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Dynamic failure behavior of glass/epoxy composites under low temperature using Charpy impact test method

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This paper demonstrates results of an experimental study on glass/epoxy laminated composites subjected to low velocity impact at energy levels equal to 10, 15 and 30 J under variable temperatures in the range of -30°C to 23°C. The configuration of specimens is quasi-isotropic. The low temperature and its influence on the maximum absorbed energy, elastic energy, crack length and delamination are highlighted. Also, the effects of geometry index (span-to-depth) and notch orientation are studied. Failure mechanisms of specimens are examined using microscopic examinations. Results indicate that impact performance of these composites is affected over the range of temperature considered. Failure mechanism is changed from matrix cracking at room temperature to delamination and fiber breakage at low temperatures.

Keywords: Dynamic failure, Glass/epoxy composites, Delamination, Notch orientation

Fiber reinforced composite materials have been increasingly used as structural members 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. The advantages of these materials are derived from their high strength, stiffness and damping together with low specific weight[1]. 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. Over the years, there has been mounting concern over the safety of laminated composites subjected to low velocity impacts. A low velocity impact on laminated composites can cause various types of damages including delamination, fiber breakage, matrix cracking and fiber-matrix interfacial de-bonding. These types of damage are very dangerous because some of them cannot be detected visually and lead to structural failure at loads well below design levels.

A number of researchers have investigated the low velocity impact behavior of laminated composites. Baker *et al.*[1] have studied the damage of laminated composites including, application of failure criteria, crack propagation, damage observation, effect of impactor mass, target geometry, impact velocity, initial stress and the residual strength. Hufenbach *et al.*[2] has illustrated an experimental and numerical investigation on Charpy impact tests for different configuration of carbon fiber composite specimens. Abrate[3] and Cantwell and Morton[4] have also given reviews on the impact of laminated composites that cover both theoretical and experimental aspects of the problem, such as impact modeling, impact damage, damage prediction and residual properties. Arnold *et al.*[5] showed the linear relationship between the damage and horizontal impact angle through the inclined impact test of chopped fiber reinforced composite materials. Broutman and Yeung[6] investigated the effect of fiber orientation angle on the impact properties of off-axis composites on E-glass/epoxy laminates. Also, they varied the interface conditions by changing the surface treatment of the glass fibers. The tensile and impact behavior of natural fiber-reinforced composite materials was studied by Tobias[7]. He concluded that if composites contained randomly oriented chopped fibers, then the energy absorption would be proportional to the fiber volume fraction. Impact response of sandwich structures at room temperature was investigated by

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some authors[8-12] and they have shown that both the face-sheet configuration and the core density control their impact behavior.

Some authors have studied the impact response of composite structures at low temperatures. Ibekwe *et al.*[13] analyzed the effect of environmental temperature on the impact damages and on the residual compressive buckling strength and elastic modulus. Khalid[14] investigated the effect of testing temperature, volume fraction, span length-to-depth ratio and fiber type on impact energy of composites. Kalthoff[15] characterized the dynamic failure behavior of a glass/epoxy composite at different temperatures by means of instrumented Charpy impact testing. He also showed the effect of notch orientation of specimen on total absorbed energy of composite specimen. Gomez *et al.*[16,17] studied the dynamic tensile behavior of CFRPs at low temperature by Hopkinson pressure bar test and drop weight tower device. Both unidirectional and quasi-isotropic laminates were considered.

With respect to literature survey, and by a gap analysis it is found that less attention was focused on behavior of composites under Charpy impact loading at low temperatures. In the earlier studies, the effect of low temperatures on absorbed energy, elastic energy and crack length of unidirectional composites were investigated. In the present study, 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. Influence of low temperature on the maximum absorbed energy, elastic energy, crack length and delamination length are highlighted in a temperature range of (-30°C to 23°C). Also the effects of geometry index and notch orientation are determined in details and finally, failure mechanisms of the specimens at each temperature are examined by a digital microscope.

Charpy Test

The principles of instrumented Charpy impact testing, in particular, the procedures for loading the specimen and for measuring and evaluating the data are briefly outlined in Fig. 1 and explained in ISO standard[25]. Tests are performed using Charpy specimens with standard size of $55 \times 10 \times 10$ mm^3 equipped with 45° V-shaped notches and 0.25 mm root radius at the tip of the notch. The specimen is supported by anvils of 40 mm support span. With Wolpert Charpy impact tester Model D-6700 by a pendulum hammer of a given mass. The specimen is impacted at velocities ranging from about 1 to 5.5 m/s, depending on the size of the pendulum test device and the chosen drop height. The total energy that is provided by the striking hammer accordingly ranges up to 300 J for a 20 kg hammer and a drop height of 1.55 m. In the original version of the test, the energy to break the specimen is simply determined from the difference of the heights of the striker before and after the test (h_1 and h_2, respectively, shown in Fig. 1).

Materials and specimen geometry

Material properties

E-Glass fibers, have been used in this investigation as the reinforcement material, while epoxy resin has been considered as a matrix material. Mechanical characterization tests have been conducted for a lamina and the results are listed in Table 1.

Specimen's fabrication

E-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. Charpy test specimens were cut from laminates with 10 mm width. The V-notch of 45° in two different directions

Table 1—Mechanical properties of unidirectional ply at room temperatures

Mechanical properties	23°C
Longitudinal modulus E_x (GPa)	19.94
Transverse modulus E_y (GPa)	5.83
Shear modulus G_{xy} (GPa)	2.11
Longitudinal tensile strength X_t (MPa)	700.11
Longitudinal compression strength X_c (MPa)	570.37
Transverse tensile strength Y_t (MPa)	69.85
Transverse compression strength Y_c (MPa)	122.12
Shear strength S (MPa)	68.89

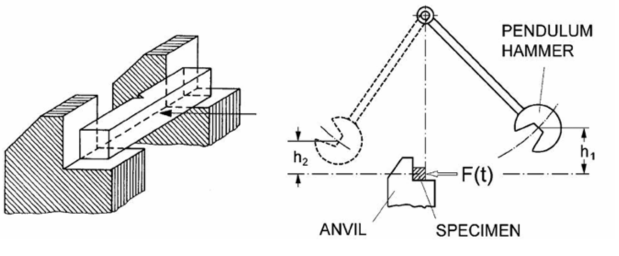

Fig. 1—Schematic of the instrumented Charpy impact test

and with different span length-to-depth ratios is prepared by a milling machine. The geometry of the specimen is shown in Fig. 2. The fiber volume fraction of the composites was evaluated experimentally after fabrication and found to be 65%. Figure 3 illustrates the prepared typical test sample for the impact tests.

Results and Discussion

Results of this study include the impact energy strength, failure mechanism and microscopic examination of glass/epoxy composite specimens. The effects of testing temperature, notch orientation, geometry index and exposed days at low temperature are also examined. A hammer of 20 kg with different impact speed and drop height was selected to reach different impact energies (Table 2)

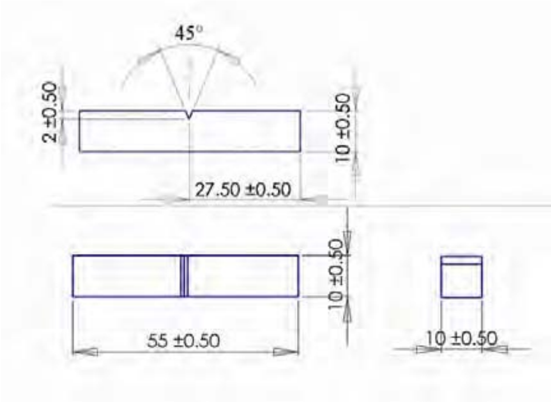

Fig. 2—The standard dimensions of an impact test specimens at different temperatures

Fig. 3—Samples of fabricated specimens for Charpy impact test

In this study for all cases, impact energy of 30 J is selected, unless otherwise specified. From the laminates in as-delivered condition, test specimens are machined with notches oriented in two different directions with respect to the plies, as shown in Fig. 4. For ‘edge-on’ notch orientations, the notch tip base line is oriented in the direction of the normal to the plane of the plies. For ‘side-on’ notch orientations, the notch tip base line is oriented perpendicular to the normal to the plane of plies. The damage and failure behavior of the glass-fiber are investigated for both notch orientations. The test temperature is varied over a large range from -30 to 23 °C. Cooling of the specimens is achieved using a special refrigerator. Testing of the specimens at these temperatures using Charpy pendulum device is performed following the specifications as given in ISO standard[25].

Tables 3 and 4 represent the maximum crack length and delamination length for various impact energy

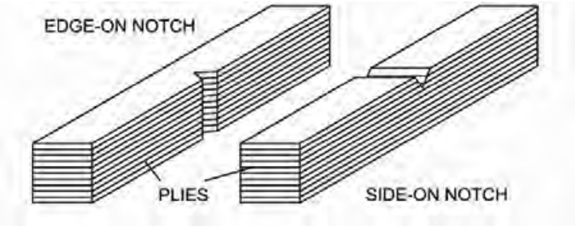

Fig. 4—Two different notch orientations on typical impact specimens

Table 2—The condition of impact test device for various impact energies

Impact energy (J)	10	15	30
Initial angle of hammer (°)	20.5	25.5	36.0
Impact speed (m/s)	1	1.22	1.73
Drop height (mm)	50.66	77.93	152.7

Table 3—Maximum crack length at different temperature and energy levels with side-on notch

Energy Level	Exposured day	Maximum crack length (nm)			
		-30°C	-15°C	0°C	23°C
10 J impact	1	20.8	19.7	17.54	16.2
	10	22.17	20.45	19.12	—
15 J impact	1	28.5	25.8	23.6	21.4
	10	29.35	27.15	24.5	—
30 J impact	1	34	31.5	30.1	28.2
	10	36.9	34.2	32.4	—

Table 4—Maximum delamination length at different temperature and energy levels with side-on notch

Energy Level	Exposured day	Maximum crack length (nm)			
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	10	22.17	20.45	19.12	—
15 J impact	1	28.5	25.8	23.6	21.4
	10	29.35	27.15	24.5	—
30 J impact	1	34	31.5	30.1	28.2
	10	36.9	34.2	32.4	—

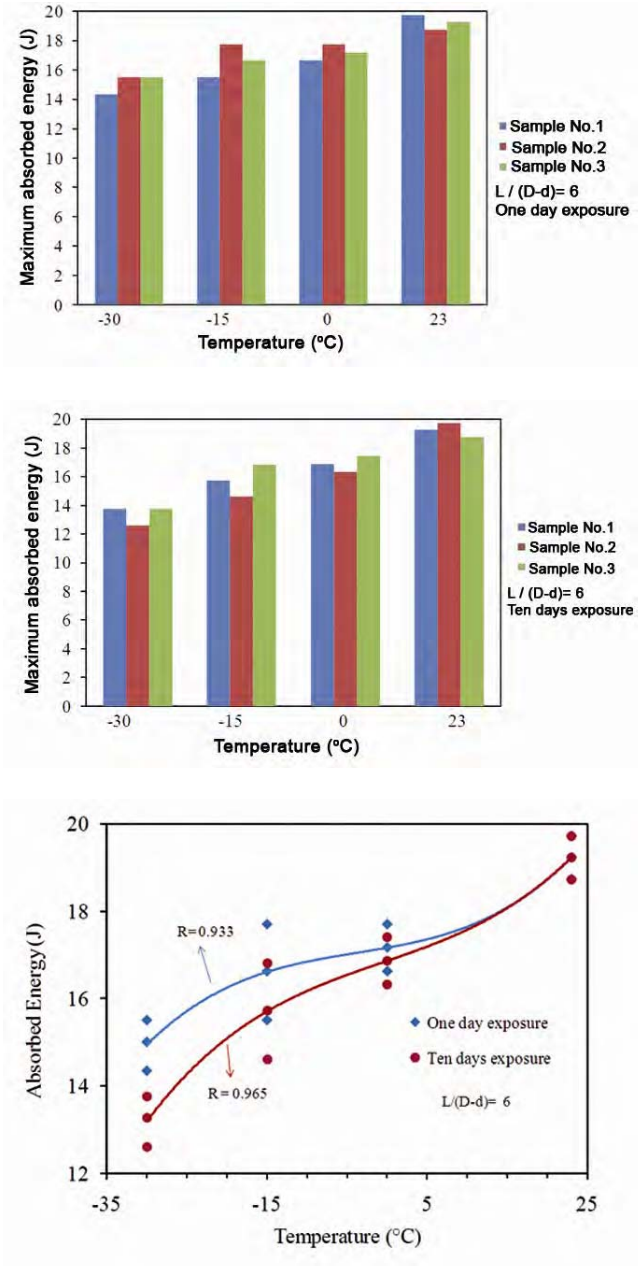


Fig. 5—Absorbed energy of impact test versus temperature for geometry index of 6

levels and different temperatures. Maximum crack length is defined as the largest crack formed along the matrix after impact and was measured with a digital microscope. Those lengths of the interlaminar cracks which lead to delamination between different plies of specimen are called delamination length and were visually measured. These results indicate that more favorable combination of crack length and delamination occurred at room temperature and less combination of them occurred at -30°C. It can be seen that with increasing temperature the maximum crack length decreased and the maximum delamination length increased considerably. This is due to a progressive decrease in microcrack accumulation within the specimen with decreasing temperature. This is because the material constituents become more brittle as temperature decreases and are less able to blunt cracks. But, maximum crack length increase with decreasing temperature. It can also be concluded that by increasing impact energy, maximum crack length and delamination length increased.

Fig. 5-8 show data for the absorbed energy by the specimens during the test for effective span-to-depth *L/(D-d)* ratios of 6, 8, 10 and 12, respectively. Where *D* is the depth of the specimen and *d* is the notch depth. The data are measured with side-on notch orientation at various test temperatures after one and ten day exposure time. In each case, by a polynomial curve fitting to experimental data, the trend of absorbed energy by temperature changes is shown. Also the values of *R* (the correlation coefficient) are given to show acceptable scatter of the tests. As shown in figures, by decreasing temperature from room temperature, the difference between absorbed energy for two test cases was increased. It can be derived that after 10 day exposure at -30°C, and at the room temperature, the absorbed energy has the lowest and highest values, respectively for all test cases. As temperature decreases, internal damage area decreases significantly. A mechanical property that is sensitive to the deformation characteristics of the composite is

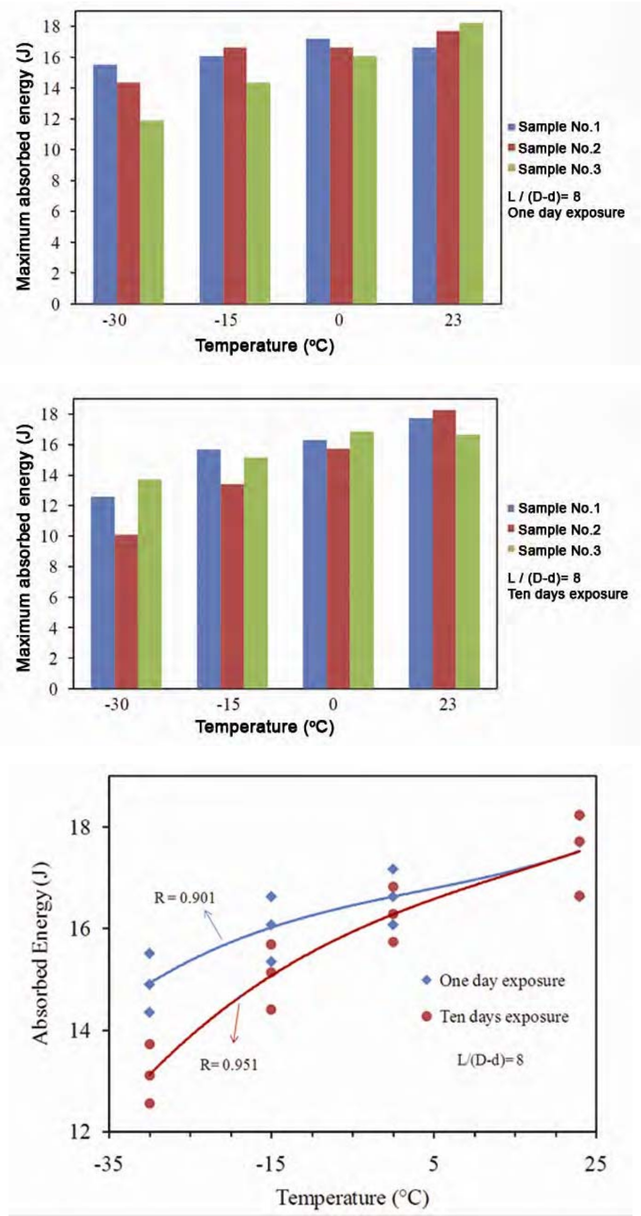


Fig. 6—Absorbed energy of impact test versus temperature for geometry index of 8

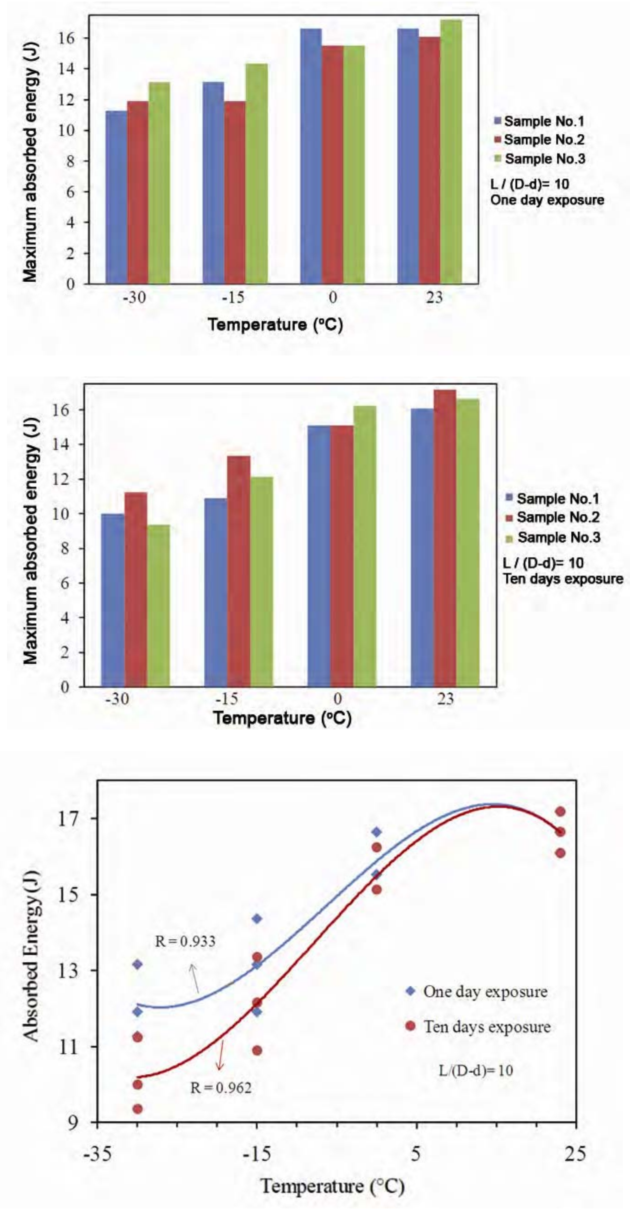


Fig. 7—Absorbed energy of impact test versus temperature for geometry index of 10

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 microcracks is one such mechanism of energy absorption. Therefore, a decrease in microcrack 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 at higher temperatures. This phenomenon is repeated for specimens tested at low temperatures after one and ten day exposure time.

The specimen span-to-depth ratio also has an effect on the impact energy performance. Changes in absorbed energy at considered temperature range after one and ten days exposure for different geometry ratio are shown in Fig. 9. It is observed that by increasing the geometry ratio, the absorbed energy by specimens decreased at considered temperature range. This is because the net area of composite against impact load is decreased by increasing geometry ratio.

Fig. 10 shows data for the total energy absorbed by specimens during the test. The data are measured for specimens with edge-on and side-on orientations at test

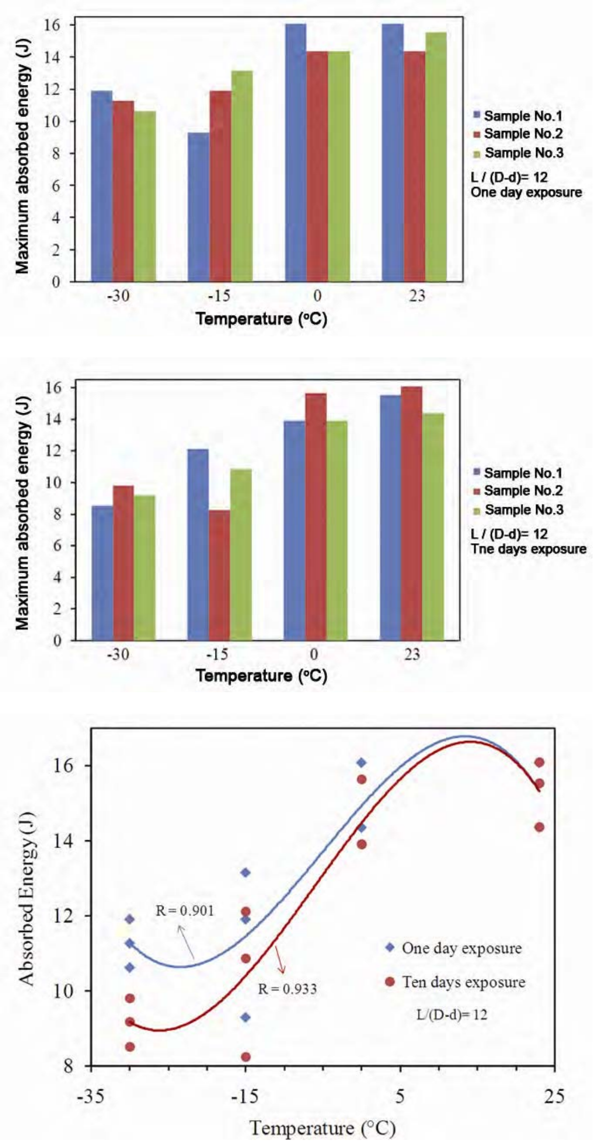


Fig. 8—Absorbed energy of impact test versus temperature for geometry index of 12

temperatures varying from -30°C up to 23°C. The total measured energies show an increasing tendency with increasing the temperature. This general tendency results for both notch orientations, namely edge-on and side-on notches, with the values for side-on orientations always being smaller than the values for edge-on orientations. The failure phenomenology of the specimens with different notch orientations is very different.

Fig. 11 shows a specimen with an edge-on oriented notch after the test. Failure takes place primarily along the glass reinforcements of the specimen. The matrix material is broken to a large extent and the glass fibers being extensively broken. The damage process is incomplete, it extends over a large portion of the glass reinforcements, but the two specimen halves are still held together by the remaining part of the fibers. The angle formed by the two halves of the broken specimen is larger than the angle the specimen had taken during the end phase of the test when being pushed by the striking hammer through the anvils (roughly 58° according to the given geometrical constraints). Thus, the specimen after the test bends slightly backwards towards its original shape.

Figure. 12 shows a specimen with a side-on oriented notch after the test. 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.

Shear stress due to geometrical constrains at large bend angles of the specimen cause the delamination failure type. Delaminated parts near the compressive side of the specimen show breaking of the glass fiber

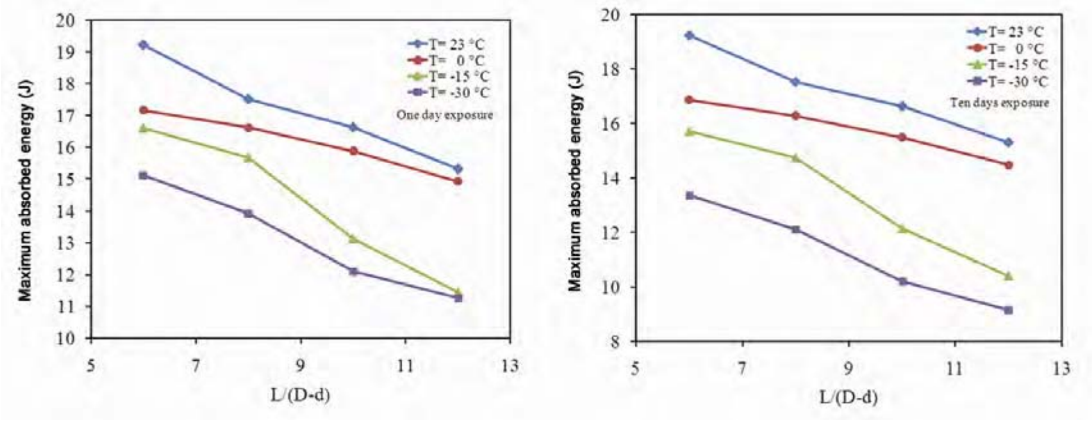


Fig. 9—Absorbed energy of impact test versus span length-to-depth ratio, *L*/(*D*-*d*)

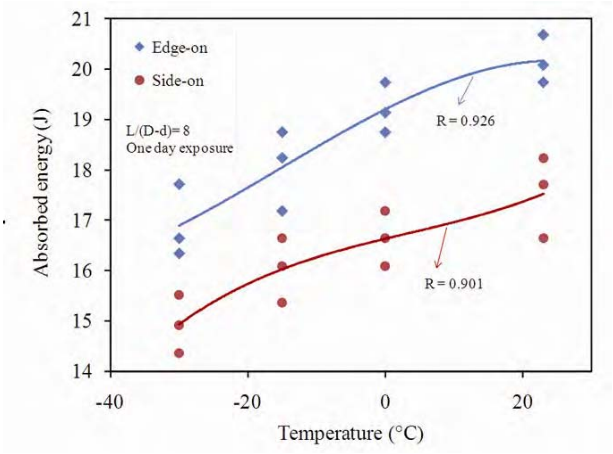


Fig. 10—Absorbed energy as a function of temperature for edge-on and side-on notch orientations

Fig. 11—Failure of a glass-epoxy specimen with edge-on oriented notch at room temperature

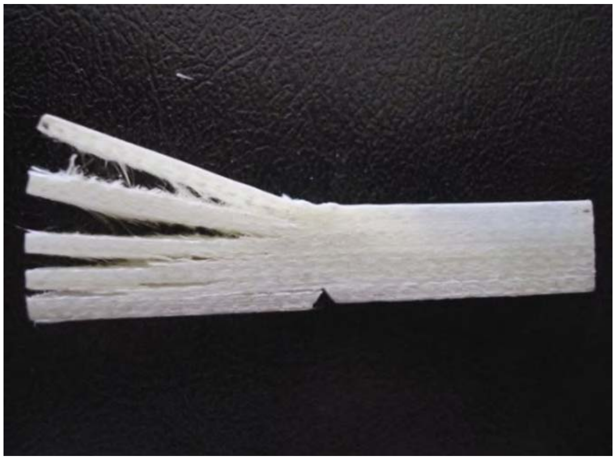


Fig. 12—Failure of a glass-epoxy specimen with side-on oriented notch at low temperature

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 extend. On the other hand, failure in the case of side-on notch orientations 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. This difference in the influence of fibers on the failure process explains the observed larger values of the absorbed energy for specimens with edge-on notch orientations compared with the equivalent data for side-on notch orientations. Figure. 13 shows sample of the fractured glass/epoxy specimens after impact testing temperature between -30 and 23°C.

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. 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 tack 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 temperature decreasing, fiber breakage is another failure mechanism which is 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.

Microscopic examination

Microscopic examination is taken for the tested specimens with Dinolite digital microscopy model AM 413 with magnification factor of 50. Figure. 14 shows glass/epoxy specimen with side-on notch after impact at -30 to 23°C. The specimen did not break into

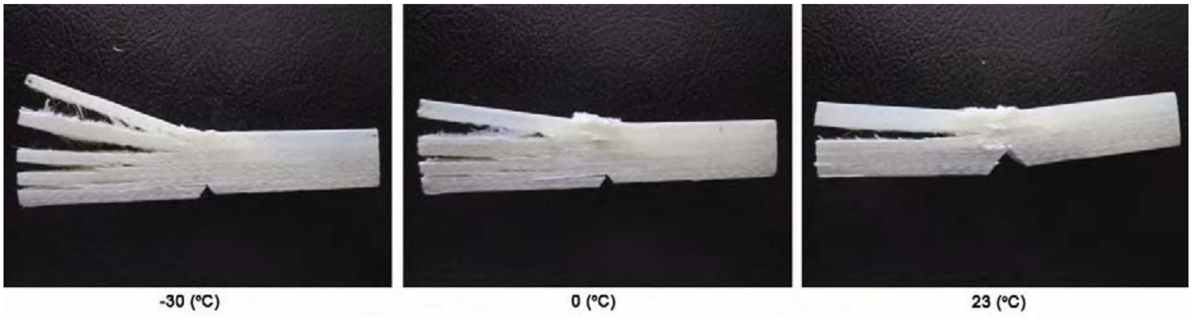
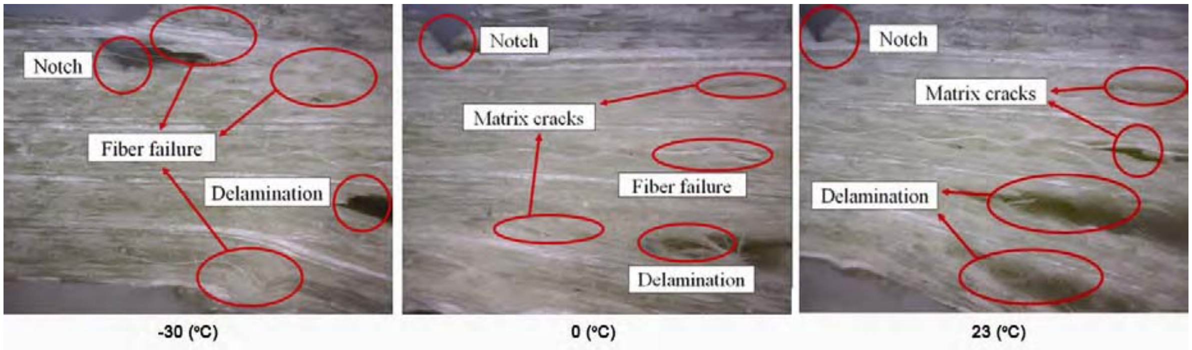

-30 (°C) 0 (°C) 23 (°C)

Fig. 13—Sample of fractured specimens with side-on notch orientation at different temperature after one day exposure



-30 (°C) 0 (°C) 23 (°C)

Fig. 14—Microscopic examination of fractured specimens with side-on notch orientation at different temperature after one day exposure

Fig. 15—Microscopic examination of fractured specimen with edge-on notch orientation after one day exposure at -30°C

two parts. As described above, slight fiber failure was found at the notch where the crack initiation occurred also at the center of the specimen. In general, the main failure mode at room temperature were matrix cracking along the weak interface planes between the plies of glass fiber reinforcements, where by decreasing the test temperature, more delamination was observed. Also at low temperatures, fiber breakage is one of the major mechanisms of failure in composites.

Also, Fig. 15 shows a sample of the edge-on tested specimens at -30°C, when subjected to impact loading. In this case, failure concentrates on the glass reinforcements; glass fiber breakage under the influence of tensile stresses ahead of the notch is the most common failure mode. No delamination and matrix cracking was observed in edge-on tested specimens.

Conclusions

Properties of glass/epoxy composite laminates subjected to low velocity impact energy levels and low temperatures by a Charpy device 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, maximum crack length and maximum delamination length are highlighted. Moreover, the effects of geometry index and notch orientation are determined. Based on the test results of the present study, the following conclusions can be drawn:

(i) Impact energy decreases with the decrease of the test temperature. On the other hand, specimens after 10 days exposure to low temperature show slightly lower impact energy absorption than the specimens with one day exposure at considered temperatures.

(ii) At each temperature, with increasing energy level, the crack length and delamination length were increased. A higher delamination on specimens was found with increasing the testing temperature. While less crack length occurred, when the specimen temperature increased.

(iii) Results show that the impact strength decreased by increasing the specimens span length to depth ratio above 6. This phenomenon was found for both case of one and ten days exposure to low temperature.

(iv) Two different failure processes were observed for specimens with side-on and edge-on notch orientations. The specimen with side-on notch orientation partly delaminates by failure of the week interface planes of matrix materials between the plies of laminate due to shear stresses. However, for edge-on notch orientations, failure concentrates on the glass reinforcements, glass fiber breakage under the influence of tensile stresses ahead of the notch represents the dominating failure process.

(v) By visual inspection, it is found that failure mechanism changes from matrix cracking at room temperature to delamination and fiber breakage at low temperatures.

(vi) Microscopic examination shows that for side-on notch orientation, by increasing test temperature, more delamination and matrix cracking were observed. In addition, more fiber breakage was found in the case of edge-on notch orientation by increasing the test temperature.

(vii) Results of the current research indicated that in spite of significant increase in mechanical properties of composites at low temperatures under static loading, but impact response of composites reduced by decreasing temperature. This can be explained such 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.

References

1 Baker A, Jones R & Callinan R J, *Compos Struct*, 4 (1985) 14-44.

2 Hufenbach W, Ibraim F M, Langkamp A, Bohm R & Hornig A, *Compos Sci Technol*, 68 (12) (2008) 2391-2400.

3 Abrate S, *Appl Mech Rev*, 444 (1991) 155-190.

4 Cantwell W J & Morton J, *Composites*, 225 (1991) 347-360.

5 Arnold W S, Madjidi S, Marshall I H & Robb M D, Low velocity impact of inclined CSM composite laminates, *Proc Int Conf Advanced Composite Materials*, The Minerals and Materials Society, 1993, 617-622.

6 Broutman L J & Yeung P, *Polym Eng Sci*, 12 (1978) 270-279.

7 Tobias B C, Tensile and impact behavior of natural fiber reinforced composite materials, *Proc Int Conf Advanced Composite Materials*, The Minerals and Materials Society, 1993, 623-627.

8 Shih W K & Jang B Z, *J Reinforced Plast Compos*, 8 (1989) 271-298.

9 Chun L & Lam K, *Shock Vib,* 4(2) (1997) 125-141.

10 Carruthers J J, *Some aspects of the energy absorption of composite materials*, Ph D thesis. Department of Mechanical Engineering, The University of Sheffield, 1997.

11 Salehi-Khojin A, Mahinfalah M, Bashirzadeh R & Freeman B, *Compos Struct*, 78 (2007) 197-206.

12 Salehi-Khojin A, Bashirzadeh R, Mahinfalah M & Nakhaei-Jazar R, *Composites: Pt B*, 37 (2006) 593-602.

13 Ibekwe S, Mensah P F, Li G, Pang S & Stubblefield M A, *Compos Struct*, 79 (2007) 12-17.

14 Khalid A, *Mater Des*, 27 (2006) 499-506.

15 Kalthoff J F, *Composites*, 35 (2004) 657-663.

16 Gomez-del Rio T, Zaera R, Barbero E & Navarro C, *Composites*, 36 (2005) 41-50.

17 Gomez-del Rio T, Barbero E, Zaera R & Navarro C, *Compos Sci Technol*, 65 (2005) 61-71.

18 Kalthoff J F, *Int J Fract*, 27 (1985) 277-298.

19 Kishimoto K, Aoki S & Sakata M, *Eng Fract Mech*, 13 (1980) 503-508.

20 Kishimoto K, Kuroda M, Aoki S & Sakata M, Simple formulas for dynamic fracture parameters of elastic and viscoelastic three-point bend specimens based on Timochenko's beam theory, *Proc of IFC6*, 5 (1984) 3177-3184.

21 Lorriot T, Matrin E, Quenisset J M, Sahraoui S & Lataillade J L, *J Phys*, 4 (1994) 125-130.

22 Lorriot T, Matrin E, Quenisset J M & Rebiere J P, *Int J Fract*, 91 (1999) 299-309.

23 Lorriot T, *Eng Fract Mech*, 65 (2000) 703-713.

24 Gopalaratnam V S, Shah S P & John R, *Exp Mech*, 24 (1984) 102-111.

25 ISO 14556, *Steel-Charpy V-notch pendulum impact test-instrumented test method.*

26 Marur P R, Simha K R Y& Nair P S, *Eng Fract Mech*, 53 (1996) 481-491.

27 Landrein P, Lorriot T & Guillaumat L, *Eng Fract Mech*, 68 (2001) 1631-1645.

28 Shokrieh M M, Torabizadeh M A & Fereidoon A, Comparison of mechanical properties of unidirectional composite predicted from analytical models and experimental evaluation at different temperatures, *Proc 19th Int Conf on Mechanical Engineering (ISME2011),* May 2011, Iran.

29 Bayraktar E, Levaillant C & Altintas S, *J Phys*, 3 (1993) 61-66.

30 Wang Z, Zhou Y & Mallick P K, *Polym Compos*, 23(5) (2002) 858-871.

31 Vermeulen R C N, Comparison of strain rate and temperature effects on modulus and ultimate strength of polyethylene-fiber based cross-ply laminates with a glassy and rubbery matrix, *WFW Reporter*, 1995.

32 Basaran C, Nie A & Hutchins C S, *J Compos Mater*, 42(19) (2008) 2003-2025.

33 Ray B C H, *J Appl Polym Sci*, 100(3) (2006) 2289-2292.

34 Sokrieh M M & Omidi M J, *Compos Struct*, 91(1) (2009) 95-102.

35 Sokrieh M M & Omidi M J, *Compos Struct*, 89 (2009) 517-523.

36 Sokrieh M M & Omidi M J, *Compos Struct*, 88 (2009) 595-601.

37 Shokrieh M M, Torabizadeh M A & Fereidoon A, Progressive failure analysis of composite plates, *Proc 8th Iranian Aerospace Society Conf (AERO2009)*, February 2009, Iran.