Effect of viscoelastic behavior of lamina on delamination rate calculation at constant load test

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The effect of viscoelastic behavior of lamina on the calculation of the delamination or debonding rate at constant loading condition is considered. A viscoelastic model was adapted experimentally to represent the Mode II end load split specimen. The rate of delamination, accelerated by elevated temperature, has been tested with the necessary corrections. Applying the linear elastic fracture mechanics theory to analyze the data was demonstrated and used to calculate the kinetic parameters, based on Paris equation, from the experimental data. The results show that the temperature is an effective accelerator in the delamination problem and the correction was required.

تم دراسة تاثير خاصية المرونة اللزجة للشريحة على حساب معدل انفصال الشرائح الملتصقة فى حالة اختبار الحمل الثابت.كما تم معمليا توفيق نموذج ليمثل العينة منفصلة الطرف فى الحالة الثانية للأنفصال Mode II .و تم اختبار معدل الأنفصال الذى تم تعجيله برفع درجة الحرارة مع عمل التصحيحات اللازمة. تم عرض طريقة تطبيق نظرية ميكانيكا الكسور الخطية المرنة لتحليل النتائج وحساب المعاملات الكناتيكية لمعادلة Paris من النتائج المعملية. وقد اظهرت النتائج ان الحراره هى معجل مؤثر لعملية انفصال الشرائح وان التصحيح موضوع البحث ضرورى.

Keywords: Delamination, Fracture mechanics, Mode II, Lifetime, Viscoelastic behavior

1. Introduction

Composites as a new material structure are mostly compound from layers of fibers that are stacked in deferent ways. These fibers are imbedded in a matrix that holds the structure in the desired form. Nearly all of these matrices are polymeric based and exhibit viscoelastic performance. Thus the mechanical behavior of composite material structure is time dependent and its performance must be considered in long-term tests where the calculations and measurements depend on elastic theories.

On the other hand, composites have various failure modes and delamination is just one of these modes. Delamination usually starts at localized defects such as matrix cracks or fiber splits. The size of such crack is however acceptable sense that the largest stress is less than the critical value. The stress and strain fields associated with delamination-causing discontinuities are readily calculable using finite element techniques [1], an area which continues to witness interesting developments [2]. Delamination propagates according to fracture mechanics rules [3] in the areas of high interlaminar stresses, which are associated with necessary discontinuities in the design, e.g., cutouts, holes, joints, ply-drops. This propagation can proceed for a long period of loading time to form an unacceptable damage area that affects the structure stiffness and/or strength. This later phenomena has recently attracted the interest of many researchers [4, 5].

To accelerate the delamination rate, tests could be conducted at high temperature, which are greater than the room temperature but below the matrix glassy temperature. This delamination could take place under Mode I, II or mixed mode loading conditions and the delamination length can be measured directly from the test specimen, if this is feasible, or calculated from the elastic deflection that can be measured using suitable transducer. In the second case, we use the elastic theories to calculate the delamination length [6].

In Mode I loading conditions, when using the standard Double Cantilever Beam (D.C.B.) specimen, the length of the two lips of the specimen was small and the effect of the viscoelastic behavior could be neglected

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provided the initiation time is not considered [4]. In Mode II loading condition, on the other hand, when using the classical End Load Split (E.L.S.) specimen, where the specimen is long and has a relatively small rectangular cross section, delamination length is calculated using the change in stiffness, which is measured by the loading points deflection [6]. In this later case the effect of the viscoelastic behavior must be considered. Thus a viscoelastic model is proposed and fitted with the experimental data to enable the use of the elastic theories when calculating delamination length.

The aim of this work is to study the viscoelastic effect in composite delamination tests, and to determine the most suitable method to manipulate the data obtained from the test under Mode II loading conditions.

2. Experimental procedure

2.1. Material and specimen

Because laminated composite samples are laborious to manufacture and are opaque, the specimens used in these experiments were manufactured from a model system using PolyMethylMethAcrylate (PMMA) beams and epoxy (Devcon S-208/20845) adhesive and prepared in an End Load Split (ELS) configuration. The initial delamination was obtained by inserting two layers of aluminum foil, 0.01 mm thickness, coated with release agent, at the desired initial delamination length [7] and at the end of the specimen as well to assure uniform adhesive thickness. A sketch of the specimen geometry is shown in fig. 1. Some of these specimens are made as model specimens without initial delamination to study the viscoelastic behavior of the beam itself and to find out the equivalent model.

2.2. Testing device

The creep setup equipped with a controlled temperature chamber is shown in fig. 2 with a test specimen loaded in Mode II. Testes were conducted at high temperatures that must not produce plastic deformation during the test duration. A proportional controller, provided with heat sensor, adjusts the temperature to a desired value up to 65°C. Specimens stay at the desired temperature for about 45 minutes before loading to allow uniform heating. Loads were applied gradually (in less than 10 seconds interval) through two loading levers using calibrated dead weights. The displacement transducer attached to the loading arms out side the oven measures the deflection. The test duration could be several days, so the deflection and temperature data were acquired by a personal computer and saved with the corresponding date and time in a text file by means of data acquisition hardware and a Lap View V5 software with automatic startup configuration. The program is designed to pick up data when there is any change in deflection signal greater than the noise that can disturb the signal or after a given period of time, two hours was convenient.

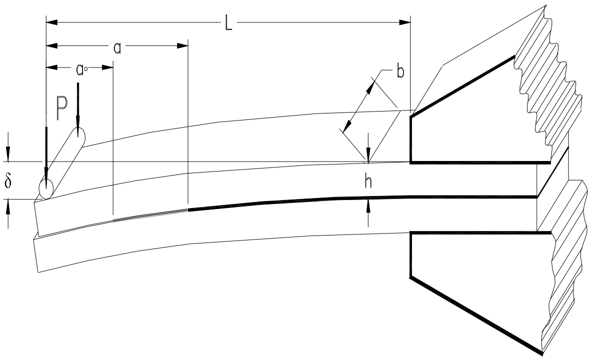

Fig. 1. Test specimen configuration.

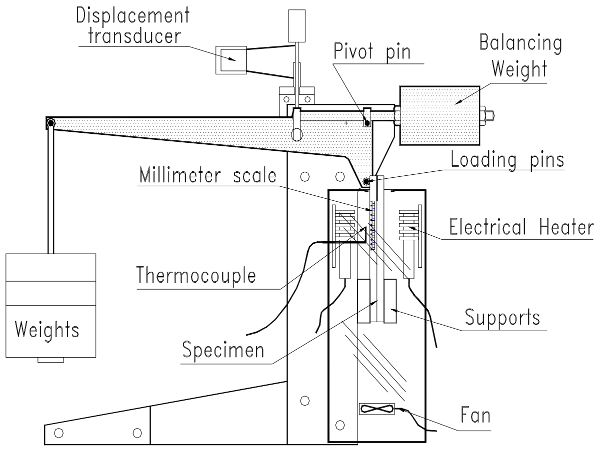

Fig. 2. Experimental setup in mode ii configuration.

2.3. Test steps

2.3.1. Test to produce the vescoelastic model

The model specimen is placed in the oven set, attached by the loading pin, at the desired temperature for about 45 minutes to allow uniform heating. The displacement transducer is then attached and set to zero reading by means of the software. The load is manually applied, very slowly to assure no impact effect, in time intervals less than 10 seconds. Then displacement data is acquired continuously.

2.3.2. Test to measure the delamination rate

Following the same procedure as described above with a delaminated specimen, the delamination growth is observed intermittently using the millimeter scale fixed to the specimen. The observed delamination length is recorded with time.

3. Modeling and calculations

3.1. Compliance calculation

Recorded deflection and time data can be used to determine the cantilever compliance as follows [6]:

$$C = \delta / P = \frac{L^3 + 3a^3}{2Ebh^3} \quad . \qquad (1)$$

Where:

C is the compliance ,
L is the cantilever length,
a is the delamination length,
E is the material modulus of elasticity,
b is the specimen width,
h is the half thickness of specimen,
P is the applied load, and
δ deflection at loading point.

3.2. Viscoelastic model

The Voigt & Maxwell viscoelastic model shown in fig. 3 is used in the present work to obtain the compliance as a function of temperature and time. According to this model, the cantilever compliance is given by the eq. (8):

$$C = \frac{L^3}{2bh^3}\left[\frac{1}{E_1} + C_1 t + \frac{1}{E_2}\left(1 - \frac{1}{e^{C_2 E_2 t}}\right)\right] .$$

Where E_1, E_2, C_1 and C_2 are constants. Four tests were conducted at four deferent loads for each temperature of 27°C, 40°C, 50°C and 60°C. Fig. 4 shows the results of the proposed viscoelastic model together with that obtained experimentally. It is obvious that the viscoelastic model has adequately described the experimental data.

The values of E_1, E_2, C_1 and C_2, were obtained as functions of temperature as shown in figs. 5-8. Polynomial fitting of the experimental data using Excel spread sheet produced the following empirical equations:

$E_1 = 2.6 - 0.01 * T$,
$E_2 = 9.57 + 0.583 * T - 0.0098 * T^2$,
$C_1 = 0.0003 * T^2 - 0.0173 * T + 0.32$,
$C_2 = 0.0072 * T^2 - 0.447 * T + 10.8$,

where T in °C; E_1 and E_2 in GPa; C_1 and C_2 in $GPa^{-1}.hr^{-1}$.

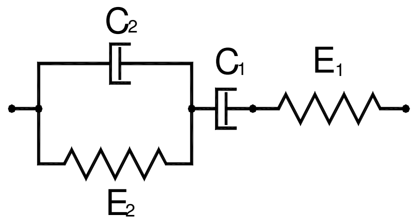

Fig. 3. Voigt and Maxwell viscoelastic model.

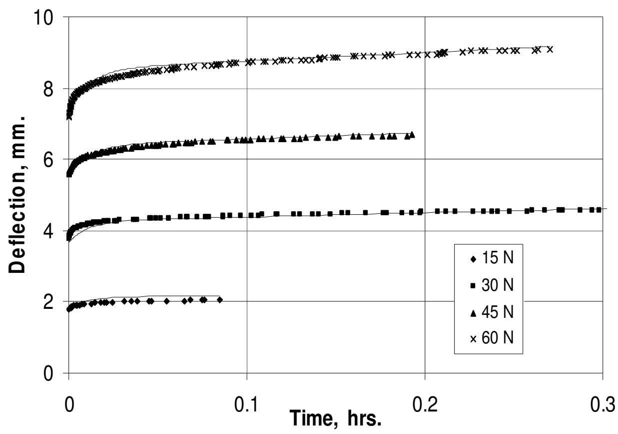

Fig. 4. Deflection versus time relation at 50° C fitted to the visoelastic model at four deflection loads.

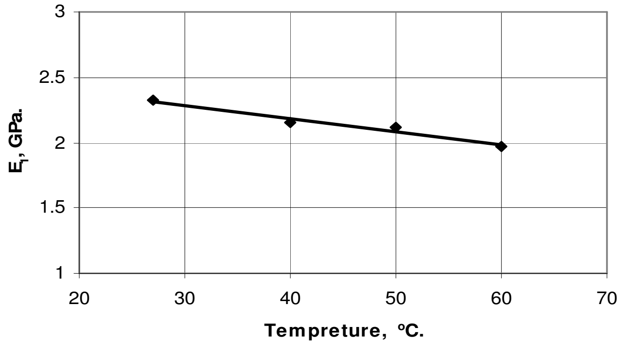

Fig. 5. E1 versus temperature.

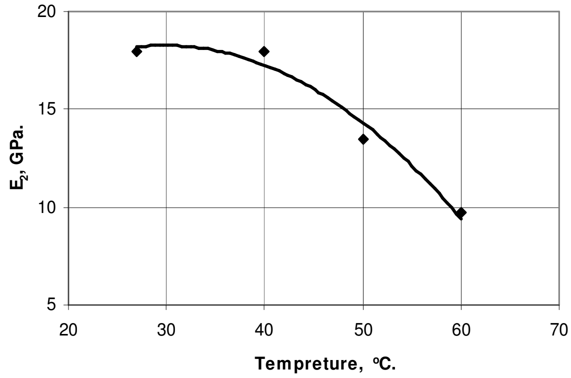

Fig. 6. E2 versus temperature.

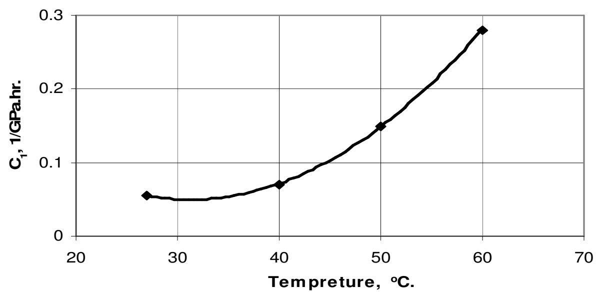

Fig. 7. C1 versus temperature.

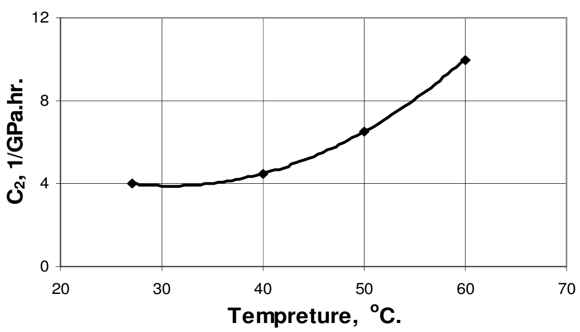

Fig. 8. C2 versus temperature.

3.3. Fracture mechanics calculation

The stress intensity factor in mode II, assuming plane strain conditions can be calculated as a function of delamination length using the following equation [6]:

$$K_{II} = \sqrt{\frac{E.G_{II}}{(1-\mu^2)}} \; . \tag{2}$$

$$G_{II} = \frac{9P^2a^2}{4Eb^2h^3} \; ,$$

where G_{II} = energy relies rate for Mode II and μ = 0.28 is the Poisson's ratio.

From eq. (1) we can get

$$a = \left[\frac{2\delta Ebh^3 - L^3P}{3P}\right]^{1/3} . \tag{3}$$

It is known that under viscoelastic condition and constant bending load, the modules is no longer constant but is rather a function of both temperature and time. In this case the modulus is given by:

$$E' = \left[\frac{1}{E_1} + C_1 t + \frac{1}{E_2}\left(1 - \frac{1}{e^{C_2E_2t}}\right)\right]^{-1} . \tag{4}$$

It is clear from the above equation that deformation increases almost linearly after an initial time period of approximately three minutes for E_2C_2 greater than 70hr^{-1}. In fact, the linear behavior dominates until the delamination length start to increase. A numerical integration was conducted to determine the initiation time at which the delamination length starts to increase. The point of initiation (t_i, δ_i) can be obtained at the instant of time corresponding to the minimum rate of deflection. The measured deflection after this point δ will be divided into three parts, δ_i, δ_c and δ_a. Where: δ_c is the deflection due to creep, considering delamination length is fixed at a_o, during the period of time $t\text{-}t_i = \int_{t_i}^{t} \frac{\partial \delta}{\partial t} dt$. δ_a is the deflection due to change in delamination length = δ - δ_c - δ_i

Neglecting the term $1/e^{C_2 E_2 t}$ in eq. (4), for t>5 minutes, the delamination length then can be obtained from eq. (3) as follows:

$$a = \sqrt[3]{a_o^3 + \frac{2}{3}(\delta_a.E`.b.h^3 / P)} \quad . \tag{5}$$

Using the above Equation together with eq. (2), G_{II} and K_{II} can be calculated for a given delamination length a. Paris-type eq. [3] was verified and its kinetic parameters were found for the tested cases.

3.4. Verification

Fig. 9 depicts both measured results as obtained experimentally by direct observation of delamination length and the calculated ones as obtained from the viscoelastic model using recorded data in eq. (5). It is obvious that there is a good agreement between the measured and calculated data.

3.5. Data analysis

Typical behavior of delamination length as function of time under three different loads at 65°C is shown in fig. 10. As expected, propagation of the delamination front starts slow and then speeds up with time. All three curves look similar and can be described by the empirical equation:

$$a = a_o\left(\frac{t^* - t_i}{t^* - t}\right)^n . \tag{6}$$

Where a_o is the initial notch length, t^* is the time spend to obtain maximum delamination through the specimen and n is an empirical constant. Eq. (6) is valid for the time interval $t^*>t>t_i$ and imposes a continuous characteristics on the delamination process, which is naturally discontinuous.

Eq. (6) can be used to obtain the rate of delamination *da/dt* as a function of the delamination length. The simplest and most commonly used method for calculation the rate of crack propagation is the Paris-type power law equation. Accordingly, the rate of delamination is plotted as a function of the stress intensity factor in accordance with Paris-type equation, i.e.,

$$da/dt = A(K_{II})^m \quad . \tag{7}$$

where A and m are empirical parameters.

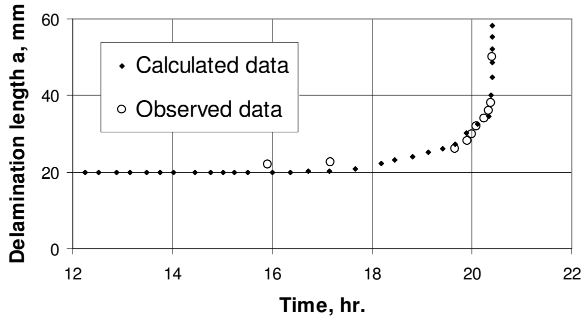

fig. 9. comparison between measured and calculated results for delamination length at 65° C and 190 N load.

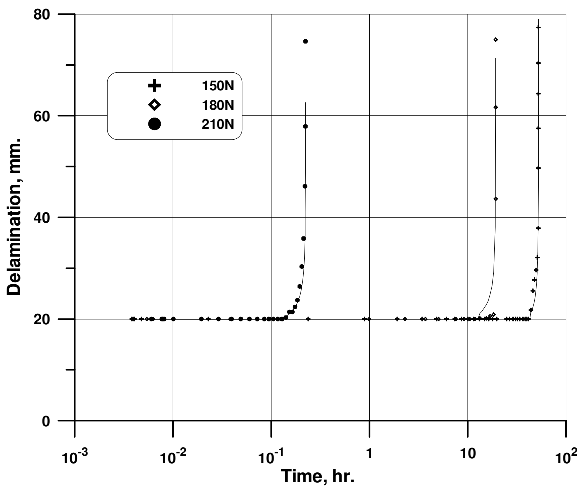

Fig. 10. Delamination length versus time at 60°C.

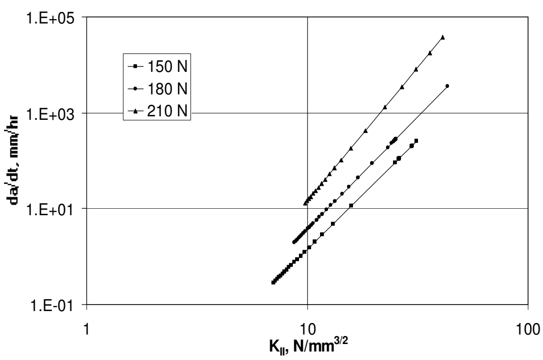

Fig. 11. Paris-type plots for mode ii at 60 °C.

The rate of delamination under three different loads at three different temperatures of 65°C, 60°C and 55°C was plotted versus K_{II} using eqs. (5) and (2). One of these plots is presented in fig. 11. Apparently the Paris-type power law provides a reasonable fit to the data. The exponent m and the intercept A of the equation, which are generally recognized as the kinetic parameters, were calculated from the data in fig. 11 and similar figures for the 65°C and 55°C.

The parameter m seems to be a function of temperature only. A plot of the average exponent as a function of temperature, as obtained experimentally, is shown in fig. 12. A polynomial of the 5th order has been found to best fit the experimental data with a correlation factor 0.9788. The obtained equation is given by:

$$m = 5*10^{-9}*T^5 + 2.2, \qquad (8)$$

where T is the temperature in degrees centigrade. As seen in fig. 12, eq. (8) seems to offer a reasonable description of the data, and may, therefore, be used to obtain the exponent at the desired temperature.

On the other hand the other kinetic parameter A (intercept of eq. (7)) exhibits significant dependence on temperature. A plot of the average exponent as a function of temperature, as obtained experimentally, is shown in fig. 13. A straight-line relation has been found to best fit the experimental data with a correlation factor 0.9640. The obtained equation is given by:

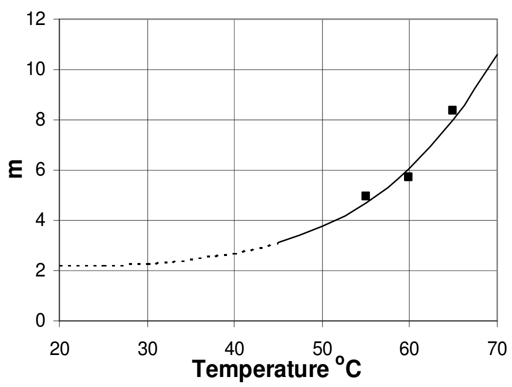

Fig. 12. Variation of the kinetic parameter m with temperature.

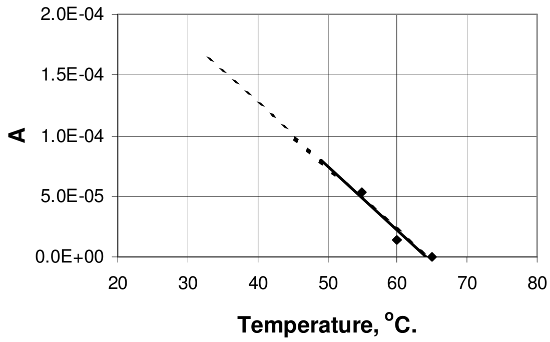

Fig. 13. Variation of the kinetic parameter A with temperature.

$$A = 3.25*10^{-4} - 5*10^{-6} *T. \qquad (9)$$

The units of K_{II} in this case must be in N/mm$^{3/2}$ and da/dt in mm/hr. This, in turn suggests that eq. (9) is probably useful to forecast the value of A at service temperature.

At this point, it must be indicated that forecasts based on the method presented above are conservative, as they do not account for initiation time, which could be a significant fraction of the total service life-time. Furthermore, in analogy with forecasting of cracks in structure, the user must determine in advance the size of delamination that is considered detrimental to the structure considered. In addition, the testing method presented here could be useful to test the durability of adhesive bonds and laminated composites as means for material development.

4. Conclusions

Modeling the PMMA test specimen, Mode II configuration, experimentally has been conducted. Experimental procedure to measure the rate of delamination under constant load, accelerated by elevated temperature, has been tested with the necessary corrections.

Applying the Linear Elastic Fracture Mechanics (LEFM) theory to analyze the data was demonstrated and used to calculate the kinetic parameters A and m, based on Paris equation, from the experimental data. These parameters were found to vary mainly with temperature, A decreases as temperature increases and m increases with temperature. The delamination rate decreases with the temperature, this means that the temperature is an effective accelerator in the delamination problems. The rate at room temperature may be deduced from simple extrapolation of the accelerated data, by integration of Paris equation. The life-time can be calculated if the initial and the maximum delamination length are defined. The tests conducted at low temperature consume too much time, several months, and of curs too much money while the tests at high temperature reduce such problems.

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