

## Thermo-Mechanical Analysis for Characterization of Dynamic Properties of FRP Composite Materials

Dr K Dileep Kumar<sup>1</sup>, D Shakeena<sup>2</sup>

<sup>1</sup>Assistant Professor, JNT University, Andhra Pradesh, INDIA

<sup>2</sup>PhD Scholar, JNT University, Andhra Pradesh, INDIA,

### Abstract:

The research study is designed to assess the delamination factor and develop strategies to mitigate or minimize delamination. When addressing the machining of composite materials, abrasive water jet machining emerges as a superior choice compared to conventional and non-conventional machining methods. Composite materials are being increasingly used in various applications like space, aircraft, marine, architectural and automobile sector because of their superior physical and mechanical properties. This work is to evaluate the mechanical properties of carbon kelvar, basalt and glass fabric reinforced composites will be fabricated using hand layup and vacuum bagging technique. In former research work TMA is widely used, thermo-mechanical analysis (TMA), applies static force to a material and watches the material change temperature or time varies. Its reports dimensional changes. Abrasive water jet machining provides some advantages over conventional and non-conventional machining process for cutting the composite materials like no thermal effect, high machining versatility and small cutting forces. In the present research work, the effect of abrasive jet machining parameters such as traverse speed, abrasive flow rate, standoff distance on delamination's of glass fiber reinforced epoxy composite is investigated. It is found that optimum water pressure together with small standoff distance between the nozzle and work piece may be used whereas, the traverse speed should be moderate in order to reduce delamination in composites.

**Index Terms:** Thermo-mechanical analysis, Glass Transition Temperature, FRP

### INTRODUCTION

In present scenario Cutting composite materials is one application where abrasive water jet machining is noted for its superior machining qualities. Using a high-pressure stream of water combined with abrasive particles, abrasive water jet machining (AWJM) is a type of machining. Due to its capacity to transport abrasive particles and dissolve the materials it contacts, the water jet, which is driven at extremely high speeds, serves as a formidable cutting tool. Optimum machining characteristics this suggests that using abrasive water jet machining for machining tasks is very effective and efficient. Precision, speed, and adaptability are just a few of the areas where it shines. The machining process involving cutting tools has the potential to damage

the surface of the work material [1]. The primary challenge arises when machining composites that consist of high-strength carbon fiber and a low-strength thermoplastic matrix,

often resulting in less-than-ideal surface finishes. Thermo-mechanical analysis is just one of several techniques used to characterize the behavior of composite materials[2]. Additional methods, such as differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA), can provide complementary information on composite material properties. Researchers frequently employ a combination of these techniques to gain a comprehensive understanding of material behavior.

Delamination, the separation of layers within a composite structure, typically occurs along the plane of the layers or plies during machining operations like drilling, milling, or cutting, and is considered a defect. Reference [3] introduces digital image analysis as an innovative approach for assessing the extent of damage and calculating the delamination factor, showcasing its effectiveness in estimating the damage incurred during the drilling of carbon fiber-reinforced plastics. The presence of delamination can significantly compromise the

performance and structural integrity of composite components. The utilization of Abrasive Water Jet (AWJ) technology in manufacturing processes for space, aircraft, boat, and automotive industries has garnered attention due to its specific advantages in machining composite materials. However, AWJ cutting of composite laminates presents several challenges, including the absence of readily available databases for composite cutting parameters from machine manufacturers research contributes valuable insights into optimizing AWJ machining for composite materials and underscores the importance of material-specific parameter adaptation [4]-[5], [6] In the study, AWJM was utilized to enhance the surface roughness (Ra) of epoxy composites bonded with glass fiber. In the experimental research, analysis of variance (ANOVA) and Taguchi's approach were also applied. Significant control factors were identified as abrasive materials, hydraulic pressure, standoff distance, and traverse rate. Attention has also been paid to the impacts of glass fiber morphologies and laminate thickness as noise generators. Predictive mathematical approach based on piecewise linear regression analysis proved effective in estimating Ra for glass/epoxy laminates. Furthermore, validation experiments demonstrated the actual implementation of the improved AWJM parameters, emphasizing their potential to improve the machining of glass fiber-reinforced epoxy composites.

After conducting a thorough review of the existing literature pertaining to conventional fiber composites, it becomes evident that extensive research has been conducted on traditional fiber-reinforced polymer composites. However, there is a noticeable absence of studies focusing on the Thermo-Mechanical analysis of these composites. This observation highlights the opportunity for the current research, which aims to investigate the impact of epoxy treatment and curing (using LY 556 + AR 951) on carbon, Kevlar, Glass, and basalt fibers, specifically concerning their dynamic mechanical performance. The study employs Thermo-Mechanical Analysis (TMA) as a technique, where the reference material experiences penetration upon melting, resulting

in a significant deformation signal. The alteration in the shape of the TMA curve serves as a temperature calibration reference point. Furthermore, abrasive water jet machining is selected as the cutting method for composite materials due to its distinct advantages over conventional and non-conventional machining processes. These advantages include the absence of thermal effects, high machining adaptability, and minimal cutting forces.

## EXPERIMENTAL INVESTIGATION

### A. Mechanical Testing of Composites

The evaluation of composite constructions for properties like strength and stiffness is time-consuming but necessary. Simple designs like flat coupons can accelerate this process. Data collected from these assessments can be associated with varying degrees of simplicity and accuracy. Several tests, including tensile, flexural, and hardness tests, are essential for assessing composite qualities.

*Tensile Test:* ASTM D3039 is used to measure the in-plane tensile characteristics of composite materials made of polymer matrix and high-modulus fibers. This test provides crucial values like transition strain, Poisson's ratio, and ultimate tensile strength. These values are critical for designing structural components and estimating stress based on observable strains.



**Fig 1:** Tensile Testing Machine



Fig 2: Sample Specimens of Tensile Test

*Flexural Test:* The flexural test, conducted as per ASTM D790 standards, measures the force required to bend a material under different loading scenarios. It assesses the material's rigidity under bending. This test is vital, especially for materials whose properties can vary with temperature. Rectangular bars of specific sizes are subjected to three-point bend tests.

*Hardness Test:* The Durometer test assesses the relative hardness of soft materials, often plastics or rubber. It measures how deeply an indenter penetrates the material under defined time and force conditions. Hardness values are used for quality control and material specifications. The Shore D hardness test is a specific example.

*Test Methodology:* In the hardness test, a sample is placed on a stable surface, and an indenter is pressed into it whereas maintaining parallel alignment with the surface. The hardness is measured after the indenter has made strong contact with the specimen for a specified time, typically 6.4 mm (1/2 inch).

These tests are crucial for characterizing composite materials, ensuring quality control, and guiding material selection and design in various industries.

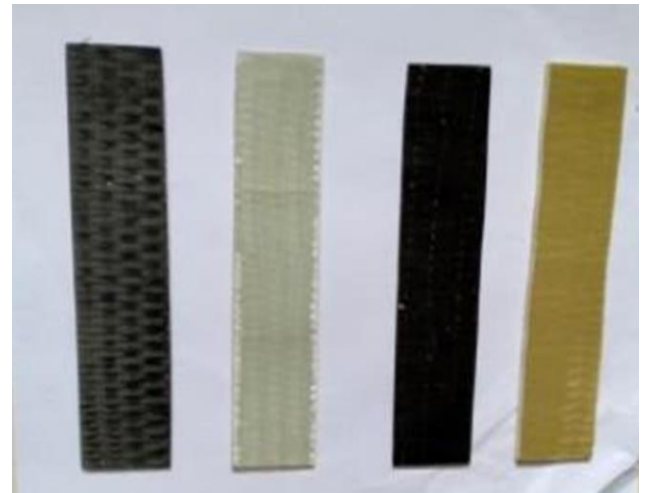


Fig 3: Before Tabs

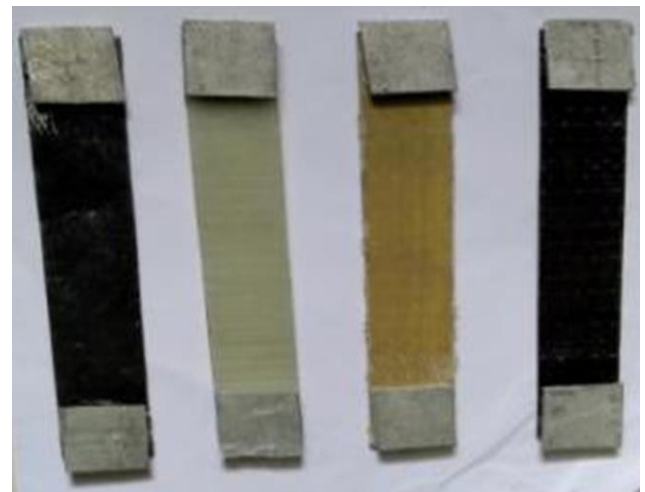


Fig 4: After Tabs

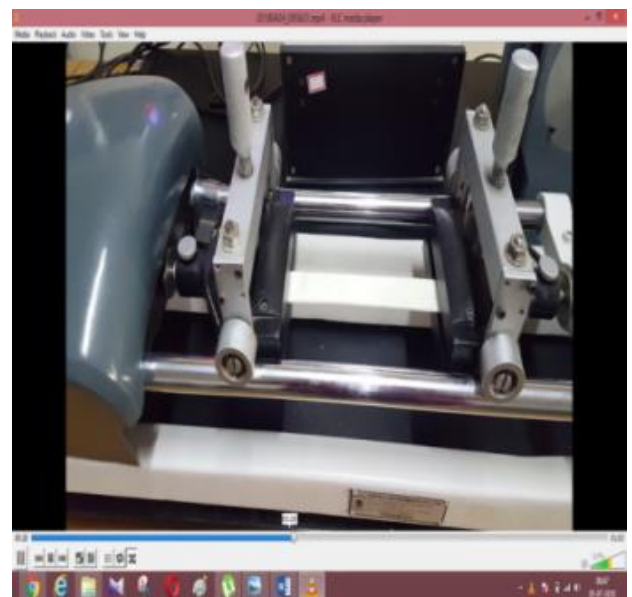


Fig 5: Testing Machine and Specimens of Tensile Test

## MODEL CALCULATIONS

In the field of materials science, the rule of mixtures serves as a weighted mean for predicting various properties of composite materials comprising continuous and unidirectional fibers. This empirical method allows for the estimation of properties in mixtures composed of two or more distinct materials with varying characteristics. The rule of mixtures primarily considers the proportion of each component in the mixture and the individual properties (such as Young's Modulus) of each component. Consequently, the property of the mixture changes based on the quantities of its components. However, it's widely recognized that additional factors, including size, shape, distribution, orientation, and interphase interactions, significantly influence the mechanical and other properties of composites. Predicting the stiffness of composites can be achieved through a micro-mechanics approach, commonly referred to as the rule of mixtures.

### B. Assumption

- Fibers are uniformly distributed throughout the matrix.
- Perfect bonding between the fibers and the fiber.
- Matrix is free of voids.
- Applied loads are either parallel or normal to the fiber direction.
- Lamina is initially in a stress-free state (no residual stresses).
- Fiber and matrix behave as linearly elastic materials.

Certain properties in multi-component materials system, including composites, obey the "Rule-of-Matrix"(ROM). Properties that obey this rule can be calculated as the sum of value of the property of each constitute multiplied by its respective volume fraction or weight fraction in the mixture.

### C. Sample Calculations (Volume Fraction Calculations):

Consider a composite consisting of fiber and matrix and take the following are defined as

$$W_c = W_f + W_m$$

Where,  $W_c$  = Weight of Composite material

$W_f$  = Weight of fiber

$W_m$  = Weight of matrix

The weight fractions of the fiber and matrix are defined as

$$w_f = W_f / W_c \text{ and } w_m = W_m / W_c$$

Weight fraction of matrix  $w_m$  =

Note that the sum of mass fractions is

$$w_f + w_m = 1$$

Fiber Volume Fraction

$V_f$  = Volume of Fiber / Volume of Composite

Matrix Volume Fraction

$V_m$  = Volume of Matrix / Volume of composite

Such that sum of volume fraction is

Matrix Volume Fraction + Fiber Volume Fraction = 100%

Note that the Sum of Volume Fractions is = 1

Where,

$V_f$  = Fiber Volume Fraction

$V_m$  = Matrix Volume Fraction

Matrix Volume Fraction = 1 - Fiber Volume Fraction

Weight Fractions of Fiber and Matrix used for fabrication of four different composite laminates with dimensions 420X500 mm<sup>2</sup>.

## II. MNUFATURING DETAILS

### A. Manufacturing Details of Composites

Based on the above mathematical equations. The calculations are going to be done as follows for Basalt Bi-directional 360 GSM Composite

Density of basalt Fiber = 2 g/cc

Weight of fiber = 544gms

Volume of Mold v = 525.0 cm<sup>3</sup>

Density ρ = Mass

(w)/Volume (v)

Volume of Fiber  $v_f$  = weight (or) mass of fiber / density of fiber

$v_m$  = 525.0 cm<sup>3</sup> - 272 cm<sup>3</sup>

= 253 cm<sup>3</sup>

Fiber Volume Fraction = 272 / 525.0

= 0.518 or 51.8%

Matrix Volume Fraction = 1 - 0.518

= 0.481 or 48.1%

**B. Carbon unidirectional fiber**

By referring the journals, I took the reference value as 40:60. In the previous statement, 60 indicates the matrix percentage and 40 indicates fiber percentage. LY556 + AR 951 should be used in ratio of 10: 1

Number of layers = 4  
Each layer weight = 19.75gm  
Total fiber weight ( $w_f$ ) = 79gm  
Epoxy weight ( $w_m$ ) = 120gm  
Total resin (epoxy + hardener) = 120 + 12 = 132gm

$$w_m = \frac{60 / \frac{120 \times 79}{40}}{120}$$

$$w_m = \frac{60 \times 79}{40}$$

$$w_m = 118.5 = 118\text{gm}$$

**C. Kevlar unidirectional fiber**

Number of layers = 4  
Each layer weight = 27.5gm  
Total fiber weight ( $w_f$ ) = 110gm  
Epoxy weight ( $w_m$ ) = 200gm  
Total resin (epoxy + hardener) = 200 + 20 = 220gm

$$w_m = \frac{60 / \frac{200 \times 110}{40}}{200}$$

$$w_m = \frac{60 \times 110}{40}$$

$$w_m = 165 \text{ gm}$$

**D. Glass unidirectional fiber:**

Number of layers = 4  
Each layer weight = 37.5gm  
Total fiber weight ( $w_f$ ) = 150gm  
Epoxy weight ( $w_m$ ) = 225gm  
Total resin (epoxy + hardener) = 225+22.5 = 247.5gm

$$w_m = \frac{60 / \frac{225 \times 150}{40}}{225}$$

$$w_m = \frac{60 \times 225}{40}$$

$$w_m = 337.5\text{gm}$$

**E. Basalt unidirectional fiber:**

Number of layers = 4  
Each layer weight = 26.5gm  
Total fiber weight ( $w_f$ ) = 105gm  
Epoxy weight ( $w_m$ ) = 160gm  
Total resin (epoxy + hardener) = 160+16 = 176gm

$$w_m = \frac{60 / \frac{160 \times 105}{40}}{160}$$

$$w_m = \frac{60 \times 105}{40}$$

$$w_m = 157.5 = 156\text{gm}$$

**III. RESULTS AND DISCUSSION**

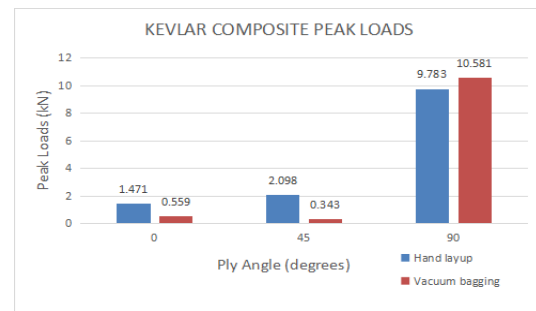
Below, the data displays the results of the experimental or mechanical testing

**A. Tensile test**

The tensile strength for carbon, Kevlar, basalt and glass fibre reinforced plastic. It is the effect of ply orientation, matrix incorporation led to an increase in tensile strength in all fibre composites.

**Table II:** Peak Loads of Tensile Test For Kevlar Composites

Ply angle \ Loads	Peak loads	
	Hand Layup	Vacuum bagging
0	1.471	0.559
45	2.098	0.343
90	9.782	10.581



**Fig 8:** Kelvar Composites Peak Load

**Table III:** Peak Loads of Tensile Test For E Glass Composites

Ply angle \ Loads	Peak loads	
	Hand Layup	Vacuum bagging
0	0.588	0.71
45	2.216	0.99
90	5.364	10.073

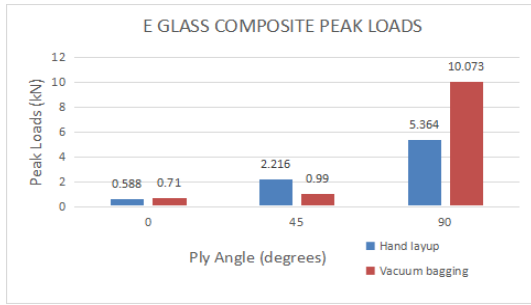


Fig 9: E Glass Composites Peak Load

Table IV: Peak Loads of Tensile Test For Basalt Composites

Ply angle\Loads	Peak loads	
	Hand Layup	Vacuum bagging
0	0.892	0.304
45	1.5	0.676
90	7.25	7.92

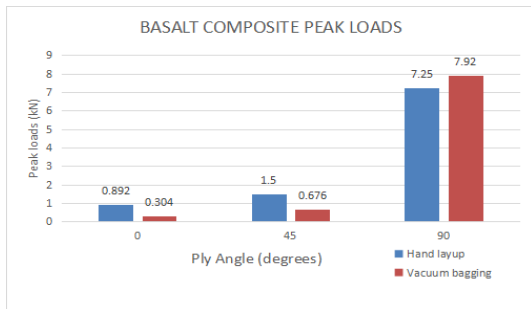


Fig 10: Basalt composite peak load

Table V: Tensile Strengths of Carbon Composite

Ply angle\Loads	Ultimate Tensile Strength	
	Hand Layup	Vacuum bagging
0	15.3	10
45	32.7	15.2
90	55.4	158.7

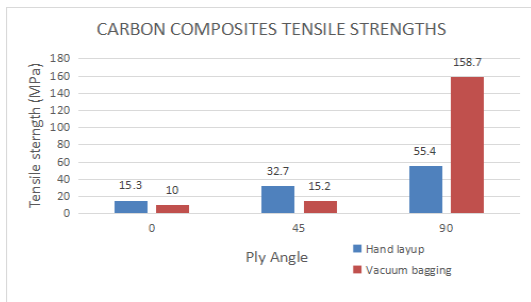


Fig 11: Carbon composites tensile strengths

Table VI: Tensile Strengths of Kevlar Composites

Ply angle\Loads	Ultimate Tensile Strength	
	Hand Layup	Vacuum bagging
0	16.8	9.8
45	25.3	6.1
90	117.8	196

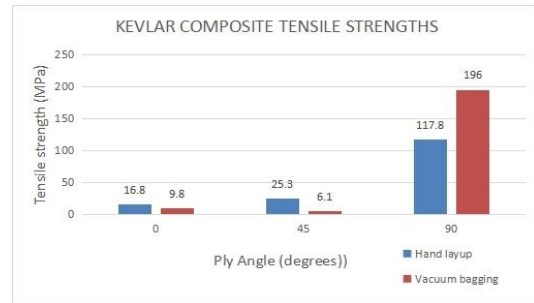


Fig 12: Kelvar composite tensile strengths

Table VII: Tensile Strengths of E Glass Composites

Ply angle\Loads	Ultimate Tensile Strength	
	Hand Layup	Vacuum bagging
0	10.8	12.6
45	33.8	16.6
90	82.1	184.9

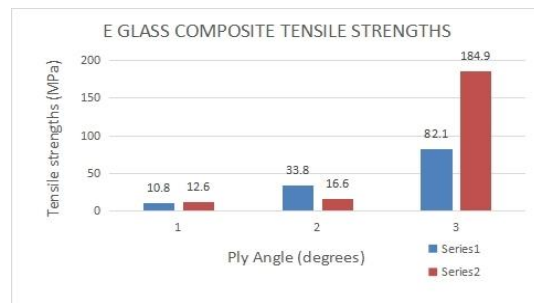
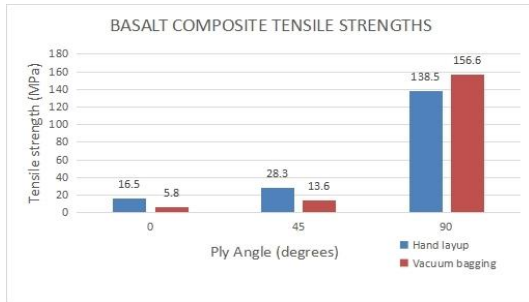


Fig 13: E Glass composite tensile strengths

Table VIII: Tensile Strengths of Basalt Composites

Ply angle\Loads	Ultimate Tensile Strength	
	Hand Layup	Vacuum bagging
0	16.5	5.8
45	28.3	13.6
90	138.5	156.6



**Fig 15:** Graphical Representation of Dimension vs Temperature for Carbon

### B. Thermo-mechanical Analysis (TMA)

Thermo-Mechanical Analysis (TMA) involves the use of thermo-mechanical analyzers (TMAs) to measure various material properties, such as coefficients of thermal expansion (CTE), melting temperatures, glass transition temperatures, thermal deflection, and high-temperature creep or stress relaxation behavior. A notable advantage of the thermo-mechanical analyzer is its ability to determine these material properties using the same test procedure. In a typical TMA Expansion: In expansion measurements, various material properties are determined, including the coefficient of thermal expansion (CTE), glass transition temperature (T<sub>g</sub>), and compression modulus.

A flat-tipped standard expansion probe is gently placed on the sample, and the sample is subjected to a controlled temperature program. The probe's movement records any expansion or contraction of the sample. This method is suitable for most solid samples. The graph below illustrates the relationship between dimensional changes and temperature for a single-layer carbon composite material. As the specimen's temperature increases, it undergoes slight changes. The graph demonstrates how the specimen responds to temperature variations. The glass transition temperature is recorded at 72.03°C, and the alpha value is approximately -1540 μm/m°C. Notably, the alpha value varies with temperature. One of the advantages of

using the expansion probe is its ease in measuring the coefficient of thermal expansion (CTE), denoted as ( $\alpha$ ), through TMA operation, a small sample with parallel and flat top and bottom surfaces is positioned on a quartz stage in close proximity to a thermocouple.

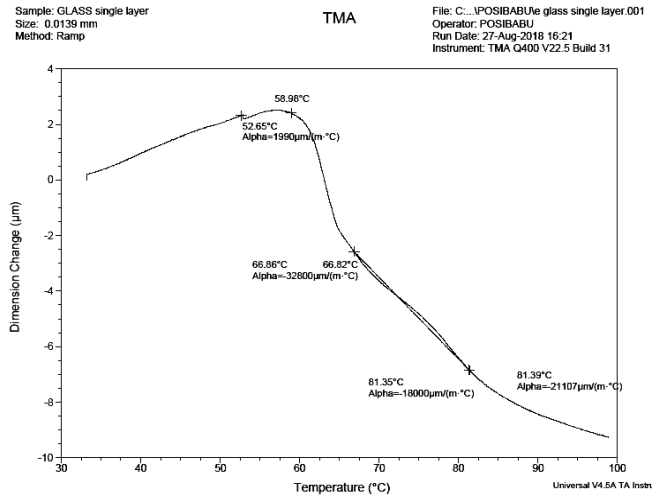
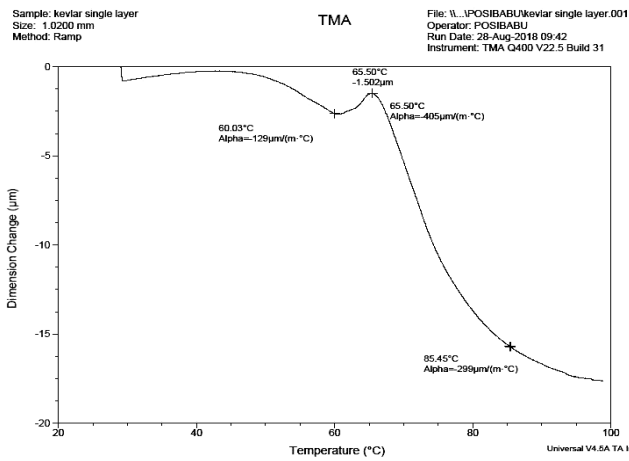
### C. Flexural Test

The Flexure Accessory, compatible with TMA, enables three-point bending studies to evaluate the flexibility and strength of various materials, including composites, plastics, and PC boards. It offers a choice between quartz and low-friction aluminum fixtures, depending on the specific experiment's needs. This mode eliminates clamping effects, representing purely deformative behavior and is primarily used to assess the bending properties of rigid materials like composites and for conducting distortion temperature measurements. Additionally, the Q400EM variant allows for dynamic measurements using a specialized low-friction metallic anvil.

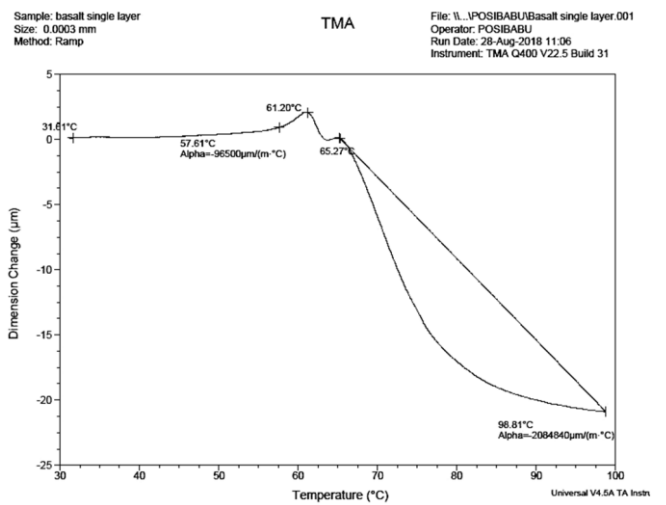
**Table IX:** Values of Hand layup and Vacuum bagging

**Fig 17:** Graphical Representation of Dimension vs Temperature for Kevlar fiber

	CARBON COMPOSITE		KEVLAR COMPOSITE		E GLASS COMPOSITE		BASALT COMPOSITE	
	Hand layup	Vacuum bagging	Hand layup	Vacuum bagging	Hand layup	Vacuum bagging	Hand layup	Vacuum bagging
0	15.3	10	16.8	9.8	10.8	12.6	16.5	5.8
4	32.7	15.2	25.3	6.1	33.8	16.6	28.3	13.6
9	55.4	158.7	117.8	196	82.1	184.9	138.5	156.6



**Fig 16:** Graphical Representation of Dimension vs Temperature for Kevlar fiber



**Fig 18:** Graphical Representation of Dimension vs Temperature for Basalt fiber

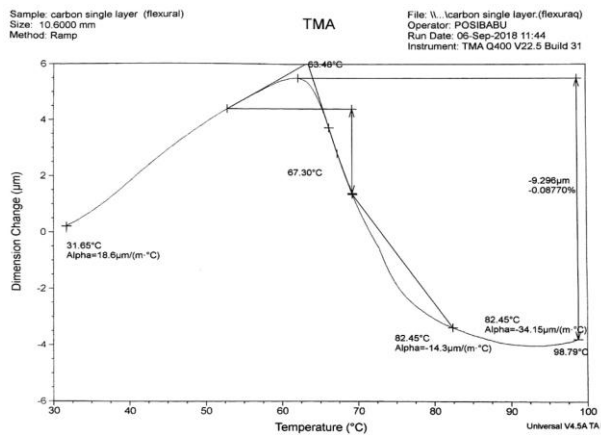


Fig19: Graphical Representation of Dimension vs Temperature for Carbon fiber

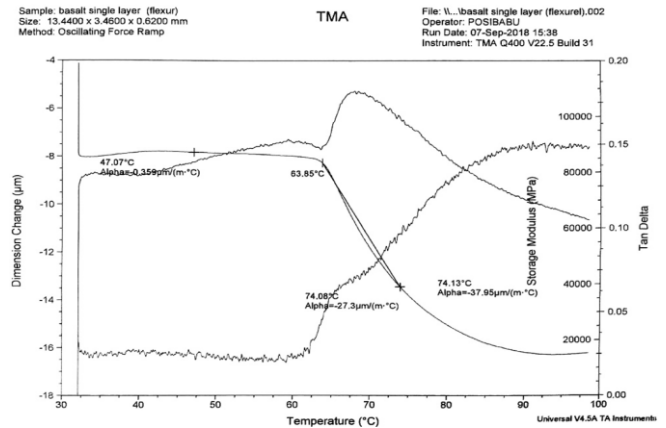


Fig 22: Graphical Representation of Dimension vs Temperature for Basalt

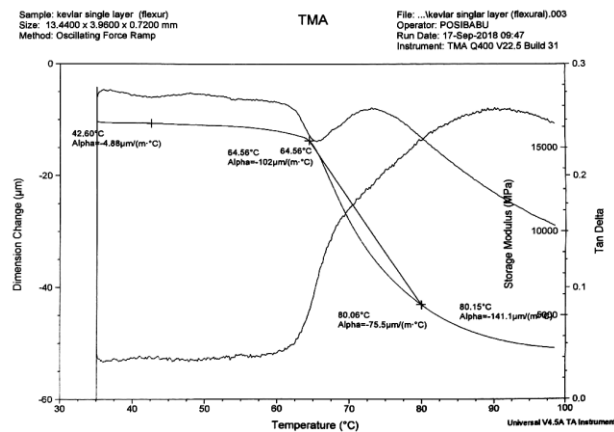


Fig 20: Graphical Representation of Dimension vs Temperature for Kevlar fiber

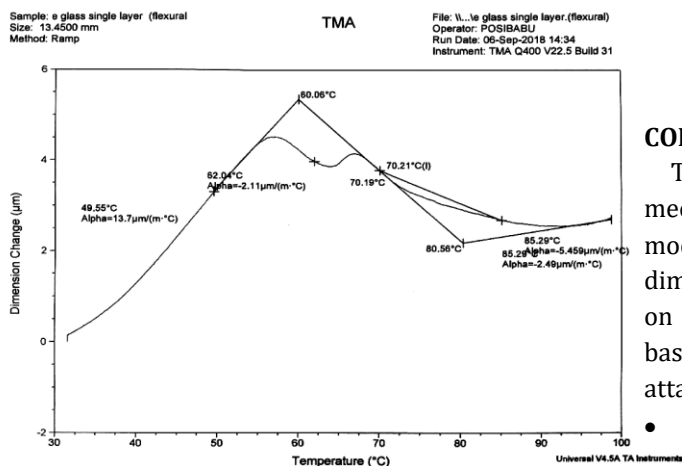


Fig 21: Graphical Representation of Dimension vs Temperature for E-Glass fiber

Table X: Thermal expansion values for composite materials

Composite	CARBON COMPOSITE	KEVLAR COMP OSITE	E GLASS COMP OSITE	BASALT COMP OSITE
Coefficient of Thermal expansion	208000	129	1990	96500

### CONCLUSION

The purpose of this study is to use thermo mechanical analysis to perform flexural storage modulus, flexural modulus, loss factor, and dimensional change temperature measurements on composites comprised of carbon, Kevlar, basalt, and glass fibers. These goals were attained by achieving the following objectives:

- Recognize the Thermo Mechanical Analysis principles and other tests used in this project.
- Use the manual hand layup method to fabricate the carbon/Kevlar epoxy composites.
- To determine what parameters to test with, test carbon fiber reinforced polymer, Kevlar fiber reinforced polymer, glass, and basalt

reinforced polymer using thermo-mechanical analysis (TMA).

- Fabricate plain carbon/epoxy and Kevlar/epoxy, glass/epoxy and basalt/epoxy composites with weight fraction of 40%
- Test the carbon/epoxy composites, Kevlar/epoxy composites with TMA.
- Compare the outcomes of basalt/epoxy composites, carbon/epoxy composites, and Kevlar/epoxy composites.

Free vibration analysis on carbon and Kevlar fiber reinforced epoxy rectangular beams is carried out under the cantilever boundary condition for finding the natural frequencies mode shapes and damping factors.

#### ACKNOWLEDGMENTS

We want to extend our sincere appreciation to everyone who helped this study paper be completed successfully, both individuals and organizations.

First and foremost, we would like to express our profound gratitude to our excellent supervisor, [Dr K. DILEEP KUMAR M.Tech, PhD.], for their important advice, encouragement, and support during this research journey. Their knowledge and perceptive criticism were very helpful in determining the course of this investigation.

We are incredibly appreciative to [Jawaharlal Nehru Technological University Kakinada] for giving us access to the facilities and resources needed to perform this study. Our study was substantially aided by the supportive research atmosphere and availability of cutting-edge technology.

Our profound gratitude goes out to everyone who voluntarily donated their time and energy to take part in this study.

#### REFERENCES

1. Venkatesh Chenrayan a , Chandru Manivannan b , Kiran Shahapurkar a,\* An experimental and empirical assessment of machining damage of hybrid glass-carbon FRP composite during abrasive water jet machining.2022;19:1148 e1161.
2. Ezgi Gürbüz, SavasErdemDevelopment and thermo-mechanical analysis of high-performance hybrid fibre engineered cementitious composites with microencapsulated phase change materials.263 (2020) 120139.
3. J. Paulo Davim a,\* , J. Campos Rubio b , A.M. Abrao b.,A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates Composites Science and Technology 67 (2007) 1939–1945.
4. D.G. Aggelis, N.-M. Barkoula, T.E. Matikas, A.S. Paipetis Acoustic structural health monitoring of composite materials : Damage identification and evaluation in cross ply laminates using acoustic emission and ultrasonics .72 (2012) 1127–1133.
5. Nagaraja Shetty a , S.M. Shahabaz b.,A review on finite element method for machining of composite materials 176 (2017) 790–802.
6. Dharmagna R. Tripathi a , Krupang H. Vachhani a „Experimental investigation on material removal rate during abrasive water jet machining of GFRP composites.
7. M.A. Azmir \* , A.K. Ahsan.,Investigation on glass/epoxy composite surfaces machined by abrasive water jet machining.198 (2008) 122–128.
8. Fermin Bañon \* , Alejandro Sambruno.,Study of the influence of cutting parameters on surface quality in AWJM machining of thermoplastic matrix composites.41 (2019) 233–240.
9. Amir Rabani, Iulian Marinescu, Dragos Axinte.,International Journal of Machine Tools & Manufacture.vol 61 (2012) pp.80–89.
10. M Ramulu ,D Arola..Water jet and abrasive water jet cutting of unidirectional graphite/epoxy composite.
11. D.K. Shanmugam, T. Nguyen, J. Wang \* ., A study of delamination on graphite/epoxy composites in abrasive waterjet machining.Part A 39 (2008) 923–929.
12. J. Schwartzentruber, J.K. Spelt, M. Papini ,Prediction of surface roughness in abrasive waterjet trimming of fiber reinforced polymer composites.
13. H. Hochenga, C.C. Tsaob.,Effects of special drill bits on drilling-induced delamination of composite materials.46 (2006) 1403–1416.

14. T. Lakshmi Narayanan, S. Madhavan, Ankur Sinha., Investigation of Thrust, Torque and Delamination on drilling of Glass fabric/Polypropylene matrix composite.
15. Huan Liu\*, Shuo Liu†, Zheng Liu†, Prognostics of Damage Growth in Composite Materials Using Machine Learning Techniques.
16. Fermin Bañón1 & Alejandro Sambruno1., Study of the surface quality of carbon fiber-reinforced thermoplastic matrix composite (CFRTP) machined by abrasive water jet (AWJM).
17. J.P. Davim \*, Pedro Reis. Study of delamination in drilling carbon fiber reinforced plastics (CFRP) using design experiments. 59 (2003) 481–487.
18. Suresh. Ra\*, Sohit Reddy. Kb , Karthik Shapur., Abrasive Jet Machining for Micro-hole Drilling on Glass and GFRP Composites. 5 (2018) 5757–5761.
19. Sezer Morkavuk, Uğur Köklü, Mehmet Bağcı, Lokman Gemi ., Cryogenic machining of carbon fiber reinforced plastic (CFRP) composites and the effects of cryogenic treatment on tensile properties: A comparative study.
20. A. Pramanik, A.K. Basak, Y. Dong, P.K. Sarker, M.S. Uddin, G. Littlefair, A.R. Dixit, S. Chattopadhyaya Joining of carbon fibre reinforced polymer (CFRP) composites and aluminium alloys-A review.
21. Weigui Zhang a, d, \*, Sai Liu b , Kun Li c , Peijie Li d , High strain-rate behavior and deformation mechanism of a multilayer composite textured AZ31B Mg alloy plate. 749 (2018) 23e39.
22. K. Rajkumara \*, N. A. Thushalb , A. Gnanavelbabuc , P. Sabarinathand., Experimental investigations on the Wire Electrochemical Micro Machining (WECM) integrity of AA6061-TiB2 composite.
23. M. Saleem a , L. Toubal b , R. Zitoune c,† , H. Bougherara a Investigating the effect of machining processes on the mechanical behavior of composite plates with circular holes. 55 (2013) 169–17.
24. V. Lopresto a,† , C. Leone a , I. De Iorio b., Mechanical characterisation of basalt fibre reinforced plastic. 42 (2011) 717–723.
25. V. Manikandan, J.T. Winowlin Jappes † , S.M. Suresh Kumar, P. Amuthakkannan., Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites, 43 (2012) 812–818.