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Investigation of Low Energy Impact Behavior of Prepreg Composite Plates at High Temperatures

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***Abstract*—CFRP (Carbon Fiber Reinforced Composites) prepreg laminated composite plates have been subjected to low energy impact test at 25°C, 40°C and 60°C. AS4 carbon is chosen as fibre material and 8552 epoxy resin as matrix. The samples have been prepared as 150 X 100 mm. width/length and 2.94 mm. (thickness) -16 layered, 1,84 mm.-10 layered and 1,47 mm.- 8 layered respectively and have been orientated as quasi-isotropic. The impact tests have been carried out with Instron Dynatup 9250 drop weight impact tester according to ASTM D7136 for samples cured at 40°C, 60°C and 25°C. It has been observed that; as the temperature increases, contact forces decreases and contact time increases. The laminate number and lay up orientation also affect the low impact energy behavior of prepregs. It has been concluded experimentally that as the temperature increases, impact strength of CFRP prepregs decreases.**

Keywords*— Carbon Fibers; Impact Behaviors; Impact Test; Prepreg Composites

I. INTRODUCTION

Pre-preg is a term for "pre-impregnated" composite fibers where a matrix material, such as epoxy, is already present. The fibers often take the form of a weave and the matrix is used to bond them together and to other components during manufacture. The matrix is only partially cured to allow easy handling and requires cold storage to prevent complete curing. B-Stage prepreg is always stored in cooled areas since heat accelerates complete polymerization. Hence, composite structures built of pre-pregs will mostly require an oven or autoclave to cure (1).

There are pros and cons of pre-preg process as compared to the hot injection process. Prepreg allows one to impregnate the fibers on a flat workable surface, or rather in an industrial process, and then later form the impregnated fibers to a shape which could prove to be problematic for the hot injection process. Prepreg also allows one to impregnate a bulk amount of fiber and then store it in a cooled area for an extended period of time to cure later. Unfortunately the process can also be time consuming in comparison to the hot injection process and the added value for prepreg preparation is at the stage of the material supplier (2).

Recently, there has been considerable interest in prepregs and mechanical tests. Belingardi ve Vadori conducted a study on the affects of glass fiber epoxy resin composites low energy impact resistance (3). Different kinds of strikers affect on the impact resistance of carbon epoxy composite laminates have recently been proposed in the literature by Mitrevski and friends (4). Dimensional affect and striker affect to the low energy impact of composites have been investigated by Aslan and friends (5). Milli and friends investigated the behaviors of epoxy glass composites at low velocity impact (6). Karim and friends studied the impact behavior and performance of epoxy composites produced by under single and repeated low-velocity impact loading (7). Kara investigated the dynamic behavior of epoxy glass composites under low velocity impact behavior and damage analysis according to the different plate dimensions (8). Cho K. and friends studied the affect of heat fluctuations (low and high temperature) of impact damage on carbon fibers (CFRP) (9). Ibekwe and friends have studied the damage affect of compression test on glass fibre reinforced composites at low temperature degrees (10). Gomez and friends have investigated the low energy impact affects of different oriented laminated CFRP composites and studied the damage analysis (11). Low energy impact behavior of CFRP prepregs at high temperatures has not been studied so far; this is the orijinal aspect of this paper.

II. MATERIALS AND METHOD

A. Preperation of Prepregs

Composite prepreg samples that were used in tests are carbon as fibre and epoxy as matrix (Table 1) within different thickness and orientation angles (Table 2). The array and layer numbers are detailed below:

Composite type: Carbon epoxy prepreg (figure 1). (%60 fibre-carbon - % 40 matrix-epoxy resin)

Dimension of samples : 100 x 150 mm.
Each layer thickness : 0,184 mm.

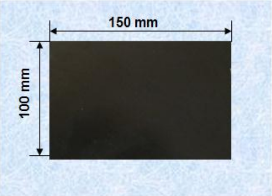
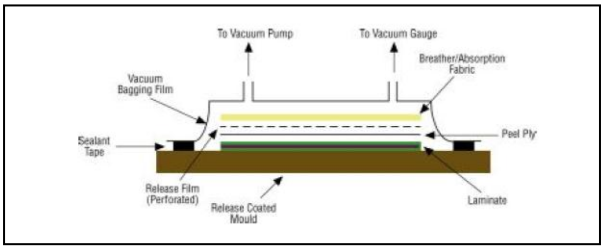


Figure 1. Test Sample (each ply thickness is 0,184 mm.)



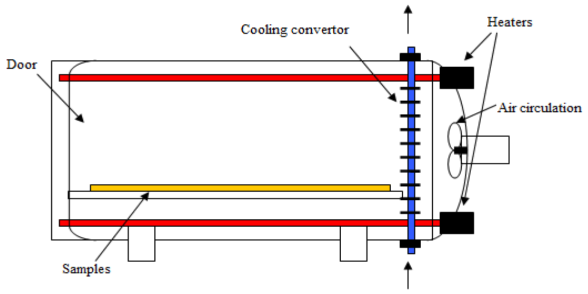


Figure 2. a) Preperation of prepregs. b) Autoclave schematic view

Table 1. Properties of the constituents of the prepregs used (data supplied by Hexcel)

Properties	**AS4 Carbon (fiber)**	**8552 Resin (epoxy)**
Tensile strength (MPa)	4410	120
Tensile modulus(GPa)	231	4,668
Tensile strain (%)	1,8	1,7
Density (g/cm^3)	1,79	1,3

Table 2. Array of samples

Array	**Number of layers**	**Thickness of sample (mm.)**	**Sample Code**
[0/+45/-45/90/+45/0/-45/90]$_s$	16	2,94	1
[+45/0/-45/90/+45/0/-45/90]$_s$	16	2,94	2
[90/+45/0/-45/+45/0/-45/90]$_s$	16	2,94	3
[0/+45/0/90/-45/90]$_s$	10	1,84	4
[45/0/0/90/-45/90]$_s$	10	1,84	5
[90/+45/0/0/-45]$_s$	10	1,84	6
[90/+45/0/-45]$_s$	8	1,47	7
[0/+45/-45/90]$_s$	8	1.47	8
[45/0/-45/90]$_s$	8	1,47	9

Prepregs samples which were prepared according to ASTM 3531 (Standard Test Method for Resin Flow of Carbon Fiber-Epoxy Prepreg) (12) and ASTM 3532 (Standard Test Method for Gel Time of Carbon Fiber-Epoxy Prepreg) (13) were vacuumed (figure 2-a), cured at autoclave (figure 2-b), applied C-Scan test (no damage observed) and then cut with high precise water jet (1800 bar, 900m/s) thanks to Cutworks_Designer.dxf programme in a clean environment. Cutworks_designer.dxf programme enables precise orientation angles affectively.

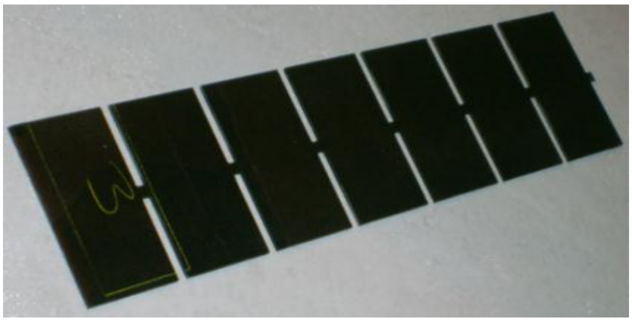


Figure 3. Samples after cut

Temperature control was obtained by a device called environmental chamber that has a control panel from -40°C to +66°C. Frame control board controls the temperature just before the test for 40°C and 60°C values.

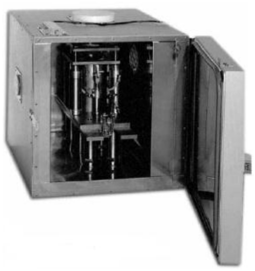


Figure 4. Environmental chamber

B. Low Energy Impact Test At High Temperatures

Instron Dynatup 9250 Drop Weight Impact Tester has been used to apply impact tests.The device has been designed so as to make damage on the materials by a substance dropped from a definite height with different velocity and mass. Test has been carried out according to the ASTM Standart 7136 (14). Data obtained have been used to evaluate the mechanical properties of the material (15).

Masses on the head-part of the device are changed to carry out the various weight values. After sometime pistons reach to the stopping-block-supports and block the second impact to the sample, then move upwards. The stopping-blocks stay at the preventing position till head mechanism elevates by the sliding blocks. Pneumatic test fixture has been used to fix the samples by clamping throughout the impact test (16).

Dimensions and some important properties of test device:
Height: 2858 mm
Width : 584 mm
Depth : 508 mm
Weight : 336,5 kg
Maximum velocity : 20 m/ s
Energy interval (low weight equipment) : 2,6 J – 826 J
Energy interval (medium weight equipment) : 4,6 J – 945 J
Energy interval (high weight equipment) : 25 J – 1603 J

Thanks to the impulse data gathering and analysis system, the results; such as energy-time, force-time, force-displacement, velocity-displacement, displacement-time and velocity-time, could be obtained. Besides, total energy, energy value in the maximum force, impact speed, total displacement, total impact duration and test temperature values are included.

Figure 5. Settlement of sample to the fixture

III. RESULTS

Figure 6. Samples subjected to low energy impact test at +25°C ,+40°C and +60°C respectively

Samples explained in Table 2 have been subjected to low impact energy test by Instron Dynatup 9250 test device. The results have been represented graphically as **load-energy-time, load-velocity-deflection** and **deflection-velocity-time** respectively. Some definitions are explained below about low energy impact test.

F_{max} : Maximum impact force (kN)
E_{Fmax}: Maximum energy in order to obtain the maximum force (J)
$E_{absorbe}$: Energy absorbed by the sample (J)
V_{impact} : Velocity applied to the sample (m/s)
d_{Fmax} : Maximum deflection in the sample (mm)
d_{total} : Total deflection (mm)
t_{Fmax} : Total time to reach the maximum force (ms)
t_{total} : Total time (ms)

A. 16-Ply Prepregs Low Energy Impact Tests Results

16-ply prepreg samples were subjected to low energy impact test at 25°C (room temperature), 40°C and 60°C respectively by 13 J energy. The responses to the impacts at room temperature are represented at the graphs (Figure 7,8,9,10) and table 3 and 4 below. The thickness of the 16-ply prepregs is 2,94 mm.

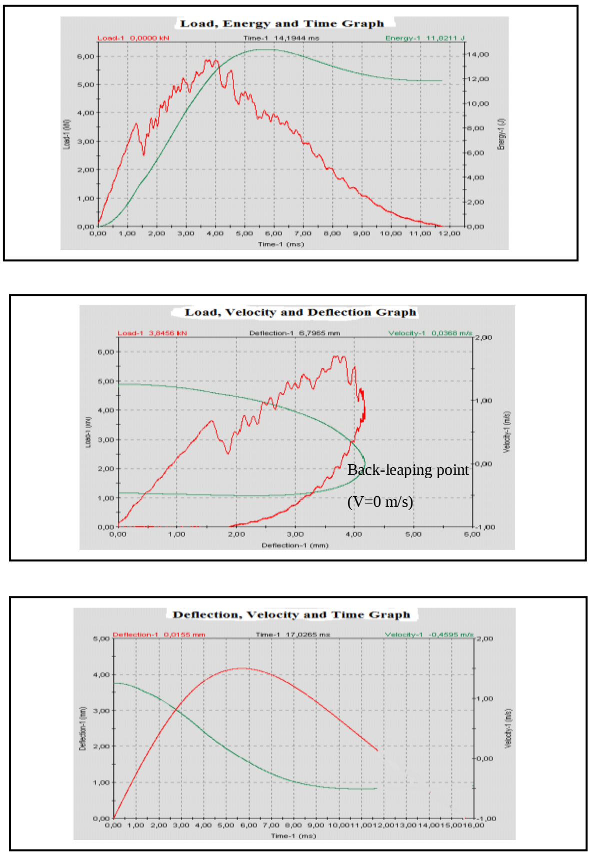


Figure 7. [0/+45/-45/90/+45/0/-45/90]$_S$ sample load-energy-time, load-velocity-deflection and deflection-velocity-time results at 25°C (room temperature)

Datas obtained by impulse data gathering system are represented in table 3.

Table 3. [0/+45/-45/90/+45/0/-45/90]$_S$ sample data obtained at 25°C (room temperature) by low energy impact test

F_{max}	E_{fmax}	V_{impact}	d_{Fmax}	d_{total}	t_{Fmax}	t_{total}
(kN)	(J)	(m/s)	(mm.)	(mm.)	(ms)	(ms)
5.863	11.676	1.213	3.647	1.904	3.672	11.685

As it is seen in figure 7, force reaches the maximum level and then drops to zero. Oscillations in graphs shows the damage mechanism when striker edge hits the sample. Till reaching the maximum force, the damage mechanism grows rapidly. Prepreg samples absorbs the impact energy and damage mechanisms occur such as fiber fracture, delaminating and matrix shear. The total time of impact is measured as 11,685 ms.

There is two threshold points in figure 7 (a). One is the 3,632 kN point where the irreversible changes occur in the graph and great oscillations begin, the second is 5,863 kN point where after the force decreases with a great speed. The first threshold point could be explained as the first material damage and the second is the first laminate damage.

It has been observed that the damages at the back of the sample is much greater than the front, since compression strength occurs at the front of the sample while tensile strength at the back (17).

Some of the energy is absorbed by the sample while some is consumed by back-leaping. 13 J. energy is used totally, and 11,813 J is absorbed, 1,187 J. is consumed at back-leaping. Maximum deflection was calculated 4,1711 mm. (Figure 7.a) to the back leaping point. At this point it is observed that velocity is zero, because back-leaping begins. At the end; force and energy values are zero, but deflection is not, because permanent damage has been observed. Total deflection was calculated as 1,904 mm.

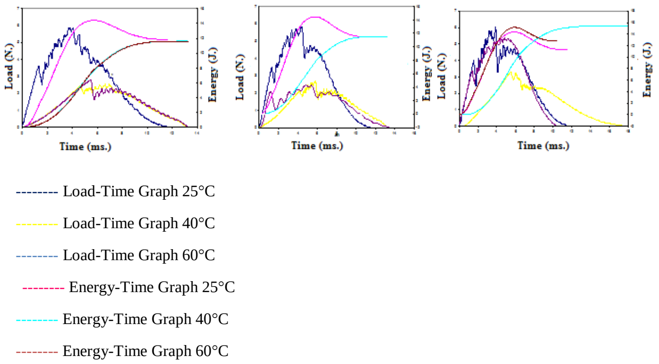


Figure 8. Load-Energy-Time Graph, a) [0/+45/-45/90/+45/0/-45/90]$_S$, b) [+45/0/-45/90/+45/0/-45/90]$_S$,c) [90/+45/0/-45/+45/0/-45/90]$_S$

As temperature increases, contact force decreases; but contact time of striker edge increases. As the force discharges, the form of graph shows differences. This is the result of different damage mechanisms, permanent damage and absorbed energy (Figure 8). [90/+45/0/-45/+45/0/-45/90]$_S$ ply array contact force is calculated more than (that means it is more resistant to low energy impact) the other two ply arrays.

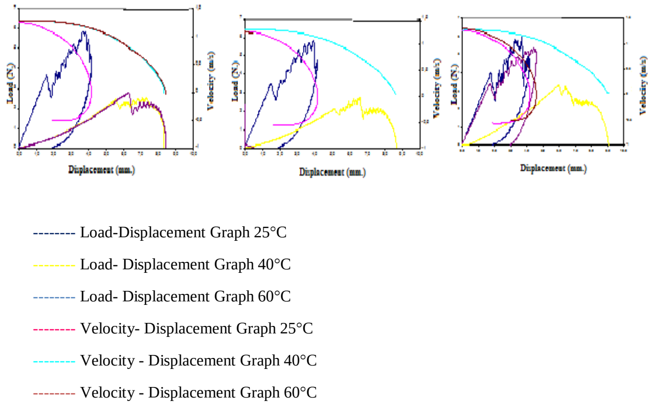


Figure 9. Load-Velocity-Displacement Graphs, a) [0/+45/-45/90/+45/0/-45/90]$_S$, b) [+45/0/-45/90/+45/0/-45/90]$_S$, c) [90/+45/0/-45/+45/0/-45/90]$_S$

As temperature increases, contact force decreases; but permanent displacement increases (figure 9). [0/+45/-45/90/+45/0/-45/90]$_S$ ply array at 40°C and 60°C, [+45/0/-45/90/+45/0/-45/90]$_S$ and [90/+45/0/-45/+45/0/-45/90]$_S$ ply array at 40°C penetration has been observed. That means the contact force caused permanent damage and no back leap was observed (Figure 9).

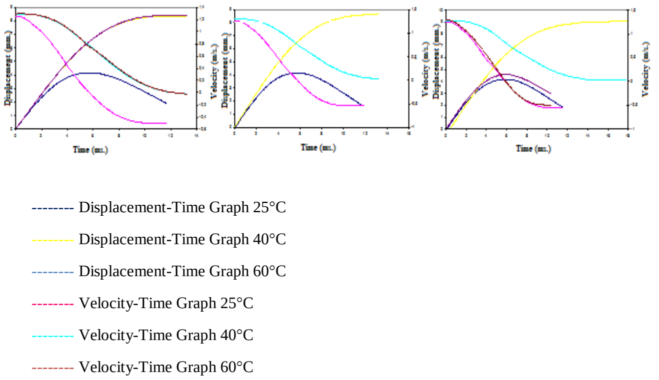


Figure 10. Displacement-Velocity-Time Graph, a) [0/+45/-45/90/+45/0/-45/90]$_S$, b) [+45/0/-45/90/+45/0/-45/90]$_S$, c) [90/+45/0/-45/+45/0/-45/90]$_S$

As it is seen in figure 10, velocity becomes zero just as striker edge hits sample and back leap. Then at reverse direction it becomes negative value when there is back-leaping and no penetration. When there is penetration, the velocity becomes zero. All result could be seen at table 4 for 16 ply array prepregs.

Table 4. 16 ply array prepregs results

T	**F_{max}**	**E_{fmax}**	**V_{impact}**	**d_{Fmax}**	**d_{total}**	**t_{Fmax}**	**t_{total}**
°C	**(kN)**	**(J)**	**(m/s)**	**(mm.)**	**(mm.)**	**(ms)**	**(ms)**
[0/+45/-45/90/+45/0/-45/90]$_S$							
25	5.863	11.676	1.213	3.647	1.904	3.672	11.685
40	2.469	5.550	1.220	5.563	8.370	4.646	12.544
60	2.805	7.236	1.222	6.295	8.423	5.461	12.544
[+45/0/-45/90/+45/0/-45/90]							
25	5.830	13.364	1.245	3.929	1.590	4.380	11.855
40	2.738	7.843	1.222	6.577	8.670	5.818	13.269
60	2.450	7.728	1.218	6.412	8.216	4.484	13.512
[90/+45/0/-45/+45/0/-45/90]							
25	6.069	12.184	1.212	3.692	1.815	3.789	11.465
40	3.311	8.324	1.214	5.957	8.888	5.139	17.908
60	5.401	14.294	1.221	4.411	2.852	4.774	10.382

B. 10-Ply Prepregs Low Energy Impact Tests Results

10-ply prepreg samples were subjected to low energy impact test at 25°C (room temperature), 40°C and 60°C respectively by 7 J energy. The responses to the impacts are represented at the graphs (Figure 11,12,13) and table 5 below. The thickness of the 10-ply prepregs is 1,84 mm.

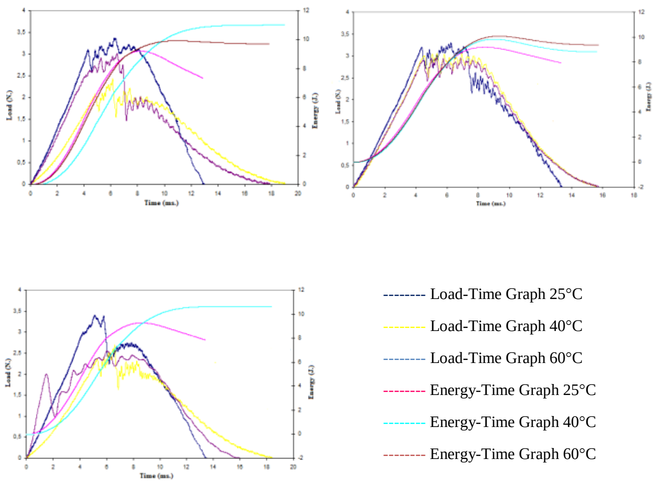


Figure 11. Force-Energy-Time Graph, a) [0/+45/0/-45/90]S, b) [+45/0/0/-45/90]S, c) [90/+45/0/0/-45]S

As it is seen in Figure 11, back-leaping has been observed in [0/+45/0/-45/90]s ply array at 25°C and 60°C, penetration at 40°C. Back-leaping has been observed in [+45/0/0/-45/90]S ply array at all temperature degrees.

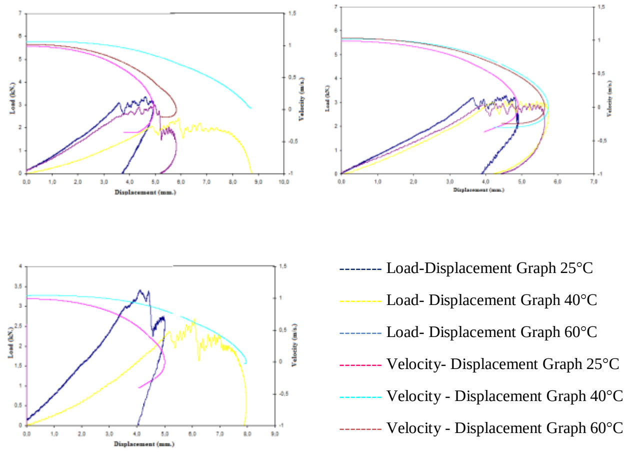


Figure 12. Force-Velocity - Displacement Graph, a)[0/+45/0/-45/90]S, b)[+45/0/0/-45/90]S, c)[90/+45/0/0/-45]S

In [0/+45/0/-45/90]S ply array, penetration has observed at 40°C. That is because no decrease in displacement is observed after striker edge contact to the sample ceased. But at 25°C and 60°C back-leaping has occurred, decrease in displacement is observed after striker edge contact to the sample ceased. In [+45/0/0/-45/90]S ply array, at all temperature degrees back-leaping was observed. In [90/+45/0/0/-45]S ply array, penetration was observed at 40°C (Figure 12).

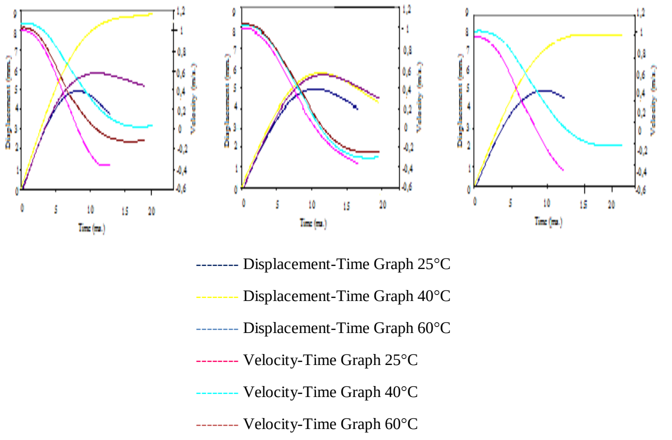


Figure 13. Displacement-Velocity-Time Graph, a) [0/+45/0/-45/90]S, b) [+45/0/0/-45/90]S, c)[90/+45/0/0/-45]S

All result could be seen at table 5 for 10 ply array prepregs.

Table 5. 10 ply array prepregs low energy impact test results

T	F_{max}	E_{fmax}	V_{impact}	d_{Fmax}	d_{total}	t_{Fmax}	t_{total}
°C	(kN)	(J)	(m/s)	(mm.)	(mm.)	(ms)	(ms)
[0/+45/0/-45/90]							
25	3.361	8.145	0.902	4.600	3.750	6.262	12.893
40	2.441	6.168	0.911	5.900	8.763	6.134	19.025
60	3.020	8.261	0.901	4.986	5.173	6.476	17.865
[+45/0//0/-45/90]							
25	3.303	8.195	0.902	4.571	3.947	6.265	13.318
40	3.056	8.901	0.901	5.414	4.217	6.940	15.631
60	2.951	8.927	0.913	5.217	4.424	6.879	15.729
[90/+45/0/0/-45]							
25	3.409	6.746	0.904	4.118	4.043	5.137	13.428
40	2.693	7.053	0.898	6.093	7.887	6.622	18.402
60	2.547	7.139	0.901	6.235	8.045	6.044	18.802

C. 8-Ply Prepregs Low Energy Impact Tests Results

8-ply prepreg samples were subjected to low energy impact test at 25°C (room temperature), 40°C and 60°C respectively by 5 J energy. The responses to the impacts are represented at the graphs (Figure 14,15,16) and table 6 below. The thickness of the 8-ply prepregs is 1,47 mm.

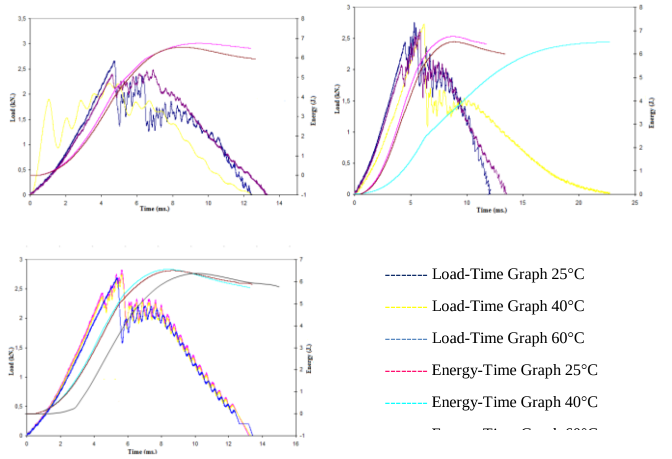


Figure 14. Load-Energy-Time Graph, a) [0/+45/-45/90]S, b) [90/+45/0/-45]S, c) [+45/0/-45/90]S

As it is seen in Figure 14; as temperature increases, contact force decreases. Only in $[90/+45/0/-45]_S$ ply array at 40°C penetration has been observed due to whole energy absorption. Back-leaping has been observed in all other 8 ply array samples.

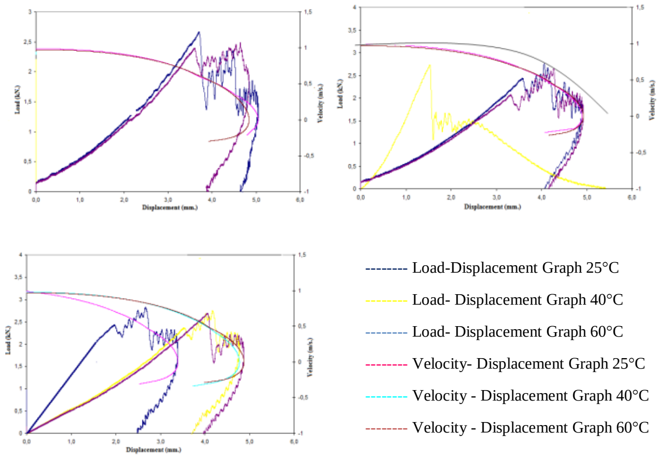


Figure 15. Force-Velocity-Displacement Graph, a) $[0/+45/-45/90]_S$, b) $[90/+45/0/-45]_S$, c)$[+45/0/-45/90]_S$

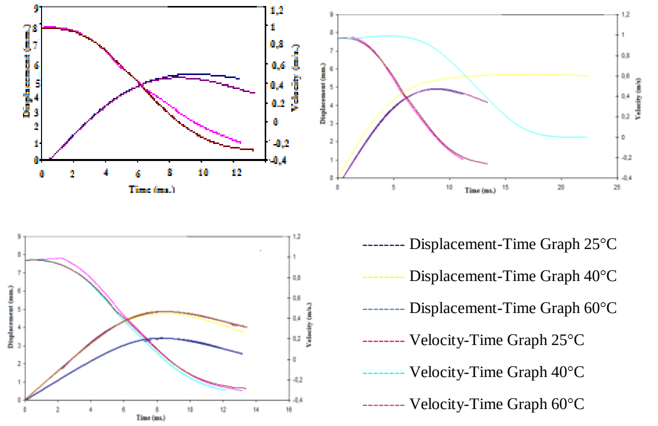


Figure 16. Displacement-Velocity- Time Graph, a) $[0/+45/-45/90]_S$, b) $[90/+45/0/-45]_S$, c)$[+45/0/-45/90]_S$

As temperature degree increases, permanent damage also increases. As passing from back leaping to the penetration, force value increases. This could be obviously seen in $[90/+45/0/-45]_S$ at 40°C.

As it is seen in Figure 16; back leaping has been observed except $[90/+45/0/-45]_S$ ply array sample at 40°C. Velocity becomes zero when penetration occurs. In back leaping, velocity turns to negative after striker edge hits the prepregs. All result could be seen at table 6 for 8 ply array prepregs.

Table 6. 8 ply array prepregs low energy impact test results

Table 6. 8 ply array prepregs low energy impact test results

T	F_{max}	E_{Fmax}	V_{impact}	d_{Fmax}	d_{total}	t_{Fmax}	t_{total}
°C	(kN)	(J)	(m/s)	(mm.)	(mm.)	(ms)	(ms)
[0/+45/-45/90]							
25	2.668	4.298	0.894	3.702	4.787	4.722	12.419
40	2.215	4.145	0.896	3.652	4.573	4.452	12.500
60	2.488	6.119	0.896	4.640	3.915	6.395	13.257
[90/+45/0/-45]							
25	2.763	5.037	0.893	4.060	4.064	5.313	11.788
40	2.731	2.386	0.894	1.536	5.418	6.207	22.760
60	2.488	5.250	0.894	4.271	13.435	5.830	4.153
[+45/0/-45/90]							
25	2.829	4.960	0.892	2.672	2.520	5.657	13.203
40	2.756	5.285	0.896	4.176	3.722	5.647	13.296
60	2.693	4.866	0.892	4.064	3.979	5.388	13.433

D. A combination of results for room temperature low impact tests

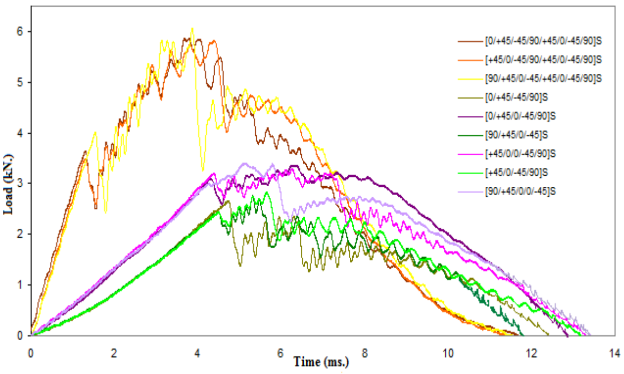


Figure 17. Force-time graph for 16,10 and 8 ply array samples at room temperature

Composite prepreg mechanical properties such as toughness, brittleness, hardness and strength is prone to change by temperature, hence these values will affect contact force according to the temperature. The difference between these mechanical properties and changes affect the bending rigidity of the prepregs; and as a result delamination ratio increases. For instance $[90/+45/0/-45/+45/0/-45/90]_S$ 16 ply-array prepregs bending rigidity is more than the others, so contact force is more than others as seen in figure 17. As it is seen in figure 17, contact force decreases going from 16 ply array to 8 array, that means from thick to thin contact forces decreases and contact time increases. Thickness is directly proportionate to contact force. It can be said generally that rigidity of a prepreg is directly proportionate to thickness. Ply orientation angles of laminates affect the impact damage more than laminate thickness. Prepregs having plyes in the same direction do not encounter delamination; but prepregs having plyes in the opposite direction, because of bending rigidity at the interface of plyes, delamination occurs. This phenomenon could be obviously seen in figure 17 and 18. As the thickness increases contact force increase and because of having plyes in the opposite direction delamination occurs as seen in the oscillation in the graphs.

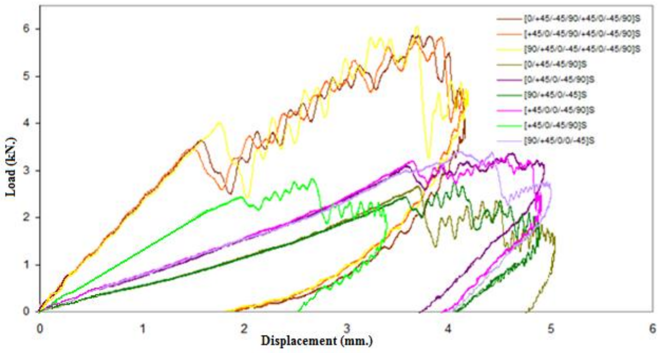


Figure 18. Force-displacement graph for 16,10 and 8 ply array samples at room temperature

As it is seen in Figure 20, as sample thickness and impact energy increase; displacement decreases. Back leaping was observed in all 16, 10 and 8 ply array prepreg samples. Different threshold points and oscillations was observed, that is because different damage mechanisms occured in samples. Displacement rate in 16 and 8 ply array samples is respective 45°, 90° and 0° oriented prepregs; 0°, 45° and 90° oriented prepregs in 10 ply array samples.

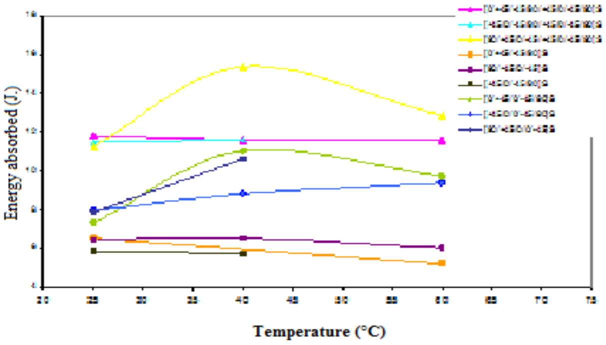


Figure 19. Energy absorbed-temperature graph for 16,10 and 8 ply array samples at room temperature

As it is seen in Figure 19, energy absorbed in high temperatures is more than room temperature samples' absorbed energy.

IV. DISCUSSION

As the temperature increases, some mechanical properties changes; for instance toughness increases, more energy is absorbed and material begins to be more unstable; that is because penetration increases. This phenomenon is observed in all 16,10 and 8 ply array prepreg samples. High temperature is not a desired property; however at 40°C and 60°C brittleness decreases, this means a tougher structure. Surely this depends on ply orientation and angles also. Thickness is an important factor that directly affects the high temperature low impact energy strength.

As we compare the prepregs with other traditional composites, we encounter a more stable structure and high impact strength relatively fibre orientation. Generally in all tests 3 basic mechanical behaviors could be observed; back leaping, penetration and perforation. Not only perforation was observed exactly; but also back leaping and penetration were observed. In back leaping; the least damage was observed, and also self-healing was observed. In penetration; after impact, no back leaping occurred. Striker edge goes into the sample by damaging the fibres and stops in the sample. Maximum penetration was obtained in this time and velocity becomes zero. All impact energy affected the sample. Perforation was observed in the beginning of the impact, but not exactly occurred. The major factor that affects the high temperature low energy impact strength is thickness, second one is temperature, third is ply array and orientation.

This was generally observed in all tests. Some important points have been discussed below:

In 16 ply array at 40 °C and 60°C temperature; contact forces are almost same, but in [90/+45/0/-45/+45/0/-45/90] ply array deflection was observed more at 40 °C than 60°C. This is interesting because generally it is assumed that as the temperature increases, deflection also increases; but here it is not valid. It could be explained that toughness increases after some threshold temperature upto the 60°C. And so deflection was observed less in 60° for [90/+45/0/-45/+45/0/-45/90] ply array.

For [90/+45/0/-45/+45/0/-45/90] ply array, penetration time is more at 40°C than 60°C. For 10 ply [90/+45/0/0/-45] and 8 ply [90/+45/0/-45] deflection and penetration time is more at 40°C than 60°C.

Prepreg samples with 90° ply array test results is somehow different than 45° and 0° ply arrays as explained above. One of the most important factor is the force controlled by energy. Thickness is important, because it affects the pressure area (Pressure = Force/Area). This is considered when test results were analysed. Velocity values were almost same in all tests, so impact strength were analysed accurately and this made easy to analyse test result and graphs. That means both energy-force relationship and velocity values supported each other to evaluate the test results.

V. CONCLUSION

Following results have been obtained generally;

1. As test temperature increases, CFRP prepreg low energy impact strength decreases.
2. Material thickness is an important factor to increase the strength.
3. Ply array and orientation angle affect the strength; especially ply array laminates beginning with 90° is most durable ones.
4. As temperature increases, toughness increases, this means low brittleness. So especially between 40° and 60°C deflection did not grow, on the contrary it decreases. This is an interesting result (see 9th paraghraph in discussion part).
5. Velocity values are almost same. This gave more accurate results and interpretation.
6. As test temperature increases, penetration and contact time increase.

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