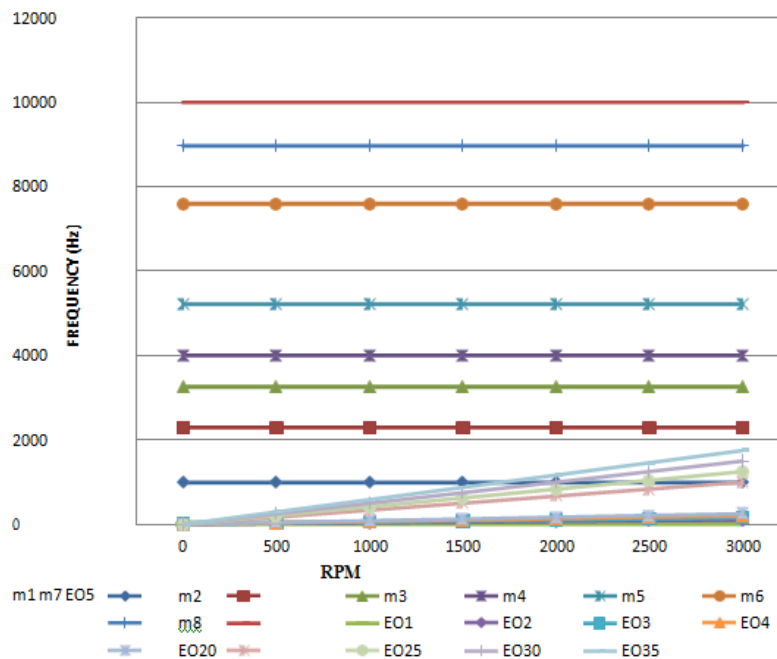


Fig 7.4: Campbell diagram of aluminum propeller

Failure Analysis

For defining the failure of composites certain failure criterion are available. Some of them are: Maximum Stress Theory, Maximum Strain Theory, Tsai-Hill, Tsai-Wu, Hoffman, Hashin, Puck etc. Some of these theories like Maximum stress theory and Maximum strain theory don't have interaction between the stress and strain components.



Fig. 7.5: Failure in composite blade

The maximum failure index obtained in the composite blade is 0.2229 that is on the outer ply used to cover the load carrying plies. The outer plies both on the top surface and bottom surface has the maximum failure index.

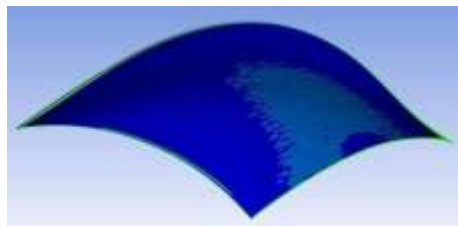


Fig. 7.6: Failure plot in the outer ply on the top surface

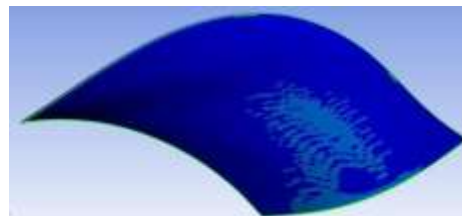


Fig 7.7: Failure plot in the outer ply on the bottom surface

Equivalent Stress Comparison

As in the case of cantilever beam the stress is maximum at the fixed end and minimum at the free end. Similarly in the propeller blade also experiences maximum stress at the root of the blade and minimum at the tip of the blade. The maximum stress obtained in the composite blade is 17.06 MPa.



Fig. 7.8: Stresses in the composite blade



Fig. 7.9: Stress variation in composite blade

In case of the aluminum blade stresses obtained are maximum at the root and minimum at the tip. The maximum equivalent stress obtained is 17.762 MPa. The stresses obtained in both the blades are approximately same.

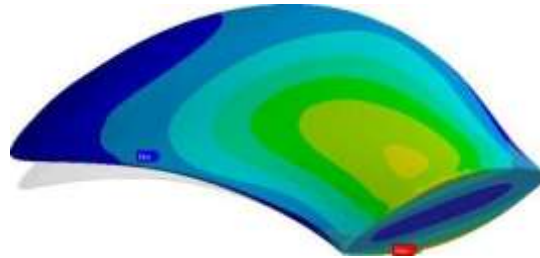


Fig. 7.10: Equivalent stress in aluminum blade

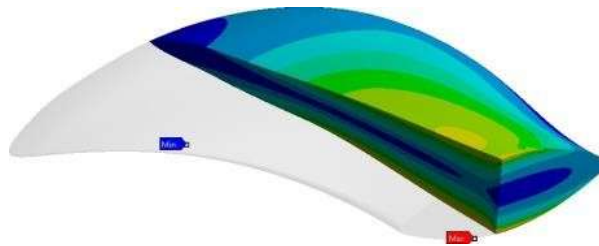
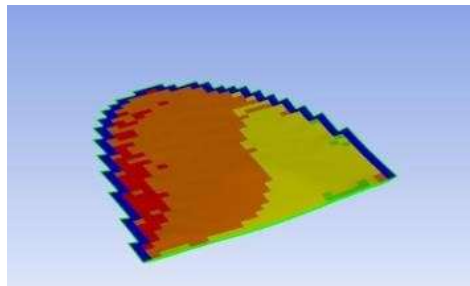


Fig. 7.11: Stress variation in aluminum blade

Inter-Laminar Stresses

Inter-laminar stresses are the stresses caused due to the application of in-plane loads to angle ply laminates. Bending-stretching couple arises which give rise to transverse stresses in the interface. This type of loading causes the rotation of the plies. This rotation generates the inter-laminar stresses, one of the main factors for delamination. This is mainly pronounced at the free edges.



.Fig. 7.12: Inter laminar stresses in the 30th ply from mid surface towards the bottom surface

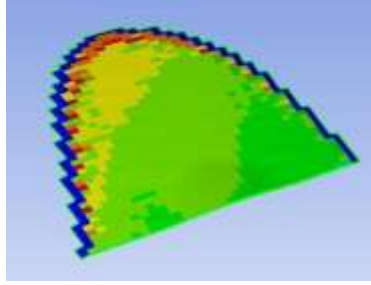


Fig 7.13: Inter laminar stresses in 29th ply from the mid surface towards top surface

CHAPTER-8

VIII. CONCLUSIONS AND FUTURE SCOPE

Conclusion

Different modelling packages have been used to design composite materials using solid elements. The best and efficient out of them has been selected in designing the complex composite structures.

A composite propeller blade using solid elements has been modelled successfully using the Ansys ACP software.

The difficulties faced while creating the solid composites has been discussed. While defining the ply layup certain guidelines have been followed in order to prevent the structure from delamination, damage from shock loads, propagation of inter laminar cracks etc.

Pressure loads have been mapped onto the composite blade which resembles the actual scenario while in operating condition. Static and dynamic analysis has been performed on the blade.

In static it is found that deflection is more in case of composite blade but it has been reduced by 25% by ply tailoring method. Stresses obtained are under the limits.

Failure analysis has been performed by using Tsai-Hill and Tsai-Wu criterion and this proved that no ply is failing in the whole structure. Weight of the structure is also reduced by 50%.

The outer surface is covered by the matrix material to prevent load carrying plies from external damages.

FUTURE SCOPE

- Analysis presented in this work can be extended to fatigue, rotor dynamics, pre-stress etc.
- Usage of multi directional fibre orientation which consists of fibres in the third direction can be applied in the propeller blade which may result in better performance.

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