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An Experimental and Numerical Study of the Dynamic Response of Glass/Epoxy Composites under Impact Loading at Low Temperatures

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An analytical method was applied to investigate the effects of strain rate and low temperature on the energy absorption of composite specimens. The performance of analytical model was found to be adequate for modeling composites before failure initiation. Results indicated that impact performance of composites is affected over the range of temperature considered. Failure mechanism was changed from matrix cracking at room temperature to delamination and fiber breakage at low temperatures. Also it was shown that about 70 percent of total energy absorbed by specimen was used for destruction of the composite under different types of failure mechanisms.
Keywords: strain rate, charpy impact, failure mechanisms, energy absorption, analytical method.

1. INTRODUCTION

Application of fiber reinforced composite materials has been increased in many structures such as airplane, which in flight condition undergoes temperature as low as -60°C or in a cryogenic tank, which may be exposed to temperature below –150 °C [1 – 2]. On the other hand, composite materials have the potential of reducing costs in construction, operation and development while improving structural reliability and enhancing safety. Because of these unique specifications, they are widely used in high technology structural applications, such as aeronautic and aerospace. A number of researchers have investigated the low velocity impact behavior of laminated composites at different temperatures. Atas, et al. [3] investigated impact response of unidirectional glass/epoxy laminates by considering energy profile diagrams and associated load–deflection curves. Aktas, et al. [4] presents an overall view on impact response of woven fabric composite plates made of E-glass as reinforcing material and epoxy resin as matrix material. Ibekwe, et al. [5] analyzed the effect of environmental temperature on the impact damages and on the residual compressive buckling strength and elastic modulus. Salehi et al. [6] demonstrated results of an experimental study on Kevlar/fiber glass composite laminates subjected to impact loading at variable temperatures. Kalthoff [7] characterized the dynamic failure behavior of a glass/epoxy composite at different temperatures by means of instrumented Charpy impact testing. Hufenbach, et al. [1] has illustrated an experimental and numerical investigation on Charpy impact tests for different configuration of carbon fiber composite specimens. Kishimoto et al. [8 – 9] illustrated a simple formula for dynamic fracture mechanics and stress intensity factor of pre-cracked Charpy specimens based on Timoshenko's beam theory. Lorriot et al. [10] investigated on a methodological improvement of dynamic fracture toughness evaluations using an instrumented Charpy impact tester. They also analyzed the dynamic behavior of instrumented Charpy impact test using specimen deflection measurement and mass-spring models [11]. Lorriot [12] determined specimen loading by displacement measurement in instrumented Charpy impact test. Kalthoff [13] illustrated a review on previous development in measurement of dynamic fracture toughness. Gopalaratnam et al. [14] developed a simple mass-spring model with two degrees of freedom for testing cement-based composites by instrumented Charpy impact device.

The major innovations of the current paper are 1) The effect of time exposure at low temperatures on the mechanical response of quasi-isotropic composites, which is a lay-up more commonly used for industrial applications, is investigated. 2) Influence of low temperature on the maximum absorbed energy, elastic energy and failure mechanism are highlighted in a temperature range of (–30 °C to 23 C). Also the effect of geometry index is determined in details. 3) Strain rate effect simultaneously with low temperature on the initiation failure energy of composites under impact loading was determined using a mass-spring model with two degrees of freedom.

2. MATERIALS AND SPECIMEN GEOMETRY

Unidirectional glass fiber-reinforced epoxy was used to prepare laminates with quasi-isotropic stack sequence. For this reason, hand lay-up method was used to fabricate thin laminate composed of fifty plies of reinforcement with epoxy resin ML-506 with hardener HA11, giving a laminate approximately 10 mm in thickness with fiber volume fraction of 65 %. Charpy test specimens were cut from laminates with 10 mm width. Test specimens geometry, the procedure of loading and evaluating the measured data are explained in ISO 14556 [15]. Fig. 1 illustrates the standard dimension and prepared typical test sample for the impact tests.

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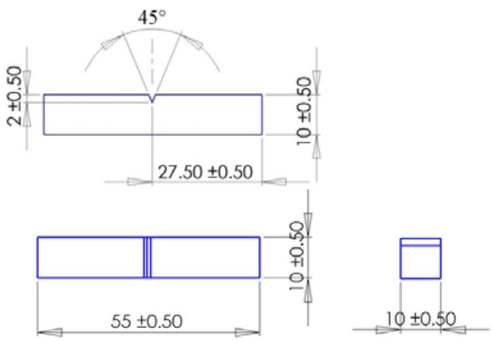

a

b

Fig. 1. Standard dimension (a) and typical fabricated specimens (b) for Charpy impact test

3. ANALYTICAL MODEL

In order to evaluate initial energy absorption of composite specimen to start failures, specimen displacement should be measured during the impact test with a laser transducer. However, as pointed out by Marur et al. [16] and Lorriot et al. [11], the influence of anvil/specimen interaction and overhang portions of specimen are not taken into account in such models. Also it seems quite difficult to refine the formulation with these new variables. Lorriot has recently proposed a procedure only based on the specimen deflection measurement during Charpy impact tests [20]. A two degrees of freedom mass-spring system as shown in Fig. 2 was applied to model the Charpy impact test. This model was evaluated and found for composite materials that can be used up to failure initiation. Because composite materials are orthotropic, many complicated failure modes occurred during failure mechanism, so the behavior of such materials will be nonlinear after the first ply failure load (FPF), which cannot be simulated by the present model.

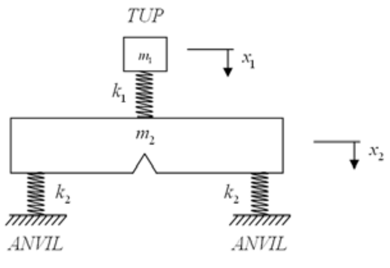

Fig. 2. The mass-spring model for analytical impact test

So by applying the current model, only initial energy needed to begin the failure can be calculated and compared at different temperatures. This analytical model is based on the following equations of motion for the mass-spring system [20]:

$$\ddot{x}_1 + \frac{\alpha}{M}\omega_s^2 x_1 = \frac{\alpha}{M}\omega_s^2 x_2\,; \tag{1}$$

$$\ddot{x}_2 + (\alpha+1)\omega_s^2 x_2 = \frac{\alpha}{M}\omega_s^2 x_1\,. \tag{2}$$

Williams [17] showed that the contact stiffness k_1 is taken as follows:

$$k_1 = \alpha k_2\,, \tag{3}$$

where α is a constant and can be determined experimentally. In the above equations M is m_1/m_2 and ω_s is the natural frequency of the specimen, which are defined as:

$$\omega_1^2 = \frac{1}{M}\frac{\alpha}{\alpha+1}\omega_s^2\,; \tag{4}$$

$$\omega_2^2 = (\alpha+1)\omega_s^2 \tag{5}$$

with the proper initial conditions for the impactor and the specimen:

$$x_1 = V_0(\alpha+1)\frac{1-M\dfrac{\alpha+1}{\alpha}}{1-M\dfrac{(\alpha+1)^2}{\alpha}}\frac{\sin\omega_1 t}{\omega_1} - \frac{\alpha V_0}{1-M\dfrac{(\alpha+1)^2}{\alpha}}\frac{\sin\omega_2 t}{\omega_2}\,; \tag{6}$$

$$x_2 = V_0\alpha\frac{1-M\dfrac{\alpha+1}{\alpha}}{1-M\dfrac{(\alpha+1)^2}{\alpha}}\left[\frac{\sin\omega_1 t}{\omega_1} - \frac{\sin\omega_2 t}{\omega_2}\right]. \tag{7}$$

The impact load p_1 and the specimen loading p_2 are expressed by:

$$p_1 = \frac{V_0\alpha k_2}{1-M\dfrac{(\alpha+1)^2}{\alpha}}\left[\left(1-M\frac{\alpha+1}{\alpha}\right)\frac{\sin\omega_1 t}{\omega_1} - M(\alpha+1)\frac{\sin\omega_2 t}{\omega_2}\right]; \tag{8}$$

$$p_2 = V_0\alpha k_2\frac{1-M\dfrac{\alpha+1}{\alpha}}{1-M\dfrac{(\alpha+1)^2}{\alpha}}\left[\frac{\sin\omega_1 t}{\omega_1} - \frac{\sin\omega_2 t}{\omega_2}\right]. \tag{9}$$

Every parameter (k_1, k_2, m_1, m_2) has to be determined first in order to use mass-spring model for specimen loading estimation. The specimen stiffness k_2 is the stiffness of a cracked bending Timoshenko beam [20]:

$$k_2 = \frac{48EI}{S^3}\frac{1}{1+\dfrac{E}{kG}\left(\dfrac{W}{S}\right)^2 + 3\dfrac{D}{I}}\,. \tag{10}$$

Following the specimen geometry given in Fig. 2, I is the moment of inertia of an un notched beam and k is a shear coefficient expressed as:

$$k = \frac{10(1+\upsilon)}{12+11\upsilon}\,. \tag{11}$$

And D is defined by:

$$D = \frac{2\left(1-\upsilon^2\right)WV\left(\dfrac{a}{W}\right)}{I}\,, \tag{12}$$

in which $V\left(\frac{a}{W}\right)$ has been determined by several papers to estimate the influence of the notch [20]. E, G, and υ are respectively off-axis Young's modulus, shear modulus and in-plane Poisson's ratio for composites. Now the specimen loading can be estimated if the contact stiffness or the specimen ratio α is known. A method without additional tests has been proposed by Lorriot et al. [12]. This procedure determined the specimen ratio based on just specimen deflection during the impact test. By this method, specimen ratio has been taken as 6.7.

Now by following Newton's law, the displacement, $x(t)$, of the specimen during the test is calculated according to the relationships:

$$v(t) = V_0 - \left(\frac{1}{m_1}\right)\int_0^t p_1(t)dt\,; \qquad (13)$$

$$x_1(t) = \int_0^t v(t)dt\,. \qquad (14)$$

$v(t)$ is velocity of the striker during the test. The energy input into the specimen during the test is then given by:

$$U = \int_0^{x_1} F(x_1)dx_1\,. \qquad (15)$$

Integration over the entire loading and failure process of the specimen, i. e. up to displacements at which the loading force has decayed to zero values again, yields the total energy U_{total} for breaking the specimen. This energy agrees with the energy that would be determined from the difference of the heights of the striker before and after the test [13]. But the presented model, as mentioned before, is only available before failure initiation in composite specimens. So by applying this model, partial energy U_{init} absorbed by the specimen from the moment of the beginning of the impact event up to FPF take place in the specimen can be calculated. This part of energy absorption U_{init} represents a quantity characterizing the initiation of failure in specimens. The rest of energy absorbed by the specimen is used for crack propagation and formation other mechanisms of failure in the composite.

4. RESULTS

Wolpert Charpy impact tester Model D-6700 is used, which provides maximum impact energy of 300 J with a maximum impact velocity of 5 m/s and a 20 kg hammer, depending on the chosen drop height up to 1.55 m (Table 1).

Table 1. The condition of impact test device for various impact energies

	Impact energy (J)		
	10	15	30
Initial angle of hammer (deg)	20.5	25.5	36.0
Impact speed (m/s)	1.00	1.22	1.73
Drop height (mm)	50.66	77.93	152.70

Experimental tests were performed at four points in desired temperature range (–30 °C, –15 °C, 0 °C and 23 °C (room temperature)). Low temperatures are performed using a special industrial refrigerator. In each case result of experimental tests, fitted curve and its correlation coefficient (R) are illustrated. Results of the current study include absorbed impact energy, failure mechanism and microscopic examination of glass/epoxy composite specimens. Also, the effects of testing temperature, geometry index and exposed days at low temperature are examined.

In this study for all cases, impact energy of 30 J is selected, unless otherwise specified. Maximum energy absorbed by specimens at different temperature and geometry index after one and ten days exposure time is shown in Fig. 3.

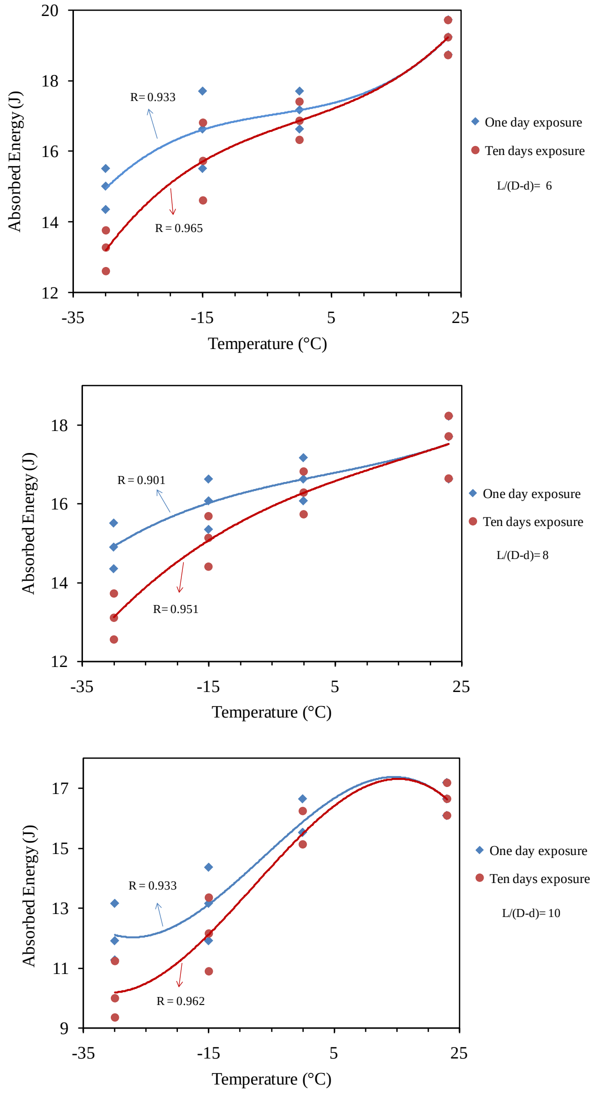

Fig. 3. Maximum absorbed energy versus temperature for longitudinal impact test at different geometry index

Geometry index is defined as effective span to depth ratio $L/(D–d)$ where D is the depth of the specimen and d is the notch depth. Tests are repeated for ratios of 6, 8 and 10. Maximum absorbed energy is also influenced by specimen span-to-depth ratio. By changing this ratio from 6 to 10, maximum absorbed energy decreases about 25 % at a constant temperature and impact energy. This is because of reducing the net area of specimens against impact loading. Fig. 4 shows the effect of geometry index on absorbed energy at different temperatures after one day exposing. As temperature decreases, internal damage area decreases significantly. A mechanical property that is used to sense fracture properties of the composite is toughness. Toughness can be defined as a measure of the ability of a material to absorb energy up to fracture. The formation and growth of micro cracks is one such mechanism of energy absorption. Therefore, a decrease in micro crack accumulation with decreasing temperature corresponds to a decrease in matrix toughness with decreasing temperature; the composite is unable to absorb as much energy before complete specimen failure at low temperatures as it is able at higher temperatures. This phenomenon is repeated for specimens tested at low temperatures after one and ten day exposure times.

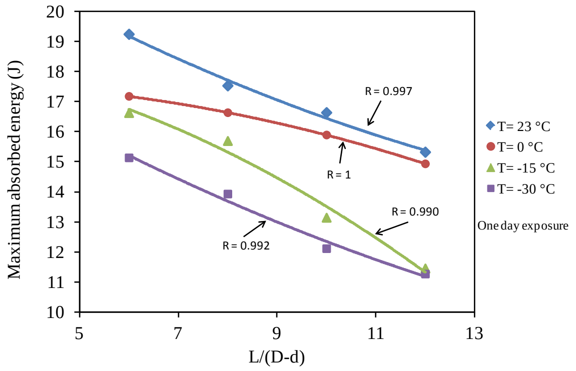

Fig. 4. Absorbed energy of impact test versus span length-to-depth ratio after one day exposing, $L/(D–d)$

Fig. 5 shows a typical specimen under longitudinal direction (the notch tip base line is oriented perpendicular to the normal of the plane) at –30 °C. Failure in this case does not take place along the glass reinforcements of the specimen. Instead, in all cases, delamination failures of the specimens are observed in one side of the specimens. The matrix material fails along the weak interface planes between the plies of glass fiber reinforcements.

Fig. 5. Failure of a glass-epoxy specimen impacted in longitudinal direction at low temperature

Shear stress due to geometrical constraints at large bends angles of the specimen cause the delamination failure type. Delaminated parts near the compressive side of the specimen show breaking of the glass fiber reinforcements near the contact area of the impacting striker with the specimen. In some cases, the specimen broke off completely and the delamination is larger at the impact side of the specimen. However, no effects of fiber breakage in the notch tip area under the influence of tensile stresses are observed at room temperature. The specimen after the test tends to resume its original straight position and almost completely bends backwards with the delaminated parts remaining deformed to a certain extent. On the other hand, failure is caused by fracturing of the matrix material along the weak interface planes between the plies of laminates and fiber breakage is of no or only little influence. At this energy level (30 J) and at room temperature, the major mechanism governing energy absorption is matrix cracking. As mentioned before, formation and growth of microcracks at different temperatures is major mechanism of energy absorption [10 – 11]. Also small delamination between plies is another failure mechanism at room temperature. But by decreasing temperature from room temperature, composite constituents become more brittle and are less able to blunt cracks. So, other failure mechanisms take place. As temperature decreases, internal damage area increases significantly. Visual examination revealed this increasing internal damage area to be associated with ply delamination. Thus, the fact that with decreasing temperature, delamination increased, suggests that the interalaminar bonds degrade with decreasing temperature. Also by decreasing temperature, fiber breakage is another failure mechanism, which occurred near specimen's notch. This indicates that at low temperatures, the mechanisms mainly responsible for absorbed energy of laminates are delamination and fiber breakage [18]. Fig. 6 depicts the specimen load-time curve obtained by this method for a notched specimen impacted with an initial impact velocity of 1 m/s. Impact loads measured on the hammer by [20] and computed with Eq. (8) are also plotted to evaluate validity of the present method. The reliability of the method depends strongly on the good match observed between the predicted and measured tup loads. In this case, the agreement between two loads is not fully satisfactory.

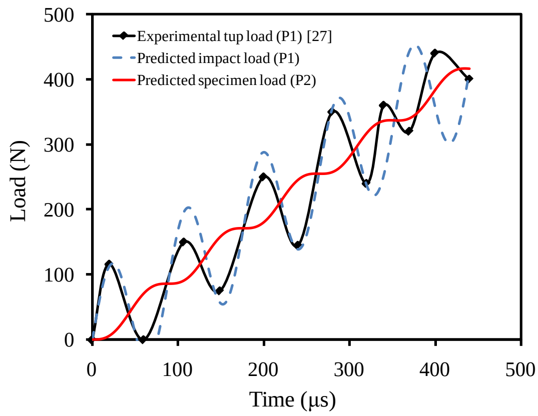

Fig. 6. Experimental measured [27] and predicted impact load-time curves and specimen load-time curve derived from Eq. (8)

Marur et al. [16] and Lorriot et al. [11] have shown that beam overhang and anvil/specimen interactions must be taken into account in the model to get more reliable results. Nevertheless, the formulation refinement with these new variables appears rather delicate.

After model evaluation with some experimental results, it can be used for composite materials to predict initial energy U_{init} absorbed by the specimen from the moment of the beginning of the impact event up to FPF take place in the specimen at room temperature and –30 °C. From available instrumented Charpy device, displacement-time curve cannot be derived. By applying the presented method, load-time and subsequently strain-time curves of specimen can be calculated from Newton's law at different temperatures. In order to do that, off-axis longitudinal stiffness (*E*) of quasi-isotropic composites at evaluated temperature was used from Ref. [18]. Based on numerical results of the model, strain rate for Charpy impact test, which is initial slope of strain-time curve, was 0.6 s^{-1} at both room temperature and –30 °C.

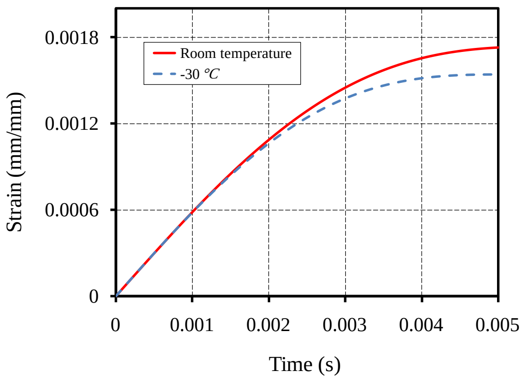

Fig. 7. Strain evolution versus time at room temperature and –30 °C

Fig. 7 shows strain-time curve for a notched glass/epoxy specimen under dynamic loading at room temperature and –30 °C.

As shown in the above figure, and reported by many other investigators, by decreasing temperature the strain to failure decreases significantly at a constant strain rate. Many researchers studied the effects of strain rates and temperature on the behaviour of UD composites [18 – 19, 22 – 26]. They demonstrated that mechanical properties of UD composite changed by both strain rate and low temperatures. Dynamic behaviour of glass/epoxy UD composites at strain rate of 0.6 s^{-1} was evaluated using experimental results reported by some authors [22 – 26] for room temperature and –30 °C. Using these data and applying classical lamination theory, FPF of quasi-isotropic at desired temperature can be calculated [27]. By these data collected from different available papers, and by integrating the area under the load-deflection curves (plotted by analytical model) at different temperatures from the moment of beginning up to outbreak of FPF of laminated composite, initial absorbed energy U_{init} by the specimen just before failure initiation will be calculated.

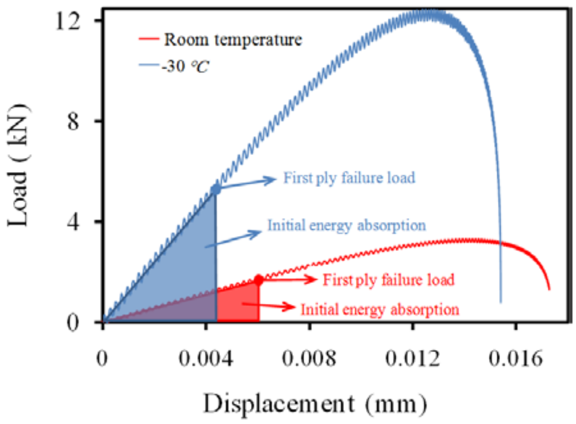

Fig. 8. Load-deflection curves for specimens under impact at room temperature and –30 °C

Fig. 8 depicts Load-deflection curves for room temperature and –30 °C. FPF loads and initial energy absorption in laminated composite specimens during impact loading are also shown in the diagram. As mentioned before, by decreasing temperature maximum deflection of specimen under impact loading decreases from 0.017 mm for room temperature to 0.0152 mm for –30 °C. This phenomenon can be explained by reducing fracture toughness of composites at low temperatures. This is because the material constituents become more brittle as temperature decreases and are less able to blunt cracks.

Table 2. First ply failure (FPF), initial energy *U*init and total energy absorption U_{total} for glass/epoxy laminated composite at different temperatures

	Mechanical properties		
	FPF (kN)	U_{init} (J)	U_{total} (J)
Room temperature	1.92	6.12	19.23
–30 °C	4.8	5.67	15.12

Table 2 summarizes results for side-on specimens with geometry index of 6 and glass/epoxy laminated composites under impact loading at different temperatures. As described by many authors [23 – 26] FPF load increased by decreasing temperature from room temperature. On the other hand, initial energy absorbed by specimen up to failure and total energy absorption decreased significantly (about 10 % for room temperature and 20 % for –30 °C) by decreasing temperature. Also it can be concluded that about 70 % of the total energy absorption by the specimen was spent to crack propagation and specimen failure at each temperature.

5. DISCUSION AND CONCLUSION

Dynamic properties of polymeric composite laminates under low rate impact at low temperatures were experimentally investigated. The configuration of laminates was quasi-isotropic. Low temperature and its weakening influence on the material properties including maximum absorbed energy, elastic energy and failure mechanism are highlighted. Moreover, the effect of geometry index is determined. An analytical mass-spring model with two degrees of freedom was applied to predict initial energy absorption of specimen (before FPF) based on dynamic behavior of UD composites at room temperature and –30 °C. The conclusions drawn from the results can be summarized as following:

1. By decreasing temperature from room temperature, maximum absorbed energy decreased about 25 %. It is also found that specimens after 10 days exposure to low temperature show slightly lower impact energy absorption (about 10 %) than the specimens with one day exposure at considered temperatures.
2. Results show that geometry index of specimens had significant influence on the ability of composite to absorb impact energy for different test temperatures.
3. By visual inspection, it is found that failure mechanism changes from matrix cracking at room temperature to delamination and fiber breakage at low temperatures.

4. Initial energy absorbed by specimen up to failure and total energy absorption decreased significantly (about 10 % for room temperature and 20 % for –30 °C) by decreasing temperature. Also it can be concluded that about 70 % of the total energy absorption by the specimen was spent to crack propagation and specimen failure at each temperature.
5. Results of the current research indicated that in spite of significant increase in mechanical properties of composites at low temperatures under static loading [18], impact response of composites reduced by decreasing temperature. This can be explained because of the fact that mechanical properties of composites are different under static and dynamic loading at low temperatures. This is because the material constituents become more brittle as temperature decreases and are less able to blunt cracks and consequently composite absorbed less energy during impact test.

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