

The temperature and pre-crack length effects on delamination resistance of woven GFRP sandwich composites

Meltem Evren Toygar*, Farshid Khosravi Maleki**

*Dokuz Eylül University, Engineering Faculty, Mechanical Engineering Department, 35397 Tinaztepe Campus Buca/Izmir, Turkey, E-mail: evren.toygar@deu.edu.tr

**Dokuz Eylül University, Engineering Faculty, Mechanical Engineering Department, 35397 Tinaztepe Campus Buca/Izmir, Turkey, E-mail: farshid.khosravi09@gmail.com

crossref <http://dx.doi.org/10.5755/j01.mech.22.5.16229>

1. Introduction

Nowadays, sandwich composites have been adopted in various areas such as aerospace, marine and automotive sectors due to the constructed with two stiff, strong face sheets and a lightweight, relatively flexible core, and a high bending stiffness and strength per unit weight. Therefore, their fuel efficiency in transportation vehicles, but at present, there is a strong interest in the development and applications of sandwich structures for civil and building material systems [1]. However, sandwich construction has a number of problems due to existence of interfaces serves as a source of problem such as failure initiation and growth. Therefore, the test methods have been developed to obtain the interlaminar fracture toughness of sandwich composites by considering environmental effects, a suitable test configuration or specimen geometry under Mode I or Mode II loading. The presence and growth of delamination in laminates significantly reduces the compressive load-carrying capacity of a structure and causes initiation of catastrophic failure [2]. Several methods have emerged in the past for computing strain energy release rates for delamination growth in a wide variety of composite structures. The strain energy release rate was obtained by using double cantilever beam (DCB) specimens for honeycomb sandwich composites. The analytical model is established by considering delamination and embedded artificial pre-crack, and the results obtained from 3D finite element analysis for various delamination lengths have been compared with the analytical results [3, 4]. To investigate the fracture behavior of honeycomb sandwich panels containing embedded artificial pre-crack, DCB test geometry was used to get strain energy release rate. Here, the facesheet is made of carbon fibre pre-preg and the core was honeycomb [4] and an experimental study is conducted on the interlaminar fracture of honeycomb sandwich. Development and evaluation of fracture mechanics test methods for sandwich composites have been done [5] to characterize Mode I and Mode II energy release rate associated with face sheet/core delamination growth in sandwich composites. An experimental study has been done to investigate the face sheet/core interfacial fracture toughness of E-Glass/Vinylester face sheet, with PVC core sandwich composites [6]. The experimental studies were performed at room temperature and cryogenic temperatures to provide basic material properties and critical fracture parameters deal with failure [7, 8]. Carbon fibre reinforced faceplate debonding under mode I loading in sandwich structures at room and high temperatures has been

investigated [9].

The virtual crack closure technique (VCCT) is widely used for computing energy release rates, based on results from continuum (2D) and solid (3D) finite element (FE) analyses, and to supply the mode separation required when using mixed-mode fracture criteria [10, 11].

In this study, the temperature and pre-crack effects on the delamination resistance of woven GFRP sandwich composites under Mode I loading was experimentally investigated and numerically modelled. GFRP sandwich panel was fabricated with vacuum assisted resin infusion melding (VARIM) at the composite laboratory of Mechanical Engineering Department, Dokuz Eylül University. The mechanical properties were obtained at room and high temperature. DCB test was adopted for the measurement of delamination resistance by evaluating the SERR value to obtain the fracture properties of woven GFRP sandwich composites. The three analytical methods, the experimental compliance calibration method (CCM), Modified Compliance Calibration Method (MCC) and Modified Beam Theory (MBT) have been used. In the finite element analysis virtual crack closure technique (VCCT) was used. The results obtained from 3D finite element analysis for various delamination lengths compare well with the experimental results. It is seen that there is an agreement between experimental and numerical results so that VCCT analysis is to be an appropriate method for analysing a SERR value of sandwich composites.

2. Material and method

2.1. Materials and specimens preparation

In this study, the sandwich composite panel was fabricated with vacuum assisted resin infusion melding (VARIM) at the composite laboratory of Mechanical Engineering Department, Dokuz Eylül University. The panel was fabricated with a woven GFRP (Glass Fibre Reinforced Polymer) face sheets that properties and plies of the upper and lower face sheets are listed in Table 1. The resin used in this study was comprised of epoxy resin (Hexion MGS L160 with a density of 1.13 gr/cm³) and hardener (Hexion MGS H160 with a density of 0.96 gr/cm³) for a resin-hardener ratio of a 100:25 by weight. As a sandwich core material, Airex® C70.55 was used. The properties of core is given in Table 2.

The laminates were cured at room temperature for 4 days and post-cured at 80°C for 8 h. To create a pre-crack, Teflon film was placed at the plane between Upper

face sheet and foam during the lay-up process. Tests were performed in a universal testing machine (Shimadzu AG-100). All samples were cut by a water-cooled tile saw for tests in accordance with ASTM's.

Table 1
The properties and sequence of upper and lower face sheets

	Order of Lamina	Distribution of fibres	Unit mass, Kg/m ²
Upper Face sheet	1	Randomly	0.45
	2	Woven	0.80
	3	Woven	0.80
	4	Woven	0.80
	5	Woven	0.80
Lower face sheet	1	Woven	0.80
	2	Woven	0.80
	3	Woven	0.80
	4	Randomly	0.45

Table 2
Properties of Airex® C70.55 foam core

Density, Kg/m ³	Tensile strength, N/mm ²	Tensile modulus, N/mm ²	Shear modulus, N/mm ²
60	1.3	45	22

2.2. Face sheet's tests

Tensile properties of face sheets were measured by ASTM D3039/3039M-08 [12] and specimens were prepared according to the ASTM suggestion. Tests were performed at room temperature 23°C and at high temperature 60°C with a crosshead speed of 2 mm/min. Shear properties were obtained according to ASTM D3518/D3518M-13 [13]. Strain gauge was used to determine the mechanical properties [14]. During tests, force versus stroke values were recorded. Obtained results are shown in Table 3.

Table 3
Mechanical properties of GFRP face sheets

	Poisson ratio		Modulus of elasticity, GPa			Shear Modulus, GPa
	ν_{12}	ν_{13}	E_{11}	E_{22}	E_{33}	G_{12}
Room temp.	0.26	0.3	21	21	10	3.7
60°C	0.24	0.28	19	19	8	3.5

2.3. DCB test procedures

DCB specimens were prepared with dimensions of $b = 25$ mm in width, $L = 200$ mm in length, and with $a_0 = 37, 57,$ and 77 mm initial crack lengths as shown in Fig. 1. Aluminium piano hinges were adhesively bonded to the face sheets. The bonding surface of the specimens were sanded with sandpaper, then wiped clean with an acetone to remove any contamination.

The test plan was constructed to investigate the strain energy release rate as a function of temperature and pre-crack. The two test temperatures, room temperature (23°C) and high temperature (60°C) and three different pre-cracks 37, 57, 77 mm (see Fig. 1) were investigated. At least 4 replicates for each test condition and pre-crack values were used to develop the final data. The mode I tests were carried out on a universal testing machine at room and high temperature condition as shown in Figs. 2 and 3 for different pre-crack values as mentioned. Displacement controlled tests were conducted at a crosshead displacement rate of 0.5 mm/min. Load and crosshead displacement were recorded throughout the test. Experiments were continued up to 50 mm crack progress. At least four each specimens were tested for each pre-crack and temperature condition.

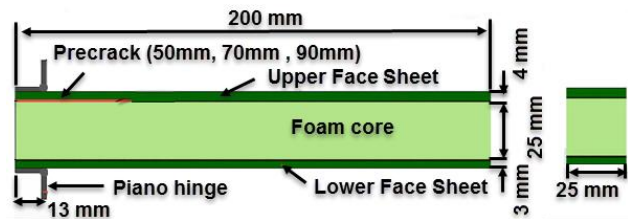


Fig. 1 DCB specimen details

At high temperature condition, after specimens were mounted to the machine, the jaws of the device and the specimen were entered into the cabin and waiting for 30 minutes to reach the stable 60°C to perform test.



Fig. 2 DCB test setup



Fig. 3 Cabin with 60°C temperature

Methods for calculating energy release rates

The mode I critical energy release rates can be calculated by methods explained in ASTM Standard D5528 [15]. These consisted of a modified beam theory (MBT), a compliance calibration method (CC) and a modified compliance calibration method (MCC).

Modified Beam Theory (MBT)

The beam theory expression for the strain energy release rate of a perfectly built-in (that is, clamped at the delamination front) double cantilever beam is as follows:

$$G_{IC} = \frac{3P\delta}{2ba}, \quad (1)$$

where P is load; δ is load point displacement; b is specimen width and a is delamination length.

In practice, this expression will overestimate GI because the beam is not perfectly built-in (that is, rotation may occur at the delamination front). One way of correcting for this rotation is to treat the DCB as if it contained a slightly longer delamination, $a + |\Delta|$, where Δ may be determined experimentally by generating a least squares plot of the cube root of compliance, $C^{1/3}$, as a function of delamination length (Fig. 4). The compliance, C , is the ratio of the load point displacement to the applied load, δ/P . The values used to generate this plot should be the load and displacements corresponding to the visually observed delamination onset at the edge and all the propagation values. Mode I interlaminar fracture toughness is calculated as follows:

$$G_{IC} = \frac{3 \times P \times \delta}{2 \times b (a_0 + |\Delta|)}, \quad (2)$$

where P is load; δ is load point displacement; b is Specimen width; a_0 is initial delamination length and Δ is effective delamination extension to correct for rotation of DCB arms at delamination front.

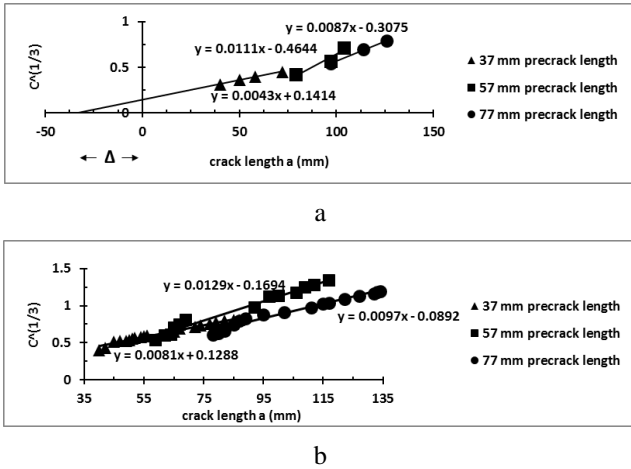


Fig. 4 Crack length versus $C^{1/3}$ for specimens: a - room temperature; b - 60°C

CC (Compliance Calibration) Method

Generate a least squares plot of $\log(\delta_i/P_i)$ versus $\log(a_i)$ using the visually observed delamination onset values and all the propagation values. Draw a straight line through the data which results in the best least-squares fit (Fig. 5). Calculate the exponent n from the slope of this line according to $n = \Delta y / \Delta x$, where Δy and Δx are defined in Fig. 5. Mode I interlaminar fracture toughness is calculated as follow:

$$G_{IC} = \frac{n \times P \times \delta}{b \times a}. \quad (3)$$

MCC (Modified Compliance Calibration) Method

Generate a least squares plot of the delamination length normalized by specimen thickness, a/h , as a func-

tion of the cube root of compliance, $C^{1/3}$, as shown in Fig. 6, using the visually observed delamination onset values and all the propagation values. The slope of this line is A^1 (Fig. 6). Mode I interlaminar fracture toughness is calculated as follows:

$$G_{IC} = \frac{3 \times P^2 \times C^{2/3}}{2 \times A^1 \times b \times h}. \quad (4)$$

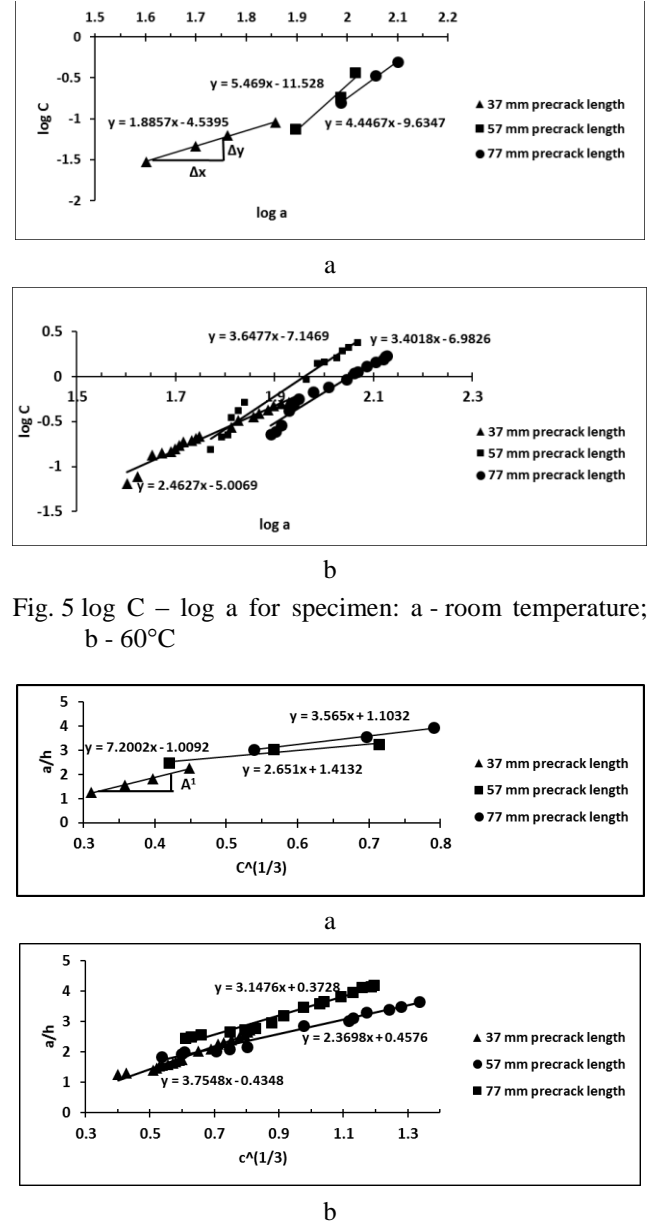


Fig. 5 $\log C - \log a$ for specimen: a - room temperature; b - 60°C

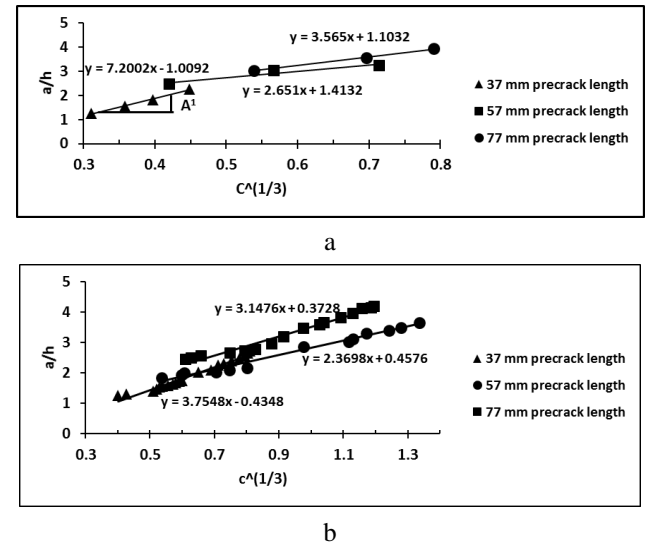


Fig. 6 a/h versus $C^{1/3}$ for specimen: a - room temperature; b - 60°C

3. Numerical analysis

The virtual crack closure technique (VCCT) is widely used for computing energy release rates, based on results from continuum (2D) and solid (3D) finite element (FE) analyses. VCCT was first proposed by Rybicki and Kanninen [16] based on the principles of Linear elastic fracture mechanics (LEFM). It is an effective method in solving delamination problems and used in modelling delamination growth in composites [17]. Krueger [10] covers the technique and its applications extensively.

VCCT is based on the assumption that the strain energy released in the crack propagation process is equal to the energy required to close the crack to its original state. The advantage of VCCT is its numerical simplicity and effectiveness. The calculation of Mode I strain energy release rate G_I for each eight node element position along the delamination front can be summarized by the following equation:

$$G_I = -\frac{1}{2\Delta A} R_y \Delta V, \quad (5)$$

where ΔA is the crack extension area; R_y is the vertical force at the crack tip and ΔV is the vertical displacements between the top and bottom nodes of the crack face in y direction. (Fig. 7).

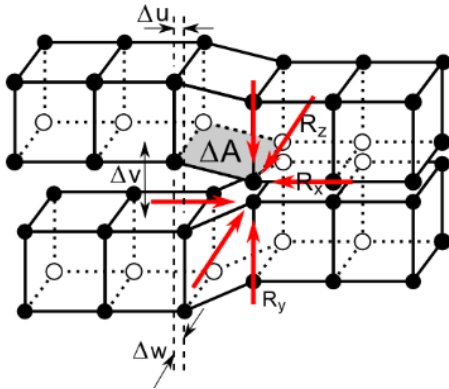


Fig. 7 VCCT for eight-node solid element [18]

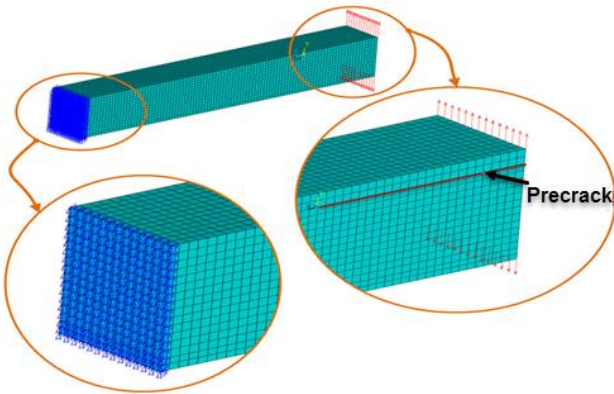


Fig. 8 3-D finite element model of DCB specimen

Mode I delamination was simulated using the Ansys 15 (Fig. 8). 3D finite element model (SOLID185, eight-node element) has been used for modelling of structure. Delamination is modelled as a discrete discontinuity in the plane between upper face sheet and foam of DCB specimen with separate unconnected nodes on the upper and lower surfaces of the delamination section. The upper face and lower face is divided into 1000 elements and core is divided into 2500 elements totally. The critical SERR has been calculated using the virtual crack closure technique (VCCT). Material properties used are shown in Tables 2 and 3. All dimensions and boundary conditions are similar to the real experimental set-up, in order to provide acceptable comparisons. In this section, the loads corresponding to the point of non-linearity of the load-displacement curve in the DCB specimen were used to calculate the critical strain energy release rates, using non-

linear elastic finite element models and Ansys implementation of VCCT.

4. Results and discussion

In order to characterize the critical SERR, mean values were computed by using all the data over the entire range of effective crack length. The critical SERR was found by using all three methods; MBT, CC and MBC. Table 4 provides the computed values of strain energy release rate for three different methods and pre-crack values at room and high temperature and the characteristic SERR versus crack propagation for one of the specimen is given in Fig. 9. It is seen that after crack initiation, the SERR values were approximately constant for different three methods.

The effect of pre-crack length on the critical SERR (G_{IC}) for DCB tests of sandwich composite specimens at room temperature is compared and the standard deviations from the mean value were shown in Fig. 10. The mean and standard deviation values are given in Table 4. DCB tests showed a negligible increase in critical SERR by increasing the pre-crack length. The specimens with 37 mm pre-crack length experienced a less SERR value (approximately 8 %, 27% and 43% in MBT, CC and MCC methods, respectively) by comparing with 57 mm and 77 mm pre-crack length. Figure 10 also shows that the results of CC and MBC methods are close each other.

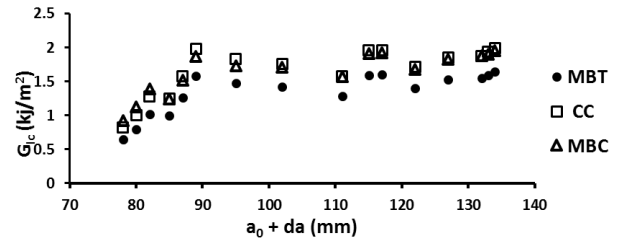


Fig. 9 Comparison of the critical SERR values G_{IC} versus crack propagation for three methods for specimen with initial crack $a_0 = 77$ mm at 60°C temperature

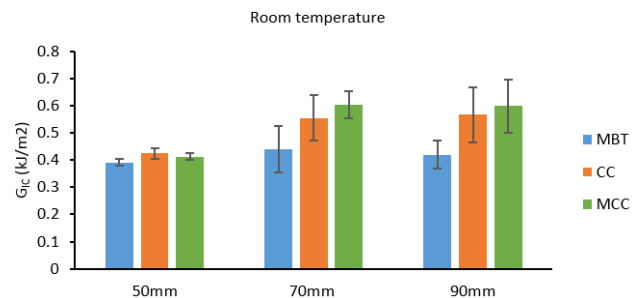


Fig. 10 Comparison of mean G_{IC} calculated from the three methods at room temperature

The effect of pre-crack length on the critical SERR (G_{IC}) for DCB test specimens at 60°C is compared in Fig. 11 with the standard deviations from the mean value. The mean and standard deviation values are given in Table 4. DCB tests showed a negligible increase in critical SERR by increasing the pre-crack length as it is seen in high temperature 60°C . The specimens with 37 mm pre-crack length experienced a less SERR value (approximately 11%, 13% and 14% in MBT, CC and MCC meth-

ods, respectively) by comparing with 57 mm and 77 mm pre-crack length. Fig. 11 also shows that the results of CC and MBC are approximately close each other.

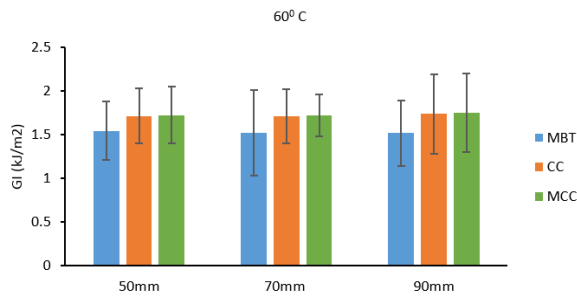


Fig. 11 Comparison of mean G_{IC} calculated from the three methods at 60°C

Table 4

Critical SERR value of GFRP sandwich composites with different pre-crack length at different temperature

Temperatures and pre-crack lengths		Room temperature			60°C		
		37 mm	57 mm	77 mm	37 mm	57 mm	77 mm
Mean G_{IC} , KJ/m ²	MBT	0.39	0.42	0.42	1.54	1.71	1.72
	CC	0.44	0.56	0.59	1.51	1.71	1.72
	MCC	0.42	0.60	0.60	1.52	1.73	1.75
	VCCT	0.44	0.58	0.58	1.45	1.84	1.89
Std dev G_{IC} , KJ/m ²	MBT	0.01	0.08	0.05	0.05	0.12	0.25
	CC	0.02	0.08	0.10	0.20	0.31	0.12
	MCC	0.01	0.04	0.09	0.26	0.23	0.17

5. Conclusions

The objective of this work was to determine the mechanical properties and delamination resistance of the facesheets/core interface at room and high temperature of sandwich panels. The woven GFRP and PVC Airex® C70.55 were used as facesheets and core, respectively to produce the sandwich composite plate. The mechanical properties were obtained at room and high temperature. It is seen that the mechanical properties; Poisson's ratio, modulus of elasticity and shear modulus decrease with increasing temperature. Experiments were performed to determine the effect of temperature and pre-crack length on the interfacial toughness of sandwich composites. MBT, CC and MCC methods were used to investigate the critical SERR, G_{IC} , from experimental results of DCB tests. The virtual crack closure technique (VCCT) was used and 3D finite element analysis has been performed to obtain the SERR value of specimens for various pre-crack lengths. It is seen that there is a good agreement between CC, MCC and VCCT. Therefore, VCCT analysis is to be an appropriate method for analyzing a SERR value of sandwich composites. Examining the SERR results from all methods of sandwich materials, it is determined that G_{IC} depends on test temperature. If the SERR values at high temperature (60°C) are compared with the SERR values at room temperature (23°C), it is seen that the results obtained at high temperature are fairly large with respect to room temperature. It is significant that SERR value increases with an increase in temperature. Fracture toughness parameter depends on temperature effect [19]. Therefore, DCB test results provided that high temperature has significant effect on the Mode I interlaminar fracture toughness of sandwich composites.

As seen in the Table 4, at room temperature, if we compare the MBT method with others, fair results were obtained with this method. The obtained results indicates that the pre-crack length has inconsiderable effect on the critical SERR value. The high temperature has considerable effect on the results of the SERR values. 37 mm pre-crack length of DCB tests at high temperature (60°C) experienced approximately 75%, 71% and 72%, reductions in MBT, CC and MCC methods, respectively by comparing results in room temperature. At high temperature we can see 57 mm and 77 mm as well as 37 mm pre-crack lengths showed 75%, 67% and 65%; 76%, 65% and 66% reductions, respectively in MBT, CC and MCC methods by comparing results in room.

It is also concluded that long pre-crack length has negligible effect on the SERR value in DCB tests. In other words, the Mode I interlaminar fracture toughness of sandwich composites was unaffected by pre-crack length. Good agreement has been found between fracture toughness values determined using finite element method VCCT and experimental DCB tests.

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Meltem Evren Toygar, Farshid Khosravi Maleki

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S u m m a r y

In this paper, the temperature and pre-crack effects on the delamination resistance of woven glass fibre reinforced polymer (GFRP) sandwich composites under Mode I loading was experimentally investigated and numerically modelled. For this purpose, the sandwich composite panel was fabricated with vacuum assisted resin infusion molding (VARIM). The mechanical properties were obtained at room and high temperature. Double cantilever beam (DCB) test was adopted for the measurement of delamination resistance by evaluating the strain energy release rate (SERR) value to obtain the fracture properties of woven GFRP sandwich composites. The three analytical methods, the experimental compliance calibration method (CCM), Modified Compliance Calibration Method (MCC) and Modified Beam Theory (MBT) have been used. In the finite element analysis virtual crack closure technique (VCCT) was used. The results obtained from 3D finite element analysis for various delamination lengths compare well with the experimental results. It is seen that there is an agreement between experimental and numerical results so that VCCT analysis is to be an appropriate method for analysing a SERR value of sandwich composites.

Keywords: Interlaminar fracture toughness, woven GFRP sandwich composites, DCB test method, virtual crack closure technique (VCCT).

Received April 07, 2016

Accepted September 07, 2016