Effect of Different Environmental Conditions on the Mechanical Properties of CFRP Composites

Hafiz Tauqeer Ali

Abstract: ***Carbon Fiber–Reinforced Polymers (CFRP) are extremely strong and stiff. They possess high corrosion resistance and their usage increase where rigidity and high strength-to-weight ratio are needed. Therefore they have been gaining wide usage in number of applications such as aerospace, marine, defense, civil and automobile as of their greater advantages. However the performances of these composites suffer when they are exposed to adverse environmental conditions such as moisture and high temperatures. This study work has been carried out to investigate the effect of environment on carbon composites. The primary purpose of this research study is to explore the degradation of Carbon-Fiber-Reinforced Polymers CFRP composites under various environmental conditions. The environmental conditions have been limited to influence of water uptake and high temperature in this study and the effect of environmental conditions on the tensile strength and modulus of the CFRP composites. For the very purpose, laminates of IM7/977-2 are designed and manufactured. Tensile testing on dry/wet coupons under room/high temperature conditions are conducted to investigate the degradation in strength and modulus of CFRP composites.***

Keywords: ***CFRP Composites, Humidity, Modulus, Tensile strength, Temperature.***

I. INTRODUCTION

The usage of fiber reinforced polymer composites is widely increasing and they are being applied in many applications successfully. Some of these applications may include aerospace, space shuttles, sports, automobiles, medical and alike. They are particularly more successful in applications where high strength materials are required. Carbon-fiber-reinforced polymers composites have two distinct parts: reinforcement and a matrix. In CFRP the reinforcement is the main source of providing strength that comes from the carbon fibers. The latter part known as matrix in CFRP is responsible for keeping and binding the reinforcement. The matrix is generally a polymer resin, such as an epoxy. Since CFRP consists of two distinct elements, therefore, the material properties depend on these two elements.

Cano and Dow [1] investigated the tension and compression characteristics of QI notched (open-hole) and un-notched laminates. They also studied the compression-after-impact strengths effects of the laminates. They used IM7/5260 , G40-800X/5255-3, IM7/E7T1-2, IM7/5255-3 and IMT/X1845 and carbon fiber/toughened matrix composites. They concluded that these five toughened composites offer improved damage tolerance and mechanical properties when compared with more brittle composite materials. Further to this they also found out that when the effect of water uptake and temperature are combined together then they degraded the notched and impacted materials strength severely. Banakar and Shivananda [2] investigated the influence of laminates with varying fiber orientation and varying thickness with different sized fibers laminates on the mechanical properties of fiber epoxy resin composites. They used experimental investigations for the analysis of tensile behaviour of glass fiber reinforced polymer laminates and concluded that the laminated specimens with lesser thickness leads to more ultimate tensile strength irrespective fiber orientations. They also found out that specimen sustain greater load in 0°/90° specimens than in other orientations and Young‟s modulus of specimens increases with decrease in thickness. Their finding also conclude that extension has minimum effect when fibers of 90° orientation was utilized while in case of fibers of 30° orientations maximum effect was noted.

Wesolowski et al [3] studied the elastic properties of laminated composites by different Non-Destructive techniques. They used two carbon fiber XP45 Turane Resin laminated composite plates. They used many different methods to characterize elastic properties. After applying different methods, their research study proposed that the most suitable technique for the identification of elastic properties accurately and more conveniently is the inverse approach.

Uleiwi [4] investigated experimentally the effect of fiber volume fraction on the flexural properties of the laminated composite and showed that fiber volume fraction increase of glass fiber for the lower layer decreased the tension stress while the tension stress increased when Kevlar volume fraction of the upper layer was increased. Paiva and Santo [5] studied mechanical and morphological characterizations of epoxy resin systems i.e. F584TM and 8552TM. They used four different laminates for this purpose. The results showed that the F584-epoxy matrix laminates present better mechanical properties in the tensile and compressive tests than 8552 composites. Furthermore it was observed that interlaminar shear and flexural properties were improved when PW laminates were used for both matrices.

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Lin et al [6] analyzed the Failure of Fiber-Reinforced Composite Laminates under Biaxial Tensile Loading. They used numerical constitutive model for a single layer of fiber-reinforced composite laminates, including nonlinear stress-strain relations, mixed failure criterion. Hitchen et al [7] investigated the fatigue effect of a short carbon/epoxy composite. For this purpose, they used fiber length as a main parameter. Their study results revealed that fiber length has almost no effect on the fatigue life at any peak strain.

The structure of the manuscripts is as follows: In section II, manufacturing of specimens is mentioned while in section III, Humidity conditions are described. Testing methodology is detailed in section IV followed by results and conclusions in sections V and VI respectively.

II. MANUFACTURING OF SPECIMENS

A Composite system IM7 12k/977-2 was used for the present study. It has a thermoset epoxy resin matrix toughened with thermoplastic material. It is used in aircraft primary and secondary structures, space structures and ballistics. Generally, it can be applied to any structure where impact resistance and light weight are desired. For end tab materials IM7/8552 and AS4/8552 were used as the supply for the former was delayed in the laboratory and the later was ordered instead. IM7 and AS4 refer to fibers while 8552 is a matrix. 8552 is a tough epoxy matrix and possess high performance is therefore commonly used in many primary aerospace structures. It exhibits good impact resistance and damage tolerance for a wide range of applications.

The lay-up angles, 0^o, $\pm45^o$ and 90^o, reported refer to the orientation of the longitudinal fiber direction. After manually manufacturing the $[0°]_4$, $[\pm45°]_{10}$ and $[90°]_{10}$ layups, the plies were cured in autoclave. Diamond saw was used to cut the laminate panels into required specimen sizes. The specimen dimensions used for the mechanical testing are summarized in Table I. Grit blasting was performed to prepare the surfaces for the composite and end tab better joint. After grit blasting, acetone was used to clean the surfaces. Improper surface is not suitable. It can lead to premature failure and careless surface preparation can also lead to cause damage to the reinforcing fibers. Therefore, it was made sure during grit blasting that that reinforcing fibers are not damaged or exposed. In present study, Letoxit LH 149 was used. It is a two-component, high-strength, paste epoxy-based adhesive. It is designed to adhesive bond a variety of metallic materials, honeycombs, fiber-reinforced composites, wood, rubber and glass. 100 weight parts of A component (thixotropic paste of yellow color) with 40 weight parts of B component (fluid of blue color) were mixed thoroughly until an even color shade is achieved. After this, it was applied to both surfaces to be bonded. The joint thickness was from 0.1-0.2 mm. The bonded parts were cured for 4 hours at 50 °C in oven.

III. HUMIDITY CONDITIONS

After taking specimens out from the oven, the specimens were cleaned from any excess end tab materials with a soft cloth. Each specimen was then weighed and recorded. After this, half of specimens from each configuration were put in the water bath to measure the effect of environment on the specimens. Initially, the water temperature was kept at room temperature then was raised to 80° C to observe the rate of water absorption in the samples and also that the samples are fully saturated in less time as rise in temperature should increase the rate of absorption. To reduce the evaporation rate, lightweight, economic PP anti-evaporation spheres which form a blanket on the water surface were used. The spheres were used as these reduce heat loss by approximately 77% and evaporation by 87%. The bath was further covered with metallic lid to avoid falling of any substance in the bath accidently and causing any damage to the specimens. Total specimens were put in the water bath were consisted of 8 specimens of 0^o, 12 specimens of $\pm45^o$ and 7 of 90^o layup. The $\pm45^o$ and 90^o layup specimens were placed in the water bath for 90 days out of which first 80 days the water temperature was kept at room temperature and for remaining 10 days the temperature was raised to 80^oC. Initially the lay up for 0^o orientation specimens was kept the same i.e. $[0°]_{10}$ and kept in the water bath for the same conditions as reported for ±45° and 90° orientations but during dry samples testing of 0° orientation 2 mm thick specimens, it was realized that expected failure load is approximately 70*kN*. The specimen started slipping from the grips after 45*kN* if the pressure on the end tab is reduced below 2 bar and specimens broke in the specimen gage section if the grip pressure is increased to achieve the expected failure load. Therefore it was decided to use only 4 plies of 0^o orientation which turn out to be 0.82 thick after curing. The water bath temperature for this orientation was maintained throughout at 80°C for 40 days to overcome the delayed period. It is worth noting that 0.82 thick specimens for 0° orientation are reported in this study. Weights of the specimens before placing in the water bath and at the time of just before testing were recorded to know moisture contents gained.

IV. TESTING METHODOLOGY

A. Mechanical Testing at Room Temperature

Specimens were mounted in the grips of a hydraulic mechanical testing machine as shown in Fig.1 and monotonically loaded in tension while recording load. The tests were run at 0.02 mm/s. The tests were repeated for a minimum of 3 times under same test and specimen conditions. The hydraulic machine of 100 *kN* load capacity is used for specimens testing at room temperature. The machine has both an essentially stationary and a moveable head. The specimens were placed in the grip of the machines. Very carefully, the long axis of the gripped specimens was aligned with the test direction. The pressure on the 0^o and $\pm45^o$ orientation specimens were kept at 2 bar to avoid the slippage of the specimens during the testing while the pressure was reduced to 0.5 bar for 90^o orientation specimens to avoid the failure or breakage in the tab section.

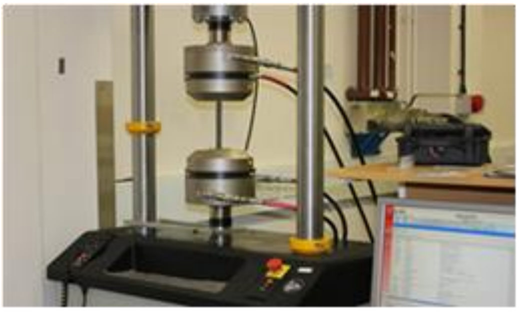

Fig.1 Testing at room temperature

Table- I: Geometry of Specimens

Orientation of fibres	Sample width *mm*	Total length *mm*	Thickness *mm*	Length of tabs *mm*	Thickness of tab *mm*	Bevel angle of tab
0^o	15	250	0.82	60	2	90°
$\pm45^o$	15	250	2	60	2	90°
90^o	15	175	2	30	2	90°

The grips in the machines are self-aligning and lightly serrated surfaced to minimize bending stresses in the specimens.

Extra care was taken to make sure that there was no induced bending in the specimen. The tests confirmed that the specimen failure occurred in or around the specimen's gage section. After testing, the testing data was converted to excel sheets and analyzed carefully and graphs of stress and strain for each configuration for dry and wet coupons were plotted and were analyzed. Scatter in the data was in the range of 3 - 5% for all the tests.

Summary of DRY and WET coupon tests at room temperature for 0, 45 and 90 orientation is reported in Table II and III respectively.

Table- II: Summary of DRY Coupons Test Data at Room Temperature

Fiber Orientation	Mean Fracture Load *kN*	Strength Mean *MPa*	Modulus Mean *GPa*
0^o	32	2590	193
$\pm45^o$	5.5	179	9.1
90^o	2.1	68	8.3

Table-III: Summary of WET Coupons Test Data at Room Temperature

Fiber Orientation	Mean Fracture Load *kN*	Strength Mean *MPa*	Modulus Mean *GPa*
0^o	29	2341	160
$\pm45^o$	4.9	158	8.5
90^o	1.5	52	7.9

B. Mechanical Testing at High Temperature (80 °C)

Specimens were mounted in the grips of fixture as shown in Fig.2. The reason for choosing different fixture and machine was because these ease the high temperature environmental chamber fitting for high temperature testing. The specimens were mounted in the fixture and a long enough metallic bar is used to connect the fixture with load cell. In this way, load cell are protected keeping them outside the environmental chamber. This chamber was essential for high temperature tests other than ambient testing laboratory conditions. The chamber used for present testing is well capable of maintaining the gage section of the test specimens at the required test environment during the mechanical testing. All the specimens (Dry and Wet) reported for high temperature (80 °C) were performed on hydraulic machine in the chamber, as shown in Fig.3. Pressure on the end tab of the specimens was manually adjusted which is a slightly less competitive feature of this fixture as there is no information available regarding pressure application on end tabs before tests to avoid the bending stresses development on the ends. More pressure on the end tabs can lead to premature failure and breakage of end tabs. Extra care was put to mount the specimen in the present fixture especially in the case of 90^o orientation. Apart from pressure, all other specifications were kept same as reported in the subsection A of section III.

Fig 2. Fixture used for mechanical testing at high temperature (Side view)

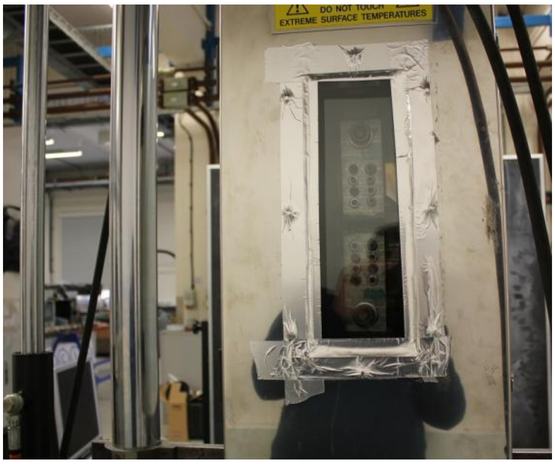

Fig.3. Mechanical testing setup for high temperature (Front view of the chamber)

Camera was used to monitor the mechanical testing and to observe the behavior of the specimens inside the chambers. After completing one test, the machine was stopped and let the fixture in which the specimens were mounted cool down and after it was cool enough then second specimen was loaded and so on and so forth. Once the new specimen is loaded in the fixture and mounted in the machine, before starting the test, it was waited until the temperature has reached 80° C as indicated on the chamber thermometer. The data after the testing was analyzed carefully and mean of the results for DRY and WET coupons tested at 80° C is presented in Table IV and V respectively.

Table- IV: Summary of DRY Coupons Test Data at High Temperature (80° C)

Fiber Orientation	Mean Fracture Load *kN*	Strength Mean *MPa*	Modulus Mean *GPa*
0^{o}	30	2453	186
$\pm45^{o}$	5	173	7.9
90^{o}	1.9	52	7.5

Table- V: Summary of WET Coupons Test Data at High Temperature (80° C)

Fiber Orientation	Mean Fracture Load *kN*	Strength Mean *MPa*	Modulus Mean *GPa*
0^{o}	27	2201	175
$\pm45^{o}$	4.2	151	6.3
90^{o}	1.3	46	6

V. RESULT AND DISCUSSION

Dry and Wet coupons of CFRP composites have been tested at room temperature as well as at high temperature (80° C). It was observed that mechanical properties have been affected greatly due to the effect of moisture penetration into the composites. Most obvious observation was made when the coupons were tested fully saturated under high temperature then stiffness and strength both reduced as shown in Table II-V. Therefore it is utmost important to take consideration of environment such as moisture content and temperature variation effects on composites when designing them for structural design applications and strength and stiffness may reduce significantly and may lead to catastrophic features.

VI. CONCLUSION

A Tensile strengths and moduli of carbon fiber/toughened matrix composite IM7 12k/977-2 were determined of dry/wet coupons in 0°, ±45° and 90° orientations under room as well as high temperature conditions. The following conclusions can be drawn from the results of this study:

1. When the effect of water uptake and temperature were combined then it degraded the tensile strength of the samples which were tested under different orientations.
2. A combination of water uptake and high temperature degraded the moduli of the samples tested under different orientations.
3. Though change in the elastic moduli was observed but that was not very significant.

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Dr Hafiz Ali is currently working as an Assistant Professor in Department of Mechanical Engineering, College of Engineering in Taif University, Kingdom of Saudi Arabia. Dr Hafiz obtained his masters and PhD degrees in Mechanical Engineering from University of Surrey, UK. His PhD research thesis entitled "Mixed Mode Fracture in Adhesively Bonded Joints in Quasi-Static and fatigue Loadings". Prior to joining Taif, Dr Hafiz was worked in University of Portsmouth and University of Bristol, UK where he had opportunity to work on many industry such as Rolls- Royce and Clean Sky funded projects. He has authored number of book chapters and his research articles have been published in peer reviewed journals such as Engineering Fracture Mechanics, International Journal of Adhesion and Adhesives, and in many national and international conference proceedings. His research interest lies in composite design, manufacturing and testing under different loading conditions.