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Dynamic behaviour of a newly developed eco-friendly unidirectional carbon fiber reinforced polymer (cfrp) composite for wing structures in aircrafts

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ABSTRACT

The development of CFRP shave modernized the engineering in aircraft industries in recent years. The major advantage is their strength to weight ratio, which reduces the overall load in the structure. Recent research are on its significance and abilities to be used in critical components i.e., replacing metals. One such is wing structures as they undergo various mechanisms ranging from vibrations to impact. These effects can be reduced if the material possesses good viscoelastic properties. In this work, aunidirectional composite is developed using abio-based polymer i.e., poly(hydroxyurethane) (PHU) as adhesive material instead of typical syntheticcompoundsin order to improve the viscoelastic property of the composite. The advantages of bio-based polymers are: better compound stability, thermal stability, short gel time andgood degradation propertyin addition to being eco-friendly to the environment. These in turn improves the ability of the polymer to absorb plastic energy when work is done i.e., damage mechanism. However, a composite has more than one material in its system and hence, the polymer becomes an intrinsic element. Therefore, the viscoelastic property of the compositesignifies its ability to dissipate the absorbed energy and regain its original physical form upon deformation. Hence, dynamic mechanical analysis (DMA) were performed on the newly developed composite to understand its viscoelastic behaviours.

KEYWORDS: Viscoelasticity; Dynamic mechanical analysis (DMA); poly(hydroxyurethane) (PHU);Carbon fiber reinforced polymer (CFRP).

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1. INTRODUCTION

Composites are widely used in non-sensitive parts of an aeronautical structure. Nowadays, methods are continuously being developed to find applications in high load bearing capacities. One of the main advantages of polymers is their viscoelastic properties. Even a minor improvement in its physio-chemical propertyresults in better interface at the cohesive zone. The aim here is to create a viable composite, where the physical properties of the material would be similar to the grades presently used but at the same time exhibits better viscoelastic properties. Typically, synthetic adhesives are used in the manufacturing of CFRPsbecause of its adhesive strength. However, they are mostly not bio-degradable friendly. Moreover, it ischallenging to recycle CFRPs, particularly if the material haslowsoluble property.In contrast, bio-based adhesives hasan advantage over synthetic adhesive with respect to recycling. This is because organic coatings have better gel time and stability in its hydroxyl groups, which signifies that they are better in terms of degradationeven in aggressive media. Recent developments in the coatings and adhesive industries has given rise to various bio-based alternatives because of the ease with functional formulations. Hence, this work focuses on creating a CFRP, where anenvironmental friendly organic polymer is used as the adhesive material.

Viscoelasti city attributes both viscos and elastic properties. The elastic component is the recovery part of the material where energy is stored. Whereas, the viscoscomponent is categorised by Newtonian response (linear) and non-Newtonian response (non-linear). When a solid material undergoes stress, the material remains a rigid body. However, soft materials such as polymers experiencesback stress. This is due to the time required by the soft material to regain its original form after undergoing deformation. Thus, attributing to the viscous part. Viscoelastic materials, just as any other, dissipates absorbed energy as heat upon loading. DMA can be used to determine the viscoelastic properties of a material by time-dependent response. In VISCOANALYSER, Kelvin-Voight model (Fig. 1) is used to determine the viscoelastic properties. The model has a parallel arrangement of Newtonian damper and Hookean elastic spring. The strains in each component are similar and the sum of the two components gives total stress. This model represents a reversible strain, which is expressed as[1]:

$$\sigma(t) = E\varepsilon(t) + \eta \frac{d\varepsilon(t)}{dt} \quad (1)$$

Whereσ = stress, ε = strain, E = modulus of elasticity, η = viscosity andt = time.

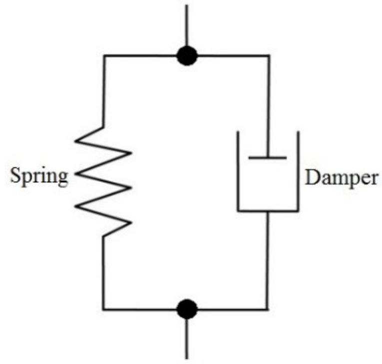

Fig. 1. Kelvin-Voight Model

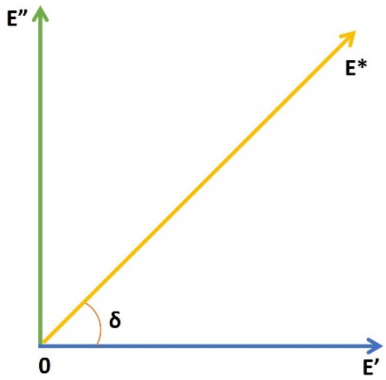

Fig. 2. Argand Diagram

The viscoelastic properties are measured as a function of strain rate, frequency, temperature and time. Complex modulus (E*) is the ratio of peak stressto peak strain and there occurs a phase difference (δ) if the material is not perfectly elastic. As illustrated in Fig. 2, E* is represented by storage modulus (E’ – in phase) and loss modulus (E” – in quadrature). E’ represents the elastic behaviour and E” represents the viscous behaviour of the material. E* is a vector quantity characterised by its magnitude and δ, which isexpressed as[2]:

$$E* = E' + iE(E' = E^* \cos \delta \; ; E'' = E * \sin \delta) \qquad (2)$$

The ratio of E” and E’ provides loss factor or mechanical damping factor (tan δ), which is the heat measure of energy deformation that is dissipated during each cycle. tan δ is measured from hysteresis of the stress-strain curve. All these measurements are based on time-temperature equivalence principle.

2. SYNTHESIS OF COMPOSITE

A CFRP composite i.e., unidirectional (UD) at 0°orientation was developed for wing structure application in commercial aircrafts. The composite has multiple layers of carbon fiber plies and polymers along with a woven fabric and anepoxy surface (Fig. 3). The goal is to use organic polymers as adhesive materialinstead of synthetic compoundsduring the preparation of composite in order to make it more eco-friendly to the environment.The selected organic polymer was PHU because of its flexibility with functional formulations to improve specific properties such as thermal stability, resistance to chemicals, corrosion and etc.

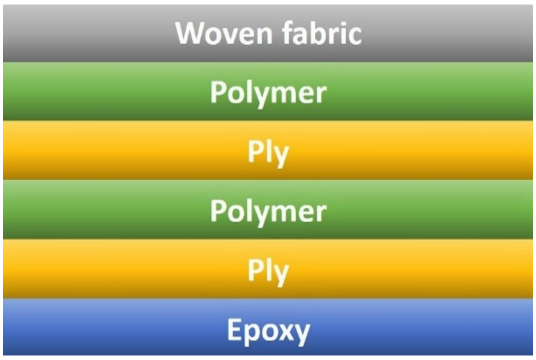

Fig. 3. Small-Scale Schematic of the Specimen

The polymer was prepared similar to the methods demonstrated by Christophe Detrembleuret al.[3]. The PHU were synthesized without solvent or isocyanate compound by mixing equimolar amounts of carbonated soybean oil (CSBO) and hexamethylenedia mine (HMDA). The difference in this PHU over others is that cyclic carbonate functional zinc oxide (CC-ZnO) fillers were incorporated to overcome adhesive failures, particularly upon contact with water because of its hydroxyl group. Such reinforcements increases the thermo-mechanical properties, which provides better gluing capabilities for PHU.Therefore, the performance of the polymer i.e., cohesive strength in multilayers depends on its crosslinking mechanism. Finally, the polymer was cured at 70°Cin order to obtain stable physio-chemical properties.

Using commercially available carbon fiber plies of 0.25 mm ± 20% thickness,plain wovenfabric(Fig. 4) and glass epoxy (Fig. 5), the multilayers(Fig. 6) was synthesized. The top surface has plain woven fabric with matte finish for a smooth, symmetrical and stable layer. Whereas, the bottom surface has a gloss finish that is fused together withepoxy in order for the layers to not peel away or delaminate during damage mechanism.This rigid coat provides high surface hardness. In between the fabric and the epoxy, the carbon fiber plies and synthesized PHUs were glued togetherone after another (Fig. 3). The resulting thickness of the specimen was 5 mm and the material contains 16 plies (Fig. 6) i.e.,orientation:45/-45/90/45/-45/0/45/-45/-45/45/0/-45/45/90/-45/45.

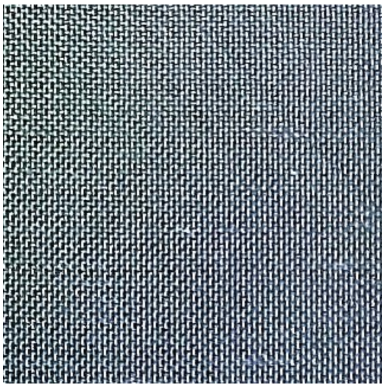

Fig. 4. Plain Woven Fabric

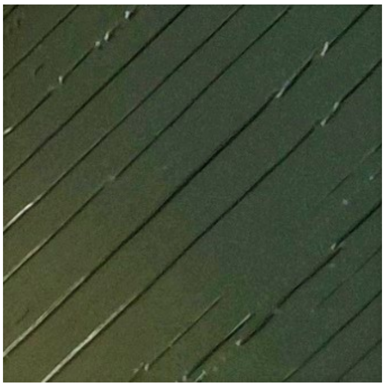

Fig. 5. Glass Epoxy Surface

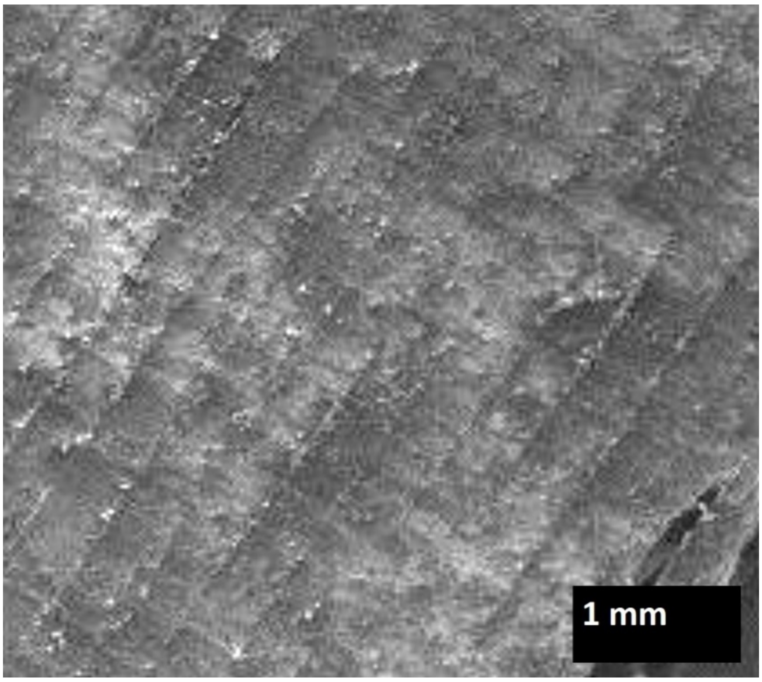

Fig. 6. Cross-Sectional View of the Final Product Under Scanning Electron Microscope (SEM)

3. EXPERIMENT

Due to the morphology of CFRPcomposites, local characterizationsare usually challenging. Hence, experiments relying on varying the oscillation frequency were performed in a 3-point bending setup (Fig. 7) with specimen dimension of 70 x 5 x 5 mm^3.The tests allow shighlighting the physical mechanisms at work by accessing the in trin sic properties. The said properties defines material–performance link. The method emphasizes on characterizing the performance and functionality of the composite.

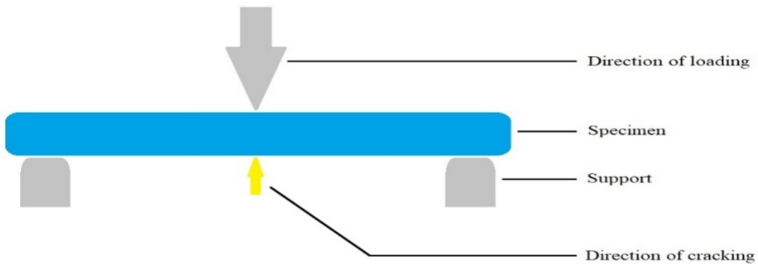

Fig. 7. Schematic of 3-Point Bending Test

4. RESULTS AND DISCUSSIONS

The temperature sweep tests were performed with a frequency of 1 Hz (Fig. 8), where the glass transition temperature (T_G) and the curing temperature (T_C) were measured as 170°C and 230°C respectively.T_G is an important thermomechanical propertyin mechanical quantificationsbecause the moduli varies with temperature. The variations in moduli signifies changesin physical properties.T_G is the phase where the properties of the material shifts rapidlybeyond the critical point i.e., the material tends to be rigid and glassy below $T_G$and, soft and flexible (amorphous)above T_G[4].The values of E' (Fig. 8) and E" (Fig. 9) were measured as 53 GPa and 9GPa respectively.

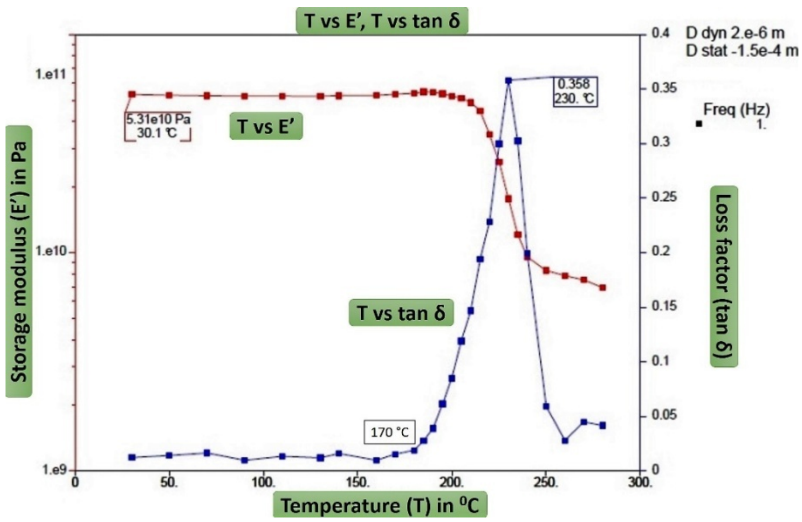

Fig. 8. T vs E', T vs tan δ at Constant Frequency

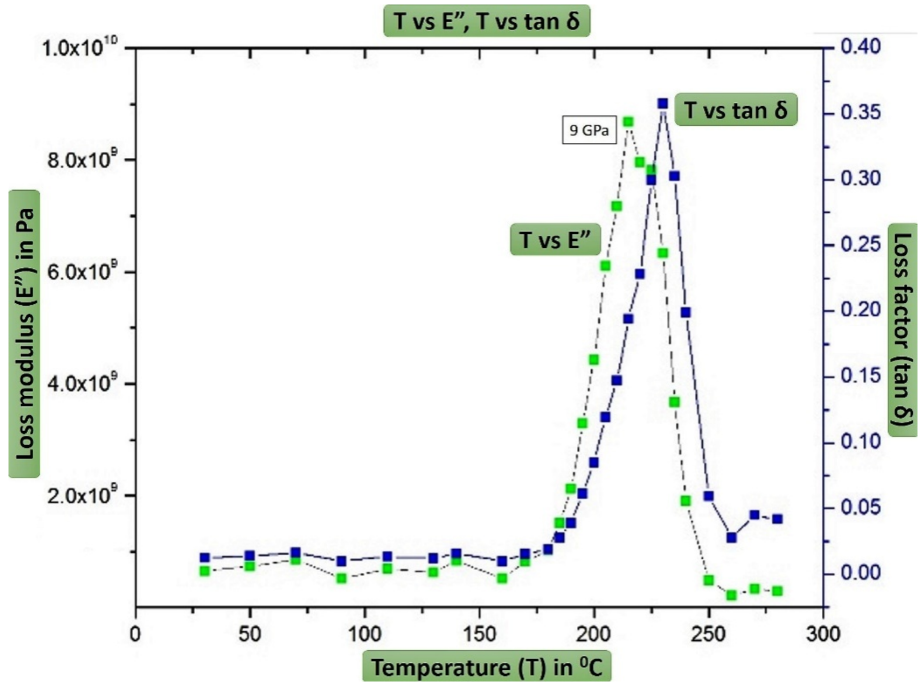

Fig. 9. T vs E", T vs tan δ at Constant Frequency

In frequency (f) sweep tests, viscosity is dominated in lower frequencies since the material is allowed to relax, whereas elasticity is dominated in higher frequencies[5]. This signifies the damping functions of the material, which in turn measures the dissipative quantities. The difference is due to the absorption of energy (loading), which is typical for viscoelastic materials. Here, the maximum tan δ was 0.67 with dynamic displacement (d) of 1 e^{-6} m (Fig. 10). In case of constant working temperature at25°C (Fig. 11), tan δ varies with increasing frequencies.This signifies the energy dissipation during propagation of damage due to vibrations. As seen from the graph (Fig. 11), the material responds well with harmonic amplitude.

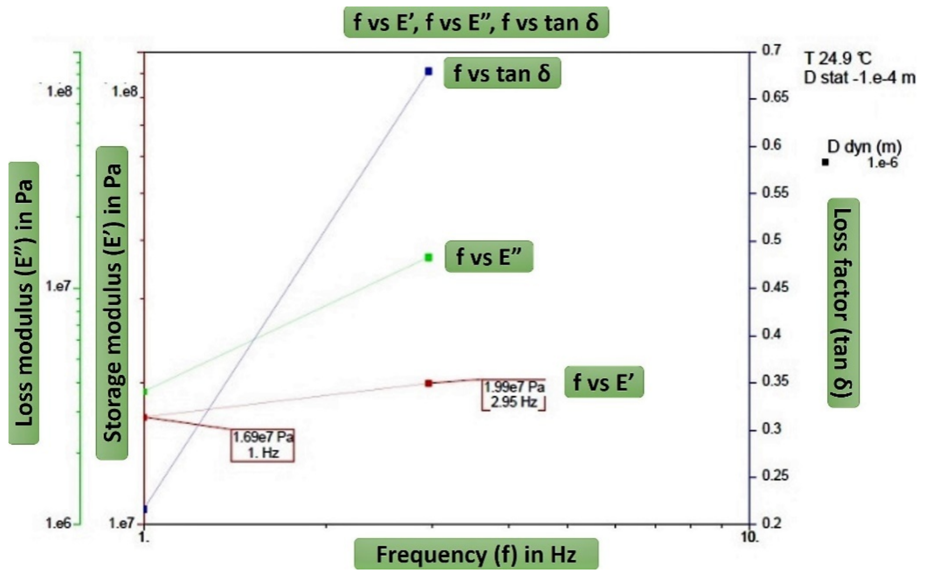

Fig. 10. f vs E', f vs E", f vs tan δ

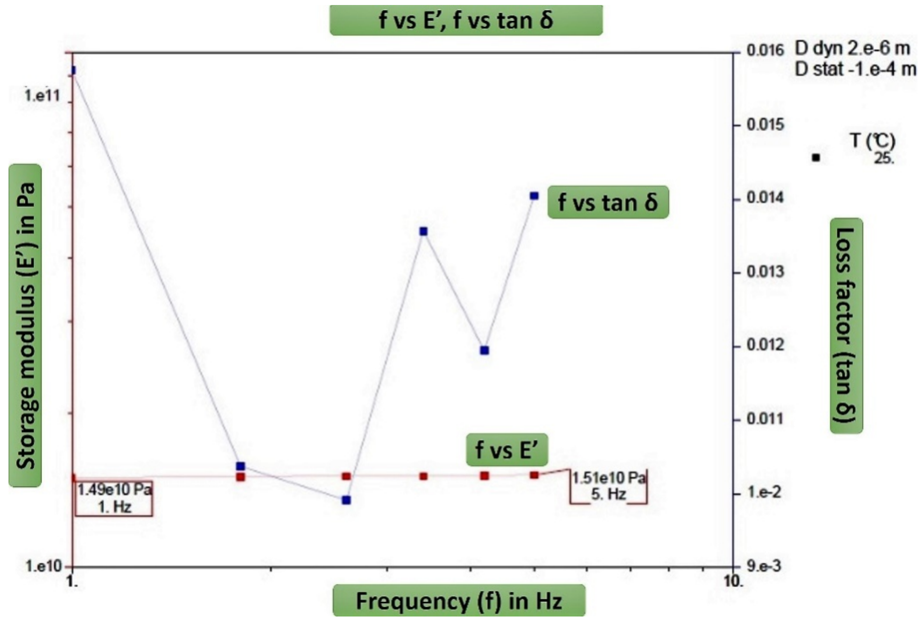

Fig. 11. f vs E', f vs tan δ at Constant Temperature

In strain sweep tests, the viscoelastic properties are independent of strain in the linearity range[6]. However, from a critical level of strain, the behaviour of the material is non-linear[7]. To confirm this property, compression module were performed on 5 x 15 x 5 mm³ specimen and the excitation was monitored with the amplitude of d. Under constant temperature of 24.4°C (Fig. 12), frequencies were increased from 1 Hz to 2.8 Hz and to 4.6 Hz in order to observe the variations in moduli of the material. E" were measured as 0.32 GPa, 0.34 GPa and 0.35 GPa respectively. This signifies that higher frequencies resulted in rapid displacement. In other words, the building up of kinetic energy as well as residual stresscontributes to rapid propagation of damage.

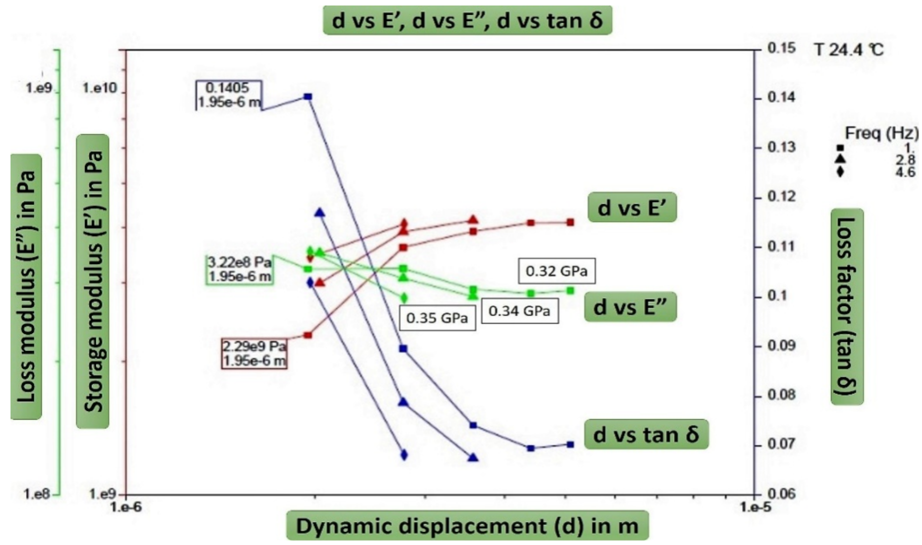

Fig. 12. d vs E', E", tan δ

5. CONCLUSION

DMA was performed on the newly synthesized composite under various test conditions. The highlight of the research is the use of bio-based organic polymer as adhesive material to make it more eco-friendly to the environment. The developed composite was characterized to understand its viscoelastic properties as a matrix. One of the interesting observations was that in terms of mechanical properties, the E (53 GPa) of the developed composite lies between E Glass UD (E = 40 GPa at 0°) and Kevlar UD (E = 75 Gpa at 0°)[8].This signifies good structural integrity of the composite.Therefore, dimensionless parametric studies are prospects of this work.

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