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Determination of Tensile Strength of Composite Laminates with Multiple Holes

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Abstract

Composite materials such as Fiber Reinforced Plastics are vastly utilized in applications such as automotive, aerospace and civil industries etc. For their advantageous parameter or property such as high strength to weight ratio they are preferred for various aircraft structural parts such as cockpit, wings, empennage etc. The holes drilled for composite joints are the primary source of structural failure in aircraft structures. In the view of the above stated condition, it becomes extremely essential or vital to study the impact of holes on the properties of the structural components. The anisotropic behaviour, stacking sequence, geometrical parameters and failure response of the composite materials makes the problem more complex. Composite materials are used in various aircraft structural parts such as wings, stabilizers, etc. Holes are often used in the structural assemblies and repair methods which require various hole patterns to carry out the repairs on the damaged areas.

In the view of above case, an investigational study was governed to determine the effect of single central holes and multiple holes with different configurations in order to predict the strength & stress concentration of CFRP. This data led to a detailed understanding of various damage criteria that resulted in the structural failure.

Keywords: Tensile Strength, Composite Laminate, Experimental Analysis, CFRP, Multiple Holes

INTRODUCTION

FRP composite laminates possess a higher factor of strength and stiffness. In many composites, fatigue strength and tolerance towards fatigue are excellent compared to most of the metals. They possess high damping property which denotes high absorption of vibrations and thus results in reduced production of noise and vibration. They have very low maintenance costs in aerospace applications, they reduce the overall weight which is one of the most crucial criteria for aerospace industries. Fiber reinforced plastics, which consist of an appreciable performance parameter can be noticeably destabilized with an introduction of holes or notches in a specific region. The destabilization of the structural component/material occurs due to an increased rate of stress concentration factor in the locality of the discontinuity which is introduced. Unlike for a unidirectional CFRP which exhibits properties of elasticity to a satisfactory extent to failure, isotropic materials demonstrate plasticity. The impact of stress concentration is to result in an increment of stress at which the material or any component fails.

On introduction of a pseudo plastic behaviour in the locality or the local region of holes the rate of stress value varying at various locations could be diminished and the efficiency of the particular component may rise to a considerable extent. Needless of an overview of complexity in the procedures of fabrication, the factors of smoothening can be merged with the fiber, oriented in multiple directions. Stress concentrations are regions in a material where the distribution of load or stresses is uneven. In simple words the stress lines are placed close to each other due to some form of deformity or defect. Due to the hole centrally placed on the material the stress lines are displaced and this displacement creates a region where the stress lines are cramped together. Because of this, the stresses at these regions are higher than on a normal material without the hole. The equivalent distribution of the stress concentration around the locality of a discontinuity or a notch or a hole or cut-out affects the tensile strength. As a consequence, composites were reviewed with consideration being given to multiple holes drilled through the specimen with discrete arrangements.

The aircraft undergoes various inspection and maintenance procedures and also in order to design an aircraft the design specifications are restricted to a particular or rather a specific value in order for the aircraft to be efficient and majority of the aircraft failures which are aimed to be considered to be under fail safe condition after the occurrence of the failures. Holes are drilled for various design purposes as well as are considered under structural failures. Inspections such as NDT (i.e. Fiberscope) are carried out on internal complex structures of an aircraft for detection of cracks and flaws. Such inspections are required to have holes on the structure for non-destructive testing procedures. The hole pattern plays an essential part while drilling onto the structural components of the aircraft. An aircraft undergoes various loads after it is airborne. The hole on the structural component results in structural failure after it exceeds the assigned loading parameters. In order to delay the failure process, the holes are drilled in discrete patterns on the specimens such that the distribution of the stress concentration factor around the region/locality of the hole evades the rapid failure of the component. The deformities tend to create these stress concentrations and cause an increase in the local stress of the material. Hence, engineers try to overcome this problem by carefully designing the layout of the material. And also, these deformities are created when there is a load acting on the material. When the load is applied, the material is either twisted or pulled. When such a phenomenon occurs the molecular structure of the material changes, giving rise to such deformities. During initiation these deformities are negligible such that the naked eye fails to spot them until it is detrimental. To reduce stress concentrations on sharp ended deformities many methods are utilized, one of the prominent methods is to drill a hole right at the edge of the deformities. Since a circular hole has a smooth curvature, it is drilled on the deformities to reduce stress concentrations and in turn ceasing the failure or increasing the life of the material.

This process is to be performed at the initial stage of the crack propagation. According to Griffith's Theory when a crack reaches a length of 2a, the propagation of the crack increases tremendously that it can fail much before the foretold strength. So, the hole drilling process must be done as soon as possible.

An extensive study had been previously carried out to rule out the effects of single central hole and multiple holes with non-identical configurations on the tensile strength of Carbon fiber Reinforced Polymer. T.A. Collings (2) conducted an experimental investigation on multidirectional Carbon Fiber Reinforced Polymer laminate to comprehend the impact of several parameters such as laminate thickness, bolt clamping pressure on the structural properties of single bolted composite laminates as well as multi-holes joints which were designed by using single hole data along with the effect of the bolt spacing. S.R. Hallett, B.G. Green, W.G. Jiang, M.R. Wisnom (8) studied the impact on scaling of the specimens which consisted several circular holes in a composite specimen. It was found that an outsized variance existed in the mechanism of failure and parameters of stresses. The specimens were scaled to three categories, one with where the thickness was increased (1Dimensional) and two where the dimensions like length, hole diameter, and width were increased (2Dimensional) and the third where all dimensions were increased simultaneously (3Dimensional). The hole diameters used were 3.175, 12.7, 25.4 and 6.35 mm. The above -mentioned diameters were used according to the categories of scaling level. The sub-laminate level scaled specimens were tested for diameters mentioned above. And selected diameters such as 3.175, 6.35 and 12.7 mm were tested for ply-level scaled specimens.

Sang--Young Kim, Jae--Mean Koo, Chang--Sung Seok (11) conducted a research stating to what extent does a hole has its impact on the properties of the material, in this case carbon fiber reinforced. The variation in the hole dimeter was further tested under the Universal Testing Machine (UTM) for tension testing. Finite Element Analysis was also done on the same and it was concluded that the analytical approach agreed to an appreciable extent with strength parameters on comparing to the experimental approach. In this paper, an attempt has been made to scrutinize the alteration in the structural properties of a CFRP laminate with multiple holes arranged in a specific pattern for detailed understanding of the failure occurring in the respective pattern at a certain application of the load and to comprehend the effects of a pattern in which holes are drilled to analyse stresses as well as failures occurring in the material.

EXPERIMENTAL METHODOLOGY

Fabrication of Laminate

Carbon Fiber mat of dimension 500mmX270mm was cut from the roll. Seven such Carbon Fiber mats were initially required in order to prepare a carbon fiber reinforced polymer laminate. The weight of all seven Carbon Fiber mats was measured using an electronic weighing machine.

The carbon fiber with the following properties:

1. Thickness 0.2mm
2. 200gsm BIDIRECTIONAL

was employed in order to fabricate the required composite panel of dimensions 500mmX270mmX2mm. The resin epoxy LY 556 and the hardener HY951 were added to provide good bond strength. The resin and hardener were blended in 10:1 ratio and the layers of this mixture were applied between the layers of fibers to provide a good bond. Curing was done at room temperature for 24 hours. A total of 7 layers were laid during the fabrication of this panel and all the layers were laid in the similar manner. The typical properties of the carbon fibers are given in Table I. The fabricated laminate is shown in figure 1.

Table I: Properties of Carbon Fibers

Sr. No.	Property	Magnitude
1.	Tensile strength (KN/mm^2)	3.53
2.	Tensile Modulus (KN/mm^2)	230.284
3.	Elongation %	1.52
4.	Density (gm/cm^3)	1.76

Figure 1. Fabricated Laminate

Preparation of Specimens

Total of 5 specimens were cut from the prepared composite laminate into the required dimensions by following the procedures mentioned in ASTM D3039 for tensile testing of FRP composite laminate. The dimensions of the specimen are shown in figure 2.

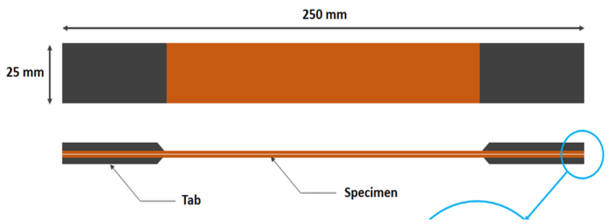


Figure 2. Specimen dimensions

Water-jet cutting technique was used to cut all the specimens to avoid generation of micro-cracks while cutting and to attain a good surface finish. After the successful cutting of specimens, holes of 5 mm diameter were introduced into the specimens by using vertical drilling machine. To eject an extremely high velocity jet through a nozzle orifice, highly pressurized water jet was passed through it at a high pressure setting of 37,000PSI. Due to heat dissipation laser cutting was not preferred as it causes delamination and various other damages to the material. The Aluminium tabs of dimensions 50mmX25mmX2 mm were attached at both edges of specimens to provide proper grip between the specimens and testing machine jaws. The specimens, before the test was initiated are shown in figure 3 and figure 4.

Figure 3. Specimens before test

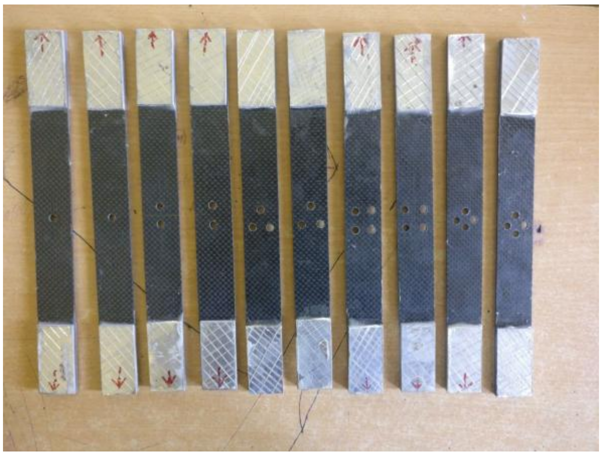


Figure 4. Specimens before test

A Standard Epoxy Araldite was applied adequately as an adhesive in order to clamp the specimens and provide the necessary bonding between the Aluminium tabs and the composite laminate. Before drilling the holes, the pitch & the row distances were referred. And the values taken for pitch and row distances are “2.5D” each. Where “D” indicates the diameter of the hole. The diameter of the hole was found to be in the range of 4-6 mm. So as to accommodate the holes on the specimen, a precise diameter of 5mm was considered. For the above chosen diameter, an appropriate W/D ratio was taken into consideration. A standard vertical drilling machine was employed to drill circular holes onto the specimen at Hindustan Institute of Technology and Science (Chennai), illustrated in figure 5. A system of high rpm and low feed was used to have the least impact on the specimen. One, two, three and four central hole configurations were drilled on the specimen. Five configurations of hole orientation patterns are illustrated in figure 6. Configuration A has one hole and is designated as SH. Configuration B has two holes vertically placed and is designated as DH. Configuration C has three holes placed on the three edges of a triangle and is designated as TH. Configuration D and E have four holes placed as a square and a diamond array respectively and are designated as FH and FDH respectively.

Figure 5. Drilling of holes

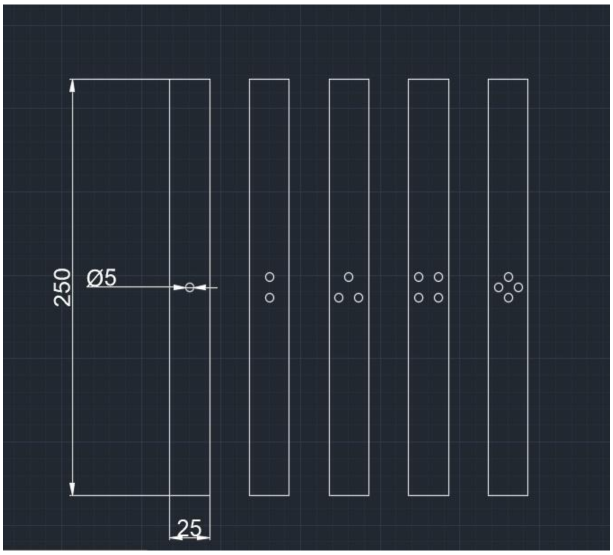


Figure 6. Specimen configuration

Tensile Test and Test Setup

A UTM (Universal Testing Machine) was used to test the tensile properties of all the specimens at Indian Institute Of Technology (Madras). The ASTM D3039 procedure was followed to perform the tensile test of all the specimens. The tensile test was performed at room temperature by placing the specimen in the jaws of the machine and it was pulled until failure. Specimens were fixed properly before starting the machine to avoid any kind of slippage during testing. The cross-head travel was maintained as 0.1inch/min throughout the test. The test setups of the notched specimens are depicted in figure 7.

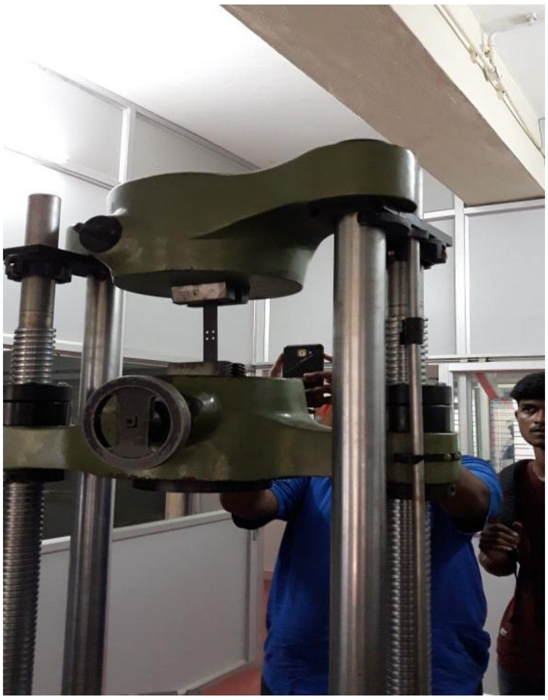


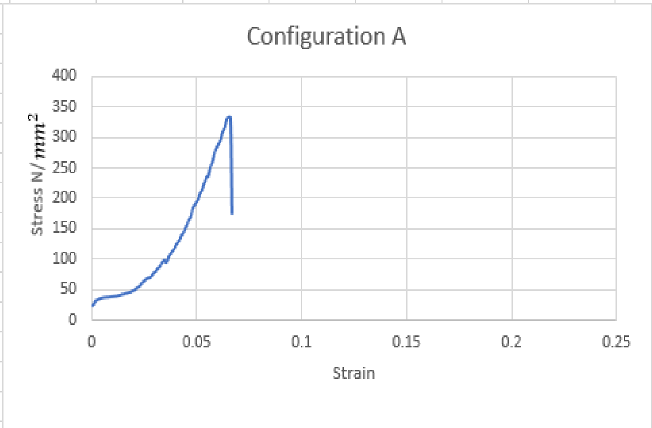
Figure 7. Test setup

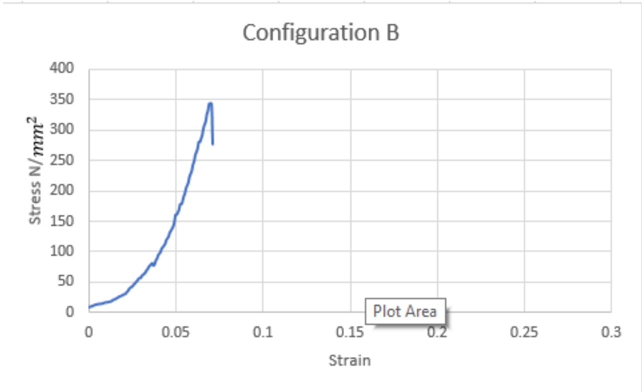
Results

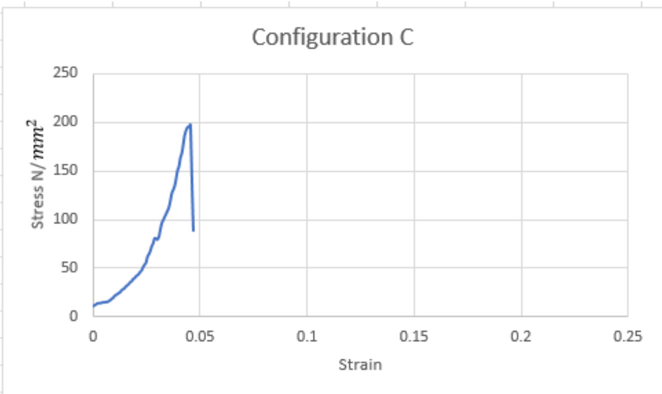
A total no. of 5 Configurations were tested and analysed under the Universal Testing Machine for Tensile Loading. Parameters such as Max. Elongation, Max. Load (KN), Strain at Ultimate strength Ultimate Strength (N/mm^2), Rate of feed (mm/min) were tabulated. The tensile properties of each configuration are shown in Table II. The Stress Strain for all the configurations have been illustrated in the figure 8.

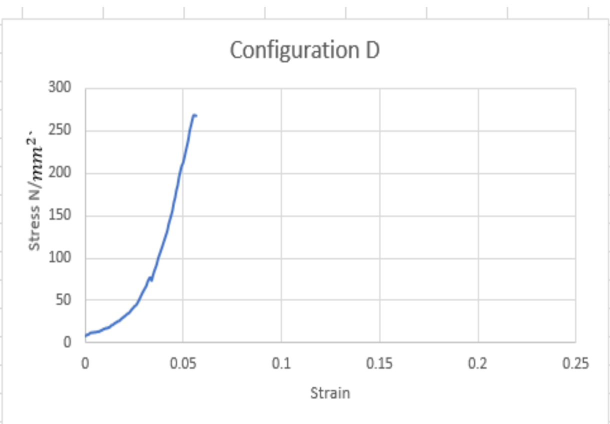
Table II: Tensile Properties

Property	**Config A**	**Config B**	**Config C**	**Config D**	**Config E**
Max. Elongation (mm)	9.9	10.6	6.8	8.5	6.6
Max. Load (KN)	16.58	17.16	9.88	13.36	8.12
Strain at Ultimate strength	0.066	0.07066	0.0453	0.0566	0.044
Ultimate Strength (N/mm^2)	331.6	343.2	197.6	267.2	162.4
Rate of feed (mm/min)	5	5	5	5	5









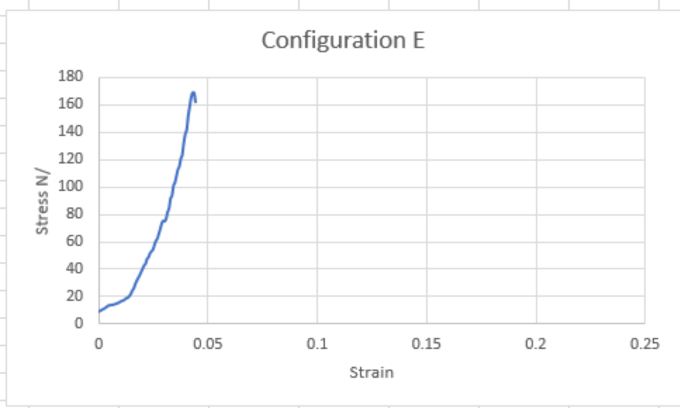


Figure 8. Stress vs strain graphs of various configurations

DISCUSSION

The data indicates that configuration B has the highest strength, whereas configuration E, consisting of four holes in a diamond array, has the lowest strength. The failure strength comparison chart is illustrated in figure 9.

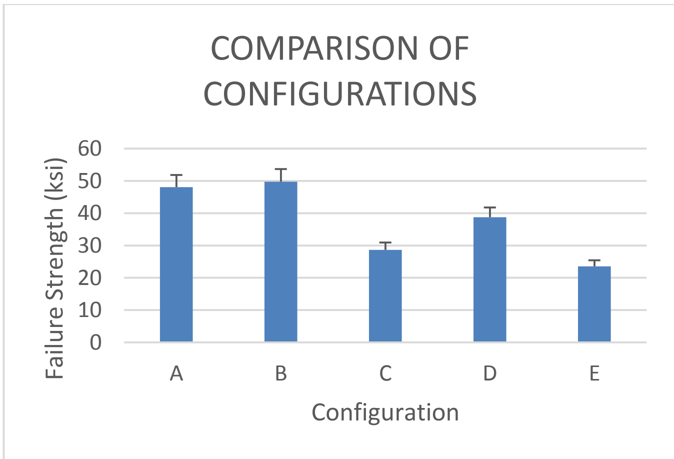


Fig.9 Failure Strength Comparison Chart

All of the test specimens exhibited an edge delamination before the presence of the visible damage around the hole. The neighbourhood of the hole was highly susceptible to failure for all the specimens except for configuration A, the specimen with SH configuration, for single hole specimen, multiple failures are observed not only in the neighbourhood of the hole but also at locations which are away from the hole. For this specimen, failure away from the hole can be attributed to the effect of edge delamination. For configuration B, significant failure was observed along the longitudinal direction. This signifies that the composite failed due to ply splitting. Configuration B has more strength because of an additional hole parallel to the load, resulting in the reduction of uttermost stress at the region of the hole or the circumference of the hole. Significant fiber breakage was observed between the two side-by-side holes in configuration D. Configuration D exhibits similar failure pattern as configuration B, more inclined towards longitudinal direction. Although configuration D laminate has four holes the laminate strength is higher than configuration C because of the fiber breakage between the holes due to which the strength of configuration C is lower than configuration. D. For the four-hole specimens, extensive fiber breakages are observed in configuration E resulting in the lowest strength among all of the configurations which is depicted in figure 10.

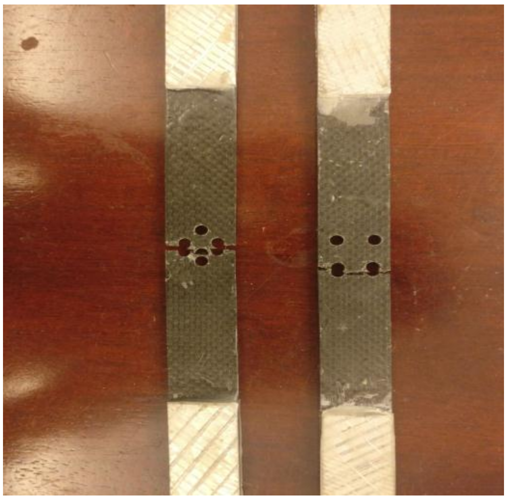


Figure 10. Failure Comparisons Of Laminates With Various Configurations

According to a research paper with the details given below:

Xu Xiwu, Sun Liangxin And Fan Xuqi, "Stress Concentration Of Finite Composite Laminates Weakened By Multiple Elliptical Holes, 13 October 1994, Department of Aircraft, Nanjing University of Aeronautics & Astronautics, Nanjing 210016, P.R. China, Copyright 0 1995 Elsevier Science Lid, Inr. J. Solids Structures Vol. 32, No. 20, pp. 3001-3014, 1995**.**

On comparing the experimental results achieved with the results of the aforesaid research paper, the study is thus concluded as below:

1. It is observed that on altering the distance between the interaction of the holes (i.e. lessening L/D), under the loading conditions σ_x , σ_y & τ_{xy} , the stress concentration varies at a hasty rate for the below stated conditions:
2. For the loading conditions σ_x stress concentration diminishes.
3. For the loading conditions σ_y & τ_{xy} , stress concentration rises to a higher degree of extent.
4. For the loading conditions σ_x, a series of hole pattern results in significant reduction in the stress concentration rate with a corresponding increase in the no. of holes.
5. Whereas, for the loading conditions σ_y & τ_{xy} a significant increment in the no. of holes provides with an outcome of excessive concentrations of stress around the circumference or periphery of the hole.
6. Effect of an arrangement of the hole pattern/configuration plays an essential role on the stress concentration factor.
7. Whereas, numerical results indicated that, when the open holes are drilled in series in the path of the loading conditions, it results in least stress concentration around the circumference of the hole. This proves that an increment in the no. of holes in the path of the loading conditions is propitious for depletion of concentration of stresses.
8. However, all the other cases provide with an outcome which contradicts the above condition. (i.e. number of holes are directly proportional to the rate of stress concentration).

CONCLUSIONS

The multiples holes are in analogy with the circular cut-outs created on the damaged laminate during composite structural repair. The stress concentrations occur at the periphery of the hole where the fibers are tangent to the hole. The magnitude of stress concentrations in the holes depend on the arrangement of the holes in the laminate. The peak stresses at the circumference of the hole with discrete arrangements are studied.

All the test specimens exhibited edge delamination before the presence of visible damage around the hole. The final failure occurs near the hole for all specimens. The final failure of SH specimen reveals a significant delamination at the neighbourhood of the hole. This may result in higher strength of the specimen.

According to the research papers of prior work, since the no. of holes placed in series in the path of the hole exhibits the maximum strength, on comparing the results, configuration B exhibits the maximum tensile strength due to least stress concentration factor around the circumference of the hole & is justified experimentally.

Effect of an arrangement of the hole pattern/configuration plays an essential role on the stress concentration factor. For tension and compressive strength, the maximum output is achieved on drilling/placing the holes in series. And thus, patterns other than the pattern of series exhibit extremely low tensile strength as well as are weakened due to high stress concentration factor.

So, to summarize:

- The peak stress occurs at the periphery of the hole.
- The arrangement of holes in the laminate plays a significant role in determining the peak stresses.
- Obtained in the following order Configuration B (Top and bottom hole) > A (single hole) >D (squared array) >C (Triangular pattern)> E (Diamond array). This sequence is in agreement with the test indication where configuration B has the highest strength and Configuration E has the least strength.

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