Studying modeling method for using nondestructive test (NDT) to determine fracture toughness of laminated carbon/ epoxy composite

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Abstract

Fiber-reinforced composites are used in many current applications due to their uniqueness, and the ability to provide definite properties to satisfy basic requirements. Like many other materials composites are prone to defects, which may drastically degrade their material properties. Therefore, to make sure that defects are neither present, nor are severe enough to compromise performance of the material, fiber-reinforced composites should be tested both prior, and during the life of the component. Delamination between layers is an important problem in applications of fiber reinforced composite laminates. Tests were carried out to determine the fracture toughness of composite laminates using mixed-mode bending tests, but this method is destructive. In this study, relationship between vibration damping and fracture toughness in polymeric composite laminated was simulated so that Vibration damping test can be used as none destructive test (NDT) to determine fracture toughness of composites without any damage of sample.

Keywords: none destructive test (NDT), vibration damping, laminated carbon/ epoxy composite, fracture toughness.

Introduction:

Fiber reinforced composite laminate are becoming a more and more important part of daily life. Because of such material characteristics such as high yield strength and low weight, composites are used in critical components of parts. And also, tendency for reliable non destructive testing procedures increases to provide the enduring composite sample, and what if any defects are present in the material that could cause failure during the life of the part. Fiber reinforced composite's complex structure cause to many forms of testing currently used to test metal components obsolete and also they are destructive.

The creation of reliable structural laminate composites for space applications requires precision design and manufacturing using an integrated, concurrent engineering approach. Since the final material characteristics are established at the same time the part or subassembly is fabricated, part design, fabrication development and material characterization must proceed concurrently. Because composite materials are custom-tailored to meet structural requirements of the assembly, stringent in-process controls are required to arrive at a configuration with optimum physical and material properties.

In specific applications, successful composite design provides design flexibility, increased strength to weight ratio, dimensional stability under thermal loading, light weight, ease of fabrication and installation, corrosion resistance, impact resistance, high fatigue strength (compared to metal structures with the same dimensions), and product simplicity when compared to conventional fabricated metal structures [1].

Like other material composites prone to defects and interlaminar delamination is a common and potentially dangerous mode of failure in composite structures. Delamination often results in the loss of stiffness and strength, which may lead to safety and reliability problems. Undetected subsurface delamination can lead to catastrophic failures without any external signs. This makes delamination a major obstacle in achieving the full weight saving potential of advanced composite materials [2, 3]. Delamination in composites is often a mixed-mode fracture. Both interlaminar tensile and shear stresses can be present at the delamination front. Interlaminar tensile stresses give rise to mode I fracture while interlaminar shear stresses result in mode II fractures. Using fracture mechanics to characterize the onset and growth of delamination has become a generally accepted practice. The fracture toughness of materials can be measured by the critical energy release rate G_{Ic} for pure mode I and G_{IIc} for pure mode II. While mode I fracture dominates the failure in isotropic materials, the interaction of shear and tensile fracture complicates the mechanism of failure in composite materials. Delamination resistance of a composite laminate under mode I fracture is different from the delamination resistance under mode II fracture. The mechanism of fracture also varies with the ratio of the different modes of fractures involved [2, 4–6]. This interaction of shear and tensile fractures complicates the mechanism of failure in composite materials [3, 7–9].

Damping is the ability of a material to resist vibration. The three most common type of damping are viscous, coulomb and hysteresis [10,11]. All the three types of damping dissipate energy during the vibration and among them viscous damping and coulomb damping depend on vibrating boundary conditions (geometries, frequencies, etc.) as well as the vibrating material themselves, whereas hysteresis damping depends only on the vibrating materials and is independent of boundary conditions, as a result hysteresis damping is not only applied in vibration control, but also has the capability to describe material characteristics such as intrinsic property. The loss factor, η, is one of the most often used terms to evaluate damping ability of a material and there are a lot of techniques to calculate loss factor which they are following:

- complex modulus notation
- complex stiffness notation
- logarithmic decrement method
- hysteresis loop method
- strain energy method
- half power band width method

By reviewing the definition of the fracture toughness it gets clear that if the fracture toughness of a material raises, the amount of mechanical energy that the material stores before fracture, increases. On the other hand, the loss factor η which evaluates damping capability of the material, shows the amount of energy that the material stores during damping. Thus both fracture toughness and loss factor relate to the amount of mechanical energy that the material can store and there should be a logical relation between these two material properties. In order to find out this relationship, survey upper methods and regarding to nature mechanical properties of fiber reinforced composite laminate, mode II (pure shear) was selected to verify fracture toughness of composite and half power band width method was preferred to determine loss factor as damping property of composite, as a final point was defined the relationship between fracture toughness and loss factor.

Materials and Methods

Two standards were used to find out fracture toughness and loss factor as mechanical properties and vibration damping of composite laminate respectively.

ASTM D: 6671/D6671M-03, which standard test method for mixed mode I- mode II interlaminar fracture toughness of unidirectional fiber reinforced polymer matrix composites, was used for determining fracture toughness of fiber reinforced composite laminate.

ASTM E756-04, standard test method for measuring vibration- damping properties of materials, was selected for determining damping properties of fiber reinforced composite laminate. This test method measures the vibration-damping properties of materials: the loss factor, h, and Young's modulus, ***E***, or the shear modulus, ***G.***

However, in this paper, the some fracture toughness of carbon/ epoxy composite results were used from [11], moreover the relationship between loss factor and fracture toughness was definite by formula, then the loss factor obtains from NDT techniques such as ultrasonic pulse- echo, eddy current and impulse frequency response technique, following fracture toughness was calculated from diagram of relationship between them.

For finding out relation between loss factor and fracture toughness, After studying papers and literatures about fracture toughness and vibration damping, curve of applied load versus opening displacement, which was taken from reference [10], was selected for obtaining the affiliation between fracture toughness and loss factor. Familiar factor between them is dissipated energy during their measurement. However, for solving this problem, following thermodynamic equilibrium energy balances:

$$G = G_1 + G_2 \qquad (1)$$

Which, G is the input energy, G_1 irreversibly dissipated energy and G_2 is the stored strain energy and for solve the problem was assumed that system is ideal and other parameters were zero. It is mention that G_{IIC} is related to dissipated energy (G_1) when the crack is initiating or propagating, so

$$G_{IIC} = G_1 / \Delta A \qquad (2)$$

And according to Eq. (1)

$$G_{IIC} = (G - G_2) / \Delta A \quad (3)$$

Result and discussion

According to curve of applied load versus opening displacement, loss factor and fracture toughness were determined graphically. In this method, loss factor and fracture toughness were obtained approximately and some curve regards right line, to calculate area under force- displacement curve, this area divided to two or more part with simple geometry such as rectangular or triangle. Figure 1 shows the applied load versus opening displacement curve of the specimen.

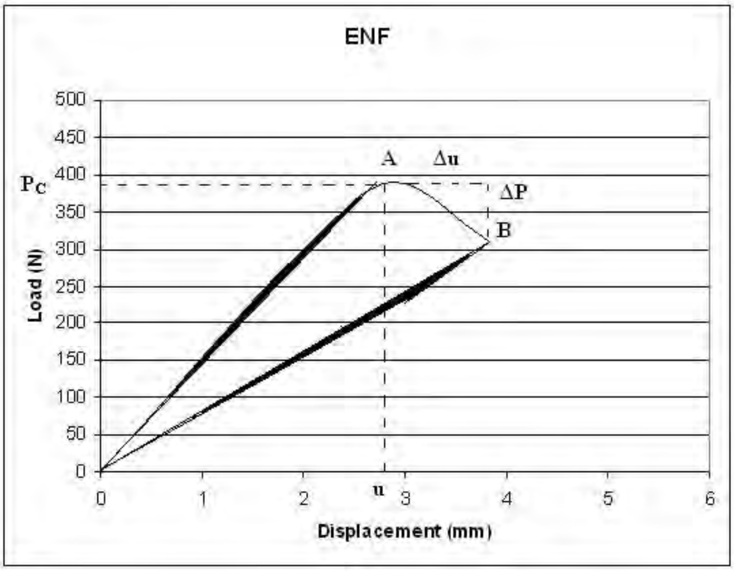

Fig 1. Curve of load and displacement of laminated carbon/ epoxy composite [12]

OA, in figure 2 shows the loading path, when the load increase to maximum level at point A the crack begins to propagation and the load coming to decrease until point B. to obtain the affiliation between loss factor and fracture toughness loading path and unloading path were assumed linear, but this theory related to elastic material, whereas composite laminate is viscoelastic material, so loading path and unloading path suppose as a curve, however to calculate the loss factor and affiliation between loss factor and fracture toughness, the shaded area of OA curve was assuming 0.001 of area under OA line (Eq.5).
Regarding to figure 2, G, G_1 and G_2 were calculated, then:

$$G = (P_C - \Delta P)\Delta u + \frac{1}{2}\Delta P \Delta u = P_C \Delta u - \frac{1}{2}\Delta P \Delta u \quad (4)$$

And the strain energy change after loading is:

$$\text{Strain energy} = G_2 = \int_0^{u+\Delta u} P_2(u)du - \int_0^{u} P_1(u)du \quad (5)$$

However, G_{IIC} is equaled with dissipating energy when the crack initiation or propagation, so

$$\Delta A = \omega \Delta a \quad (6)$$

According other equation (4) and (5) following with assume that the shaded area is 0.001 of area under OA line, therefore the area under curve loading of composite laminate is

Area under curve loading of composite = (1.001) (area under OA line)

And the area under curve unloading composite laminate is:

The area under cure unloading composite laminate = (0.999) (area under OB line)

Both of them cause to calculation of equation (4) was simple, so

$$G_{IIC} = \frac{1}{w\Delta a}(P_C \Delta u - \frac{1}{2}\Delta P \Delta u - \int_0^{u+\Delta u} P_2 du + \int_0^u P_1 du) \tag{7}$$

The shaded area under curve loading of composite laminate = $\int_0^u P_1 du$ = 1.001 ($\frac{1}{2} P_C u$) (8)

The shaded area under unloading curve of composite = $\int_0^{u+\Delta u} P_2 du$ = 0.999 ($\frac{P_2(u+\Delta u)}{2}$) (9)

It is mention that both OA and OB lines regards as a linear in the elastic material, but in the viscoelastic composite, both OA and OB lines are curve, therefore the difference between linear and curve used for calculating loss factor(η), so:

$$\eta = \frac{2(\int_0^u P_1 du - \frac{1}{2} P_C u)}{\int_0^u P_1 du} \tag{10}$$

After substituting equation 10 into equation 7, the relationship between loss factor and fracture toughness found to be:

$$G_{IIC} = \frac{\int_0^u P_1 du}{2w\Delta a}\eta - \frac{1}{w\Delta a}(\int_0^{u+\Delta u} P_2 du + \frac{1}{2}\Delta P \Delta u - P_C \Delta u - \frac{1}{2} P_C u) \tag{11}$$

Equation 11 shows the relationship between loss factor and fracture toughness is linear and this equation can be written in form:

$$G_{IIC} = A\eta + B \tag{12}$$

Where

$$A = \frac{\int_0^u P_1 du}{2w\Delta a} \tag{13}$$

And

$$B = -\frac{1}{w\Delta a}(\int_0^{u+\Delta u} P_2 du + \frac{1}{2}\Delta P \Delta u - P_C \Delta u - \frac{1}{2} P_C u) \tag{14}$$

If the parameters A and B are constants for a given material, geometry and loading, then the plot of η versus G_{IIC} will be a straight line with slope A and intercept B which calculated from equation 13 and 14. Consequently, fracture toughness can be estimated by measuring the damping parameter η (loss factor).

Following relationship between the loss factor and fracture toughness of a laminated carbon/ epoxy composite was calculated by equations (12),(13) and (14), and curve of applied load versus opening displacement which was shown in figure 2.

A= 0.2828 and B= 0.3069

So, the final equation was written in the form:

$$G_{IIC} = 0.2828\eta + 0.3069 \quad (15)$$

Then the loss factor of composite was calculated from equation 15 and their results were listed in the table 1, subsequently the affiliation between loss factor and fracture toughness of laminated carbon/ epoxy composite was shown graphically in the figure 2.

Table1. Fracture toughness and loss factor data of laminated carbon/ epoxy composite [12].

Test	G_{II} (J/m^2)	η x 10^{-3}
Modified beam theory	683	1.33
ENF	729	1.49
	555	0.88
	584	0.98
	712	1.43
	674	1.30
MMB	102	-0.72
	104	-0.72
	110	-0.70
	111	-0.69
	128	-0.63
	196	-0.39
	217	-0.32
	222	-0.30
	258	-0.17
	278	-0.10
	290	-0.06
	394	0.31
	412	0.37
	454	0.52
	437	0.46
	434	0.45

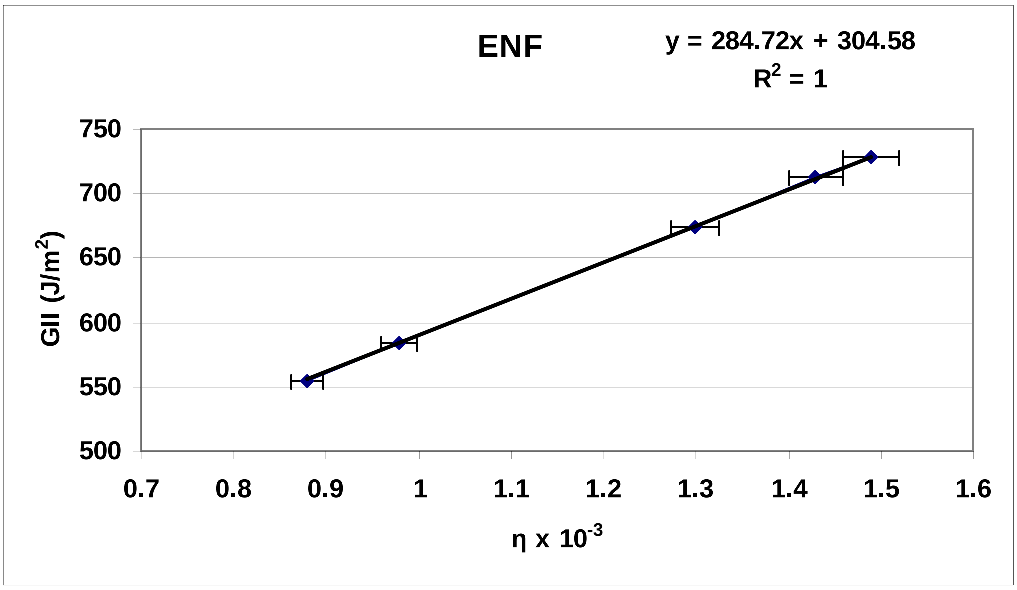

Figure2. Relationship between fracture toughness and loss factor of laminated carbon/ epoxy composite

Finally according to the fig 2, the fracture toughness of composite carbon/epoxy during working hour can be obtained by using nondestructive system such as ultrasonic pulse- echo, eddy current and impulse frequency response technique, to determine loss factor η and then fracture toughness was calculated from fig.2. Really, this method is a nondestructive method to measurement fracture toughness of laminated carbon/ epoxy composite. Finally must be founded that these results are completely similar to some literature in this field [11].

Conclusion:

Some measurement methods of fracture toughness are destructive and they are not using during work of composite, so in this paper the relationship between loss factor and fracture toughness in viscoelastic materials was modeling, then Using NDT technique such as ultrasonic pulse- echo, eddy current and impulse frequency response technique, to achieve loss factor and then fracture toughness was calculated from relationship between η and G_{IIC} that was drawn as curve.

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