Compression After Impact (CAI) Performance of Prepreg Carbon Fiber Reinforced Polymers (CFRP) at Different Temperatures

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***Abstract*—CAI (Compression After Impact) tests have been carried out to carbon prepreg laminated composite plates which were subjected to low energy impact test at high and low temperatures (0°C, -40°C, -60°C, 25°C, 40°C and 60°C). Prepreg laminates were orientated with quasi-isothropic layup as 16, 10 and 8 layered. AS4 carbon as fibre and 8552 epoxy resin as matrix have been used for experiments as prepreg. The samples have been prepared 150 X 100 mm. 2.94 mm., 0,184 mm. and 0,147 mm thickness respectively then vacuumed. High temperature samples have been cured at autoclave and low temperature samples in a 8 m^3 cooling cabin. The damaged areas have been identified with C-Scan, impact depth measured with comparator. CAI tests are applied according to ASTM (American Society For Testing Materials) D 695-02 and SACMA (Suppliers of Advanced Composite Materials Association) SRM 2R-94. The results have been represented grafically and as equation with the evaluation programme. Generally, it is observed that as the temperature increases and decreases, CAI strength decreases. CAI strength varies according to the laminate orientation and layup number also. That the laminates recover the low impact damages by time has been observed.**

Keywords*— *CAI test; low and high temperature; C-scan; CFRP; prepreg composites

I. INTRODUCTION

Prepregs are specially formulated resin matrix systems that are reinforced with man-made fibers such as carbon, glass and aramids. Prepreg is one of the ultimate composite materials. The thermoset resin cures at elevated temperature, undergoing a chemical reaction that transforms the prepreg into a solid structural material that is highly durable, temperature resistant, exceptionally stiff and extremely lightweight [1].

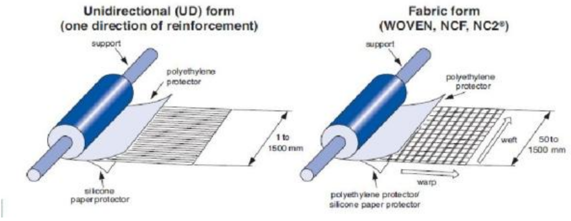

Figure 1. A Schematic View Of Prepregs Production [1]

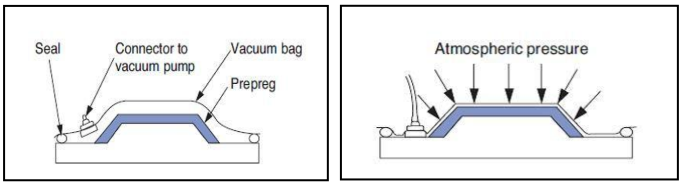

Figure 2. A Prepreg Preparation Process (Sealing Flexible Beg Over Lay-Up and Applying Vacuum To The System) [1]

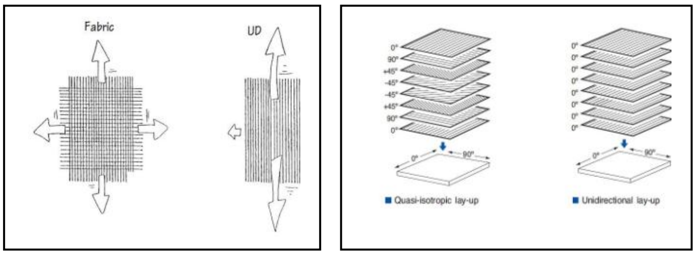

Figure 3. Equal and Unequal Properties Of A Laid Up Prepreg and Orientation [1]

Prepregs are specially formulated resin matrix systems that are reinforced with man-made fibers such as carbon, glass and aramids. Prepreg is one of the ultimate composite materials. The thermoset resin cures at elevated temperature,

Prepregs provide better mechanical properties over a wide temperature range than wet layups, that is, dry fabric with manually-applied resin. Because the resin is applied to the reinforcement in exact, precise quantities in a uniform way, an optimum fiber-matrix ratio is attained. One of the main factors against prepreg use is their poor damage tolerance, impact damage and reduced compression strength in the presence of impact damage [2].

Impacts on an airframe can occur from various hazards, ranging from the impact of a ballistic projectile to the fall of a screwdriver during a maintenance procedure [3].

The compression after impact (CAI) test has become a key experiment to gather damage tolerance performance data during the design or certification phase of prepregs. CAI performance is first of all dependent on the behaviour of the material under impact loading conditions [4].

CAI values of carbon-fiber (CF)/polymer-matrix composites are rated as one of the major screening parameters for material selection. Two types of testing procedures, the NASA and SACMA methods, are therefore proposed as standards, and enormous numbers of CAI tests are currently being conducted by aerospace industries and advanced material suppliers [5].

This paper is mostly considered on CAI behavior of prepregs at high and low temperatures, so low energy impact tests analyses is not worked through.

II. LITERATURE REVIEW

There are some studies and investigations on impact and strength performance of prepregs. Some of them are represented below:

Kan HP studied on parameters influencing the impact performance of a composite structure. Some are related to the structure being impacted (material constituents, lay-up sequence, laminate thickness, structure design), others are related to the impacting object (mass and shape of the striker, velocity and energy of the impact) [6]. Fuoss E. and friends have studied parameters such as the stacking sequence [7], the impact velocity [8].

Abrate and Schoeppner and Abrate showed the existence of a damage initiation threshold force on the load history traces of an impact event; identifiable with the first load drop. This threshold force is related to initial damage in the form of matrix cracking, ibre breakage and mainly delamination. The observation of this delamination threshold force, independent of the specimen dimension and boundary conditions, has been supported by extensive experimental evidence [9]. Experimental results obtained by Olsson [10] and Schoeppner and Abrate [11] on a range of materials including CF/epoxy, CF/BMI and CF/PEEK. Davies et al. [12] proposed a model based on fracture mechanics to predict the critical load. Predictions from this model showed good agreement with experimental results by Zhang and friends [13]. This model is the first step of a procedure for the prediction of a threshold impact energy for onset of delamination in quasi-isotropic laminates under low-velocity impact [14].

High and low temperature behavior of prepregs is an original aspect for this paper. We have not encountered any research on behavior of temperature behavior of prepregs for CAI test.

III. MATERIALS AND METHOD

Epoxy pre-impregnated carbon fibre (AS4 carbon and matrix is 8552 epoxy resin) was used in experiments. The fiber percent is % 60 in all laminates. Quasi-isotropic (QI) plates (Fig. 3) (150 x 100 x 2.94 mm. =16 ply, 150 x 100 x 1.84 mm =10 ply and 150 x 100 x 1.47 mm= 8 ply) were manufactured using hand lay-up method (Table 1 and 2) [15].

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

Properties	AS4 Carbon	8552 Resin
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(a). Array of prepregs used subjected to low energy impact and CAI test

Sample Name	Array Of Plies	Application Temperature (°C)	Low Impact Application Energy (J)	Layer Number	Thickness (mm.)
1A1	[0/+45/-45/90/+45/0/-45/90]s	25°C	13	16	2,94
1A2		40°C			
1A3		60°C			
1A4		0°C			
1A5		-25°C			
1A6		-40°C			
2A1	[+45/0/-45/90/+45/0/-45/90]	25°C	13	16	2,94
2A2		40°C			
2A3		60°C			
2A4		0°C			
2A5		-25°C			
2A6		-40°C			
3A1	[90/+45/0/-45/+45/0/-45/90]$_s$	25°C	13	16	2,94
3A2		40°C			
3A3		60°C			
3A4		0°C			
3A5		-25°C			
3A6		-40°C			
4A1	[0/+45/-45/90]s	25°C	5	8	1,47
4A2		40°C			
4A3		60°C			
4A4		0°C			
4A5		-25°C			
4A6		-40°C			
5A1	[0/+45/0/-45/90]s	25°C	7	10	1,84
5A2		40°C			
5A3		60°C			
5A4		0°C			
5A5		-25°C			
5A6		-40°C			

Table 2(b). Array of prepregs used subjected to low energy impact and CAI test

Sample Name	Array Of Plies	Application Temperature (°C)	Low Impact Application Energy (J)	Layer Number	Thickness (mm.)
6A1	[90/+45/0/-45]s	25°C	5	8	1,47
6A2		40°C			
6A3		60°C			
6A4		0°C			
6A5		-25°C			
6A6		-40°C			
7A1	[+45/0/0/-45/90]s	25°C	7	10	1,84
7A2		40°C			
7A3		60°C			
7A4		0°C			
7A5		-25°C			
7A6		-40°C			
8A1	[+45/0/-45/90]s	25°C	5	8	1,47
8A2		40°C			
8A3		60°C			
8A4		0°C			
8A5		-25°C			
8A6		-40°C			
9A1	[90/+45/0/0/-45]s	25°C	7	10	1,84
9A2		40°C			
9A3		60°C			
9A4		0°C			
9A5		-25°C			
9A6		-40°C			

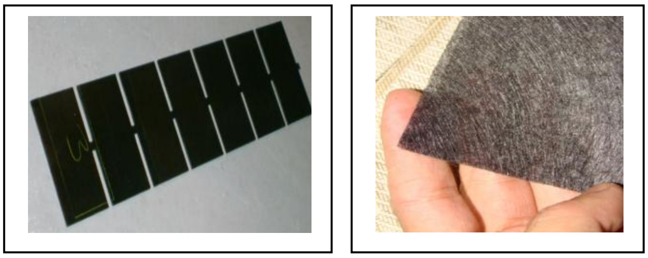

Figure 4. Prepreg samples cut and prepared by water jet

Epoxy pre-impregnated carbon fibres (Hexcel AS4/8522 resin) were selected to carry out the low energy impact and CAI tests. Prepreg composite fibre material is AS4 carbon and matrix is 8552 epoxy resin. The samples have been prepared 150 X 100 mm., 2.94 mm., 0,184 mm. and 0,147 mm thickness respectively, then have been vacuumed and cured at autoclave.

Figure 5. Autoclave used for heating and tool for prepregs

Samples were prepared in a cabin for each temperature degree (40°C and 60°C) till reaching the desired temperature then were waited 15 minute for stability then subjected to low energy impact respectively.

The tool (back up material in autoclave) material for prepregs can be either metal or carbon according to their expansion ratio. For instance, for carbon fibre it can be carbon and for hybrid metal. Expansion ratio value of tool should be near to prepreg material.

For low temperature degrees (0°C, -25°C and -40°C) a coolant device was used and as the high temperature degrees the samples were kept in it till reaching the desired temperature then were waited for 15 minute for stability and subjected to low energy impact and CAI tests respectively.

The properties of the coolant device is below:
Brand : Vötsch VC40008 Climate Test Coolant Cabin
Volume : 8 m^3
Dimensions : 2 m. X 2 m. X 2 m.
Temp. Inter. : Min. -40°C - Max. 95°C

Impact tests were performed with an Instron Dynatup 9250 drop weight impact machine. The impact velocity was kept between 1 and 3 m/s. The impactor has a hemispherical tip with a diameter of 16 mm. The impactor tip is instrumented with a load cell. The force applied by the striker to the specimen was recorded as well as the initial velocity at the time of impact. Energy, velocity and delection are numerically deduced from the force/time data.

This paper's point of interest is CAI, therefore low impact energy test results and discussion is no concern. Low energy impact tests were conducted for each sample, C-Scans were carried out, after that CAI tests were conducted and analysed in detailed.

CAI tests were performed using a digitally controlled servo hydraulic testing machine. The specimens were supported using a jig following SACMA standart [15] for CAI recommendations and compressed at a constant displacement rate of 0.5 mm/min. CAI tests have been conducted for 16, 10 and 8 layered prepreg laminates orientated with different angles (Table 2). CAI tests for 0°C, -40°C, -60°C 25°C, 40°C and 60°C samples are applied according to ASTM D 695-02 [16] and SACMA SRM 2R-94 respectively.

CAI strength is calculated as below:

$$\sigma_c = F_{max}/b.t \qquad [17]$$

F_{max} = Maximum compression force (N)
σ_c = CAI strength (N/m^2)
b = sample width (m)
t = sample thickness (m)

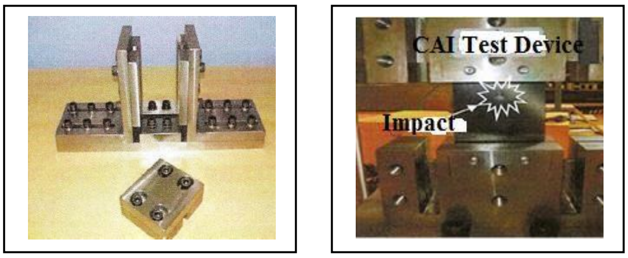

Figure 6. CAI Test Equipment and emplacement the sample

IV. RESULTS

A. C-Scan Results

The datas were obtained by the C-Scan system which is used in ultrasonic tests. This system is used in high speed scans to obtain permanent record after low energy impact tests.

There is recording system named "printing bar" in C-Scan device. One side of the printing bar is attached to the ultrasonic test device amplifier, while the other one to the helical drum. As the drum rotates, the recording side of the printing bar marks a line moving on the paper on each period. After scanning, the damage area sizes of the samples were obtained by "Evaluation" software.

The damage sizes of the samples is shown on figure 7 through figure 15.

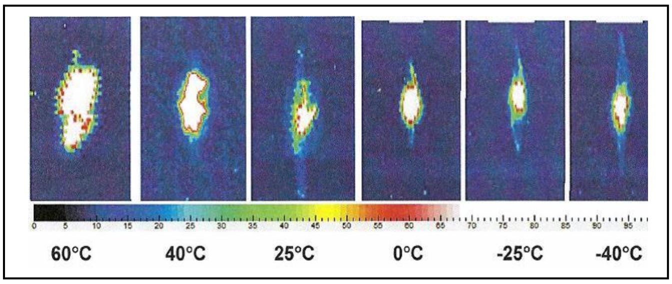

Figure 7. [0/+45/-45/90/+45/0/-45/90]s array impact damage areas

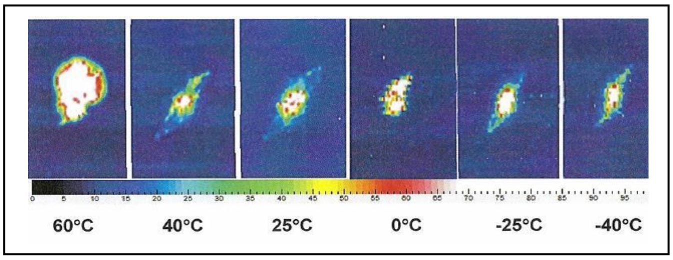

Figure 8. [+45/0/-45/90/+45/0/-45/90]s array impact damage areas

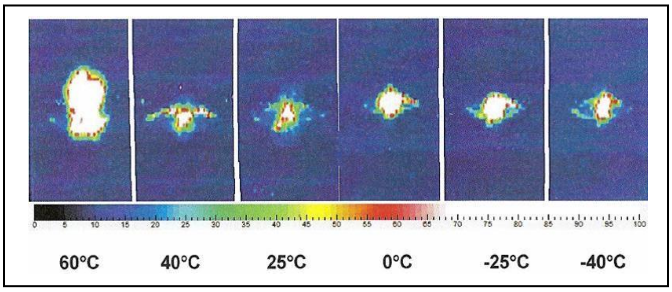

Figure 9. [90/+45/0/-45/+45/0/-45/90]s array impact damage areas

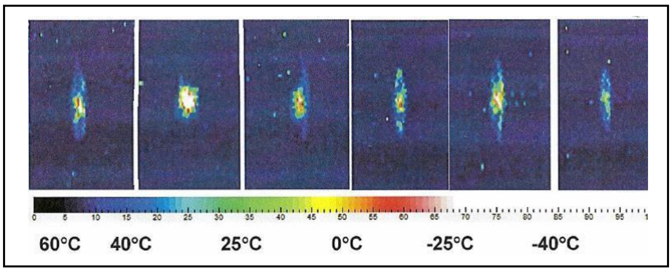

Figure 10. [0/+45/-45/90]s array impact damage areas

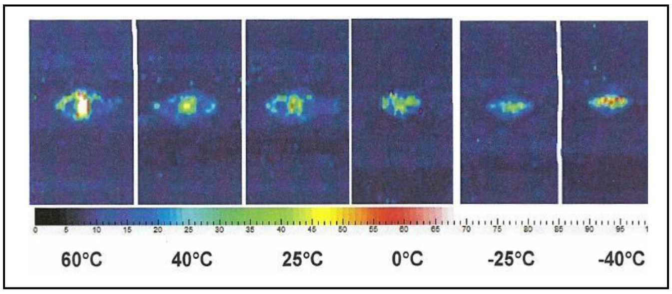

Figure 11. $[90/+45/0/-45]_s$ array impact damage areas

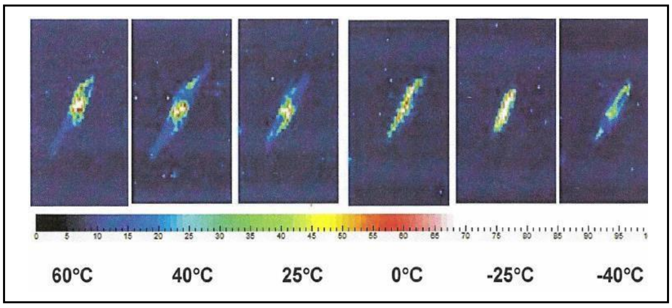

Figure 12. $[+45/0/-45/90]_s$ array impact damage areas

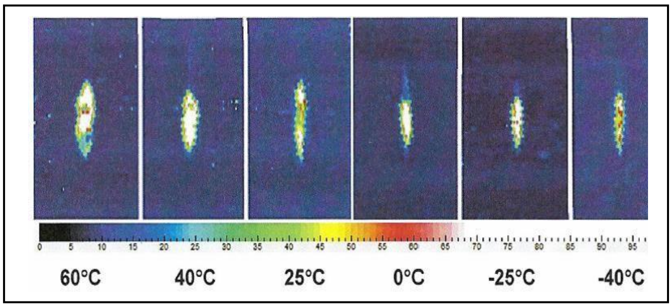

Figure 13. $[0/+45/0/-45/90]_s$ array impact damage areas

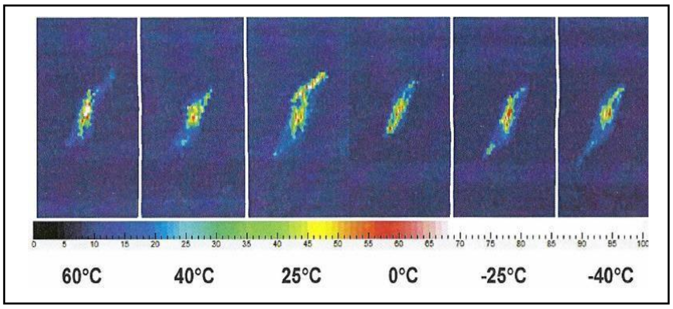

Figure 14. [+45/0/0/-45/90]$_s$ array impact damage areas

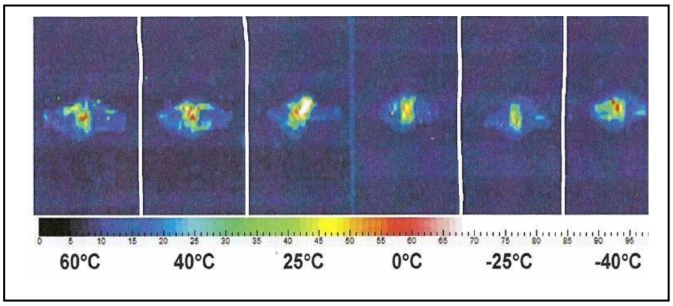

Figure 15. [90/+45/0/0/-45]s array impact damage areas

The depth and distrubition of the damage area could be analysed thanks to C-Scan tests; but not shape, length and width.

When the damage area examined in figure 7 through figure 15, and the figure 16, the distrubition of damage occur according to the lower layer fibre direction, in other words; the first orientation angle of the sample and the distribution of the damage area is parallel to each other. It has an eliptical shape. And surely the damage in inner layers is also parallel to the orientation. **We can say; as the damage area is reduced on account of different orientation angle of laminated composites fibers, the absorbed energy is increases.**

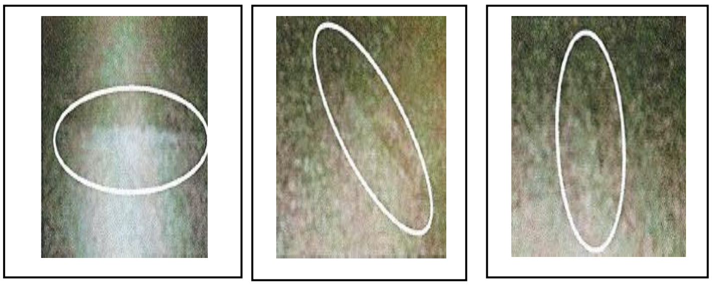

Figure 16. Damage areas on the back sides of some samples

The damage area-temperature graphs are shown in figure 17. It is generally appearent that as the temperature increases, the damage (impact) area increases.

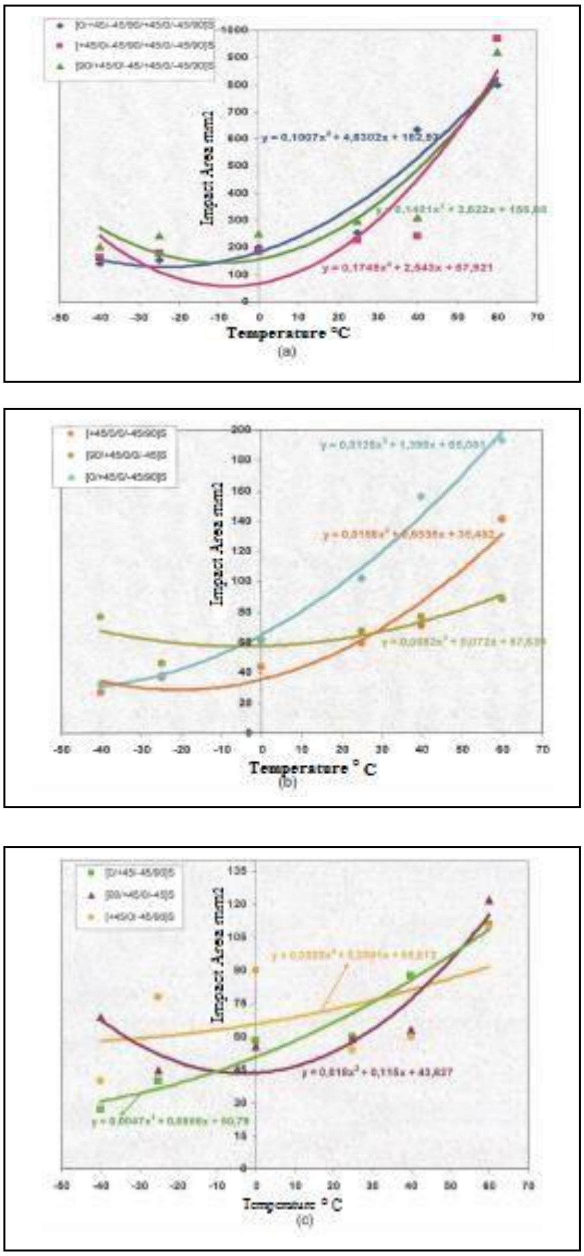

Figure 17. Impact Damage Areas
a)16 layered prepregs
b)10 layered prepreg
c) 8 layered prepregs

The 60°C temperature slope of all of the 16,10, 8 layered prepregs have the most damaged areas. We think this is a result of the low elastic modulus at high temperature degrees. Because as the elastic modulus declines, energy absorbed increses; so maximum strain of prepregs also increases. High damaged area is a conclusion of this high strain.

It is observed that the same number layers have the same temperature effects. The most effected damage area according to the orientation of layers is 90°,45° and 0° angles. The most impact damaged area is observed in 90° oriented prepregs and the least is at the 0° oriented layers.

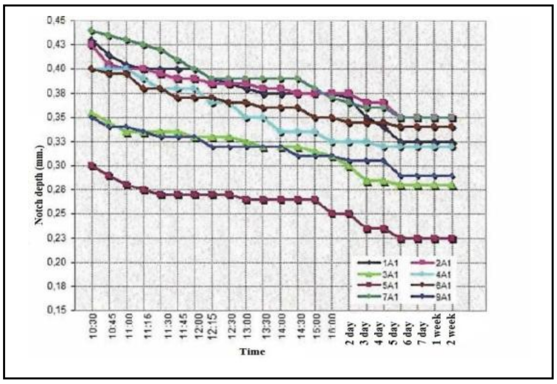

Figure 18. Notch depth-time graph (an obvious decrease in impact depth has been observed)

As stated in figure 17, there is appearent self-healing of prepregs to the 5th day after the low energy impact test. The percent of self-healing (diminishing)- applied energy graph is seen in table 3. The percent of self healing is observed between %15-25. The diminishing stops in 5_{th} day and no longer self-healing was observed till the 2nd week.

Table 3. Percent of Self-Healing- Energy Graph

Self-healing (%)	24,4	17,6	21,1	20,0	25,0	15,0	20,4	17,1
Energy (J)	14,5	14,5	14,5	7	10	7	10	10

B. CAI Test Results

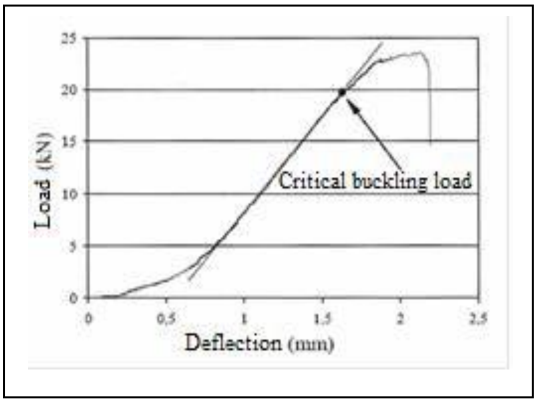

Figure 19. A Typical Buckling Load and Deflection Graph [18]

If the strength in a system exceed the safety limit, yield or fracture may occur. This kind of problems characterised as stress problems. But in the buckling, a balance state is the subject of interest. If the balance state is not stable, the lowest change in the system could cause large deflections and generally the system cannot come to its first state. This kind of problems are called stability problems. The comparison criteria is the critical buckling load in buckling as a stability problem [19].

The samples have been subjected to compression test by preventing buckling in the CAI test. Samples are constrained by both sides for avoiding buckling and subjected to compression from up and down [20].

The compression load has been applied to the samples through 0° and Similar to figure 17, deflection and load graphs have been obtained. Maximum compression loads (buckling loads) was obtained. Deflection and load graphs like figure 19. were obtained for each sample. Then the maximum loads were taken and temperature-load graphs (figure 20.) were drawn.

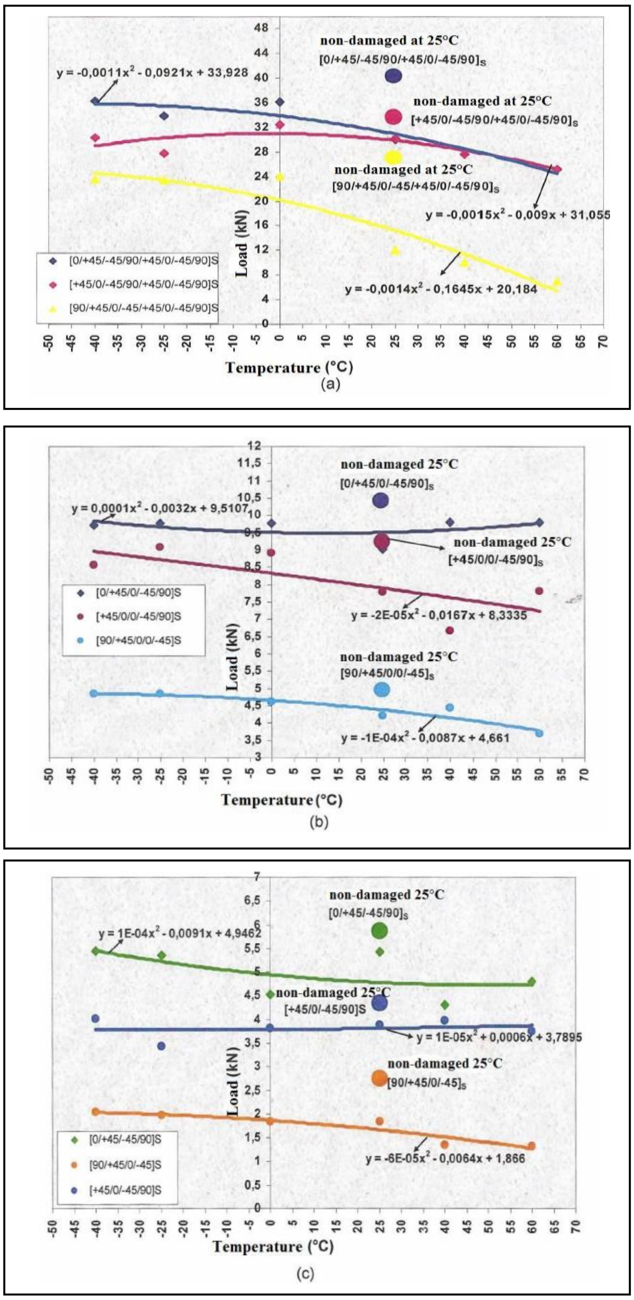

Figure 20. Change of compression (buckling) loads according to temperature
a)16 layered prepregs
b)10 layered prepregs
c) 8 layered prepregs

Compression (buckling) loads change according to the temperature change and undamaged samples compression (buckling) loads at 20°C is shown in figure 19; a,b and c respectively**. As seen in figure 19, generally it is observed that, as the temperature decrease and increase, regardless of the fibre orientation and layer number, compression (buckling) loads decrease. Temperature fluctuations decline the strength of prepregs. This is an important result for us.**

When figure 20 is analysed, it is seen that the most enduring layer orientation in the same thickness is respectively 0°, 45° and 90°. This can be explained as; compression (buckling) load is parallel to 0° and it means they are at the same direction. So 0° orientation fibre is the most durable orientation. This could be seen obviosly in figure 17.
Sample array (16, 10, 8 layered and 0°, 45° , 90° orientation) versus compression (buckling) loads is shown in figure 21.

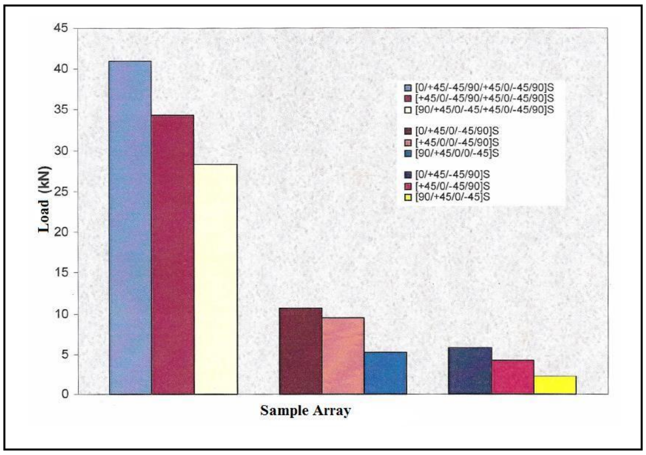

Figure 21. Sample Array-Load Graph

In figure 22 (a,b,c), prepreg samples subjected to compression (buckling) loads in different temperature degrees and in room temperature are compared according to the % change of compression (buckling) load. In graphs polynomial curves derived from equations. The lonely points are % change of undamaged prepreg samples subjected to load at room temperature.

As it is seen in figure 22 (a,b,c) difference between the most and least temperature is the most in 90° oriented layered prepregs and the least is the 45° oriented ones. This means that % change (decreasing amount in compression-buckling load) is less at the 45° oriented ones than the 90° oriented ones at high temperatures. The reverse is true; that is; % change (incresing amount in compression-buckling load) is more at the 90° oriented ones than the 45° oriented ones at high temperatures. Generally it can be said that 90° oriented prepreg composites compression (buckling) strength change interval is wider than 45° and 0° oriented prepregs.

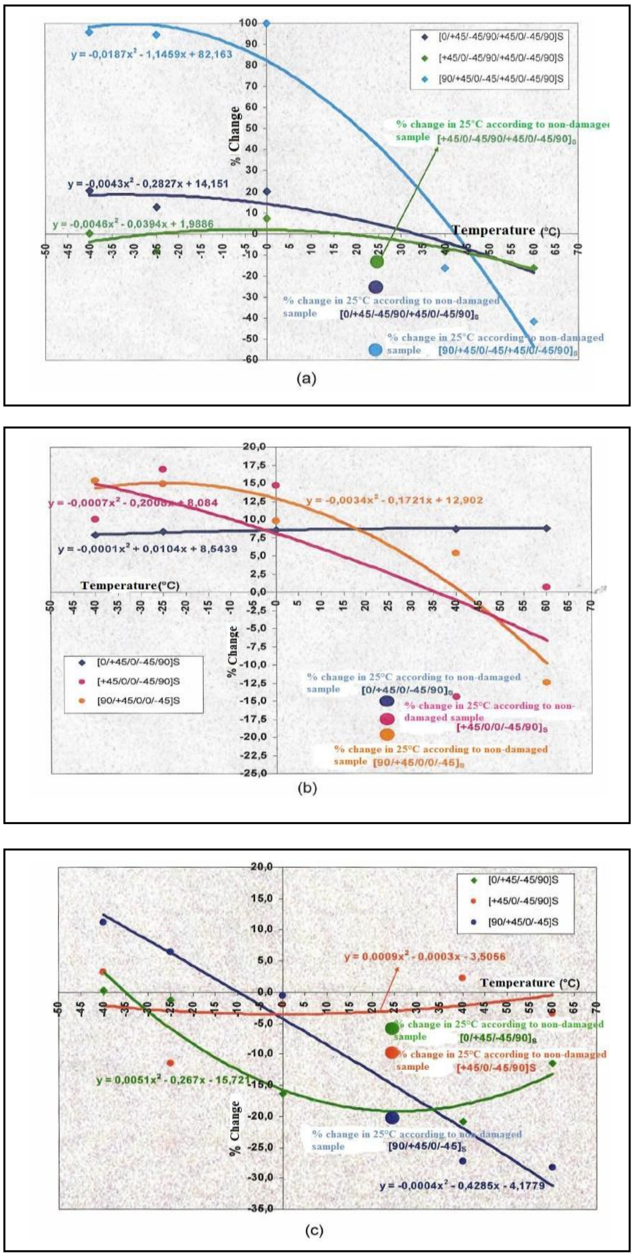

Figure 22. Temperature-% Change of compression (buckling) loads according to the sample array
a)16 layered prepregs
b)10 layered prepregs
c) 8 layered prepregs

V. DISCUSSION

Although prepregs are one of the ultimate composites, CAI strength decresases as diverging from room temperature. Also contact time, fiber orientation and fiber thickness are the important constituents for CAI strength. Elasticity modulus decreases at high and low temperatures. That is because, matrix and fibres are prone to damage and fracture at high and low temperatures. Prepregs are used as durable composites in aerospace industry. Aeroplanes fly especially

at low temperatures. So resistance to damage and self-healing is considered important for especially low temperatures.
The most durable orientation for quasi-isotropic lay-out is 0°lay-up. This is an expected result for us, because compresssive load is parallel to fibres in this direction.

Since the contact time decreases and impact load increases at high temperatures, impact area increases. This could be obviosly seeen in figure 7 through figure 15.

The damage after test is because of compression not buckling. The CAI damage has continued following the damage of low energy impact test. The maximum compression load is the maximum damage load. Damage load is divided to section area, so the maximum compression strength is obtained.

Self-healing was observed at room temperature. This is an important result also, because acording to this result more compact and self-healing prepregs with different kind of fibres-matrixes could be produced. Different variations of quasi-isotropic lay-ups could be obtained.

90°oriented fibres are the least durable for CAI; because as the orientation angle go up, it is difficult to become stable for prepreg composites. Contact area is less in 90° orientations than 0° and 45°.

CAI strength of 8 and 10 laminated prepreg composites changes according to the temperature is less then 16 laminated prepregs. We can say as the laminate number decreases, the temperature effect also decreases. This is an important **phenomenon; so it can be said the laminate number is directly proportional to the temperature change interval.**

VI. CONCLUSION

CAI tests have been carried out on quasi-isotropic CFRP prepreg composite laminates at low and high temperature degrees and following results have been obtained:
1. CAI performance of prepregs is free from laminate array and thickness. It decreases as deviated from room temperature. This is more obvious in 90° oriented laminates.
2.The best performance is 0°oriented laminates.
3.An obvious partially self-healing has been observed in all prepreg laminates at room temperatures.
4.The most stable CAI performance orientation is 0°laminates, while the least is 90° according to % change from -40°C to 60°C.
5. Low temperature CAI performance of prepregs is better than high temperature CAI performance.
6. Laminate number effects the CAI strength, as laminate number increases, temperature effect increase.

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