THE EFFECT OF STACKING SEQUENCE AND TEMPERATURE ON THE MECHANICAL AND LOW VELOCITY IMPACT RESPONSE OF GLASS/EPOXY LAMINATES

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ABSTRACT

This paper demonstrates both low velocity impact and mechanical test results of glass/epoxy composites at room and high temperatures. Square specimens of glass/epoxy composite laminates with lay-ups $[0/0/90]_s$, $[90/0/0]_s$, $[0/90/45]_s$ were subjected to low velocity impact energy range of 4 J to 22 J using an impact test machine at temperatures of 20°C, 50°C and 90°C. Load-deflection and energy profile diagrams were plotted for each stacking sequence and temperature. After impact, a high-intensity light was used to measure the projected delamination areas in the impacted glass/epoxy composite laminates. In order to investigate effects of temperature on mechanical properties and impact resistance, mechanical tests were also performed using unidirectional glass/epoxy composite plates composed of eight plies produced according to ASTM Standards. In addition, to understand the contribution of thermal residual stresses occurring during and after manufacturing of composite laminates on impact-induced delamination, SX and SY stresses in the composite laminates at 20, 50 and 90°C were determined by using ANSYS software. It can be concluded from this study that temperature has significant effects on the impact behaviour and mechanical properties of glass fibre-reinforced epoxy composite laminates. Besides, an increase in temperature decreases both the delamination area and the contribution of thermal residual stresses on delamination under the same impact loading.

Keywords: Impact energy, glass/epoxy composite, delamination area, thermal residual stress

1. INTRODUCTION

Fibre reinforced composite plates have been widely used under different environmental conditions in technology applications for nearly four decades, owing to their high strength and light weight. Environmental conditions, for instance, high and low temperature or moisture, affect material strength and impact damage resistance considerably. In addition, during their service life, impact loadings like tool drops, runway debris, bird strikes, and hailstorms induce significant damage in composite plates. The damage that might be left undetected and invisible considerably reduces the residual mechanical properties of composite plates. Therefore, it is a very important issue to investigate how the damage mechanisms and impact responds of these materials change under varying environmental conditions.

Many authors have studied impact induced damage mechanisms and the impact response of composite plates at room temperature [1-5]. These studies showed that the impact tests on laminated composites up to perforation energy level can cause various types of damages including delamination, fibre breakage, matrix cracking, intra-ply cracking, ply splits, fibre debonding and pull out [6-8]. However, some authors pointed out that the fracture behaviour and mechanism of the laminate composites at low and high temperature levels are complicated when compared with those obtained at room temperature [9-10]. Therefore, the effects of variations in thermal residual stresses and mechanical properties of composite laminates on impact tolerance and resistance at different conditions must be understood.

There are only a few studies paying attention to the effect of temperature on the impact response and impact induced damages of laminated composites. Gomez et al. [11] examined the response of carbon fibre-reinforced epoxy matrix (CFRP) laminates at low impact velocity and at low temperature. The experimental results obtained in this work showed that cooling the laminate before impact has an effect on damage similar to that of increasing the impact energy: larger matrix cracking and delamination extension, deeper indentation on the impacted side, and more severe fibre–matrix debonding and fibre fracture on the opposite side. Kwang et al. [12]

studied the effect of temperature variations (-30 to 120 °C) on damage to orthotropic CFRP laminates at non-penetrating impact velocities (up to 100 m/s). They observed a linear relationship between the impact energy and the delaminated area, as well as an increase in the damage area as the temperature decreases. Khojin et al. [13] presented the results of a research on impacted sandwich composites with Kevlar/hybrid and carbon face sheets subjected to different temperatures. Results showed that the impact performance of these composite sandwiches changed over the range of temperature from -50 °C to 120 °C. For instance, at a higher energy level where full penetration on the back surface occurred, the amount of maximum absorbed energy with increasing temperature level for C–C and C–K increased and for C–H decreased. Therefore, testing at ambient temperature is not sufficient in the development and full understanding of composite sandwich damage properties. Matthew et al. [14] investigated the effects of core material, temperature, and impact velocity on the absorbed energy, peak impact force, and damage mechanisms in composite sandwich panels subjected to low velocity impact. It was found that the temperature has a significant effect on the energy absorbed and maximum force encountered during impact. Also, the effect of impact temperature was less evident on the residual bending stiffness and strength of the sandwich composites after impact. A slight reduction in the stiffness was noted with increasing impact temperature at the highest energy level. Khojin et al. [15] presented results of an experimental study on Kevlar/fibreglass composite laminates subjected to impact loading at temperatures ranging from -50 °C to 120 °C. Results indicated that impact performance of these composites was affected over the range of temperature. At low impact energy, the amount of maximum absorbed energy is almost constant and independent of temperature. With increasing energy level absorbed energy becomes more and more dependent on temperature.

In this study, in order to understand the effect of temperature on impact behaviour of glass/epoxy composite laminates, mechanical and impact tests were performed at room and high temperatures. Square specimens of glass/epoxy composite laminates with lay-ups $[0/0/90]_s$, $[90/0/0]_s$, $[0/90/45]_s$ were subjected to low velocity impact energy range of 4 J to 22 J using an impact test machine at temperatures of 20 °C, 50 °C and 90 °C. After impact, a high-intensity light was used to measure the projected delamination areas in the impacted glass/epoxy composite laminates. Mechanical tests were also carried out using unidirectional glass/epoxy composite plates composed of eight plies produced according to ASTM Standards.

In impact phenomenon, longitudinal and transverse moduli have significant effects on indentation and deflection. While longitudinal and transverse tensile strengths specify impact damage resistance of lower layers in composite plates, longitudinal and transverse compressive strengths specify that of upper layers. Interlaminar shear strength plays an important role in delamination and debonding resistance. Also, thermal residual stresses occurring during and after manufacturing may influence impact resistance of the plates.

In unidirectional glass/epoxy composite plates, the thermal expansion coefficient in the fibre direction α_1 is normally much smaller than that in the transverse direction, α_2. Also, the longitudinal modulus, E_1 is much greater than the transverse modulus, E_2. Therefore, while the composite plates are cooled from its cure temperature during manufacturing, thermal residual stresses do occur. The stresses may influence the impact behaviour and impact induced damage modes of the composites. To investigate the effects, the thermal residual stresses of glass fibre/epoxy laminates with lay-ups $[0/0/90]_s$, $[90/0/0]_s$, [0/90/45]s were determined at 20, 50 and 90 °C by using the assumptions of classical plate theory in ANSYS software.

2. FABRICATION OF COMPOSITE LAMINATES

Glass/epoxy laminated composites with lay-ups $[0/0/90]_s$, $[90/0/0]_s$, $[0/90/45]_s$ for impact tests were manufactured from unidirectional E-glass fabric having a weight of 509 g/m^2 and epoxy resin CY225 with HY225 hardener. Furthermore, to determine mechanical properties, a unidirectional glass/epoxy composite plate composed of eight plies was produced. For fabrication of laminates, the hand lay-up technique was utilized. After applying this method, the composite plates were cured by using a hot lamination press at 120 °C for 2 hours under a pressure of 0.15 MPa. Then, they were cooled to room temperature at the same pressure.

3. MECHANICAL TEST PROCEDURE

To interpret the impact behaviours and damage mechanisms of the laminated composites easily, mechanical properties of the composite plates were determined experimentally at temperatures of 20 and 90 °C.

Test samples were prepared according to the ASTM standards. All the mechanical tests were performed by using INSTRON tensile test machine. The load was applied to the samples at a constant cross-head speed of 1 mm/min. The test machine had a thermostatic chamber in which the temperature of the specimens can be adjusted. All tests were performed three times and mean values were obtained.

Longitudinal Young modulus E_1, poison's ratio υ_{12}, longitudinal tensile strengths X_t, transverse Young modulus E_2 and transverse tensile strengths Y_t were measured by using longitudinal and transverse $[0_8]$ unidirectional composite specimens according to the ASTM D3039-76 standard. The specimens were loaded up to failure in the axial direction. A biaxial video extensometer was used to measure strains in the fibre and normal to fibre directions.

IITRI (The Illinois Institute of Technology Research Institute) compression fixture was used to measure the compressive strength of the unidirectional glass/epoxy laminated composites. The compression test specimens with 140 mm length were prepared according to ASTM D3410 standard. The width was taken as 6.4 and 12.7 mm for the longitudinal and transverse specimens, respectively. After the specimens were set into the compression fixture by fastening screws in wedge clamps, the compressive loads as shown in Fig. 1 were applied up to the occurrence of failure at a constant cross-head speed of 1 mm/min. The longitudinal and transverse compressive strengths, X_c and Y_c, are obtained by dividing the failure load to the cross-sectional area of the specimens.

Fig. 1: IITRI compression fixture

The in-plane shear modulus and strength were measured by using the Arcan test fixture shown in Fig. 2. For the tests, specimens with two 90° notches were cut from $[0_8]$ unidirectional glass/epoxy laminated composites. The dimensions of the specimen are given in Fig. 3. The tensile force was applied to Arcan test fixture up to failure, so that a shear force transmitted through a section between two edge notches produces a nearly uniform shear stress along the section. The in-plane shear strength S_{12} was calculated using Eq. 1.

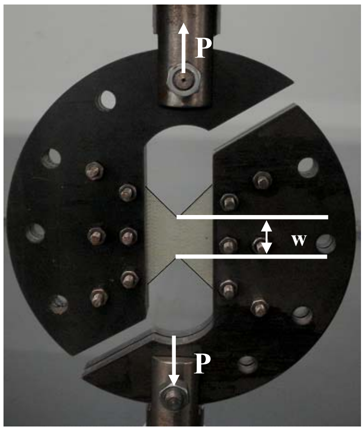

Fig. 2: The Arcan test fixture

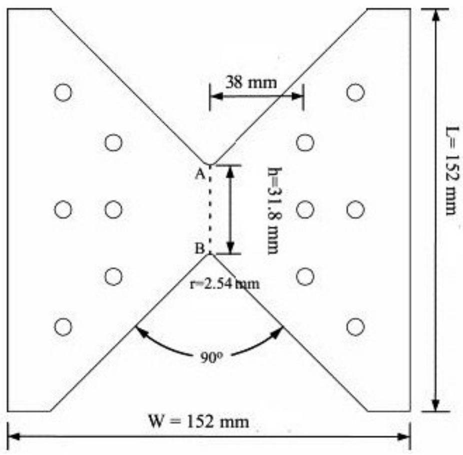

Fig. 3: The dimensions of the Arcan test specimen

$$S_{12} = \frac{P_{max}}{wt} \quad (1)$$

Where P_{max} is the failure load, w is the width of the specimen at notch location and t is the specimen thickness. Shear modulus G_{12} was measured by using two strain gage located at the centre of the notched section at 45° and -45° to the loading direction. While tensile load was applied to the Arcan apparatus, force and stain values were read from the monitor and indicator, respectively. Shear strain γ_{12} is equal to the sum of the absolute values of normal strains, ε_{45} and ε_{-45}. Shear stress τ_{12} was obtained by using Eq 1. The shear modulus was calculated using Equation 2.

$$G_{12} = \frac{\tau_{12}}{\gamma_{12}} \tag{2}$$

To determine the interlaminar shear strength, S_i, the double-notch shear test was performed as described in ASTM D3846-79. Specimens having dimensions of a 79.5 mm length, 12.7 mm width and 2.6 mm thickness were prepared from unidirectional reinforced composites. Two parallel notches were machined, one on each face of the specimen, 6.4 mm apart and with a depth equal to half the specimen thickness. While the axial tensile load was applied to the specimen, shear failure occurred along the midplane of the specimen between the notches. The interlaminar shear strength was determined using Eq. 3

$$S_i = \frac{P_{max}}{wl} \tag{3}$$

Where, P_{max} is the failure load, l is the distance between notches, and w the width of the specimen.

To determine the out-of-plane shear moduli G_{13} and G_{23}, specimens with 15 mm width, 50 mm length and 10 mm thickness were manufactured by using Standard Test Method for Short-Beam Strength as described in ASTM D2344/D2344M. The strain-gage was glued along the natural axis of longitudinal lateral surface of the specimen at angle of 45° with transverse direction as shown in Figures 4a and 4b (In plane 1-3 for G_{13}, in plane 2-3 for G23). Maximum shear stresses in natural axis were calculated as given in Equation 4. Shear strains are taken two times as normal strain (reading value) as given in Equation 5. G_{13} and G_{23} can be calculated by using Equation 6.

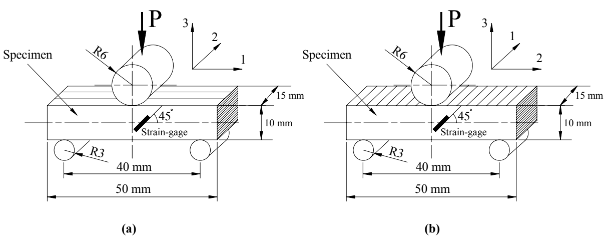

Fig. 4: Schematic view of the three-point bending test for G_{13} and G_{23}

$$\tau_{13} = \frac{3P}{4A} \tag{4}$$

A: Cross-sectional area (width×thickness) [mm^2]

P: Static force [N]

$$\gamma_{13} = 2\varepsilon \tag{5}$$

$$G_{13} = \frac{\tau_{13}}{\gamma_{13}} \quad [\text{MPa}] \tag{6}$$

Thermal expansion coefficients of composite materials at 20 and 90 °C were measured by reading strains in the fibre directions (ε_1) and in the transverse directions (ε_2) in indicator while increasing the temperature of chamber in the impact machine step by step.

Apart from the mechanical tests, by performing weight and volume measurements, the fibre volume fraction and the density of unidirectional glass/epoxy composite plates were determined as 58.2% and 1.98 g/cm^3, respectively.

3.1 Thermal residual stress analysis of the composite laminates

To investigate the effects of the thermal stresses on pre-impact damage, the thermal residual stress analysis of glass fibre/epoxy laminates with lay-ups $[0/0/90]_s$, $[90/0/0]_s$, $[0/90/45]_s$ was carried out at 20, 50 and 90 °C by using the assumptions of classical plate theory in ANSYS software.

Square specimens of 100×100 mm^2 having 1.8 mm thickness were modelled in ANSYS software. SOLID46 element was selected for meshing. The elements were considered to consist of 6 layers each of which has 0.3 mm thickness and oriented with respect to mentioned fibre angles. Mechanical properties of the plates were entered into the program by using properties of the unidirectional glass/epoxy composites given in Table 1. Initial temperature at which curing starts was taken as 120 °C. Considering impact test conditions of composite plates, final temperatures were applied onto the model as 20, 50 and 90 °C. Boundary conditions were not applied to the edges of the model since the composite plates were not subjected to in-plane loading and constrains during and after fabrication. After the finite element models of the composite plates were completed, thermal stress analysis was performed.

3.2 Low velocity impact tests

FRACTOVIS PLUS impact test machine which has a climatic chamber was used for low velocity impact testing at different temperatures in the Composite Research Laboratory of Dokuz Eylül University. The test machine has a force transducer with a capacity of 22.24 kN. The cylindrical impactor

Table 1: Mechanical Properties of Glass/Epoxy Composite Plate at 20 and 90 °C

Mechanical Properties of Glass/Epoxy Composite Plate	20 °C Temperature	90 °C Temperature
Longitudinal modulus, E_1 (GPa)	41.9	36.5
Transverse modulus, E_2 (GPa)	14.3	9.6
Longitudinal tensile strength, X_t (MPa)	1092.2	753.2
Transverse tensile strength, Y_t (MPa)	72.5	77.4
Longitudinal compressive strength, X_c (MPa)	473	374
Transverse compressive strength, Y_c (MPa)	171.6	142
In-plane shear modulus, G_{12} (GPa)	4.9	3.4
Out-plane shear modulus, G_{13} (GPa)	4.9	3.4
Out-plane shear modulus, G_{23} (GPa)	1.2	1.0
Interlaminar Shear Strength S_i [MPa]	32.3	15.7
In-plane shear Strength, S_{12} (GPa)	74.3	48.4
Poisson's ratio (ν_{12})	0.25	0.22
Longitudinal thermal expansion coefficient α_1 [1/□C□10^{-6}]	3.83	2.64
Transverse thermal expansion coefficient α_2 [1/□C□10^{-6}]	17.7	20.8

weighs 5.22 kg and has a semi-spherical nose of 12.7 mm in diameter. For the tests, 100×100 mm square specimens were cut from glass/epoxy composite laminates with lay-ups $[0/0/90]_s$, $[90/0/0]_s$ and $[0/90/45]_s$. While conducting the impact tests, all specimens were placed inside the chamber on a steel support and clamped by using a pneumatic clamping fixture with a 76.2 mm diameter opening. Since the drop weight was not changed, the different impact energies were achieved by adjusting the drop height. Temperature of climatic chamber was adjusted by means of heating the climatic chamber. After impact, an anti-rebound system held the cylindrical impactor to avoid multi-hits on the specimen

Visual IMPACT software was used to display and store the impact data. The impact force value at each time step, *F(t),* is recorded by data acquisition system (DAS). Deflection is derived from a double integration of force curve as

$$\delta_i = \iint_i \frac{F(t) - g.M_{total}}{M_{total}} dt^2 \quad (7)$$

Where δ_i is the deflection of the specimen up to point *i, F(t)* is the force acquired by data acquisition system, *g* is the gravity acceleration and M_{total} is the total impact mass. The absorbed energy up to point *i* is calculated as the area under the force-deflection F(δ) curve,

$$E_i = \int_i F(\delta) d\delta \quad (8)$$

The impact energies ranged between 4 J and 22 J. For each laminate type, test temperatures were selected as 20, 50 and 90 C. Three tests were made for each type of laminate, for each energy and temperature.

4. RESULTS AND DISCUSSION

4.1 Mechanical Test Results

The mechanical test results show that when the temperature increases from 20 °C to 90 °C, significant decreases in mechanical properties of the unidirectional glass/epoxy composite plates take place, except from a small increase in transverse tensile strength. Also, it is apparent that at 90 °C, the value of longitudinal thermal expansion coefficient, α_1 is lower while the value of transverse thermal expansion coefficient, α_2 is higher in comparison with that at 20 °C. All the results obtained from the mechanical tests are given in Table 1.

4.2 Results of thermal stress analysis

Due to temperature difference and since the laminates have different thermal expansion coefficient in fibre and normal to fibre directions, thermal stresses occur in each ply. Distributions of SX and SY residual thermal stresses through the thickness are given in Fig. 5. It is seen from the graphs that thermal stress distributions are dependent on fibre orientations and layer sequences. Because layer sequences of the composite plates are symmetric, stress distribution for each layer is constant throughout the thickness. If adjacent layers have the same orientations, the stress distributions are the same within the layers. For instance, the composite plate with lay-up $[0/0/90]_s$ has the same stress distributions for 1-2 and 5-6 layers.

When variations of the residual stresses versus temperatures of 20, 50 and 90 °C are investigated, it can be noticed that SX and SY thermal residual stresses decrease with increasing temperature since ambient (final) temperature is getting closer to the curing (initial) temperature. The thermal residual stresses at 50 and 90 °C are approximately 26% and

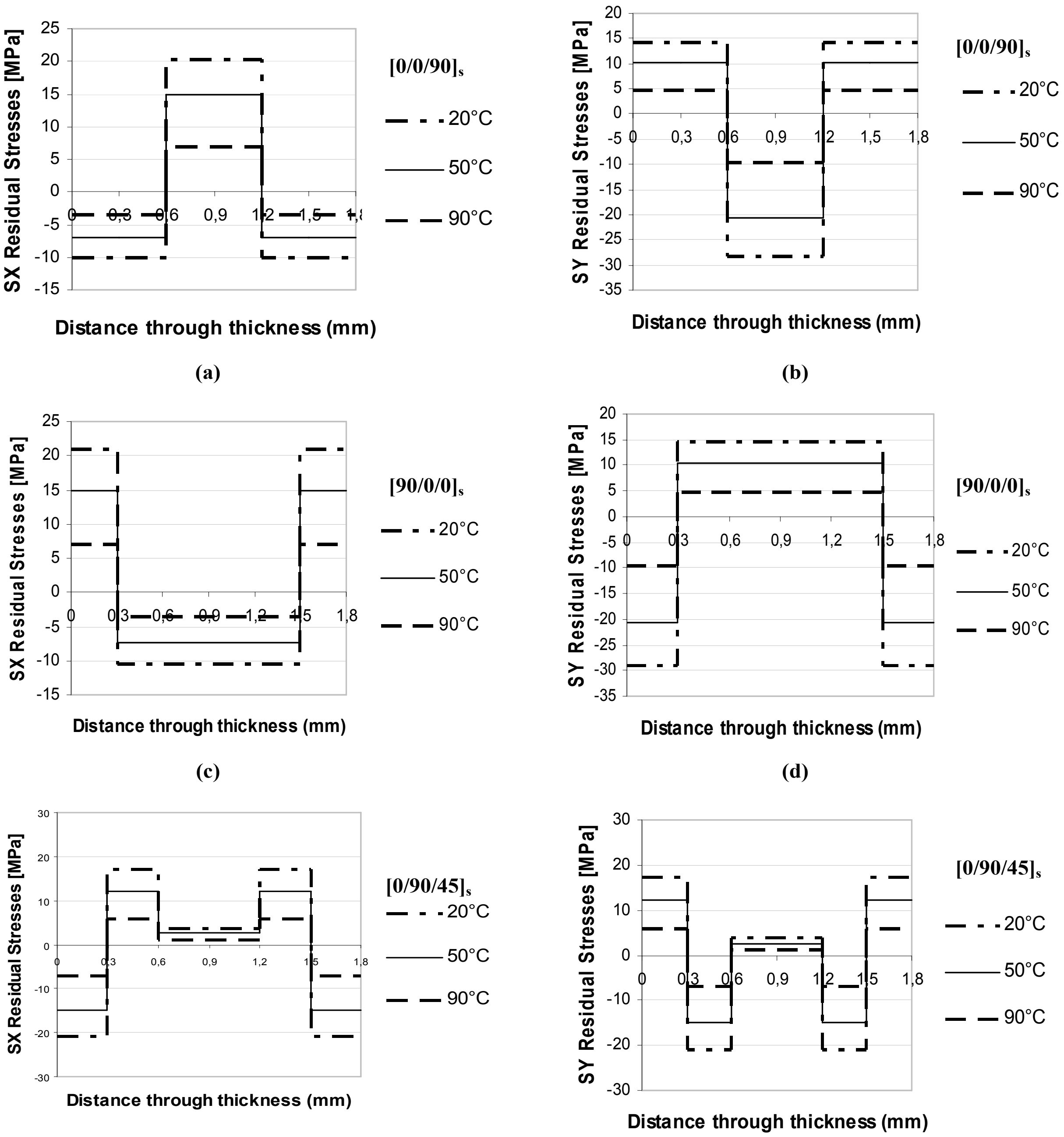

Fig. 5: Distributions of SX and SY residual thermal stresses through thickness

% 66 lower, respectively, for all orientations in comparison with that at 20 °C. In addition, interlaminar shear stresses satisfying static equilibrium between adjacent layers with different orientations decrease with increasing final temperature. Therefore, contribution of temperature to impact induced delamination and damage areas are expected to decrease in the composite plates when plates are impacted at high temperatures.

4.3 Impact test results

After subjecting the specimens to 20, 50 and 90 °C temperature conditions in the climatic chamber, three specimens from each type were tested at impact energies ranging from 4 J to 22 J and the average of the three was taken to determine the absorbed energy and damage areas. Contact force versus deflection and energy profile diagrams were plotted for each type and temperature in order to compare and understand stacking sequence and temperature effects on impact behaviour of glass/epoxy composite laminates in an impact event. In addition, variations of damage areas were investigated through impact energy levels ranging from 4 J to 22 J under the temperatures.

4.3.1 Contact force -deflection curves

Contact force–deflection (F–d) curves under various impact energies provide an understanding of the impact response and impact-induced damage mechanisms of composite laminates. Contact force–deflection (F–d) curve at energy levels ranging from 4 J to 22 J at 20 °C for $[0/0/90]_s$ orientation is illustrated in Fig. 6.

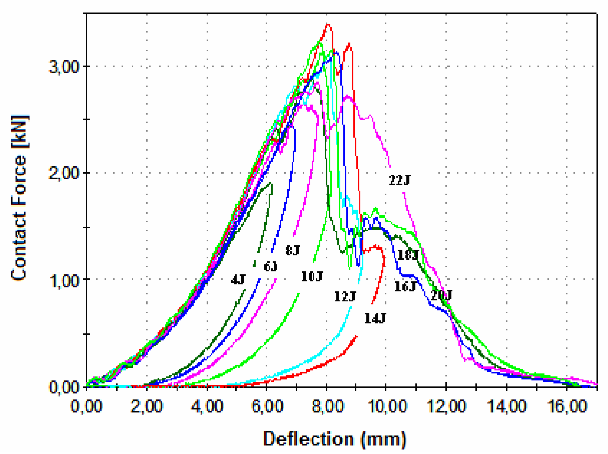

Fig. 6: Contact Force–Deflection (F–d) curve at energy levels ranging from 4 J to 22 J at 20 °C for $[0/0/90]_s$ orientation

The curves collectively have a mountain-like shape and can be classified into two basic types; closed curve and open curve through impact process. Curves at energy levels ranging from 4J to 14 J are closed type and the entire descending section consists of rebounding, since both the load and deflection decrease. As the impact energy increases from 16 J to 22 J the F–d curves become open and do not contain any rebounding part. The curve at about 16 J corresponds to the initiation of perforation while that at about 20 J to the complete perforation. Similar results were also obtained for other orientations and temperatures. Since the energy profile diagrams are more explanatory, the other force-deflection curves are not given here.

4.3.2 Energy Profile Diagrams

Energy profile is a diagram that shows the relationship between the impact energy and the absorbed energy. Impact energy (Ei) and absorbed energy (Ea) are two main parameters that can be used to assess damage process in composite structures after an impact event. The impact energy (E_i) is equal to the kinetic energy of the impactor right before contact–impact takes place, whereas the energy absorbed by the specimen, i.e. the absorbed energy (E_a), can be calculated from the associated load–deflection curve.

Energy profile diagrams of glass/epoxy laminated composite plates with lay-up $[0/0/90]_s$, $[90/0/0]_s$, $[0/90/45]_s$ are drawn as shown in Fig. 7 for all temperatures. The curves indicate that up to the impact energy of 10 J, absorbed energy increases with increasing temperature. However, at impact energies ranging from 12 to 22 J, variation of absorbed energy is different for all orientations. For example, with increasing temperature, while absorbed energy decreases for $[0/90/45]_s$, it increases for $[90/0/0]_s$. This indicates that not only variation with temperature in material properties of composite laminates but also stacking sequences influence the absorbed energy under the same impact energy. Also, another important result is that at room temperature and low energy levels, the highest absorbed energy is obtained in composite plate with lay-up $[0/0/90]_s$, as shown in Fig. 8.

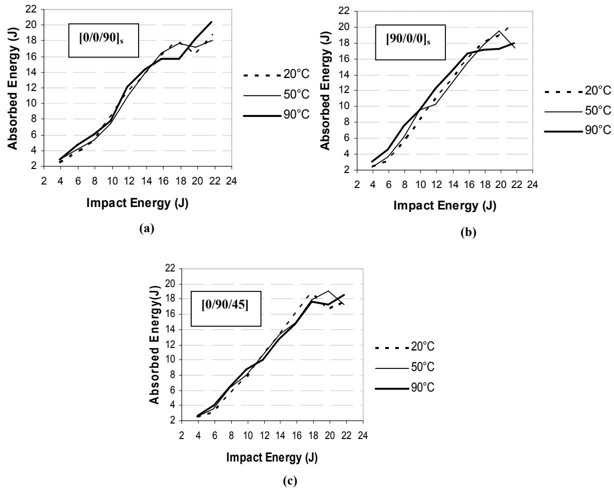

Fig. 7: Variations of energy profile diagrams with temperature in glass/epoxy laminated composite plates with lay-up $[0/0/90]_s$, $[90/0/0]_s$ and $[0/90/45]_s$

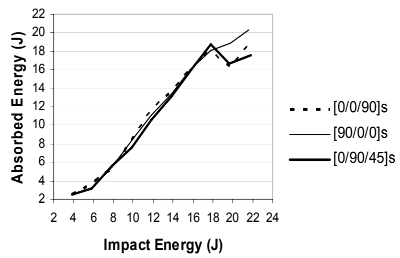

Fig. 8: Energy profile diagrams in glass/epoxy laminated composite plates with lay-up $[0/0/90]_s$, $[90/0/0]_s$ and $[0/90/45]_s$ at 20 °C

4.3.3 Visual examination

External damages occurring in glass/epoxy laminated composites under impact loading were observed by visual inspection of the specimens. Generally, the impacted surface of the specimen shows a concave indentation caused by the impactor. The curvature of the indentation zone coincides with that of the impactor tip. In addition, Indentation grows as the impact energy increases. In all the laminates and test temperature conditions, fibre fracture and matrix cracks transverse to the fibres are seen in the indentation crater at high impact energies (from 12 J up to 22 J). On the back surfaces of all the specimens subjected to high impact energies, it is observed that, matrix cracking, fibre fracture and fibre pull-out concentrated on a large zone centred around the impact point. In addition, a kind of delamination (debonding), resulting from the local deformation of the fibres rather than the difference between the rigidities of two bottom plies at point of impact is also observed. For lower impact energies (less than 12 J), the main damage mode is detected as delamination and matrix cracks rather than fibre fracture.

Fig. 9 shows the delaminations occurring on the back surface of the specimens subjected to impact energy of 12 J. at temperatures of 20 and 90 °C. Specimens with lay-up $[0/90/45]_s$ have higher delamination areas in comparison with $[0/0/90]_s$ and $[90/0/0]_s$. In addition, it is clearly observed that damage area decreases with increasing temperature.

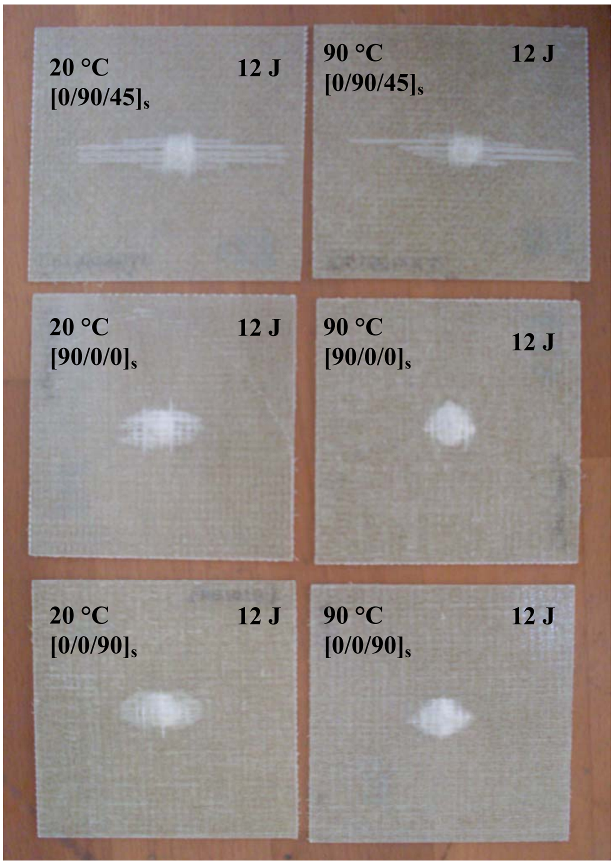

Fig. 9: Delaminations occurring on back surface of the specimens subjected to impact energy of 12 J at temperatures of 20 and 90 °C

4.3.4 Measurement of Delamination Areas

In order to measure delamination areas in different kinds of composite materials, several techniques, such as high-intensity light, penetrant-enhenced X-ray radiography, an ultrasonic imaging system and edge replication are used [16]. In this investigation, a high-intensity light was used to identify the projected delamination areas in the impacted glass/epoxy composite laminates. By this method, delamination area versus impact energy curves were obtained for each type of composite laminates and temperature for impact energy levels from 4 J to 22 J as shown in Figures 10-12.

From the curves, it is observed that, up to 12 J, as impact energy increases, delamination area increases for all orientations. On the other hand, after 12 J, irregular variations in the curves are noticed. The irregularity in stacking sequences $[0/0/90]_s$ and $[90/0/0]_s$ seem to be more than $[0/45/90]_s$ due to higher mismatch between adjacent layers with different orientation which play significant role in

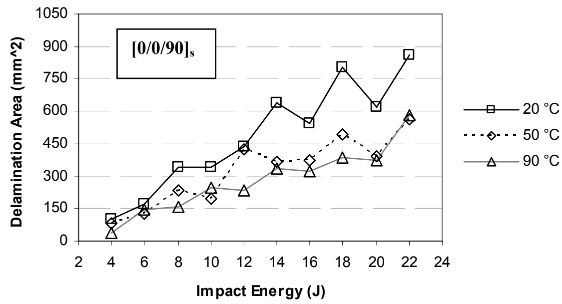

Fig. 10: Delamination area versus impact energy curves for $[0/0/90]_s$ orientation

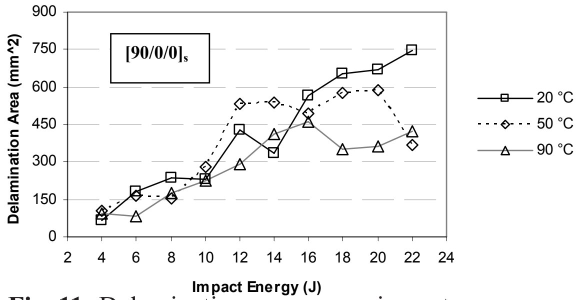

Fig. 11: Delamination area versus impact energy curves for $[90/0/0]_s$ orientation

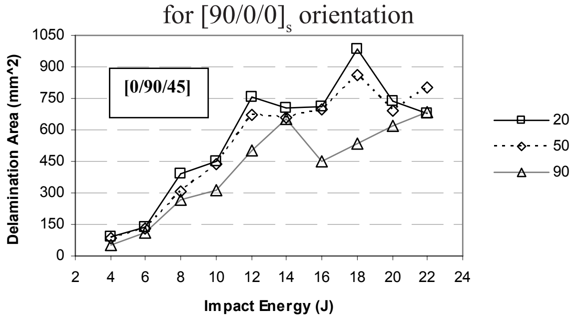

Fig. 12: Delamination area versus impact energy curves for $[0/90/45]_s$ orientation

delamination damage. Besides, as the variation of the delamination area with temperature is considered for the same orientation and impact energy, it is seen that delamination area decreases with increasing temperature. At high temperatures, elastic properties and strength of composite laminates, especially, in the fibre direction, decreased; impactor tip caused damage on a smaller area. Furthermore, as indicated earlier, thermal residual stresses and thermal-induced interlaminar shear stresses at high temperatures are lower. This trend also contributes to the reduction in the delamination area.

5. CONCLUSIONS

In this investigation, both mechanical and impact tests of glass/epoxy composite laminates were performed at room and high temperatures. The important results obtained can be summarized as follows:

The mechanical test results indicate that when the temperature increases from 20 °C to 90 °C, significant decrease in mechanical properties of the unidirectional glass/epoxy composite plates take place, except from a small increase in transverse tensile strength. Therefore, impact resistance of glass/epoxy composite laminates decreases with increasing temperature.

The energy profile diagrams obtained from impact tests show that at low impact energies, absorbed energy increases with increasing temperature. However, at high impact energies, variation of absorbed energy is different for all orientations. For example, with increasing temperature, while absorbed energy decreases for $[0/90/45]_s$, it increases for $[90/0/0]_s$. This indicates that not only variation with temperature in material properties of composite laminates but also stacking sequences influence the absorbed energy under the same impact energy.

When the variation of delamination area with temperature is investigated for the same orientation and impact energy, it is seen that the delamination area decreases with increasing temperature. Furthermore, thermal residual stresses and thermal-induced interlaminar shear stresses at higher temperature are lower. This trend also contributes to reduction in the delamination area.

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