Experimental Investigation of Open-Hole Compression Strength of Carbon Epoxy Composite Material and Determination of Localized Strains Using Digital Image Correlation Technique

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The biggest application of the fiber-reinforced composites is in the field of military and commercial aircrafts, in which weight reduction is required for higher speeds and increased payloads. Carbon fibers, either alone or with the Kevlar 49 fibers, are widely used as main material in many aero plane wing, fuselage and empennage components. Composites materials have wide applications in different industries because of it has very different properties from the metals and polymers. In the drilling of Carbon/Epoxy Composites the cut surface quality is very much dependent on the drilling parameters set during drilling which further effect the strength of the hole during extension/compression loading. In this research, Carbon Fiber Epoxy Composite material is drilled with the standard carbide drill bit and Open Hole Compression (OHC) tests are performed on the Universal Testing Machine. The Digital Image Correlation (DIC) technique is used to find out the strain distribution around the hole during compression loading. From the experimental method and DIC, maximum strength of carbon epoxy composite is achieved by drilling at 1600-2400 mm/min in presence of notch. It was also observed that failure of the structure is dependent on the drilling feed rate and 1600-2400 mm/min was the optimized drilling range.

**Keywords:** - Composite Materials strength, Carbon Epoxy Composite, Digital Image Correlation, Carbon fibers, Compression strength
Nomenclature

\[ F_x = \text{Compressive Strength in MPa.} \]

\[ P_{\text{max}} = \text{Maximum force in N.} \]

\[ A = \text{Gross cross-sectional area, mm}^2 \]

1. Introduction

Fiber-reinforced composites materials are generally formed with the fibers of high strength & modulus bonded together with the matrix in the form of interfaces (boundary). The physical and chemical identity of the constituent (fiber & matrix) remains the same in the composite’s material yet the combination of properties could not be attained by any one constituent only. Fibers are the main component in any composite and act as the load carrying member, while the matrix bond together the fibers and keep them on the proper orientation also act as the protective media for the fibers. The applications of composites are so vast that it is impossible to list them all. The major applications areas are the aircraft, space, automotive, sporting goods & marine engineering [1]. The main purpose of composites in engineering is weight saving. Some major applications are discussed below.

The biggest application of the fiber-reinforced composites is in the field of military and commercial aircrafts, in which weight reduction is required for higher speeds and increased payloads. Carbon fibers, either alone or with the Kevlar 49 fibers, are widely used as main material in many aero plane wing, fuselage and empennage components [2-5]. Fiber reinforced epoxies are widely used in the helicopter rotor blades in order to reduce the weight and to tailor the dynamic frequencies of the blade. Weight reduction is very significant factor in the space vehicles, for this particular purpose many composite materials are used like the boron fiber-reinforced aluminum
tubes for the mid-fuselage truss structure, aluminum honeycomb in combination with the carbon fiber-reinforced epoxy face-sheets for the payload bay door [6-7]. Another important aspect of preferring the composites over the metals is its thermal stability over the wide range of temperature changes.

In automotive industry the composite materials can be split up into the three groups: body components, chassis components & engine components.

a) Exterior body components, such as hood or door panels require high stiffness and damage tolerance (dent resistance). The damage tolerance is achieved by using the flexible resins, polyurethanes.

b) In chassis components the composites were first used in the leaf spring, by using uni-leaf E-glass-reinforced epoxy, which replaced the ten-leaf steel spring with nearly 80% weight saving.

c) The application of composites in the engine parts is in the development process, the challenging area of application for which different composites need to be developed are fatigue loading conditions at very high temperatures [8].

Over the last few years, use of fiber-reinforced polymeric composites in the sporting goods have been substantially increased, the advantages of using composites are weight reduction, vibration damping and design flexibility [9]. The major products are Tennis rackets, Golf club shafts, Fishing rods, Bicycle frames, Snow & water skis, Hockey Sticks, Oars, Surfboards, Arrows, Helmets & Athletic shoe soles and heels. Glass-fiber-reinforced polyester laminates are widely used in the marine applications but now a days Kevlar 49 is replacing the glass fiber in some of the applications because of the higher tensile strength-weight and modulus-weight ratios than glass
fiber. The areas of applications are boat hulls, decks, bulkheads, frames, masts and spars. The advantages involve the reduction in weight which increases the cruising speed, acceleration and fuel efficiency.

A wide range of fibers are used as reinforcements in composite materials [10]. Fibers are classified according to their lengths as short, long, and continuous fibers, according to their strength and stiffness or by their chemical composition organic & inorganic. The commonly used fibers in inorganic category are glass, carbon, boron, ceramic, mineral & metallic. The organic fibers are usually of polymeric material. The selection of the fiber type is a tradeoff among the many properties like mechanical, environmental and cost as well [11-14]. Carbon fibers also called graphite fibers are widely used in aerospace applications due to their lightweight and strong fibers with excellent chemical resistance. The mechanical properties of carbon fibers can be found by the atomic structure of carbon molecules chains and their inter linkages. The strength of carbon fibers can be altered by the orientation of the carbon atomic structures with their strongest atomic bond along the carbon fiber direction.

The properties of carbon fibers depend on the raw material and manufacturing process used, two main categories of raw materials are Polyacrylonitrile (PAN) and Pitch. Pitch fibers are cheaper and usually less strong than the PAN. Carbon fibers are available with a broad range of stiffness values unlike the glass fibers. The stiffness of fibers can be controlled by the thermal treatment of both PAN and Pitch-based carbon fibers. The thermal treatment actually effects on the carbon content and orientation of the strongest carbon links along the fiber direction. The main driving force behind using high modulus fibers is to make composite that can replace steel or aluminum, so that a substantial reduction in part weight. For example, a composite material with a 50% fiber
volume fraction of M50 fibers would have approximately same stiffness as that of steel and one-fourth of the weight.

The maximum operating temperature of carbon fibers varies from 315°C to 537°C but this limit is further affected by the operating temperature of the matrix. As the carbon fibers are stiffer than the glass fiber hence provides the better fatigue characteristics to the composites by reducing the amount of strain in the polymer matrix at a given loading condition. Some of the limitations of carbon fibers are their low shock resistance due to their high rigidity & high fragility and possibility of chemical attack in the presence of oxygen and other oxidizing agents. Galvanic corrosion is another factor which takes place if carbon fiber composite is in electrical contact with metals, due to their good electrical resistance. Therefore, it needs an electrical barrier like glass fiber material to avoid the direct carbon fiber composite and metal contact. The major limiting factor in carbon fiber composite applications is the cost. The carbon fiber composite cost can be justified only when weight savings offer a large payoff, such as in aerospace applications, or when high temperature performance, corrosion resistance, improved fatigue strength or the long term retention of strength are necessary for the specific application. Costs savings in carbon fiber composite can be made by part integration and reduced installation & maintenance cost [15].

In composites continuous and discontinuous reinforcements are very common although textile reinforcements provide the extra strength, increase performance while reducing the overall manufacturing cost. The resin transfer molding process is particularly designed for the woven fabric reinforcements. The designs of the composite depend on the thread design and manufacturing, in which properties of threads play an important role in overall performance of the composite [16]. For example, an increase in thread twist reduces its modulus but improves the
fatigue properties of the composite. The textile design and manufacturing process leads to the following classification of textiles types:

- **1D textile**, or individual thread, these are also called the strand, tow, end, yarn or roving.
- **2D textile**, or fabric, it uses the 1D threads on different patterns on a surface. The resulting plate or shell-like shape is called the 2D structure.
- **3D textile**, it uses the 1D textile, arranging the threads in complex 3D formation by the different textile processing methods. The resulting material features a 3D structure [17].

A wide variety of textile fabric forms can be used as reinforcements for composite materials. The simplest and inexpensive form is the nonwoven fabrics. A nonwoven fabric is called the mat, which usually constitute the randomly oriented chopped fibers such as chopped strand mat, randomly oriented short fibers or swirled tows or roving. The other form is the continuous strand mat (CSM) and it can be formed by continuous tows or roving swirled on a flat surface and pressed or loosely held together with a very small amount of binder. Sometimes veil, a thin mat used as the surfacing media to enhance the corrosion resistance of the composite material. The veil layer is smooth and usually without the textured appearance of the fabric, also serves the purpose of appearance enhancement by hiding the underneath fabric structure.

The woven fabric is a two-dimensional plane surface made by the weaving of the yarns in a weaving machine. Properties of the woven fabrics are usually lower than the unidirectional continuous fibers. The yarn is weaved by interlacing along the two orthogonal directions, yarn which held along the weaving direction is called warp yarn and perpendicular yarn to the direction of weaving is called the fill or weft yarn. Balance in properties can be obtained by using the same yarn in the warp & weft direction, this is called the biaxial woven fabric. The different types of
patterns are common in the biaxial woven fabric’s structures; the most common are plain weave, twill weave and satin weave. This is shown in Figure 1. The different patterns of the weave are responsible for the different properties of the fabric and the composite finally [17].

The matrix material performs the function of binding together the fiber layers and transfer of forces from the external sources. It carries some stresses which are transverse stress, intralaminar shear stress and bearing stress. The important properties like transverse stiffness and strength are largely depend on the matrix selection. Properties of matrix also determines the service conditions of composite which include temperature range, chemical resistance, abrasion resistance and weathering capability and also electrical conductivity & external characteristics such as appearance. Matrices are of different types like polymers, metals, or ceramics. Polymers are most widely used due to their ease of manufacturing complex shapes with low tooling cost and low capital cost. Matrix properties depend on the range of temperature bearing capability of the matrix.

The performance of the composites varies drastically when it approaches or exceeds the temperature limits. Thermoset polymer matrices such as polyester resins and epoxy resins lose modulus and thus the ability to transfer load when they are exposed to alleviated temperatures. Ceramic matrices self-destruct themselves when subjected to the cryogenic conditions. Advanced composite materials (ACM) are more expensive and high-performance materials used in the field of aerospace, these are mostly carbon-epoxy and carbon-thermoplastic systems. Fiber Reinforced Plastics (FRP) are usually less expensive materials used in the consumer goods and mass markets, largely include fiberglass-polyester systems. The different types of thermoset matrices are polyester resins, vinyl ester resins, epoxy resins and phenolic resins [17].
Epoxy resins are very widely used due to versatility they exhibit, high mechanical properties and high corrosion resistance. The shrinkage in epoxies is very less compared to other materials (1.2-4% by volume). An epoxy resin also has a very attractive property of curing at wide temperature range from 5 to 150°C. One of the main application areas of the epoxies is in the aircraft industry where it used as a adhesive for honeycomb structures and as laminating resins for missiles and airframes, for filament wound structures and tooling. They are used as body solders and caulking compounds for the building and repair of plastic and metal boats and automobiles.

Epoxy resins also have applications in the fabrication of short-run and prototype molds, stamping dies, patterns & tooling. They are used as insulation material, so it has wide application in the field of electrical insulation as well. The cost of the epoxy resins is justified, as compared with the performance of the resin that varies over a broad range, but it is more expensive than the other resins like vinyl esters. Epoxy matrices can withstand the temperature limit of 175°C. For the increase in the stiffness of the resin and composite, thermoplastic additives are included, the service temperature also reduced as compared to the brittle epoxies up to 125°C [17].

2. Literature Review

In this section, literature studies of the Open Hole Compression (OHC) Strength of the Carbon Fiber Composite Material have been studied. The data is collected in such a manner that it is representing the historical background of the Drilling of Composites, along with its effects on the parameters like, Thrust Force, Delamination effect, Fiber/Resin Pull out, Excessive Tool Wear, Open Hole Compression Strength etc.

2.1 Various Composite Drilling Findings:
Back in the 1990s, S. K. Malhotra worked on the Glass Fiber/Epoxy & Carbon Fiber/Epoxy laminates, the material was cut by the High-Speed Steel and Tungsten Carbide Coated Drills. The main parameters under observations were cutting speed, feed & number of holes machined on tool wear, thrust & torque. The finding from this research was that tool wear increases with the number of holes and flank wear is higher than chisel edge wear. Carbide drills performance was much better than the HSS drill bits on both the materials. Tool wear was more in the CFRP as compared to GFRP, the main reason behind this is the higher abrasiveness of carbon fibers than the glass fibers [18].

In 1990, V. Tagliaferri with his companions found the effect of machining parameters on the cutting quality and on the mechanical behavior of the glass fiber reinforced plastic composites (GFRP). The lower ratio of speed and feed result in the poor cut quality. The limit of ratio is independent of resin type, fiber format, composite thickness and fabrication method. The tensile strength of GFRP containing hole does not play a role in damage extent. The material will exhibit the maximum bearing strength for the lower drilling speeds [19].

In this research chip formation and assessment of machinability was compared with metal cutting. The study was done on the reinforced thermoset and thermoplastics for characterizing their response to machining, it was investigated from the cutting chips formed that the carbon fiber reinforced thermoplastics presents a large amount of deformation in chips formation while the carbon fiber reinforced thermosets tend to fracture. Thermosets based composites requires a larger cutting force due to higher strength and is more responsive to chip size because of the sensitivity to micro defects in fracturing chips. A mathematical model was made to predict torque and thrust in drilling of composite materials as a function of cutting parameters and material strength [20].
G. Caprino & V. Tagliaferri in 1995, conducted research on the damage development in drilling glass fiber reinforced plastics and found that the quality of the cut surface is strongly dependent on the appropriate drilling parameters. Tests were carried out on glass-polyester composites using the HSS drill bit. The research further revealed that damage induced in a composite material during drilling is totally dependent on the feed rate for the drilling, with high feed rates the failure modes are more likely of impact damage, with step like delamination, intralaminar cracks and high density micro failure zones [21]. In 2000 R. Piquet et al. conducted experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. Drilling tool geometry plays an important role in drill quality. For the conventional double fluted twist drill, it is necessary to make pre-drill hole to neutralize chisel effect. Machining conditions can be further improved by using variable feed rate on CNC drill [22].

Frederic Lachaud et al. conducted study on the drilling of composite structures in 2001. The model is made to show the relation between drill’s thrust force and localized bending of the last few plies. The penetration and delamination condition of last few plies is studied [23]. J. Paulo Davim & Pedro Reis in 2003 conducted the experimental and statistical study of drilling on carbon fiber reinforced plastics manufactured by autoclave. "Straight shank" drill presents less power & specific cutting pressure then "Brad & Spur". The feed rate is the cutting parameter that has greater influence on power for both drills. Power increases with velocity and feed rate. Delamination is high for high cutting speed & high feed. The feed rate is the cutting parameter which has highest influence on delamination during entrance on CFRD [24].

I. Singh et al. studied the effects of drilling on unidirectional glass fiber reinforced plastics. The thrust force depends on the drill point angle and the feed rate and increases with the increase in both the point angle and the feed rate. It was proven statistically using ANOVA that the drill point
angle, the feed rate and their interactions significantly influence the drilling forces. The torque decreases with increase in drill point angle for all feed rates [25].

Thiagarajan Rajmohan & Kayaroganam Palanikumar worked on the application of central composite design in optimization of machining parameters in drilling hybrid metal matrix composites. The mathematical model is presented for predicting thrust force, surface roughness & burr height. ANOVA shows feed rate and speed a dominant parameter & improve surface quality, reduce thrust force & burr height. The analysis of drilled surface shows the existence of cracks, particle pull out and shearing of particles [26].

A. Sadek et al. in 2012 conducted research on the orbital drilling of woven carbon fiber reinforced epoxy laminates. The emerging process of orbital drilling (OD) can greatly reduce or eliminate the defects associated with the drilling of composites, e.g., delamination, and thermal damage. The axial force is reduced in the orbital drilling and produces the delamination free holes. High speed and high axial feeds are still challenge in orbital drilling [27].

Vaibhav A. Phadnis et al. experimentally investigated the damage effects on the carbon/epoxy composite. Critical modes of damage in CFRP, was quantified experimentally from microtomography images after image processing. The FE model predicted the drilling thrust force and torque with reasonable accuracy when compared to experimental results. It was observed that the thrust force, torque and delamination damage increased abruptly with an increase in the feed rate but reduced gradually with increasing cutting speeds. The numerical studies indicate that low feed rates (<150 mm/min) and high cutting speeds (>600 rpm) are ideal for drilling carbon/epoxy laminates [28].
Navid Zarif Karimi et al. experimentally investigated the effect of drilling parameters on the thrust force, adjusted delamination factor and compressive residual strength of drilled laminates. The parameters drill point angle, cutting speed and feed rate at three levels, based on the Taguchi method were used. Acoustic Emission (AE) technique was used as intelligent method to monitor the drilling and compression test. The feed rate has a direct effect on the delamination factor. Compressive residual strength is best on low feed rates, and influence of drill point angle and cutting speed is almost negligible. Acoustic emission can be used as tool to detect failure mechanisms before they happen, without damage no AE signal occurs [29].

In 2013, Luis Miguel P. Durao et al. found that the drilling process that reducing the drill thrust force can lessen the risk of delamination. The delamination assessment methods based on radiographic data are compared and correlated with mechanical test results. Unidirectional carbon fiber/epoxy laminate plates were drilled with the objective of comparing the performance of three different tool geometries, combined with three feed rates. The higher feed rates correspond to higher delamination extension. For HSS drill the damage region was higher while carbide drills have no influence of tool geometry. Higher strength was found for the plates drilled with carbide twist drill and lower feed rate [30].

N. Feito et al. in 2014 worked on the finite element modeling of drilling of carbon fiber reinforced polymer (CFRP) composites to predict the damage prediction. Computational expenses of these complex models are big disadvantage when comparing them with simplified models that consider the drill acting like a punch that pierces the laminate of composite. Two different approaches used to develop the model, a complete model of drilling, include feed and rotation movements of the drill were developed. Secondly, a simplified model if the drill acts likes a punch. Simplified model slightly overestimates the value of delamination factor. The results are substantial when the
complexity and the calculation expense of both models are compared. Simulations can be solved in several minutes while the complete model needs several days’ time [31].

In 2014, Zhenchao Qi et al. studied about the delamination during drilling metal-FRP stacks, with the effect of metal stack in drilling. Two cases were considered in this research, drilling direction during drilling metal-FRP stacks, drilling from metal to FRP & from FRP to metal and mechanical models for predicting the CTF were established based on linear fracture mechanics, classical bending plate theory and the mechanics of composites. Delamination will not occur during drilling from FRP to metal when the thickness of the metal plate exceeds the critical thickness, regardless of the drilling process parameters [32].

Goutianos et al worked on microscopic compressive behavior of unidirectional CFRC. The focus was to understand effect of fiber damage in compression in adjacent fibers, and on fiber and matrix interfacial properties. Results from experiments and numerical solutions it is concluded that compressive failure of high modulus carbon fiber composites is due to compressive response. Shear failure in fibers signifies the higher stress transfer rate in compression. Conclusion of their work is that relation between stress and strain is linear at low compressive stress, and its behavior deviate as the compressive stress increase [33].

Suemasu et al conducted numerical and experimental study to find open-hole compressive (OHC) damage initiation and propagation in quasi-isotropic composite laminates. Experiments were carried out by using Open Hole Compression Testing fixture suggested by National Aerospace Laboratory (NAL III) it was inferred that the damage starts unstably which become stable after propagation becomes stable [34]. Saha et al conducted the OPH test by using Institute for Aerospace Research testing setup. Studies was carried out on the influence of Hole Size on
compressive strength of E-glass fiber composite sheet made by pultrusion using Isophthalic Polyester Resin Matrix. It was found that strain at hole edges increased with increasing hole diameter. Other major failure mechanisms observed were delamination of ply, micro fiber bulking and shearing between layers [35].

Poon et al performed open hole compression tests of laminates and numerical simulations to investigate the damage propagation in compression using MTS testing machine and fixture suggested by Institute of Aerospace Research. When ultimate failure load reaches at 90%, the compressive damage occurs. Furthermore it was concluded that by increasing the number of plies in laminate strain to initial failure decreases [36].

Zako et al conducted numerical study and found that stress concentrations at geometrical discontinuities are caused by compressive loading. Stress increases at geometrical discontinuity such as holes and is used to determine the composites material strength by using open hole compression test. Tri-axial stress produced due to any discontinuity within laminates of specimen [37]. Carvalho et al has conducted experiments and simulations to find compressive damages in orthogonal orderly stacked and randomly stacked 2D woven composites. He found that strain behavior in both types of materials is very different. In orderly stacked 2D composites besides cracking, delamination and yarn bending is also significant [38].

**2.2 OHC Strength of the Composite Specimens:**

The Open Hole Compression strength can be found by the stress formula [39];

\[ F_x = \frac{P_{max}}{A} \]

Where,

\[ F_x = \text{Ultimate Open Hole Compressive Strength of Specimen [MPa]} \]
\[ P_{\text{max}} = \text{Maximum force before failure \[N]} \]

\[ A = \text{Gross cross-sectional area (without considering hole) \[mm^2\]} \]

Total cross-sectional area of the specimen is 2.90 x 30 mm, which is equal to the 87\(mm^2\). The values of Open Hole Compression Strength are given in the

![Figure 2 Test Fixture Disassembled View](image-url)
Figure 3 Test Fixture different parts in Assembly View

Figure 4 Failure Modes in Compression Test a) LGM, b) AGM, c) MGM
Figure 5 Image Prepared for DIC

Figure 6 Experimental Setup for Compression Test & DIC
Figure 7 Stress-Strain Plot of Specimen 1
Figure 8 Stress-Strain Plot of Specimen 12
Figure 9 Graph Between Speed, Feed & OHC Strength

Figure 10 Graph between Speeds, Feed & Strains

Figure 11 Contour Plot of Strain Percentage for Specimen 1
Figure 12 Line Scan Graph for Specimen 1

Figure 13 Spatial Average Graph for Specimen 1
Figure 14 Contour plot of strain percentage for Specimen 2

Figure 15 Line Scan Graph of Specimen 2
Figure 16 Spatial Average Graph of Specimen 2

Figure 17 Contour Plot of Strain Percentage for Specimen 3
Figure 18 Line Scan Graph of Specimen 3
3. Experimental Methodology

The test method adopted was D6484/D6484M which is a standard test method of ASTM for the Open Hole Compression Strength.

3.1 ASTM Standard D6484/D6484M

This test method is used to find out the Open Hole Compression (OHC) strength of the multidirectional polymer composites. Limitation of this testing standard is that it is valid for only
continuous fibers, discontinuous fibers (tape or fabric, or both) and laminate should be balanced and symmetric along the test direction when conducting this test. The purpose of this test method is to estimate notched compressive strength data for the structural design, material specifications and for the research & quality assurance [40].

### 3.2 Testing Procedure

The uniaxial compression test of balanced, symmetric composite specimens with hole in a center is performed. The extensometer can also be used to find out the displacement. Ultimate strength of the specimen is calculated on gross cross-sectional area, ignoring the presence of the hole. The hole causes the stress concentration, in aerospace notched designs are very common due to assembly of different parts.

The test specimen’s face is supported by a fixture shown in Figure 2. In this fixture specimen is placed inside the fixture, bolted the fixture to hold it and transmits shear loading during the compression test. The fixture is placed in the two flat platens and compression force is applied which transferred from fixture into the test specimen. The dismantled fixture for ASTM D6484/D6484M is shown in the Figure 2.

The two pieces of the fixture are joined by the supporting plates & bolt. Different parts and assembly of fixture is shown in the Figure 3.

The drilling parameters were selected from the research of J.P. Davim & Pedro Reis et al [24]. The parameters are shown in the Table 2

### 3.3 Failure Modes
The acceptable failure modes of the ASTM standard D6484/D6484M are shown in the Figure 4 and discussed below [40].

3.4 Specimen Preparation for DIC

To apply DIC technique on the composite specimens, they need to be prepared with the random pattern grid which is also known as speckle pattern. For this purpose white paint was utilized to make the random pattern on the specimen, as the specimen material is carbon fiber that’s why its original color is black, otherwise it will have to be colored black first before making the random white dotted speckle pattern on it. For making the random dots pattern teeth brush was utilized. The teeth brush is dipped in the white paint, its fibers were pulled and released that sprinkle the paint dots on the specimen, and this process is repeated until the required grid of speckle pattern is achieved on the specimen surface. The specimen with the dotted pattern is shown in the Figure 5.

The testing was performed on the Super L- 200KN Trinius Olsen (American manufactured) universal testing machine in material testing laboratory in School of Chemical & Material Engineering, NUST H-12, Islamabad.

In the experiment, a test fixture was used to hold the specimen in the vertical position, to avoid the bucking effect in the specimen. The shear load is applied on the specimen in the vertical direction. The shear force is transmitted in the specimen. The specimen were already prepared for the Digital Image Correlation (DIC). For the Digital Image Correlation setup, a Kodak EasyShare M 340, 16 mega pixel standard digital camera was used to capture the video during the testing of composite specimens. A Velborn® tripod was used to position the camera in front of the fixture for the
smooth video capturing. The light was sufficient in the laboratory environment to illuminate the specimen surface, so there was no need of any extra light for the video capturing.

Load is applied on the fixture gradually and values are recorded in the machine’s data acquisition system using Intel Pentium IV processor. Values obtained from the machine was in the form of stress-strain points. The machine’s data acquisition system also plots the stress-strain behavior of the composite material.

During testing, the video of experiment was made to apply the Digital Image Correlation technique. The digital camera was fixed on the tripod, in front of machine close to the fixture so that it can capture displacements produced in the specimen. Video is converted into the digital images by extracting the frames from the video, by using digital image processing tool box in the MATLAB 2012b®. Digital image correlation technique is applied by using GUI developed by Elizabeth Jones in MATLAB 2012b® in August 2013 at University of Illinois, Chicago, USA [40]. The experimental setup is shown in the Figure 6.

3.5 Digital Image Correlation (DIC)

The conventional method use for the determination of the material properties is with the help of extensometers. This method only provides the average strain on the total gauge length of the specimen not after the necking. The digital Image Correlation is a technique which can be applied to find the high accuracy strain results. Due to fast data acquisition system this technique can be used to find material properties in elastic as well as plastic ranges. This technique is also helpful in full field, non-contact and high accuracy determination of displacement and strain measurement [41].

3.6 MATLAB Code for Digital Image Correlation
For the DIC MATLAB code is used developed by the Elizabeth Jones of University of Illinois USA [40]. The video was recorded during the compression tests of the carbon epoxy fiber reinforced composite on the Universal Testing Machine by the digital camera. The images were extracted from the video using the MATLAB. The images format was JPG and used for the image processing in the MATLAB code.

4. Results and Discussion

The carbon Epoxy composite specimens were tested on the 300 KN Tinius Olsen’s Universal Testing Machine in the Material Testing Laboratory in School of Chemical & Materials Engineering, NUST H-12, Islamabad. The objective of testing was to find out the compressive failure load of the specimens. The total numbers of specimens were 27, a set of 9 specimens drilled on 9 different parameters.

The result of the specimen 1 is shown in Figure 7 in the stress-strain graph, the graph represent three lines, the red line shows the elastic behavior, the black line shows the stress-strain relationship & blue line shows the strain at 0.2%. The total strain produced in the specimen 1 is 1.015%.

The stress strain graph for the specimen 12 is shown in the Figure 8 shows the values for the stress is 281 MPa & total strain produces is 0.845%. Mean strain of specimens is shown in Table 3. Mean Stresses of the Composite Specimens is shown in Table 4.

4.1 Comparison of drilling parameters with the OHC strength:

There are three drilling speeds 1600, 2400 & 3200 and three feed rates 64, 192 & 480, the combination of these speed and feeds along with the comparison with Open Hole Compression Strength is given in the Table 5.
The blue line in the graph represents the 1600 mm/min speed, the maroon color line represents the 2400 mm/min speed and green color line represents the 3200 mm/min. The three speeds, feeds and OHC strength relation are plotted in the Figure 9.

4.2 Comparison of OHC Strength with the Delamination:

The table 6 represents the comparison between the OHC strength and delamination produced due the drilling of the specimens. The results show that the OHC strength is maximum on the lower feed rates on 64 mm/min for all the three speeds 1600, 2400 & 3200 mm/min and strength drops to 21315 N on the 3200 mm/min speed and 480 mm/min speed. Pictures shown in Table 6 represent maximum strength where delamination is lesser on the specimen 1, 4 & 7. The results show that the maximum delamination occurs on the greater feed rates i.e 480 mm/min whereas the delamination is minimum on the lesser feed rates i.e 64 mm/min. The optimized results are obtained on the higher drilling speeds and lower feed rates as shown in the Table 6.

4.3 DIC Output Graphs

The three types of outputs are obtained from the Matlab Code, contour plot, line scan & spatial average, these three graphs are obtained for every specimen and are explained below.

4.3.1 Specimen # 1

The speed and feed combination for the specimen 1 is 1600 mm/min and 64 mm/min respectively, OHC strength is given by 26013 N. The graph is shown in Figure 10, represents the strain distribution in the selected area. The strain distribution is highlighted by colors. X & Y axis takes the pixels as a location for strain distribution. The area which is selected for the DIC is divided into the pixels by the Matlab Code, the correlation is done by comparing the speckle pattern on each image, the strain percentage graph, line scan & spatial average is computed.

The contour strain plot in YY direction is shown in Figure 11 and strain percentage is given on the last correlated image. The yellow spot near the center shows the -5 percent strains on that area. In
Figure 11, line scan of the specimen 1 shows the finite strain in the YY direction along the horizontal line 0.5 from the top of the region of interest (ROI). Each line shows the strain distribution for a single image. X-axis shows the pixel scale which is equal to the 1 µm/pixel. The legend represents every line color by the data series, by fading the line color for every next image strain distribution. Y-axis represents the strain percentage. The lines are dropping in the center which shows the negative strain in the center of the ROI.

The Figure 12 represents the spatial average of finite strain on the horizontal line 0.5 from the top of the image. The X-axis represents the total number of images for the DIC and Y-axis for the strain percentage in the YY direction. The graph shows that the strain increases in negative direction for the image number 2 to 7 then it decreases till the last as shown in Figure 13.

4.3.2 Specimen # 2

The graph is shown in Figure 14, represents the Contour plot of strain percentage for Specimen 2. Line Scan Graph of Specimen 2 is shown in Figure 15. Spatial Average Graph of Specimen 2 is shown in Figure 16.

4.3.3 Specimen # 3

The graph is shown in Figure 17, represents the Contour plot of strain percentage for Specimen 3. Line Scan Graph of Specimen 3 is shown in Figure 18. Spatial Average Graph of Specimen 3 is shown in Figure 19.

Limitations

The testing stander technique applied in the current research is limited to the continuous fibers. For discontinuous fibers and laminates, fibers should be symmetric and balanced in the test direction while conducting this test.

Conclusion

- It is concluded from the experimental & DIC results that the maximum strength for the Carbon Epoxy Composite with notch (hole) present in it achieved by drilling from
1600-2400 mm/min speed & low feed rates. The contour plots show the distribution of strain around the hole.

- The strain percentage is higher in the specimens which are weaker in OHC strength due to the delamination and internal fiber pull out. The line scan plot shows the distribution of strain around the hole, the line shows the higher compressive behavior around the hole.

- The 4 cutting methods were employed to cut the composite sheet to get the best method out of them; i.e by End Mill Cutter, by Hack Saw, by HSS Disc & by SiC Abrasive Disc.

- The best cutting results were found by the SiC abrasive disc of 1 mm thickness.

- It is found from the experimental results show that at higher feed rates the Delamination is higher because of the chisel effect.

- Failure is dependent on the feed rate of drilling, the optimized drilling range is from 1600 to 2400 mm/min.

- The OHC strength values are very close for all speeds at 64 mm/min feed rate. At higher feed rates strength values are minimum.

References


[40] Jones, E. "Documentation for Matlab-based DIC code", University or Illinoispp, (2013)

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Figure 4 Failure Modes in Compression Test a) LGM, b) AGM, c) MGM
Figure 5 Image Prepared for DIC

Figure 6 Experimental Setup for Compression Test & DIC
Figure 7 Stress-Strain Plot of Specimen 1
Figure 8 Stress-Strain Plot of Specimen 12

Speed Vs Feed Vs Strength

- 1600 mm/min
- 2400 mm/min
- 3200 mm/min
Figure 9 Graph Between Speed, Feed & OHC Strength

![Graph Between Speed, Feed & OHC Strength](image9.png)

Figure 10 Graph between Speeds, Feed & Strains

![Graph between Speeds, Feed & Strains](image10.png)

Figure 11 Contour Plot of Strain Percentage for Specimen 1

![Contour Plot of Strain Percentage for Specimen 1](image11.png)
Figure 12 Line Scan Graph for Specimen 1

Figure 13 Spatial Average Graph for Specimen 1
Figure 14 Contour plot of strain percentage for Specimen 2

Figure 15 Line Scan Graph of Specimen 2
Figure 16 Spatial Average Graph of Specimen 2

Figure 17 Contour Plot of Strain Percentage for Specimen 3
Figure 18 Line Scan Graph of Specimen 3
Figure 19 Spatial Average Graph of Specimen 3

Table 1 Open Hole Compression Strengths

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
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</thead>
<tbody>
<tr>
<td>OHC Strength [N]</td>
<td>26013</td>
<td>21837</td>
<td>24795</td>
<td>26448</td>
<td>23403</td>
<td>22359</td>
<td>25143</td>
<td>25839</td>
<td>21315</td>
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Table 2 Drilling Parameters
<table>
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<tr>
<th>Sr. #</th>
<th>Specimen #</th>
<th>Speed (S) mm/min</th>
<th>Feed (F) mm/min</th>
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<td>1,10,19</td>
<td>1600</td>
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Table 3 Mean Strain of Specimens

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<th>S6</th>
<th>S7</th>
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<th>S9</th>
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<tbody>
<tr>
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### Table 5 Comparison of Speed, Feed & OHC Strength

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<th>1600 mm/min</th>
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<tbody>
<tr>
<td>Feed (F) mm/min</td>
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<tr>
<td>OHC Strength [N]</td>
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<td>21837</td>
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### Table 6 Comparison of OHC Strength with the Delamination

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<th>OHC Strength</th>
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</tr>
<tr>
<td>9</td>
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<td>21315</td>
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</tr>
</tbody>
</table>
Biographies

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