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INVESTIGATIONS ON MECHANICAL PROPERTIES OF ADVANCED COMPOSITE FOR AEROSPACE APPLICATIONS

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ABSTRACT

Heat resistant composites are widely used for high temperature thermal protection systems and as flame deflectors for aerospace applications. Advanced composites made of fiber reinforced polymer matrix composites because of their strength, stiffness, low weight and their excellent thermal properties made them to replace metallic components. In this project work E-glass (v-9) phenolic and Rayon phenolic laminates were made by wet hand lay-up auto clave vacuum bagging process and their properties were evaluated by destructive and non-destructive testing methods. Laminate with known defect was examined by Ultrasonic method. Effect of modification of matrix system was studied on laminate properties. Composite made with modified phenolic resin was compared with conventional phenolic composite. Defect in the composite was analyzed by Ultrasonic Test and Radiography methods Oxy-acetylene erosion tests were carried out on laminate specimens and data was generated for ablative materials characterization.

Keywords: *Heat Resistant, Aerospace Applications, Non-Destructive Testing, Ultrasonic Testing, Fibres, Composites.*

I. INTRODUCTION

Heat resistant composites are essential for the successful launch and operation of all space vehicles. The selection of a composite material depends upon the mission of the space craft. While often the temperature capability is a major concern, the goal remains to protect the internal components at a minimal weight. This means extra insulation if the exterior material has a high heat capacity. In order to meet the mission objectives and the criteria the heat resistant material essential properties are it should have high heat of ablation, specific heat and low thermal conductivity, expansion coefficient, erosion rate.

Fiber reinforced polymer matrix composite materials has constituted a major breakthrough in the construction of lightweight structures. In particular significant benefits have been realized in the aerospace sector to meet the severe performance requirements with stringent demands of reliability. Almost all aerospace structural components – airframes of fighter aircraft, helicopters, control surface and fins of civil aircraft, various planes in satellites, antennas, rocket motor casings and some complete airframes of small aircraft are witnessing an increasing use of the advanced composites. An important technological development that has contributed significantly to this growth of composites is the development of strong and stiff fibers such as Glass, Carbon and Aramid along with concurrent developments in the polymer chemistry resulting in a various polymeric materials to serve as matrix materials. In particular the versatility of the technology of the carbon fibers having various properties has played a key role in this growth. With complimentary developments in computer hardware and software technology, and in computational methods of analysis rendering help to the analyze and understand the material behavior and to provide predictive as well as design tools, the complexity of the polymer – matrix composites has been overcome to facilitate the extensive applications. Composites have the applications in many fields some of them are given in the following, since we are interested in aerospace applications it illustrated briefly.The creation of reliable heat resistant laminate composites for space applications requires precision design and proper tests. Because composite materials are

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necessary to meet heat resistant requirements for the aerospace applications such as nose cones, flame deflectors, airframes etc., some of aerospace applications where different types of materials are being used are shown below.

II. AEROSPACE APPLICATIONS

- Use of composites in LCA Tejas:

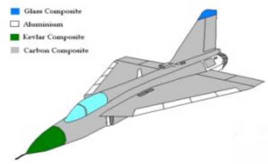


Fig 1. Composites in Light Combat Aeroplane (Tejas)

Fig. 2 Light Combat Helicopter

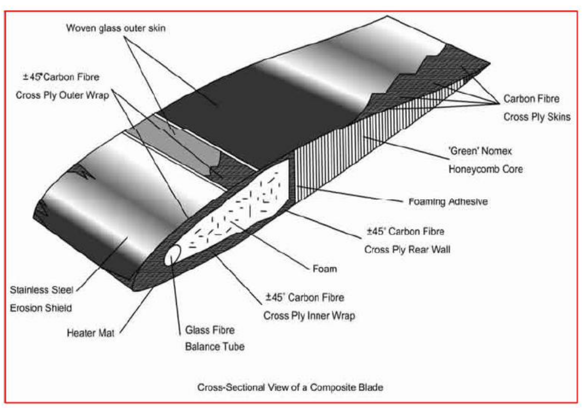


Fig .3 Helicopter Blade

III. COMPOSITE MATERIALS

A composite material can be defined as a macroscopic combination of two or more distinct materials, having a recognizable interface between them. However, because composites are usually used for their structural properties, the definition can be restricted to include only those materials that contain reinforcement (such as fibres or particles) supported by a binder (matrix) material.

Composite materials generally consist of a bulk material, called matrix, and a filler of some type, viz., fibres, whiskers, or particles. Composite materials are usually divided into three broad groups identified by the matrix material: viz., polymer matrix composite (PMC), metal matrix composite (MMC) and ceramic matrix composite (CMC). These composite can have fibres, whiskers, or particulates in a matrix forming a single thin lamina, or a laminated composite consisting of layers of various laminae. The fibres, whiskers, or particulates are usually the material that carries the major stresses and loads, while the matrix holds them together to facilitate the transfer of stresses to the fibres/whiskers/particulates.

It can be defined as a heterogeneous solid structural material consisting of two or more distinct components that are mechanically or metallurgically bonded together such as wire or filament of high melting substance embedded in a metal or non metal matrix.

IV. CLASSIFICATION OF COMPOSITES

Composite materials are classified based on the matrix materials as well as the reinforcements as follows.

A) Based on the Matrix material
B) Based on the Reinforcement

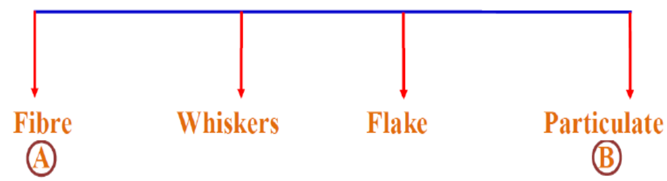


Fig 4.1 Classification Of Composites

- Fibre - a filament with L/D very high (of the order 1000)
- A composite with fibre-reinforcement is called Fibrous Composite
- Particle – non fibrous with no long dimension
- A composite with particles as reinforcement is called Particulate Composite
- Whiskers – nearly perfect single crystal fibre
- Short, discontinuous, polygonal cross-section

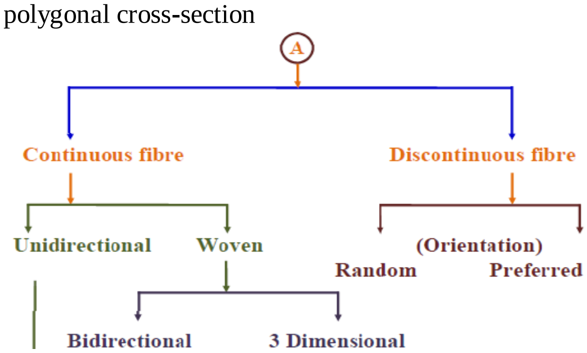


Fig.4.2 Types Of Fibres

Fibre as reinforcement:

a). As the diameter decreases the inherent flaws in the material also decreases and the strength increases.

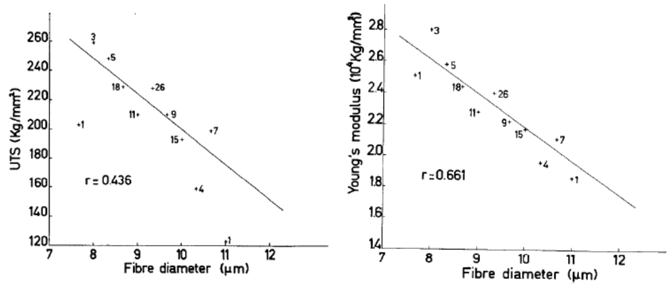


Fig 2.3Strength vs Fibre diameter graph

b). For better load transfer from matrix to fibre composites require larger surface area of the fibre matrix interface.

Fibre matrix interface area: A = N π D L

(N – No. of fibres, D – fibre diameter, L – length of fibres)

Replace D by d (smaller diameter fibres)

For same Fibre Volume Fraction*: n = N(D/d)2

New fibre matrix interface area: A= N π D2 L/d = 4 * Volume of fibres / d

Thus, for a given fibre volume fraction, the area of the fibre-matrix interface is inversely proportional to the diameter of the fibre.

* Fibre Volume Fraction (Vf) = Volume of Fibres/Volume of Composite

Matrix Volume Fraction (Vm) = Volume of matrix/Volume of composite

Vf + Vm = 1

c). The fibres should be flexible/pliant so that they can be bend easily without breaking. For example, woven fibre composites needs flexible fibres.

Flexibility is defined as inverse of bending stiffness.

Consider a fibre as beam under pure bending, then

EI – Bending stiffness or Flexural rigidity

Flexibility α 1/EI

Where, I = π d4/64

Flexibility α 1/Ed4

Thus, flexibility of a fibre is inversely proportional to 4th power of the fibrediameter.

Types of fibres:

- Advanced Fibres:

Fibres possessing high specific stiffness [E/ρ] and specific strength [σ/ρ])

a) Glass
b) Carbon
c) Organic
d) Ceramic

- Natural Fibres:

a) Animal fibres

i) Silk ii)Wool iii) Spider silk
iv) Sinew v) Camel hair

b) Vegetable fibres

i) Cotton ii) Jute iii) Bamboo
iv) Sisal v) Maze vi) Hemp
vii) Sugarcane viii) Banana ix) Ramie
x) Kapok xi) Coir xii) Abaca
xii) Kenaf xiv) Flax xv) Raffia palm…………..

c) Mineral fibres

i) Asbestos ii) Basalt

iii) Mineral wool iv) Glass wool

In the figure 4.3 given below the elements with which the fibres are made is shown by the rounded up oval. They are used for advanced fibre reinforcements for the composites.

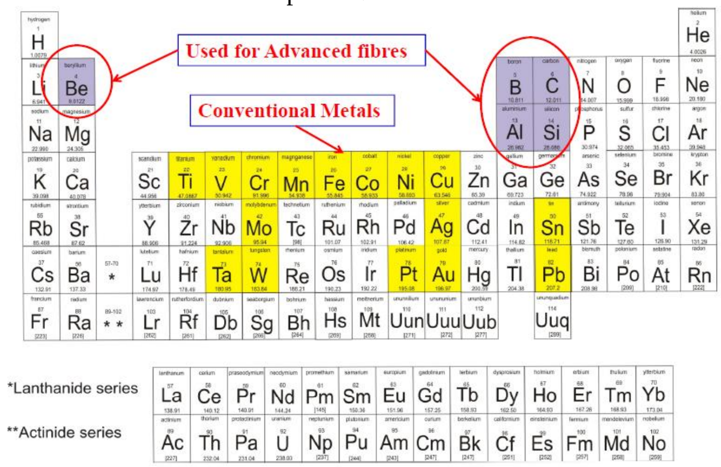


Fig 4.3 Periodic Table

Properties of fibre and matrix materials:

Properties of fibre and matrix materials are given in below table 2.1

Material	Density g/cm	Modulus Gpa	Poissons Ratio	Strength Mpa	Specific Stiffness	Specific Strength	Thermal Expansion Coefficient
				METALS			
Steel	7.8	200	0.32	1724	1.0	1.2	12.8
Aluminium	2.7	69	0.33	483	1.0	1.0	23.4
Titanium	4.5	91	0.36	758	0.95	1.2	8.8
				FIBERS			
AS4	1.80	235	0.20	3599	5.1	11.1	-0.8
T300	1.76	231	0.20	3655	5.1	11.5	-0.5
P100S	2.15	724	0.20	2199	13.2	5.5	-1.4
IM8	1.8	310	0.20	5171	6.7	16.1	---
Boron	2.6	385	0.21	3799	5.8	8.3	8.3
Kevlar 49	1.44	124	0.34	3620	3.6	13.9	-2.0

SCS-6	3.3	400	0.25	3496	5.1	6.1	5.0
Nicalon	2.55	180	0.25	2000	2.8	4.4	4.0
Alumina	3.95	379	0.25	1585	3.7	1.9	7.5
S-2 Glass	2.46	86.8	0.23	4585	1.4	10.4	1.6
E-Glass	2.58	69	0.22	3450	1.05	7.5	5.4
Sapphire	3.97	435	0.28	3600	4.3	5.1	8.8
MATRIX MATERIALS							
Epoxy	1.38	4.6	0.36	58.6	0.08	0.4	63
Polyimide	1.46	3.5	0.35	103	0.03	0.4	36
Copper	8.9	117	0.33	400	0.5	0.3	17
Si-Carbide	3.2	400	0.25	310	4.9	0.5	4.8

Selection of materials
Since E-Glass V-9 is a conventional fibre for structural applications at high temperatures, it is also the insulating and since it is cheap in cost and easily available which is being used for many aerospace applications, hence it is selected.

Though the rayon carbon is very expensive, it is amorphous material for ablative purpose and is having vast applications in aerospace industry, hence it is selected.

Phenolic resin is the conventional matrix material which is used for aerospace applications to with stand high temperatures.

The properties and specifications of these materials are as follows.

Acceptance test procedure

4.1.2.1visual inspection:
(i) APPEARANCE:
The fabric shall be reasonably free from yarn defects and defects of weaving. holes, smashes, abrasions, stains, oil and grease spots or other contamination's, torn selvedges, excessive ends out, missing picks and other permanent distortions.

(ii) HOLES AND TEARS:
Fabric shall be inspected (100%) and shall not have more than one hole and one torn selvedge per one metre of fabric length. Holes 25mm in maximum dimension or less shall not be cause for rejection unless the holes are of a greater frequency of 10 per roll. The distance between a hole and a tear should not be less than 50 mm. Tears larger than 75 mm in any dimension shall be removed. Abrasions are defined visually as local areas of gross broken filaments. Abrasions marks less than 25 mm in any dimension shall not be cause for rejection unless there are more than 3 in any one meter.

(iii) LENGTH AND WIDTH:
The length and width of the fabric shall be inspected during visual inspection and the roll length shall not be less than 40 meters nor more than 200 meters.

(iv) ANTECEDENTS:
Antecedents of each roll of material shall be identified with an unambiguous number and relevant information like Roll No., Date of manufacturing and Date of expiry in indelible ink or with non-removable stickers. It must be ensured that test reports from the supply agency has been provided.

V. FABRICATION OF FIBROUS COMPOSITES

There are more than 50 processes depending upon fibre and matrix material type and nature. Some of them are illustrated below.

- Wet/Hand Lay-Up
- Spray Lay-Up
- Vacuum Bagging
- Filament Winding
- Pultrusion
- Resin Transfer Molding (RTM)
- Pre-pregg
- Resin Film Infussion

5.1.1 WET/HAND LAY-UP

Description:
Resins are impregnated by hand into fibres which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions.

Main Advantages:

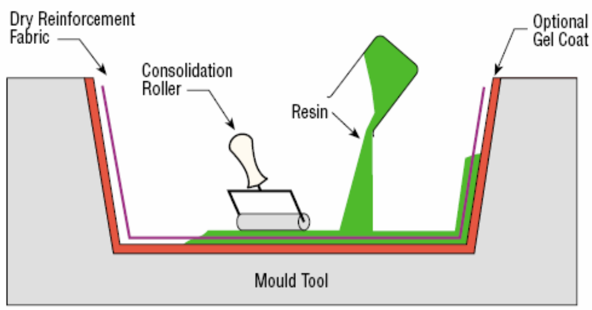
- Widely used for many years.
- Simple principles to teach.
- Low cost tooling, if room-temperature cure resins are used.
- Wide choice of suppliers and material types.
- Higher fibre contents, and longer fibres than with spray lay-up

Main Disadvantages:

- Resin mixing, laminate resin contents, and laminate quality are very dependent on the skills of laminators. Low resin content laminates cannot usually be achieved without the incorporation of excessive quantities of voids.
- Health and safety considerations of resins. The lower molecular weights of hand lay-up resins generally means that they have the potential to be more harmful than higher molecular weight products. The lower viscosity of the resins also means that they have an increased tendency to penetrate clothing etc.
- Limiting airborne styrene concentrations to legislated levels from polyesters and vinylesters is becoming increasingly hard without expensive extraction systems.
- Resins need to be low in viscosity to be workable by hand. This generally compromises their mechanical/thermal properties due to the need for high diluent/styrene levels.

Typical Applications:

Standard wind-turbine blades, production boats, architectural mouldings



VI. SELECTION OF THE FABRICATION PROCESS:

Several factors should be considered before selecting the manufacturing process for a particular part;

- User requirements
- Performance requirements
- Total production volume
- Production rate
- Cost of production
- Size of the production
- Surface finish of the final product
- Geometry of the product
- Material

These are important for all manufacturing processes, and even more so for composite materials Ideally, structural design of the product, and design of the required manufacturing process should be completed using a concurrent approach.

Table-4.1 Selection of manufacturing process

PROCESS	PRODUCTION SPEED	COST	STRENGTH	SIZE
Filament winding	Slow to fast	Low to high	High	Small to large
Pultrusion	Fast	Low to medium	High	No restriction on length
Wet lay up	Slow	Medium	Medium to high	Medium to large
Spray up	Medium to fast	Low	Low	Small to medium
Rtm	Medium	Low to medium	Medium	Small to medium
Srim	Fast	Low	Medium	Small to medium
Compression molding	Fast	Medium	Medium	Small to medium
Stamping	Fast	Low	Medium	Medium
Injection moulding	Fast	Low	Low to medium	Small
Roll wrapping	Medium to fast	Low to medium	High	Small to medium

VII. EXPERIMENTAL WORK

In this project the matrix is conventional phenolic resin and it is modified with Di-amine and ether. By this modification it is observed that when phenolic resin is modified with Di- amine the gel time is increased. And point of trouble is decreased considerably. Similar changes are observed in the properties of the resin by modifying with ether.

In this experimental work the following types of laminates were made:
a) E-Glass (V-9)/Phenolic composite
b) E-Glass (V-9)/Di-amine modified phenolic composite
c) E-Glass (V-9)/ether modified phenolic composite
d) Rayon carbon/ether modified Phenolic composite
e) Rayon carbon/Di-amine modified Phenolic composite

VIII. NON DESTRUCTIVE TESTS

NDT is used to detect defects and as a check either in new items or in items already in service, as maintenance checks. In both cases the items is not damaged in any way by the test procedure. The main aim is to detect poor compaction leading to resin-rich areas or low fibre loading, bad surface appearance or internal defect such as:

a) Lack of reinforcement:
b) Porosity:
c) Poor fibre- matrix bonding (delamination)
d) Cracks of all sizes:
e) Failure of the adhesive bond between components
f) Inclusions

Note that the notion of defect or discontinuity in a composite material is enhanced since these materials are characterized by their heterogeneous nature.
Any defect that is detected must be determined:

a) In area or volume
b) By its location within the structure in relation to the laryers of reinforcement
c) By its relation to the mechanical stresses to which the material may be subjected.

Non Destructive Tests on Laminates:

a) Ultrasonics
b) X-ray, radiography;

Ultrasonic tests (US):
Low- frequency ultrasonic (0.2 to 15MHz) can propagate through composites. The anisotropic, heterogeneous nature of the material causes alteration and dispersion of the beam. From a theoretical point of view, propagation is a complex phenomenon because of the two- phase nature of the system (fibre and resin). Structural defect interfere with the propagation of US and partially reflect the sound waves. Hence two methods have been develop based on reflection and transmission of the signal. At best lamination defects measuring 0.2mm can be detected. The presence of voids reduces the transmission of US, and the method used can be used to quantify void content. The transmission speed of US increases with increasing fibre loading and the method can be used to determine the fibre loading of a unidirectional composite. The US method is complementary to X-ray or IR thermography, and is suitable for the detection of internal delamination.

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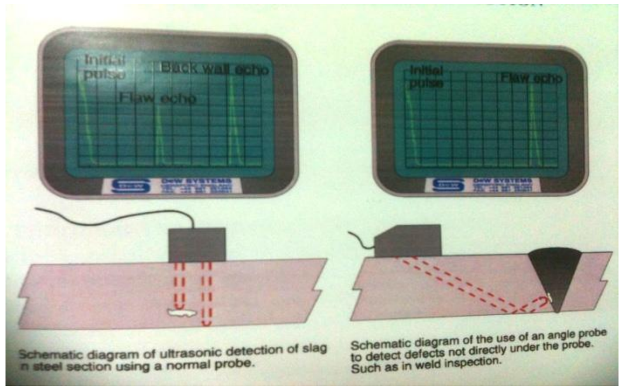


Fig. Illustration of ultrasonic flaw detection

Radiography-X and Gamma ray tests:
This technique is suitable for the detection of internal defects in ferrous and non ferrous metals and other materials.

X-rays, generated electrical, and gamma rays emitted from radio-active isotopes, are penetrating radiation which is differentially observed by the material through which it passes the greater the thickness, the greater the absorption. Furthermore, the denser the material has the greater the absorption. X and gamma rays also have the property, like light, of partially converting silver halide crystals in a photographic film to metallic silver, in proportion to the intensity of the radiation reaching the film, and therefore forming a latent image. This can be developed and fixed in a similar way to normal photographic film.

Material with internal voids is tested by placing the subject between the sources of radiation and the film. The principles are the same for both X and Gamma radiography.

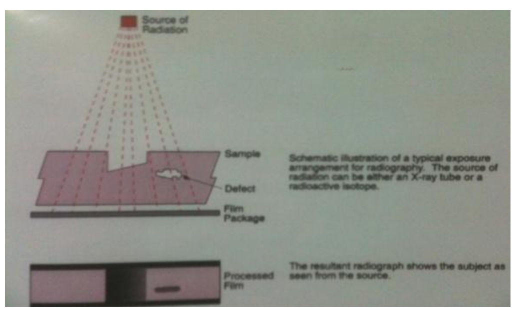


Fig . An illustration of radiography test

IX. RESULTS AND DISCUSSION

The following are the test results of composite laminates made for this project work. These test results are obtained by destructive testing process, the test results are given in below tables for comparison. Flexural load and inter laminar shear strength graphs are given in below figures.

Table 8.1 Test results comparison

S.NO.	Material	Density (gm/cc)	Resin content (% of wt)	Fiber content (% of wt)	Vf (% of Vol.)
1	E-GlassV-9/Ph(DA)	1.92	19.16	80.84	61.1
2	E-GlassV-9/Ph(E)	1.767	19.1	80.9	56.27
3	Rayon/Ph(DA)	1.3	28.49	71.51	53.12
4	Rayon/Ph(E)	1.29	29.13	70.87	52.24

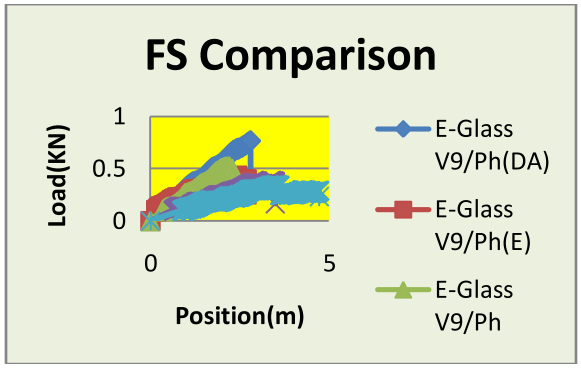
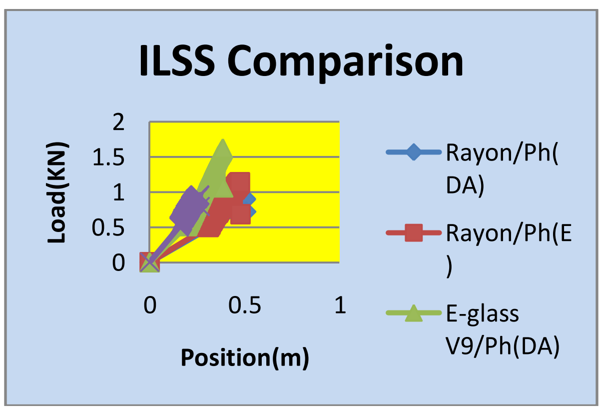


Table 8.2Test results comparison

S.NO.	Material	ILSS (Mpa)	F.S (Mpa)	Young's Modulus E (Gpa)	Impact Energy I (KJ/sq.m)	Erosion rate (m/s)
1	E-GlassV-9/Ph(DA)	29.53	462.78	44.01	265.35	0.000374
2	E-GlassV-9/Ph(E)	14.45	220.92	26.74	121.83	0.000436
3	Rayon/Ph(DA)	16.32	205.69	23.43	48.74	0.000126
4	Rayon/Ph(E)	13.13	106.64	19.9	61.54	0.000133
5	E-GlassV-9/Ph	32.79	365.72	30.54	223.51	0.000294



X. RESULTS AND DISCUSSION

It is observed from the tested data E-glass V-9/phenolic conventional composite compared with modified phenolic E-glass V-9 composite, the Flexural strength and Impact strength of the Di-amine modified phenolic composite gave higher values. Whereas ether modified phenolic composite with E-glass V-9 gave poor values indicates the compatibility problem of the matrix to reinforcements. Where ever Impact application is more one can go for Di-amine modified phenolic composite. The density variation in the composite is because of the compatibility of the matrix to reinforcements. Consolidation of composite during fabrication plays a major role on properties of the material. It is obvious from the test data better compaction has high density and will have low porosity. Composite density is calculated theoretically may not always be same with the experimentally determined value. This is due to poor compaction and voids present in the composite. A good composite for better properties should have higher density. Composite with modified Di-amine is having is having good compatibility so is its density. Even though E-glass V-9 is having high density its composites are used as insulating applications particularly where large amounts of heat to be absorbed or deflected.

Rayon carbon/phenolic composite erosion rate is low due to amorphous nature of the material. Aerospace applications such as heat shields, nose cones and nozzles where ablative property is important these rayon/phenolics are used because they absorb large quantity of heat with the sacrificial loss of minimum material. A Known defect which was identified with NDT tests such as Ultrasonic test and Radiography test. Ultra sonic through transmission loss observed at particular zone gave the resemblance of introduced defect. This is studied by Radiography which shown the defect by the difference of the material densities. Both these NDT tests are complimentary to each other. Defect in the composite leads to bad performance so composite products for aerospace applications should meet all quality control checks before being inducted into the machine.

XI. CONCLUSION

Applications of fibre reinforced polymer matrix composites for aerospace structures have been studied. Different fibre reinforced polymer matrix composite laminates were fabricated by Autoclave vacuum bagging process. Specimens were cut by diamond edge cutter as per ASTM standards and their physical, mechanical and thermal properties were evaluated by destructive and non-destructive techniques. Conventional phenolic resin and modified phenolic resin were studied with E-glass V-9 and Rayon carbon fabrics. Phenolic resin is used as a matrix material because of its excellent thermal properties. Phenolic resin modified by Di-amine exhibited high flexural and impact strength. Composites made of E-glass V-9 and Rayon carbon replaced many metallic components because of their low density and high heat capacity. For high temperature applications in aerospace carbon phenolics are used as ablative materials because of their low erosion. E-glass composites because of their insulating character utilized for heat resistant composite. Quality control checks play crucial role in the fabrication of aerospace components. Defect free components ensure better performance of the mission.

In this project work we dealt with fabrication and testing of aerospace composite materials. Composite laminate properties were evaluated both by destructive and non-destructive techniques. Fibre volume fraction, density, non-destructive evaluations are essential for the acceptance of any composite product for its intended end use.

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