

Experimental Investigation of Notch Tensile Strength of CFRP Laminated Composites

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Abstract

This paper presents, by experimentally investigating, the effect of notch dimension and fiber orientation on the tensile strength of laminated CFRP composites. In the present study, notch tensile strength of unidirectional CFRP laminated composites with epoxy matrix is evaluated. Three fiber orientations viz 0o, 45o and 90o with two central circular holes/notches of 6 mm and 10 mm diameter are considered. An experimental program has been carried out to investigate their effect on the tensile strength of laminated composites in the presence of central circular notch. Investigations on the tensile strength of composite laminates containing circular holes show that there is a large difference in failure stress and mode of failure mechanism. It has been observed that the notch tensile strength decreases with increase in hole diameter/notch size and with the increase in fiber orientation. Considerable variation in strength has also been observed between 0o and 45o fiber orientations as compared to that between 45o and 90o which is very small. In addition to the variation in strength, two different failure mechanisms are observed: fibre pull out in 0o loading condition, debonding along the fiber orientation with matrix damage in other two conditions. It is observed that the damage propagated across the gauge section via delamination at the hole, which is controlled by the ply direction.

Keywords: *CFRP, Fiber Orientation, Notch, NTS, Damage*

INTRODUCTION

The prediction of composite materials is a vital part for composite structure designing, especially in the aerospace industry which strives for accurate physically-based and fast strength prediction methods for composite laminates with stress concentration

- 1) The desire for lower production costs and higher production rate in high-volume markets such as the aircraft and construction industries, combined with the possibility of fast molding processes, high damage tolerance (especially at sub-zero temperatures) and high chemical and environmental resistance make fiber reinforced composites as very attractive materials
- 2) Fiber-reinforced plastic has great quality such as ratio of strength and ratio of stiffness unlike metal materials and used in many areas because of improving the strength by orienting in certain direction. And, it is possible to mould the parts because the flexibility of molding is wide. The cost of production also can be decreased, because of its high productivity. So, the use of molding of fiber-reinforced plastic is

expanding to the structural material of airplanes, cars, sports, and something related to energy instead of molding of the press

- 3) Composites are being utilized as viable alternatives to metallic materials in structures where weight is a major consideration, e.g., aerospace structures, high speed boats and trains. FRP will be used as the outer skin of the rocket airframe mainly to stabilize and protect the airframe by serving as a stiffening component. Also, the smooth surface of FRP composites will serve to reduce drag on the rocket during flight. The skin will experience bending, compression and tension loads during the supersonic flight. Many researchers studied in this field, showed that the orientation of fibres had a major role in increasing some properties
- 4) The tensile or compressive deformation in the longitudinal (fiber) orientation is controlled by the fibers leading to a linear stress-strain response which ends abruptly when the fibers fail by tensile fracture or kinking in compression. Conversely, major non-linear deformations can develop under

transverse compression or in-plane shear because deformation is controlled by the polymeric matrix and/or the interface

- 5) The tensile tests are used to determine both strength and modulus values to be used in component projects and also to verify technical specifications and quality assurance of projects. The fracture surfaces, resultant of the tests, are used to support the failure mode analysis
- 6) In industrial applications, rivets are used to join components that are made of isotropic or anisotropic materials. In contrast to the isotropic materials, the mechanical, physical and thermal properties of anisotropic materials such as fibrous composites are directional, which complicates the stress analysis in the neighbourhood of holes
- 7) Numerous structural applications of composite materials require the presence of holes and cut-outs, whose effect on laminate strength is not, however, fully mastered. The stress distribution around the hole and the resulting damage progression and failure of composite

laminates under loading is of obvious interest to engineers and designers

- 8) Investigations of the effect of size on the tensile strength of composite laminates containing circular holes show that there is a large difference both in failure stress and mechanism due to changes in test configuration. This is particularly true of the ply and laminate thickness, and hole diameter
- 9) The sensitivity of a laminate to a notch, in terms of its mechanical performance, is dependent on many factors, including: laminate size and thickness, notch size and geometry, ply orientation and thickness, machining quality, and material constituents. All of these factors affect the mechanical properties by changing the extent of damage growth during loading, and interact with each other to enhance the individual effects
- 10) Failure behaviour of notched composite laminates depends on a variety of factors, the most important being laminate configuration, specimen geometry and notch shape. Due to the complex fracture behaviour in the

vicinity of the notch, a number of assumptions and approximations are made in the most commonly used failure models. Most of the popular models are based on the characteristic length concept

11) Because of their importance in design applications, continuous-fibre reinforced-resin matrix composite laminates containing holes and subjected to tensile or compressive loadings have been studied extensively. This is due to the fact that, in monotonic loading, notches have an important effect on the growth of damage zones. In brittle matrix composite laminates, the mechanisms that form a damage zone consist of many interacting matrix cracks, delamination, splits, transverse ply cracks and so forth; these types of damage are depending on the lay-up, material properties and geometry of the specimens

12) Many failure models have been developed for the prediction of the notched strengths of composite laminates. Most of them are proposed for tensile loading. A composite laminate containing a notch normally

goes through a very complicated damage process before it reaches ultimate failure

13) Notwithstanding the large number of experimental observations on size effects of composite laminates, there is still the need to compare the effect of size on the strength of composite laminates with open-holes under both tensile and compressive loading. Such a comparison should be based on the same material, lay-up and geometry. Also, there is the need to have additional information on the relation between the applied load and the sequence of failure mechanisms that occur in notched composite laminates

14) The sensitivity of a laminate to a notch, in terms of its mechanical performance, is dependent on many factors, including: laminate size and thickness, notch size and geometry, ply orientation and thickness, machining quality, and material constituents

15) From the literature, it is observed that, the strength of a notched specimen with an open hole is a function of many factors, including the varying

orientations, stiffness, coefficients of thermal expansion, the amount of absorbed moisture, the dimension of the specimen including the hole size and width, the progressive failure and the fracture form of the specimen and so on. Also, it is evident that, with the importance of the long fiber laminated composite structures, presence of notch play a very significant role in designing of such composites. Hence, in the present study an experimental work has been carried to study the scaling effect strength of notched composites. The most important variables have been identified as notch size (in the form of a circular hole of two different diameters 6 mm and 10 mm) and ply orientation (three fiber orientations of 0°, 45° and 90°). Both are scaled independently and simultaneously. The test results of tensile strengths obtained have been compared on simple models to predict the notched strength so as to assess their applicability.

MATERIALS SELECTION

Unidirectional Carbon fabric with the gram weight of 270 g/m² and a nominal ply thickness of 0.2 mm are used as reinforcement. The fabric was made of

continuous fiber available in the form of rolls. The carbon fiber, available with 400 mm width, was expurgated into 110 mm in length from the rolls and was spread in one direction during layup. One laminate of composite contained 4 layers of fabric to maintain a thickness of 1 mm. Unsaturated polyester resin LY556 was used as a matrix.

The resin was mixed with the hardener HY951 in a ratio of 10:1. Four layers of fabric were used to prepare the laminate via hand lay-up method. A vacuum bag, with breather assemblies, is placed over the layup and attached to the tool to evacuate voids and to remove extra resin, which may be present in the layup, using a vacuum pump. The suction pressure maintained was 550 Hg/mm².

The composite laminates were cured in room temperature for 24 hours, and were heated in an oven at 90°C (for 2 hours) as post-cure. Thus, quasi-isotropic laminate with stacking sequence [0/0]₂ was used, with 0° being in the applied loading direction. The lay-up process is as shown in the Figure 1.

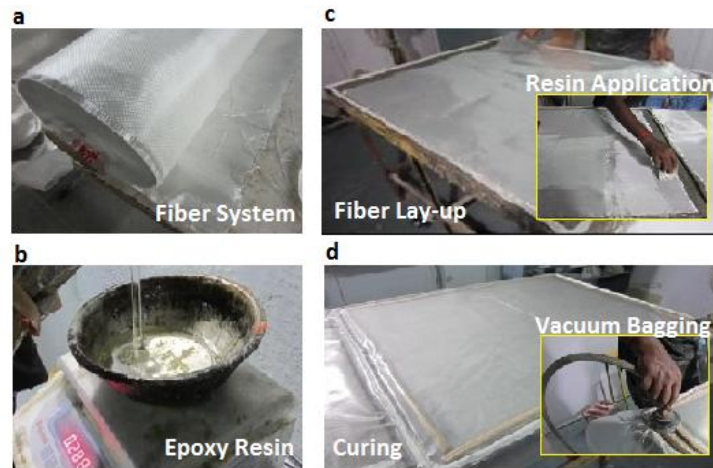


Figure 1 - Hand lay-up with vacuum bagging technique

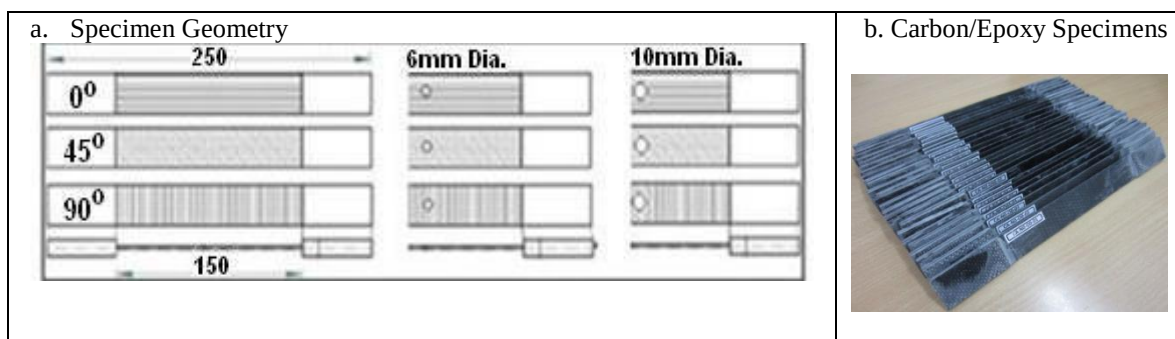


Figure 2 - Tensile Test Specimen –Carbon/Epoxy Composites

SPECIMEN PREPARATION

From the fabricated composite laminates, rectangular tensile test specimens (250 mm x 25 mm) were cut in longitudinal (0°), inclined (at 45°) and transverse (90°) direction. Three sets of test specimens were prepared, first set without any notch, second and third set with centrally located circular hole of 6 mm and 10 mm diameter respectively as shown in the Figure 2. Each

test specimen has been provided with composite end-tabs by locally bonding the tabs at the ends on each side of the test specimens. The tabs are used to clamp the specimens in the test equipment. They allow a smooth transmission of load from the grips to the specimen during testing. Bi-woven glass/epoxy has been used to prepare the tabs.

EXPERIMENTAL METHODS

Uniaxial tensile properties of materials are used directly as one measure of material performance and as part of the material property input required for analysis of complex structures. In principle, the uniaxial test method used to obtain a reliable tensile strength value is simple to perform. A specimen with large length to width ratio is loaded along its axis until failure occurs. However, there are many issues that can affect the reliability of the measured value. Homogeneous, isotropic materials are the simplest to test. For these materials, surface flaws resulting from specimen preparation can have a large effect on measured strength. In addition, the specimen geometry must be properly designed to ensure failure within the gage region of the specimen rather than in the transition from the gage region to the gripped ends of the specimen. Alignment of the specimen in the test rig is also important, especially for brittle materials. There is also a possibility of a dependence of the measured value on specimen size because of the statistical nature of failure initiation at local defect sites. Testing of

unidirectional, continuous fiber composite materials presents additional challenges because these materials are strong along the fiber direction but weak transverse to the fiber direction. Tabs are generally recommended for testing unidirectional material in the fiber direction to avoid failure due to stresses induced at the grips, but failure initiation can occur as a result of peel stresses at the ends of these tabs[16].

In this work, rectangular specimens of polymeric composites with end-tabs were used. Generally, rectangular specimens are required for the composite material characterization. The test specimens were mounted in the UTM by gripping the tabs in the gripper mechanism. The specimen was held in the gripper of the testing machine, care was taken to align the longitudinal axis of the specimen and the grips with an imaginary line joining the points of attachment of the grips to the machine. The grips were tightened evenly and firmly to the degree necessary to prevent slippage of the specimen during the test, but not to the point where the specimen would be crushed [17].



Figure 3 -Tensile test set up

Tensile tests were conducted at room-temperature in ambient air one servo-hydraulic Universal Testing Machine (UTM) with 100kN loading capacity as shown in Figure 3. The mechanical load was applied via a wedge-type gripping device. A constant displacement rate was maintained by setting the cross head speed of the loading arm at 2 mm/min in accordance with ASTM D3039 for constant head-speed tests. The loading direction was varied from 0°, 45° and 90° from the fiber longitudinal axis.

The load and deformation data were acquired and recorded for each specimen to plot the Load Vs Displacement Plot and then the respective Stress Vs Strain and graphs of load v/s deflection and stress v/s strain were plotted.

RESULTS & DISCUSSIONS

Tensile test was conducted on unnotched and notched CFRP test specimens with three different fiber orientations of 0°, 45°, 90°. The load vs deformation results are plotted as shown in the Figure 4 and crack initiation

and failure of the composite for corresponding fiber orientation are shown in the Figure 5. The experimental values (tensile strength) of Carbon/Epoxy composite obtained for fiber orientation i.e. 0° , 45° , 90° with and without notches are also tabulated as shown in Table 1 and are shown in the Figure 6. It is evident from the

results that the tensile strength is superior in case of 0° orientation. Tensile strength of 90° orientation is the lowest. The percentage deviation of tensile strength of Carbon/Epoxy for ply orientations (0° , 45° , 90°) with and without notches is given in Table 2.

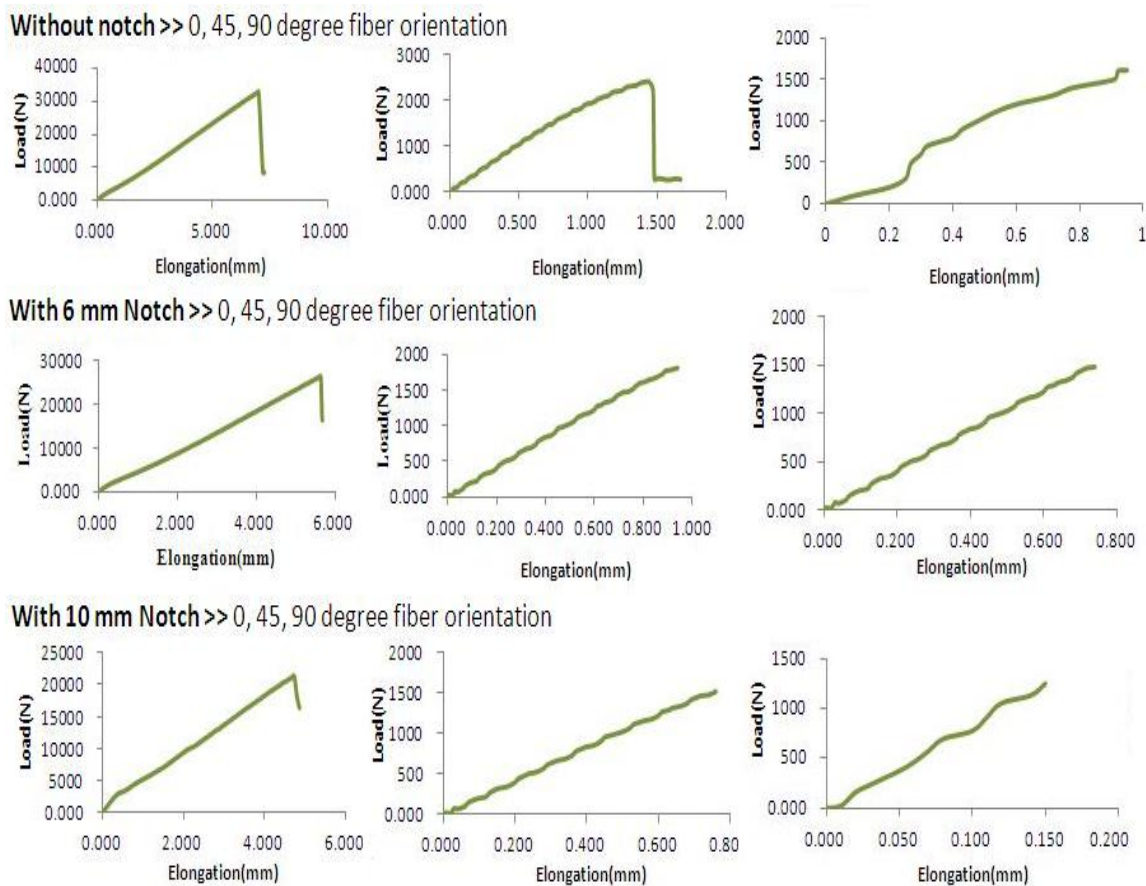


Figure 4 - Carbon/Epoxy failed specimens

Table 1 Tensile strengths of Carbon/Epoxy for different fiber orientations

Sl No	Particulars	σ_{u0}	σ_{u45}	σ_{u90}
1	WITHOUT NOTCH	735.2	96.58	70.76
2	6mm NOTCH	660.7	62.75	46.45
3	10mm NOTCH	615.9	53.51	41.24

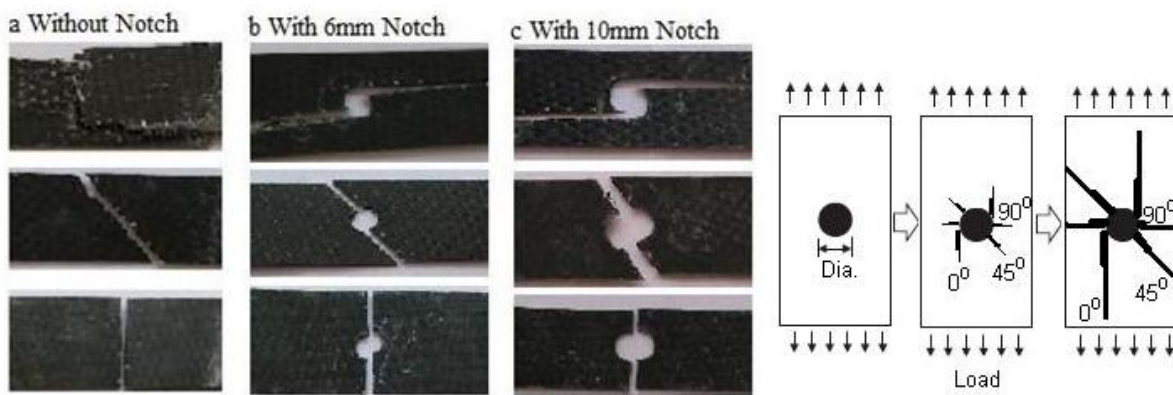


**Figure - Carbon/Epoxy failed specimens and crack propagation direction
(for 0°, 45° and 90° fiber orientation)**

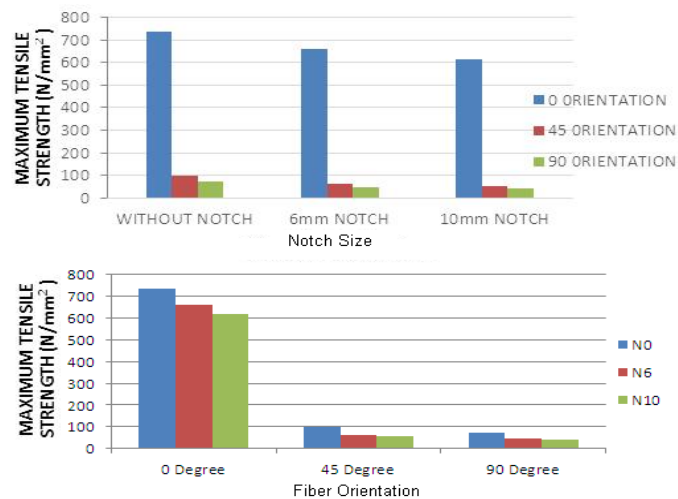


Figure -6 Tensile Strength Carbon/Epoxy composite (for orientations of 0°, 45°, 90°)

Table 2 Percentage Variation of Tensile strengths of Carbon/Epoxy Composites

Sl No	Particulars	σ_{u0}	σ_{u45}	% Chang e	σ_{u45}	σ_{u90}	% Chang e	σ_{u0}	σ_{u90}	% Chang e
1	WITHOUT NOTCH	735.2	96.58	86.87	96.58	70.76	26.73	735.2	70.76	90.37
2	6mm NOTCH	660.7	62.75	90.52	62.75	46.45	25.97	660.7	46.45	92.96
3	10mm NOTCH	615.9	53.51	91.31	53.51	41.24	22.93	615.9	41.24	93.30

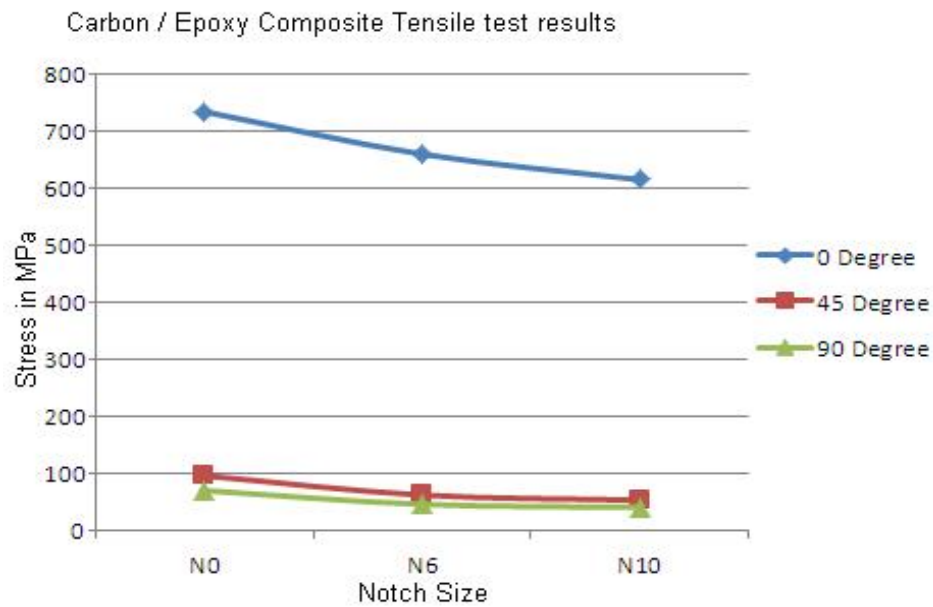


Figure 7 - Stress Vs Notch Size

The main objective of the above experiments is to perform strength analysis of composite laminates under uniaxial loading for different fiber orientation viz. $0^\circ, 45^\circ, 90^\circ$ of Carbon/Epoxy composite

laminates. Figure 7 and Figure 8 shows the results of uniaxial loading in tension on the proposed CFRP composite laminate system.

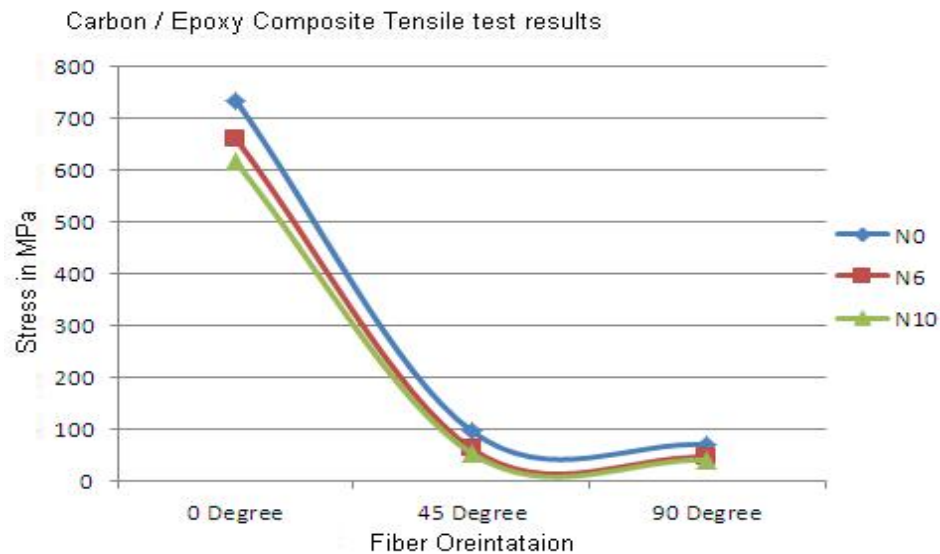


Figure 8 - Stress Vs Fiber Orientation

Table 3: Notch Strength Ratio (for different fiber orientation)

Sl No	Fiber Orientation	Without Notch N0	With Notch of 6 mm diameter N6	With Notch of 10 mm diameter N10
1	0 Degree	1	0.8986	0.8365
2	45 Degree	1	0.6497	0.5541
3	90 Degree	1	0.6564	0.5828

NOTCH STRENGTH RATIO (NSR):

The table 3 gives the notch strength ratio of CFRP composite laminates under uniaxial tensile load for three different fiber

orientations wherein circular notch/hole of two different diameters of 6 mm and 10 mm are considered.

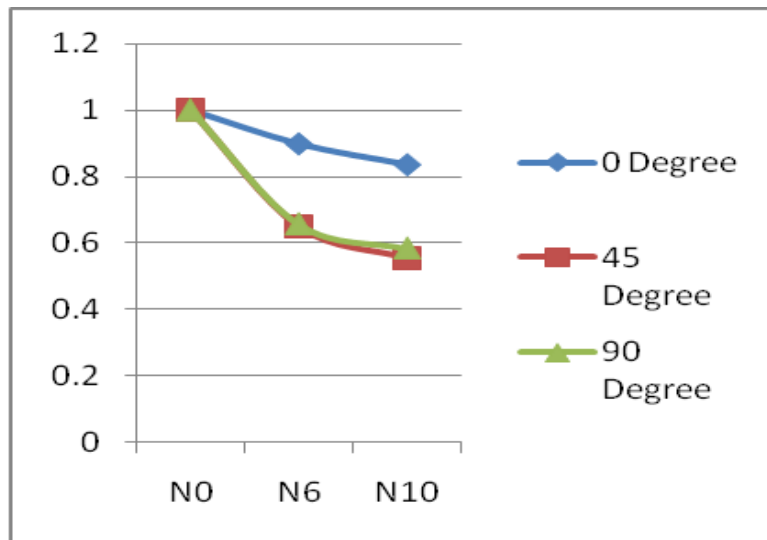


Figure 9 - NSR Vs Notch Size

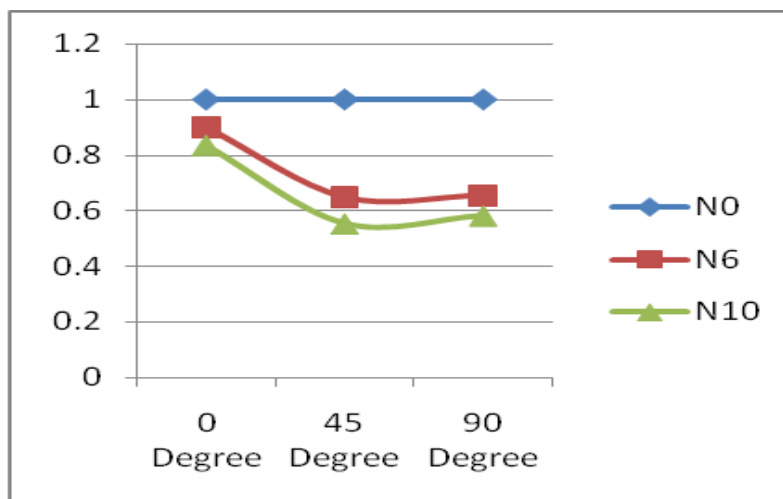


Figure10 - NSR Vs Fiber Orientation

CONCLUSIONS

The present work carried out can be summarized as below:

- A general approach in analyzing composite laminates under uniaxial loading for carbonfiber system with $0^\circ/45^\circ/90^\circ$ ply orientation is successfully carried out.
- It is evident from the Tables 2, 3 and Figure 6, 7 & 8 that the load carrying capacity and hence the tensile strength for different fiber orientation viz. $0^\circ, 45^\circ, 90^\circ$ of Carbon/Epoxy composite laminate is higher in case of laminates without notch and is decreasing with increase of notch size viz., 6 mm, 10 mm.
- It is observed that tensile strength is much higher in 0° fiber orientation both in case of with and without notch under uniaxial loading conditions as fibers are oriented in the load direction which takes up the load resulting in higher strength as compared to other fiber orientations.
- It is observed during a tensile test of notched specimen that the damage initially occurred at the edge of the circular hole and extended to the outside along the fiber orientation. The load and hence the stress was increased till the crack propagates in the specimens. It was further increased to reach maximum value causing the failure in the specimen.
- It is also observed that the failure occurred by fiber pull out in 0° ply orientation whereas failure is by debonding of resin along the ply orientation in 45° and 90° composite laminates.

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