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THE EFFECTS OF TEMPERATURE AND THERMAL STRESSES ON IMPACT DAMAGE IN LAMINATED COMPOSITES

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Abstract- The aim of this study is to investigate the effects of temperature and thermal residual stresses on the impact behavior and damage of unidirectional glass/epoxy laminated composites. To this end, thermal stress analyses of the laminates with lay-ups $[90/0/0/90]_s$, $[90/0/45/45]_s$, $[0/90/45/-45]_s$ were carried out under temperatures of 20, 90 and -50 °C by using ANSYS software. Damage parameters proposed by Hou et al. [13] were used for failure analyses. Also, the impact tests on the laminated composites were performed at the impact energies ranging from 5 J to 55 J under the mentioned temperatures. The specific energy values and impact parameters were obtained and compared for each type of specimens and temperatures. The results obtained from both thermal stress analyses and impact tests indicated that the contribution of thermal stresses to impact damage increases with decreasing temperature and therefore, the stresses at low temperatures have a significant effect on the impact damage and parameters of unidirectional laminated composites.

Key Words- Thermal Residual Stress, Failure Analysis, Laminated Composites, Impact Damage,

1. INTRODUCTION

The use of laminated composite materials has become increasingly common in a wide range of structural components for nearly four decades due to their superior specific properties; such as high strength and stiffness to weight ratio, improved corrosion, and environmental resistance. Nowadays, airframe manufactures utilize composite materials external areas such as wing flaps, elevators, rudders, spoilers, and landing gear doors [1]. With this increased use of composite materials on the exterior of aircraft, it is very important that designer understand how these materials behave under all loading conditions. One of these loading conditions is a low velocity impact loading due to foreign object impact. The type of loading could be created by tool drops, collision with runway derbies, or encounters with hail during their service life. If a composite laminate is subjected to low velocity impact of sufficient energy, impact could cause various damages, such as matrix cracks, delaminations, fiber fracture, fiber-matrix debonding and fiber pull-out. The damage modes cause the reduction of the compression, bending and buckling strengths because they produce the separation of the plies and an overall reduction of the laminate stiffness [2]. Therefore, a lot of studies have been carried out to help understand and improve the impact response of composite materials and structures [3-6].

In addition to significant dynamic loads due to impact by foreign objects, composite laminates are often subjected to thermal loading due to the environment. There are studies paying attention to the effect of temperature on the impact response and impact induced damages of laminated composites. A decrease in delamination area was reported [7] with increase in temperature in the range between -40 and 70 °C for a carbon-fiber composite laminate subjected to high energy impact. In a similar high velocity impact study on cross ply laminates of polyethylene fiber/epoxy matrix system [8], it was found that the damage initiation energy doubled when the temperature was increased from -50 to 100 °C. In contrast, laminates containing plain-weave fabrics showed very little influence of temperature on the total impact energy required for complete penetration of the specimen. Puente et al. [9] analyzed the influence of low temperature on the damage produced on CFRPs by intermediate and high velocity impacts. Experimental tests were done at temperatures ranging from 25 to -150 °C. The extension of the damage was measured by C-Scan. Results showed a clear dependence of damage on temperature, impact velocity and the type of the laminate. Gomez et al. [10] examined the response of carbon fiber-reinforced epoxy matrix (CFRP) laminates at low impact velocity and in low temperature condition. 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 fiber-matrix debonding and fibre fracture on the opposite side. Kwang et al. [11] studied the effect of temperature variations on impact damage to CFRP laminates. The results demonstrated that as the temperature of a CFRP laminates increases, delamination areas of impact-induced damages decreases. Khojin et al. [12] presented results of an experimental study on Kevlar/fiberglass 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.

In this study, the effects of temperature and thermal residual stresses on the impact behavior and damage of unidirectional glass/epoxy laminated composites were investigated. For this, thermal stress analyses of the laminates were carried out under temperatures of 20, 90 and -50 °C. As well, the impact tests of the laminated composites were performed at mentioned temperatures.

2. MATERIALS AND METHODS

For impact tests, glass/epoxy laminated composites with lay-ups $[90/0/0/90]_s$, $[90/0/45/45]_s$, $[0/90/45/-45]_s$ are manufactured from unidirectional E-glass fabric having a weight of 509 g/m^2 and epoxy resin CY225 with HY225 hardener. For fabrication of laminates, the hand lay-up technique was utilized. After applying this method, these 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.

The impact test specimens of 100×100 mm^2 were prepared by cutting from the composite laminates fabricated in size of 1×1 m^2. Nomenclatures, thicknesses and densities of the composite laminates are given in Table 1.

Table 1. Glass/Epoxy Laminated Composites with eight layers

Layup	Nomenclature	Thickness (mm)	Density (kg/m^3)
$[90/0/0/90]_s$	G1	2,81	1907
$[90/0/45/45]_s$	G2	2,80	1882
$[90/0/45/-45]_s$	G3	2,83	1904

Mechanical properties of a unidirectional glass/epoxy composite plate at room temperature were determined to calculate thermal stresses occurring in glass/epoxy laminated composites with lay-ups $[90/0/0/90]_s$, $[90/0/45/45]_s$ and $[0/90/45/-45]_s$ during cooling from curing temperature. For the mechanical tests, $[0°]_8$ oriented glass/epoxy composite plate of 0,6×0,6 m^2 were produced. Then, test specimens were prepared by cutting from the composite plate according to the ASTM standards. All the mechanical tests were performed by using INSTRON tensile test machine. Besides, by performing weight and volume measurements, fiber volume fraction and the density of $[0°]_8$ oriented glass/epoxy composite plate was determined as 58.2% and 1980 kg/m^3, respectively. The result indicates that the density of the 0° oriented plate is higher then that of the angle-ply laminated plates since they have different lay-ups. All the mechanical test results are presented in Table 2.

Table 2. Mechanical Properties of $[0°]_8$ Oriented Glass/Epoxy Composite Plate

Longitudinal modulus, E_1 (GPa)	41.9
Transverse modulus, E_2 (GPa)	14.3
Longitudinal tensile strength, X_t (MPa)	1092.2
Transverse tensile strength, Y_t (MPa)	72.5
Longitudinal compressive strength, X_c (MPa)	473
Transverse compressive strength, Y_c (MPa)	171.6
In-plane shear modulus, G_{12} (GPa)	4.9
Out-plane shear modulus, G_{13} (GPa)	4.9
Out-plane shear modulus, G_{23} (GPa)	1.2
Interlaminar Shear Strength S_i [MPa]	32.3
In-plane shear Strength, S_{12} (GPa)	74.3
Poisson's ratio (ν_{12})	0.25
Longitudinal thermal expansion coefficient α_1 [1/ºC×10^{-6}]	3.83
Transverse thermal expansion coefficient α_2 [1/ºC×10^{-6}]	17.7

To investigate the effects of temperature and thermal residual stresses on impact parameters and damage areas, impact tests on glass/epoxy laminated composites with lay-ups $[90/0/0/90]_s$, $[90/0/45/45]_s$, $[0/90/45/-45]_s$ were performed at low velocity impact energies ranging from 5 J to 55 J. For each laminate type, test temperatures were selected as 20, 90 and -50 °C. Three tests were performed for each type of laminate, energy and temperature.

CEAST Fractovis Plus impact test machine was used for impact testing. This machine has a climatic chamber for carrying out impact tests under low and high temperatures. Since the drop weight was not changed, the different impact energies were achieved by adjusting the drop height. A pneumatic clamping fixture, with a 76.2 mm diameter opening, secured each sample during impact. The samples were impacted with a 12.7 mm diameter striker with a hemispherical tip, constructed out of high strength steel. After impact, an anti-rebound system held the cylindrical striker to avoid multi-hits on the specimen. Temperature of climatic chamber was adjusted by means of heating in the climatic chamber. For tests at -50 °C, specimens were cooled in climatic chamber achieved by utilizing liquefied nitrogen. A data acquisition system was used to acquire the contact force-real time history. Other impact parameters such as acceleration, impact velocity, displacement and energy were calculated by using contact force-real time history based on Newton's second law and kinematics with the assumption that the striker is perfectly rigid.

3. ANALYSIS OF THERMAL RESIDUAL STRESSES

In unidirectional glass/epoxy reinforced composite plates, the thermal expansion coefficient in the direction of fibers α_1 is normally much smaller than that in the transverse direction α_2. In addition, longitudinal modulus E_1 is much greater than transverse modulus, E_2. As the specimens are cooled from cure temperature, each layer tends to contract in the transverse direction much more than in the fiber direction. However, this transverse contraction is constrained by the adjacent layer, and this produces in-plane thermal residual stresses in the laminate. These stresses may be great enough to cause interfacial debonding in the composite and nano-cracks within the matrix during cool-down [10]. Moreover, the thermal residual stresses may influence the impact behavior and impact induced damage modes of unidirectional glass/epoxy reinforced composite plates. Therefore, it is significant to determine the thermal residual stresses occurring in the laminates at impact test temperatures of 20, 90 and -50 °C.

Thermal stress analyses of composite laminates in stacking sequences $[90/0/0/90]_s$, $[90/0/45/45]_s$ and $[0/90/45/-45]_s$ were performed by using ANSYS software. To this end, finite element models of square specimens of 100×100 mm^2 having 2.8 mm thickness were formed in ANSYS software, as shown in Figure 1. SOLID46 element was selected for meshing. The elements are considered to consist of 8 layers each of which has 0.35 mm thickness and oriented with respect to mentioned fiber angles. Mechanical properties of the plates were entered into the program by using properties of $[0°]_8$ oriented glass/epoxy composite plate given in Table 2. Variation of the mechanical properties with temperature was not included into the model to simply the computation. Curing temperature 120 °C at which the laminate is stress-free was taken as initial temperature. Considering impact test conditions of composite plates, final temperatures were applied onto the model as 20, 90, -50 °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. During solution, the three-dimensional thermo elastic anisotropic strain-stress relation given in equation (1) was used.

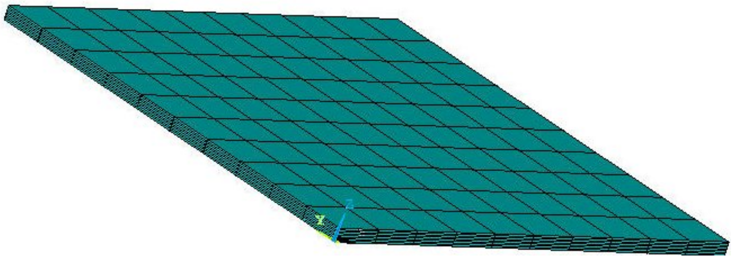


Figure 1. Finite element models of square specimens

$$\sigma_j = C_{ij}(\varepsilon_j - \alpha_j \Delta T) \qquad i, j = 1,2,...,6 \tag{1}$$

4. RESULTS OF THERMAL STRESS ANALYSIS

Maximum and minimum stress components were obtained from the results of thermal stress analyses. Stress components of σ_1 and σ_2 are compressive and tensile stresses occurring in fiber and transverse directions, respectively. The results show that σ_1 and σ_2 have the same value in all the plies expect for G2 laminate with a lay-up $[90/0/45/45]_s$. In addition, stress components of σ_3, τ_{12}, τ_{13} and τ_{23} have negligible values. Thermal residual stresses occurring at 20, 90 and -50 °C temperatures are given for all the laminates in Table 3.

Table 3. Thermal residual stresses occurring at 20, 90 and -50 °C temperatures

Layer	Stress Component [MPa]	Nomenclature and Temperature (°C)								
		G1 90	G1 20	G1 -50	G2 90	G2 20	G2 -50	G3 90	G3 20	G3 -50
1	σ_2	5.24	17.47	29.71	4.75	15.82	26.89	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-6.78	-22.61	-38.44	-5.24	-17.47	-29.71
2	σ_2	5.24	17.47	29.71	4.75	15.82	26.89	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-6.78	-22.61	-38.44	-5.24	-17.47	-29.71
3	σ_2	5.24	17.47	29.71	2.40	5.01	13.61	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-0.37	-1.22	-2.07	-5.24	-17.47	-29.71
4	σ_2	5.24	17.47	29.71	2.40	5.01	13.61	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-0.37	-1.22	-2.07	-5.24	-17.47	-29.71
5	σ_2	5.24	17.47	29.71	2.40	5.01	13.61	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-0.37	-1.22	-2.07	-5.24	-17.47	-29.71
6	σ_2	5.24	17.47	29.71	2.40	5.01	13.61	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-0.37	-1.22	-2.07	-5.24	-17.47	-29.71
7	σ_2	5.24	17.47	29.71	4.75	15.82	26.89	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-6.78	-22.61	-38.44	-5.24	-17.47	-29.71
8	σ_2	5.24	17.47	29.71	4.75	15.82	26.89	5.24	17.47	29.71
	σ_1	-5.24	-17.47	-29.71	-6.78	-22.61	-38.44	-5.24	-17.47	-29.71

When variations of the residual stresses versus temperatures of 90, 20 and -50 °C are investigated, it is noticed that σ_1 and σ_2 thermal residual stresses decrease with increasing temperature since ambient (final) temperature is getting closer to the curing (initial) temperature. Some of these values could be high enough to have influence on the onset of damage during impact. Therefore, the effect was analyzed using damage parameters proposed by Hou et al. [13] based on the Chang–Chang failure criteria [14]. These criteria consist of four damage parameters given in equation (2), (3), (4) and (5).

Fiber Failure: $$e_f^2 = \left(\frac{\sigma_1}{X_T}\right)^2 + \left(\frac{\tau_{12}+\tau_{23}}{S_f}\right)^2 \geq 1 \quad (2)$$

Transverse matrix cracking ($\sigma_2 > 0$): $$e_m^2 = \left(\frac{\sigma_2}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{23}}{S_{m23}}\right)^2 \geq 1 \quad (3)$$

Matrix crushing ($\sigma_2 \leq 0$): $$e_d^2 = \frac{1}{4}\left(\frac{\sigma_2}{S_{12}}\right)^2 + \frac{Y_C\sigma_2}{4S_{12}^2} - \frac{\sigma_2}{Y_C} + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1 \quad (4)$$

Delamination: $$e_l^2 = \left(\frac{\sigma_3}{Z_T}\right)^2 + \left(\frac{\tau_{13}}{S_{13}}\right)^2 + \left(\frac{\tau_{23}}{S_{l23}}\right)^2 \geq 1 \quad (5)$$

Each failure type take places when the associated damage parameter equals 1. Where S_f is shear strength involving fiber failure, S_{m23} is shear strength for matrix cracking in the transverse and through-thickness plane, S_{l23} is shear strength for delamination in the transverse and through-thickness plane and Z_T tensile strength in the through-thickness direction. Mechanical tests for these properties were not performed because their contributions to damage parameters are negligible. For example, since stress components of τ_{12}, and τ_{23} in equation (2) are close to zero, value of $\left(\frac{\tau_{12}+\tau_{23}}{S_f}\right)^2$ is negligible and fiber failure factor, e_f^2 can be taken equal to $\left(\frac{\sigma_1}{X_t}\right)^2$. Therefore, determination of S_f was not required. While the value of each damage parameter was calculated, only X_T, Y_T and Y_C were used since stress components of σ_3, τ_{12}, τ_{13} and τ_{23} are close to zero. In addition, as σ_2 have positive values, transverse matrix cracking parameter was used for calculation of matrix failure criteria. The results obtained from the analysis reveal that while values of delamination and fiber failure parameters are negligible, transverse matrix cracking damage parameters have high values especially before impact at -50 °C temperature. Therefore, only values of the matrix cracking parameter e_m^2 were presented in Table 4. The magnitude of this parameter is the same for each ply of G1 and G3 laminates while that is different for each ply of G2 laminate. It is seen from the table that the type of the damage parameter e_m^2 approaches critical value while the temperature is decreasing from 90 to -50 °C. For example, the magnitude of this parameter for G1 and G3 laminates at 90 °C is 0.005 but, at -50 °C it rises to around 0.168.

Table 4. Matrix Cracking Damage Parameter due to thermal residual stresses

Matrix Cracking Factor	**Nomenclature and Temperature (°C)**								
	G1 90	**G1 20**	**G1 -50**	**G2 90**	**G2 20**	**G2 -50**	**G3 90**	**G3 20**	**G3 -50**
e_m^2	0.005	0.058	0.168	0.009	0.097	0.281	0.005	0.058	0.168

Matrix cracks caused by impact on composite laminates do not significant contribute to the reduction in residual properties of the laminate. However, the damage process is initiated by matrix cracks which then induce delaminations at ply interfaces [2]. Therefore, when impacted at low temperatures, greater damage extension is expected to be taken place in the composite laminates because of higher values of the matrix cracking parameter e_m^2. In addition, the high value has influence on impact parameters such as initial, perforation and dissipation energy. To investigate the effects, impact tests on the composite laminates were carried out at 20, 90 and -50 °C.

5. IMPACT TEST RESULTS

The composite laminates in stacking sequences $[90/0/0/90]_s$, $[90/0/45/45]_s$, $[0/90/45/-45]_s$ were subjected to various impact energies increasing systematically from 5 J to 55 J in intervals of 5 J until complete perforation take place. The impact tests at temperatures of 20, 90 and -50 °C were performed by means of the instrumented Drop-Weight Tower device (CEAST, Fractovis Plus).

Contact force-deflection curves were obtained by using the contact force-real time history. Characteristic of load–deflection curves includes some useful tips in assessing damage process of composite structures. Load–deflection curves of the specimens for impact energies of 30 and 55 J are given in Fig. 2. The curves collectively have a mountain-like shape. Individually, however, there are two basic types, closed curve and open curve. Closed curves given in Figure 2-a and b represent the rebounding of the impactor from the specimen at impact energy of 30 J. If load–deflection curve is an open curve, the impactor penetrates into the specimen or even perforates the specimen. Open curves in Fig. 2-c and d specify perforation case of the specimens at impact energy of 55 J. The curves consist of an ascending section of loading and a descending section combining loading and unloading. The ascending section represents the bending stiffness history of the composite material under impact loading. The slope of load-deflection curve in ascending section is associated with the stiffness. Therefore, the bending stiffness of the laminates can be compared by means of the curve. As shown in Figure 2-a, the slope of the load-deflection curve of G3 laminate at 30 J impact energy is higher in comparison with that of G1 and G2 laminates. Therefore, G3 laminate has the highest bending stiffness. However, maximum contact force has the highest value in G2 laminate in spite of its lower bending stiffness than G3 laminates. This is because mismatching effects which start delamination are lower and initial energy required to cause the damage are greater in G2 laminate. When variation of contact force-deflection curve with temperature is investigated for G1 laminate, it is seen in Figure 2-b that both maximum contact force and the slope of the curve are higher at -50 °C, compared to 90 and 20 °C. Also, permanent indentation depth decreases while the temperature is decreasing from 90 °C to -50 °C. For instance, permanent indentation occurring in G1 laminate at impact energy of 30 J is 2.8 mm at -50 °C while 6.8 mm at 90 °C. This is since glass/epoxy laminated composites resist impact load in a brittle manner at low temperature. The close results were also obtained for G2 and G3 laminates.

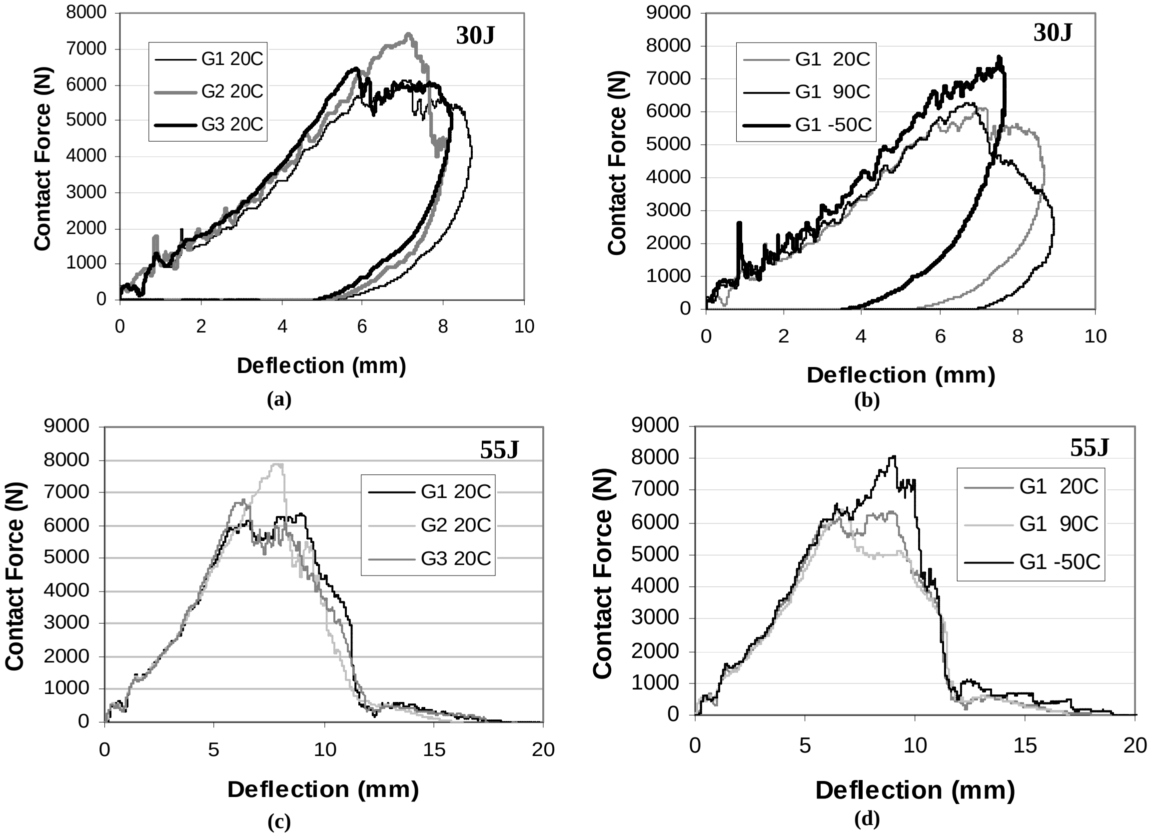


Figure 2. Force-deflection curves at impact energies of 30 and 55 J

Initiation, perforation and propagation energy values of the specimens were determined by using contact force-deflection and energy-deflection curves at impact energy of 55 J. Herein, Perforation energy i.e. total energy absorbed by specimen in case of perforation is considered by the sum of two regions; the initiation energy before maximum contact load and the cumulative propagation energy after maximum contact load. However, for the composite laminates used in this study, the composite failure process was initiated earlier than the maximum load point, as shown in Figure 3. Therefore, the energy to yield point was used as the initiation energy, where the contact force versus deflection curve starts to change slope.

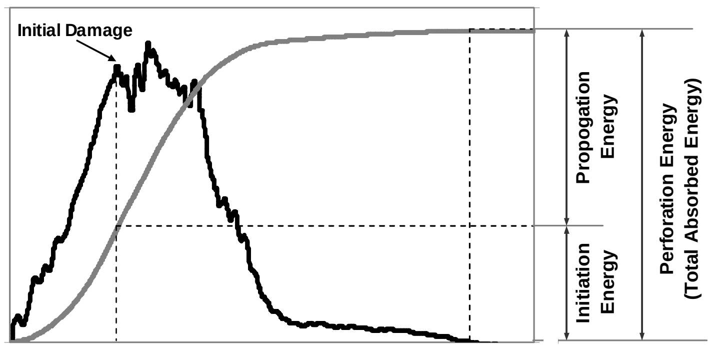


Figure 3. Contact force-deflection and energy-deflection curves in case of perforation

The mentioned specific energy values were obtained for each type of specimens and temperature, as shown in Table 4. It is seen from the table that with decreasing temperature from 90 °C to -50 °C, perforation energy increases and initial energy decreases. The reason for higher perforation energy at lower temperature is that damage area is greater and impact energy dissipates on larger area. Also, reduction of initial energy with decreasing temperature is due to high in-plane thermal stresses at low temperature and therefore, delamination is generated easily since the energy required to cause damage reduces as the temperature decreases. When effects of orientations on the specific energies are investigated, it is seen that initiation energy of G2 laminate are greater than that of G1 and G3 laminates. This is since angle difference between adjacent layers for the orientation is lower in comparison with the others and delamination does not take place between adjacent layers having the same orientation angle. Perforation energy of G2 laminate is lower than other orientations. This is owing to occurrence of more matrix cracks in laminates with a lay up $[90/0/45/45]_s$. It is concluded that cross-ply laminated composites are advantageous in terms of perforation energy threshold. The results also can be obtained from force-deflection curves at impact energy of 55 J, as seen in Figure 2-c and d.

. **Table 4.** The specific energy values for each type of specimens and temperature

Nomenclature and Temperature (°C)	**Initial Energy (J)**	**Perforation Energy (J)**	**Propagation Energy (J)**
G1 20°C	16.30	46.46	30.16
G1 90°C	20.07	44.1	24.03
G1 -50°C	15.18	53.86	38.68
G2 20°C	27.62	44.8	17.18
G2 90°C	31.63	42.38	10.75
G2 -50°C	21.34	50.32	28.98
G3 20°C	18.55	44.5	25.95
G3 90°C	20.69	39.32	18.63
G3 -50°C	17.43	54.05	36.62

Impact responses of the composite specimens were characterized in terms of impact parameters such as maximum contact force, maximum contact time, energy to maximum contact force, and total energy absorption at low, intermediate, and high impact energy levels of 5, 30, 55 J, respectively. It can be seen from Table 5 that the trends of absorbed energy versus temperature are different at different impact energy levels. This is because of variation of the damage area and mechanism with changing impact energy level and temperature. For example, at low energy levels, back surface cracking, bending of laminates and plastic deformation of matrix are the most important factors governing energy absorption while at high impact energy (55 J), fiber breakage is the main contributor to energy absorption. When the variation of maximum contact force with temperature and impact energy is investigated for the same orientation, it can be seen from Table 5 with increasing impact energy at the same temperature, the amount of maximum contact force increases, except for G2 at -50 °C. Also, for the same impact energy and orientation, while the temperature is decreasing from 20 °C to -50 °C, the value of maximum contact force increases. This is because laminates become stiffer and resist the impact load in a brittle manner at low temperature. When considering the effect of stacking sequences at 20 °C temperature, maximum contact force has the highest value in G2 laminate at impact energies of 30 and 55 J in spite of its lower bending stiffness than G3 laminate. This is because mismatching effects are lower in G2 laminate compared to G1 and G3 laminates.

Table 5. Impact parameters for each temperature and the type of specimens

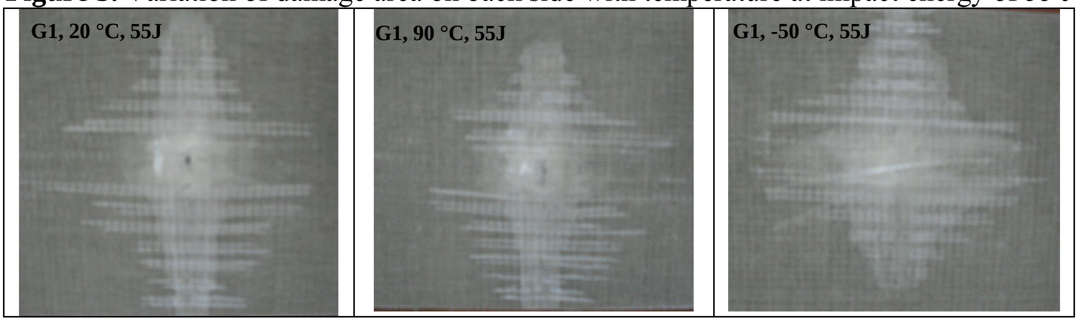
Nomenclature and Temperature (°C)	Impact Energy (J)	Max. Contact Time (ms)	Max. Contact Force (N)	Energy to Max. Contact Force (J)	Absorbed Energy (J)
G1 20°C	5	3.45	2381.09	4.88	3.95
	30	2.37	6131.32	21.29	26.92
	55	2.10	6343.92	33.65	46.46
G1 90°C	5	2.88	2304.56	4.41	4.38
	30	2.24	6284.39	20.35	29.08
	55	1.48	6437.46	19.95	44.13
G1 -50°C	5	3.52	2565.35	4.71	3.46
	30	3.04	7676.19	29.26	23.39
	55	2.16	8084.38	37.64	53.88
G2 20°C	5	3.00	2539.83	4.62	3.92
	30	2.68	7557.14	26.45	24.62
	55	1.77	7885.96	28.45	44.79
G2 90°C	5	3.31	2488.81	4.84	3.82
	30	2.53	7426.75	24.86	27.24
	55	1.91	7591.16	31.26	42.38
G2 -50°C	5	3.53	2588.02	4.85	3.35
	30	3.00	9014.14	30.03	18.36
	55	1.63	8013.52	26.19	50.05
G3 20°C	5	3.39	2551.17	4.87	3.79
	30	1.99	6207.85	18.17	26.47
	55	1.38	6794.62	18.83	44.57
G3 90°C	5	3.30	2502.98	4.81	3.75
	30	1.89	6298.56	16.77	29.24
	55	1.40	6434.62	19.36	39.35
G3 -50°C	5	3.53	2607.87	4.82	3.43
	30	2.99	7157.46	28.94	22.61
	55	1.69	8214.78	28.18	54.08

Thanks to the optically transparent nature of glass/epoxy composites, the impacted samples were visually inspected and photographs of them were taken by using a strong backlighting. Each overall damage areas were contoured and obtained by using AutoCAD software. Variation of the overall damage area values with impact energy and temperature are shown in Table 6. It is seen from the table that damage area increases while impact energy increases for the same temperature and orientation. If damage area is compared in terms of orientations of the laminates for the same impact energy and temperature, in general, it is seen that damage area of G1 laminate is greater than that of G2 and G3 laminates because of more mismatching effect. When variation of damage area with temperature is investigated for the same orientation, different results are obtained for low and high impact energies. At low impact energies (up to 15 J), as damage area is small and matrix cracks take place only, a correlation between damage area and temperature could not be determined. However, for intermediate and high impact energies (from 20 J to 55 J) at which delamination and fiber breakage as well matrix cracks take place, damage area increases while the temperature is decreasing from 90 °C to -50 °C. This is because embrittlement of the polymeric matrix, together with the interlaminar thermal stresses generated in the laminate at low temperature, contributes to facilitate the generation and propagation of damage when subjected to impact loads. Variation of damage area on back side of G1 laminate with temperature at impact energy of 55 J is shown in Figure 3.

Table 6. Variation of damage area with temperature, orientation and impact energy

Impact Energy	**5J**	**10J**	**15J**	**20J**	**30J**	**40J**	**50J**	**55J**
Nomenclature and Temperature (°C)	**Damage Area (mm^2)**							
G1 90°C	165	275	445	566	1060	1451	1630	1664
G1 20°C	200	351	600	605	1272	1867	2244	2300
G1 -50°C	222	310	476	662	1515	2152	2380	2601
G2 90°C	124	255	374	499	1181	1520	1585	1586
G2 20°C	133	268	483	677	1193	1772	1856	2020
G2 -50°C	45	171	468	722	1275	1807	2285	2723
G3 90°C	145	206	381	515	1203	1259	1449	1352
G3 20°C	133	259	392	655	1220	1516	1532	1636
G3 -50°C	32	19	418	761	1278	1808	1977	2053

Figure 3. Variation of damage area on back side with temperature at impact energy of 55 J



6. CONCLUSIONS

In this study, the effects of temperature and thermal residual stresses on the impact behavior and damage of unidirectional glass/epoxy laminated composites were investigated. To this end, thermal stress analyses of the laminates were carried out under temperatures of 20, 90 and -50 °C by using ANSYS software. Also, the impact tests on the laminated composites were performed at the impact energies ranging from 5 J to 55 J under the mentioned temperatures. The specific energy values and impact parameters were obtained and compared for each type of specimens and temperatures. The results obtained from both thermal stress analyses and impact tests show that the contribution of thermal stresses to impact damage increases with decreasing temperature and therefore, the stresses at low temperatures have a significant effect on the impact damage and impact parameters of unidirectional laminated composites. Besides, it is seen that testing temperature and stacking sequence of the laminated composites have considerable effects on impact parameters, specific energy values and damage areas.

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