RESEARCH ARTICLE | FEBRUARY 24 2017

The effect of the impactor diameter and temperature on low velocity impact behavior of CFRP laminates

C. Evci; İ. Uyandıran

AIP Conf. Proc. 1809, 020014 (2017)

https://doi.org/10.1063/1.4975429

The Effect of the Impactor Diameter and Temperature on Low Velocity Impact Behavior of CFRP Laminates

C. Evci[1,*] and İ. Uyandıran[2]

[1]Atilim University, Mechanical Engineering Department, Ankara, Turkey
[2]Turkish Military Academy, Defense Sciences Institute, Ankara, Turkey
[*]Corresponding author: celal.evci@atilim.edu.tr

Abstract. Impact damage is one of the major concerns that should be taken into account with the new aircraft and spacecraft structures which employ ever-growing use of composite materials. Considering the thermal loads encountered at different altitudes, both low and high temperatures can affect the properties and impact behavior of composite materials. This study aims to investigate the effect of temperature and impactor diameter on the impact behavior and damage development in balanced and symmetrical CFRP laminates which were manufactured by employing vacuum bagging process with autoclave cure. Instrumented drop-weight impact testing system is used to perform the low velocity impact tests in a range of temperatures ranged from 60 down to -50 °C. Impact tests for each temperature level were conducted using three different hemispherical impactor diameters varying from 10 to 20 mm. Energy profile method is employed to determine the impact threshold energies for damage evolution. The level of impact damage is determined from the dent depth on the impacted face and delamination damage detected using ultrasonic C-Scan technique. Test results reveal that the threshold of penetration energy, main failure force and delamination area increase with impactor diameter at all temperature levels. No clear influence of temperature on the critical force thresholds could be derived. However, penetration threshold energy decreased as the temperature was lowered. Drop in the penetration threshold was more obvious with quite low temperatures. Delamination damage area increased while the temperature decreased from +60 °C to -50 °C.

Keywords: Impact behavior; CFRP laminates; Impact damage; Energy thresholds; Temperature effect.
PACS: 46, 81, 44.

INTRODUCTION

Advances in materials science and manufacturing processes have enabled the composite materials to be widely used for a variety of applications in automotive, aerospace, marine, defense, medical and sports industries [1-5]. By combining different functions such as high strength, chemical resistance, insulation, limited thermal expansion, radar tranparency and fatique resistance in one product, more cost and maintenance effective composite solutions compared to the traditional material solutions can be obtained.

Design criteria essential for unique and extreme operating environments, high stiffness and strength to weight ratios, tailorable mechanical properties and fatique resistance make the composites the material of choice to replace the steel and aluminum.

Proceedings of the 6th International Advances in Applied Physics and Materials Science Congress & Exhibition
AIP Conf. Proc. 1809, 020014-1–020014-10; doi: 10.1063/1.4975429
Published by AIP Publishing. 978-0-7354-1477-8/$30.00

Fiber reinforced polymer (FRP) composites are extremely versatile to specifically tailor the mechanical properties by adjusting a set of material parameters such as fiber reinforcement and resin matrix materials, fiber volume fraction, orientation of the fiber and fabrication process.

Governing failure mechanisms in FRP composites are substantially different from that in metals. Fiber reinforced composites with thermosetting matrix material, which have so far found the widest range of applications in engineering, are brittle. Unlike the brittle metallic materials, FRP composites have complex damage modes such as delamination and microbuckling due to the orthotropic mechanical properties [2].

Air vehicles face the most extreme environmental conditions including vibration, shock, humidity, moisture, temperature and electromagnetic interference. A wide range of temperature applications may be effective across large geographical areas. Even under these extreme conditions, fiber reinforced polymer composites are extremely versatile to specifically tailor the thermo-mechanical properties.

The impact characterization is not straightforward because it involves many parameters related to both the target material and the impactor characteristics such as shape and mass [6, 7]. Material response to impact loading and consequent failure mechanisms are also sensitive to loading rate [1]. Low velocity impact may be either defined with striking velocities up to 100 m/s or the extent of damage formation on the material [8, 9]. Impact energies involved in low velocity impact are generally quite low in the order of a few kJ. The contact time between the impactor and the material is relatively long which enables to obtain the load & time, load & deflection and energy & deflection curves using instrumented test systems like drop-weight tower. Using the load and deflection history of the composites damage initiation and growth, main damage and failure may be obtained in relation to critical force and energy thresholds. Low velocity impact on composite materials may produce barely visible damage while serious internal damage can occur.

The new generation of aircrafts employs the use of composite materials on different structures with an increasing percentage of the whole body. Since the structures of aircrafts are exposed to external sources of impact, impact damage should be a major concern due to the probable internal damage without any sign of damage on the outer skins. The internal damage in the composite structure makes it important to determine how this damage could affect the performance of the skin.

Considering the thermal loads encountered at different altitudes during a flight, both low and high temperatures can significantly affect the properties and impact behavior of composite materials. This study aims to investigate the effect of temperature and impactor diameter on the impact behavior and damage development in balanced and symmetrical CFRP laminates. Instrumented drop-weight impact testing system is used to perform the low velocity impact tests in a range of temperatures ranged from 60 down to -50 °C. Impact tests for each temperature level were conducted using three different hemispherical impactor diameters varying from 10 to 20 mm. Energy profile method is employed to determine the impact threshold energies for damage evolution. The level of delamination damage is determined using ultrasonic C-Scan technique.

MATERIAL and METHOD

Composite laminates were made up of high strength carbon fiber in five-harness woven fabric impregnated with a toughened epoxy and fabricated utilizing vacuum bagging process with autoclave cure. Material properties of composite laminates are given in Table 1. Some of the manufacturing steps of composite laminates are shown in Fig. 1. Test samples were cut to the dimensions of 150x100 mm. Thickness of the laminates were 4.3 mm. Within the scope of this study, low velocity impact behavior of composite laminates is determined through an instrumented impact test system, Instron Dynatup 9250 (See Fig. 2-a). Low velocity impact tests were performed in a range of temperatures ranged from 60 down to -50 °C employing a temperature conditioning unit (See Fig. 2-b). Impact tests for each temperature level were conducted using three different hemispherical impactor diameters varying from 10 to 20 mm (See Fig. 2-c).

Table 1. Material properties of composite laminates.

Composite Material Properties	
manufacturer	Hexcel
fabric type	G0926(style)
fiber type	High strength carbon
resin type	6376 epoxy, toughened
fiber volume fraction (V_f)	58.73%
fiber density	1.80 ± 0.04 g/cm^3
resin density	1.27 ± 0.07 g/cm^3
prepreg mass per unit area	570 ± 35 g/m^2
nominal cured ply thickness	0.35 mm

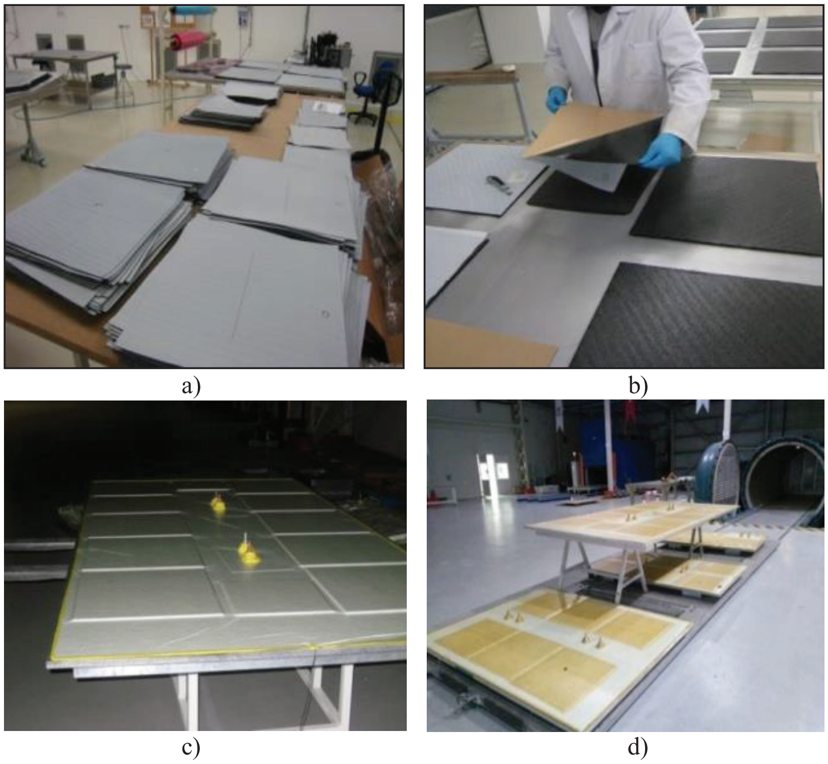

a) b) c) d)

Figure 1. Steps of composite manufacturing: a) Pregreg cutting with ply cutter machine; b) Prepreg lay-up process; c) Vacuum bagging process; d) Autoclave curing process.

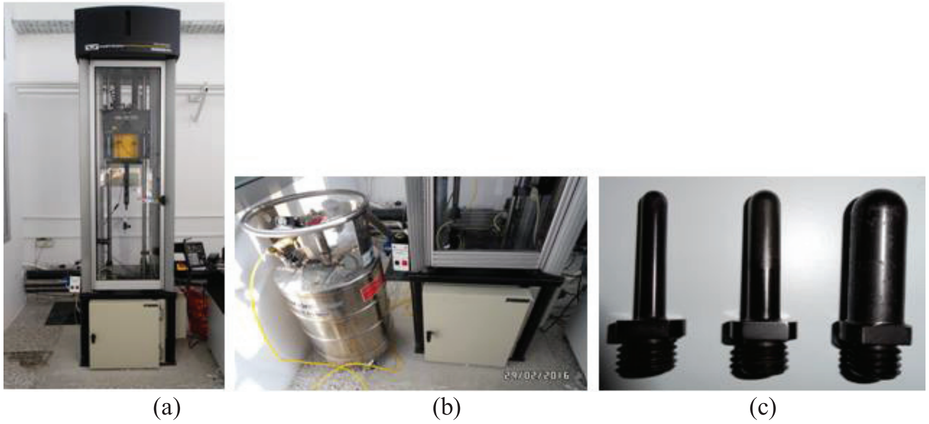
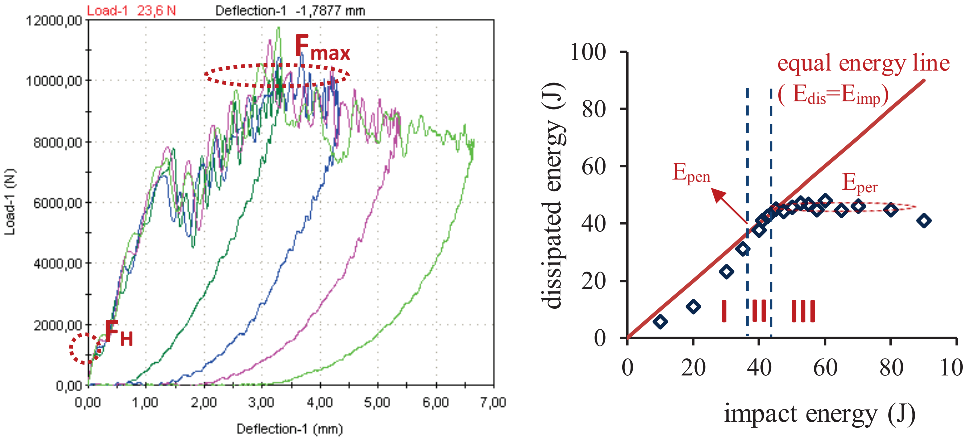

(a) (b) (c)

Figure 2. Test system: a) Drop weight tower; b) Climatic chamber; c) Hemispherical impactors.

The load and energy histories obtained from low velocity impact testing yield important information concerning damage initiation and growth [10-12]. The impulse data acquisition system which is composed of an impact force transducer, velocity detector and impulse signal conditioning unit provides the user with force-time information and incipient impact velocity. Impulse analysis software uses the force (impact load) - time history to calculate the acceleration, velocity, deflection and energy information respectively.

RESULTS and DISCUSSION

A typical force history of low velocity impact on the composite material reveals two critical thresholds which are Hertzian failure threshold (F_H, See Fig. 3-a) and maximum impact force threshold (F_{max}, See Fig. 3-a). Hertzian failure threshold is responsible of the initial material damage in the form of delamination failure [10-12]. The main damage (laminate failure) in the form of fiber fracture occurs as the maximum force threshold is reached. Although matrix cracking which occurs under fairly low impact energies does not cause a significant degradation of mechanical properties, delamination may affect the laminate performance seriously. Fiber damage, on the other hand, results in the laminate failure in the composite.

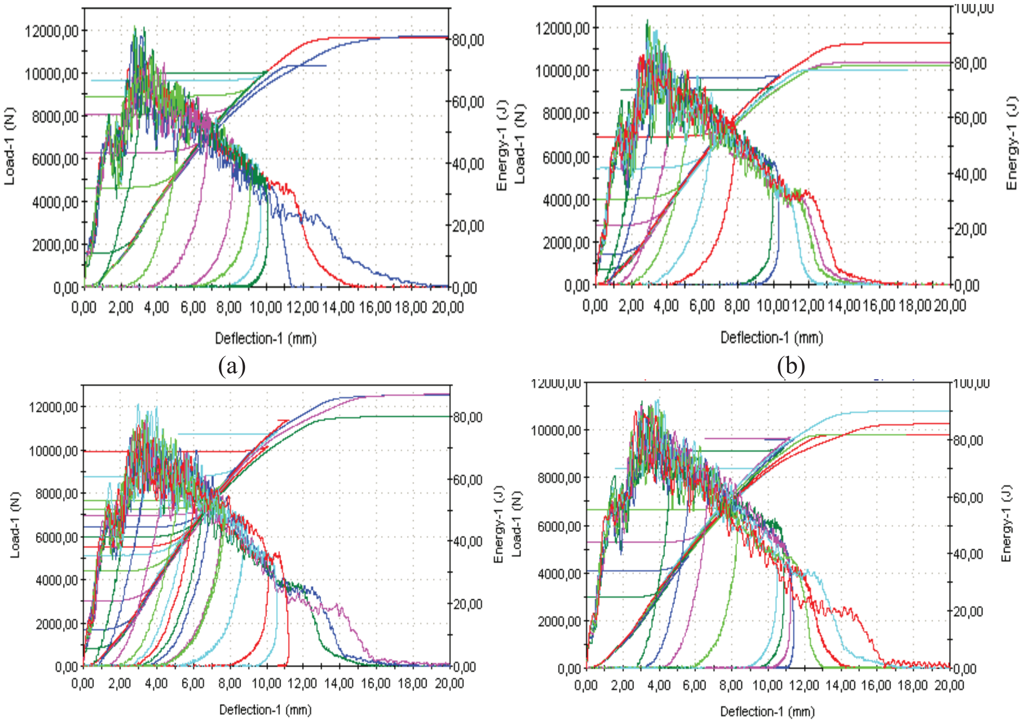


(a) (b)

Figure 3. a) Typical force-deflection graphs of low velocity impact tests; b) Energy profile diagram of CFRP laminates subjected to impact using an impactor of 10 mm diameter at room temperature.

Energy profile method is employed to determine the impact threshold energies for damage evolution. Energy profile diagram is obtained by plotting the dissipated energy in the composite laminate versus the initial impact energy. Energy profile diagram of composite laminates subjected to impact loading using an impactor diameter of 10 mm at room temperature is displayed in Fig. 3-b. Penetration and perforation threshold energies, and three subsequent energy zones which are rebound (I), penetration (II), and perforation (III) zones can be easily determined from an energy profile diagram. The threshold at which dissipated energy in the laminate is almost equal to the impact energy is named as penetration threshold. Further increase of impact energy beyond penetration threshold causes full penetration of the composite which is called as perforation. Perforation threshold energy is smaller than the impact energy.

Results of low velocity impact tests using an impactor diameter of 20 mm in a range of temperatures ranged from 60 down to -50 °C are presented in Fig. 4. The nature and magnitudes of load-deflection curves almost remain the same. No clear influence of temperature on the critical force thresholds can be derived. To know whether the temperature has a clear effect on damage extension, a close inspection of energy dissipation and damage development is needed. Table 2 presents the penetration energy thresholds and main damage force values for composite laminates impacted with different impactor diameters at different temperatures. Although maximum force does not change significantly with temperature, penetration threshold energy decreases as the temperature is lowered. Drop in the penetration threshold is more obvious with quite low temperatures. At a certain temperature, both penetration energy and maximum force increase with impactor diameter.



(a) (b)

(c) (d)

Figure 4. Load/energy-deflection graphs of impact tests using an impactor diameter of 20 mm at temperatures of: a) -50ºC; b) - 25ºC; c) 25ºC; d) 60ºC.

Table 2. Penetration energy thresholds and main damage force values for composite laminates impacted with different impactor diameters at different temperatures.

impactor diameter	10 mm		12.7 mm		20 mm	
temperature	Penetration Energy (J)	Maximum force (N)	Penetration Energy (J)	Maximum force (N)	Penetration Energy (J)	Maximum force (N)
-50	42	8124	49	8943	70	11246
-25	44	8265	51.5	9487	76	11004
+23	45	8358	52.5	9233	77	10810
+60	45.5	8310	54	8919	77.5	10785

Delamination damage area increases with impact energy up to the main damage threshold. After the main failure threshold, the delamination area does not change much with increasing impact energy as it's clear from the ultrasonic C-Scan views given by Fig. 5. For impact tests using impactor diameter of 10 mm at room temperature, penetration threshold is found as 45 J. After this energy level, dominating damage mode is fiber fracture. Consequently, delamination area does not change much with increasing impact energy. Delamination areas at 60 J and 90 J are almost equal to each other.

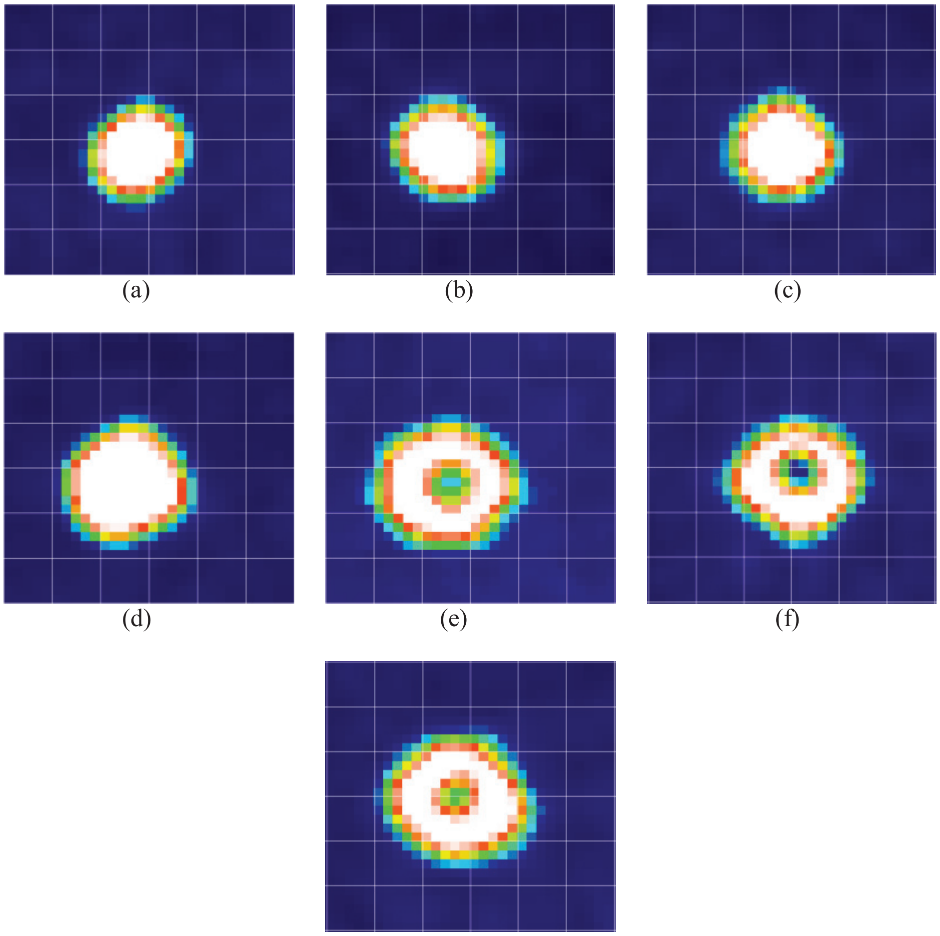

(a) (b) (c)
(d) (e) (f)
(g)

Figure 5. Delamination growth with impact energy as detected by ultrasonic C-Scan (using an impactor of 10 mm diameter at room temperature): a) E_i= 10 J; b) E_i= 20 J; c) E_i= 30 J; d) E_i= 45 J; e) E_i= 60 J; f) E_i= 80 J; g) E_i= 90 J.

Delamination growth in composite laminates impacted with an impactor diameter of 20 mm at varying impact energies and temperatures is presented in Fig. 6. This figure obviously shows that damage area increases while the temperature is decreasing from +60 °C to -50 °C. This behavior is attributed to the embrittlement of the polymeric matrix and thermal stresses generated in the laminate at low temperatures. This figure also indicates that delamination damage area initially increases sharply with impact energy. As the damage mechanism is governed by fiber damage, delamination area remains almost stable. Ultrasonic C-Scanning of all damaged laminates revealed that delamination area increased with increasing impactor diameters at all the test temperatures.

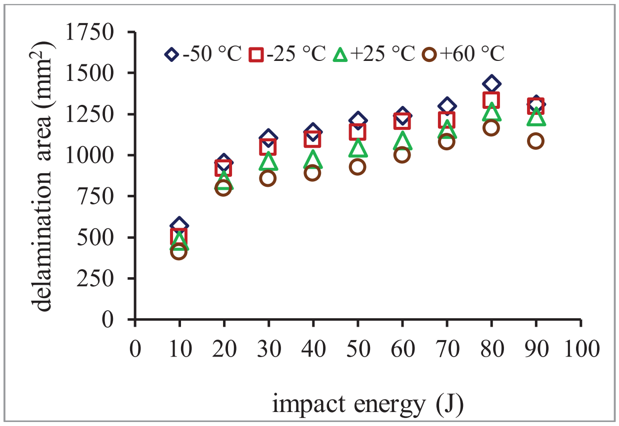


Figure 6. Delamination growth under varying impact energies and temperatures (impactor diameter of 20 mm).

CONCLUSION

Test results revealed that the threshold of penetration energy, main failure force and delamination area increased with impactor diameter at all temperature levels. For a specific impactor diameter, penetration threshold energy decreased with lower temperatures while the maximum force corresponding to the laminate failure did not change significantly with temperature. Delamination damage area increased as the temperature is decreased from 60 °C to -50 °C. This behavior is attributed to the embrittlement of the polymeric matrix and thermal stresses generated in the laminate at low temperatures. Energy profile method is used to determine the penetration threshold energies for damage evolution. Delamination damage growth was effective with lower impact energies whereas delamination could not further develop after the main damage threshold.

REFERENCES

1. C. Evci, M. Gülgeç, *International Journal of Impact Engineering*, **43**, 40-51 (2012).

2. C. Evci, *Composite Structures*, **133**, 508-521 (2015).

3. R. Suvarna, V. Arumugam, D.J. Bull, A.R. Chambers, C. Santulli, *Composites: Part B*, **66**, 58-64 (2014).

4. S. Benli, O. Sayman, *Mathematical and Computational Applications*, **16**, 392-403 (2011).

5. T. Go´mez, R. Zaera, E. Barbero, C. Navarro, *Composites: Part B*, **36**, 41-50 (2005).

6. T. Mitrevski, I.H. Marshall, R. Thomson, *Composite Structures*, **76**, 116-122 (2006).

7. L. S. Sutherland, C. G. Soares, *Composites Science and Technology*, **63**, 1-18 (2003).

8. W. J. Cantwell, J. Morton, *Composites*, **22** (5), 347-362 (1991).

9. S. Abrate, *Applied Mechanics Reviews*, **44** (4), 155-190 (1991).

10. T. W. Shyr, Y. H. Pan, *Composite Structures*, **62**, 193-203 (2003).

11. G. Belingardi, R. Vadori, *International Journal of Impact Engineering,* **27**, 213-229 (2002).

12. G.A. Schoeppner, S. Abrate, *Composites Part A*, **31**, 903-915 (2000).