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Acoustic Emission based Monitoring of Cut-out Geometry Effects in Carbon/Epoxy Laminates under Uni-axial Compression

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ABSTRACT:

In this paper, symmetric cross ply CFRP laminates were fabricated using hand layup with LY556 epoxy resin as matrix and the specimens were cut without cut-out, with circular, vertical elliptical and horizontal elliptical cut-outs according to the ASTM D 7137 standard using water jet cutting. The CFRP specimens with and without cut-outs were subjected to compression under controlled condition accompanied by acoustic emission (AE) monitoring. The ultimate compressive strength for specimens with and without cut-outs were determined and compared. The optimum cut-out with lesser reduction in compressive strength was determined. The nature and dominance of different failure modes in each type of cut-out were investigated using AE. Finally the result gives useful information about improved design of laminated composites with cut-outs suitable for different applications.

KEYWORDS:

CFRP; Cut-outs; Acoustic emission; Peak frequency analysis; Compression test

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1. Introduction

The material properties like strength and stiffness characteristics for most of the composites are superior when compared to conventional metals and alloys. This behaviour is mainly due to the fibers which are the primary load carrying members. Composite laminates with cut-outs used for certain specific application suffers from local stress concentrations and show worst performance when they are subjected to compressive load. The effects of hole sizes, plate aspect ratios, plate boundary conditions, hole geometry and plate support conditions play an important role in affecting the compression strengths of the plates with cut-outs. Composite specimen with different ply orientation also shows varying strength to compression load.

Waas et al. [1] investigated the failure mechanism in laminated plates with circular cut-outs subjected to compressive load experimentally. They noticed that the failure takes place in the zero degree plies at the free edge of the hole surface perpendicular to the loading direction. Delamination initiation takes place near to the zero degree ply at free edge of the hole. On further loading this delamination area propagates to the undamaged adjacent area combined with local buckling. Pein et al. [2] studied experimental behaviour of composite laminate subjected to various cut-out sizes under compression loading. They noticed that the ultimate load of the composite plate decreases as the cut-out size increases. They also observed that cross ply laminates resist more compression load when compared to other orientation laminates. Al Qablan et al. [3] looked up the effect of cut-out size, cut-out location, and fiber orientation angle on square cross-ply laminated plates with circular cut-outs. Uni-axial compression, biaxial compression and shear loading were also considered in the study. Small cut outs near the edges and larger cut-out at the center of the laminate shows a better performance when they are subjected buckling load.

Liu et al. [4] surveyed the effect of varying number of cut-outs, ply orientations and lay-up configurations in laminated cut out composites. They came to an important conclusion that if the adjacent cut-outs have no interaction under applied load the number of cut outs can be increased with reduced stress concentration. They also stated that angle ply composite laminates with cut-outs are less effective to stress concentration. Ghannadpour et al. [5] addressed the size, shape and the plate aspect ratio of the circular cut-outs in affecting the compression behaviour of the laminates. They find that the plate with cut-outs requires high load than corresponding plate without cut-outs.

The continuous failure mode investigation of composite curved panels with and without circular cut-outs subjected to axial compression loading was studied by Damodar et al. [6]. They concluded that delamination failure mode is taking place predominantly in specimens with cut-outs. The residual stress investigation of the cut-out specimens can be well studied using delamination parameter. Khamseh et al. [7] investigated the effect of circular hole in uni-ply graphite-epoxy composite plates subjected to compression. They found that the type of failure is a function of hole size. In case of small holes global failure can be noticed and in case of large holes local buckling of fibers, delamination propagation is predominant.

Talib et al. [8] studied the effect of cut-out hole and fiber orientation angle on Kevlar/epoxy composite laminated plates. The influence of these effects on the compression and tensile performance was studied. The cross ply laminates show better strength and stiffness performance on compression than angle ply laminates. The initial failure takes place very earlier in compression test, stating that Kevlar has high resistance towards tensile test. Arslan et al. [9] analyzed the stress state on fiber-reinforced laminated composite plates containing circular holes. They concluded that as the fiber orientation increases from zero degree, the ultimate load for failure decreases and takes a low value when the fibers are arranged perpendicular to the compressive load. Kaltakc et al. [10] in quested the maximum stress value around the hole and angular location of that stress value changes in a symmetrically laminated composite plates with various fiber orientation angles. The same analysis was done for a single orthotropic layer and a single layer in a composite laminate plate with same fiber orientation. They concluded that maximum stress value and stress distribution is different for a single orthotropic layer and a single layer in a composite laminate plate with same fiber orientation and same material properties.

Lopes et al. [11] analyzed the difference in stress concentration between the cut out specimen with localized thickness variation around cut-outs and fiber steered cut-out specimen. They concluded that the nominal panel strength has increased by several times and an improvement in the specimen weight in fiber steered when compared to localized thickened specimen. Eslami et al. [12] studied the effect of harsh environmental conditions on fiber-reinforced composite materials subjected to compression load and analyzed their effect on their mechanical and physical properties. They came to a conclusion that the load carrying capacity decrease with an increase in aging.

Sadeghpour et al. [13] investigated the failure mechanism in fiber metal laminate with circular, elliptic and square notch shape .They observed that aluminium plate get failed initially before the fiber and the material losses its homogeneity. Suemasu et al. [14] optimized the shape of holes in carbon/epoxy composite panels. The stress levels of basic square shear panel to panels with circular holes were determined. Starting with a baseline square shear panel with a circular hole, the optimization has resulted in a larger non-circular hole that gives the same maximum stress level in the laminate. Fazilati et al. [15] investigated the dynamic instability of rectangular cut-out with longitudinally stiffened panels .They revealed that stability of the cut-out specimen is more sensitive to thickness of the stiffener when compared to number of stiffener. Large number of stiffeners with smaller thickness is less stiff than single stiffener with larger thickness.

Acoustic emission (AE) technique has been applied for inspecting damage initiation, detection, damage progression and accumulation, volume inspection, real time monitoring, damage accumulation, assessment and possibility of damage localization, first damage detection, strength prediction, damage history estimation and quality control of composite materials and structures. Moreover warning against failure together with failure localization makes it possible to repair the composite under consideration. Aggelis et al. [16] investigated the failure modes such as matrix cracking, delamination and fibre rupture of cross ply CFRP composite laminates by AE. They noticed that the cumulative count increases as the loading is progressed, the same result was correlated with the decrease in the elastic modulus as the loading is increased. Arumugam et al. [17] suggested a global method to determine different failure modes in laminated composites using peak frequency analysis. Berthelot et al. [18] used AE parameters to discriminate the failure modes from different stacking sequences (0°, cross-ply, 0°/45°, 90°/45°). Arumugam et al. [19] investigated the different failure modes in CFRP specimens which were subjected to impact using both peak frequency and parametric analysis. FFT analysis was employed chiefly to discriminate the failure modes.

A review of existing literature indicates the scope to explore more in the area of failure modes in composite cut-outs using AE. So in this study, the fabricated CFRP specimens were subjected to uni-axial compression loading. The ultimate compressive strength for specimens with and without cut-outs were determined and compared. The optimum cut-out with lesser reduction in compressive strength was determined. Non destructive AE technique is used in this study as a unique tool to determine different damage mechanisms like fiber breakage, matrix cracking, delamination, debonding using the energy of the acoustic signal developed from the stressed composite laminates. The nature and dominance of different failure modes in each type of cut-out were also investigated.

2. Compression test with AE monitoring

CFRP composite laminates with 8 plies were fabricated by hand layup technique. This method consists of applying successively into a mould surface, a layer of resin (LY556) with hardener (HY951), and a layer of reinforcement (carbon fiber) with tensile modulus of 230GPa and to impregnate the reinforcement by hand with the aid of rollers. For the present study, cross ply carbon fabric is used. The fabric was of plain weave, unidirectional (400mm x 450mm) weighed 44 gram per layer, and 8 plies of carbon fabric were used to make laminates of 3.5 mm thickness. After curing, the specimens were cut without cut-outs and with circular, vertical elliptical and horizontal elliptical cut-outs according to the ASTM D 7137 (150 mm x 100mm) standard. Compression test specimen of dimension 100x150x3.5mm have been prepared according to ASTM D-3039 standard from the fabricated laminate using a water jet cutter, which uses abrasive sand mixed with water as the cutting tool. For circular cut-out specimen the diameter of the hole is maintained at 40 mm. The major and minor axis of the horizontal ellipse cut-out specimen is maintained at 40 and 20 mm respectively. For vertical ellipse cut-out specimen the major and minor axis is maintained at 20 and 40 mm respectively. Fig 1 shows the prepared specimens.

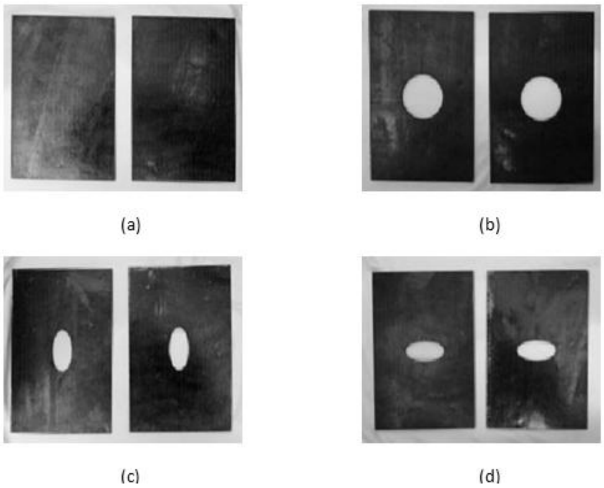

Fig. 1: Test specimens - (a) Pristine, (b) Circular hole, (c) Vertical elliptical hole, (d) Horizontal elliptical hole

The specimens are subjected to compression load in Tinius Olsen Universal Test Machine (UTM) with maximum force capacity of 100 kN under AE monitoring using an 8-channel AE setup supplied by Physical Acoustics Corporation. The minimum and the maximum test speed of the UTM corresponds to 0.1 and 500 mm/min respectively. The horizontal and vertical test space of the UTM is 650 and 1200 mm respectively. The specimens with and without cut-outs are placed in specially prepared compression fixture as shown in Fig. 2 and they are subjected to gradually increasing compressive load.

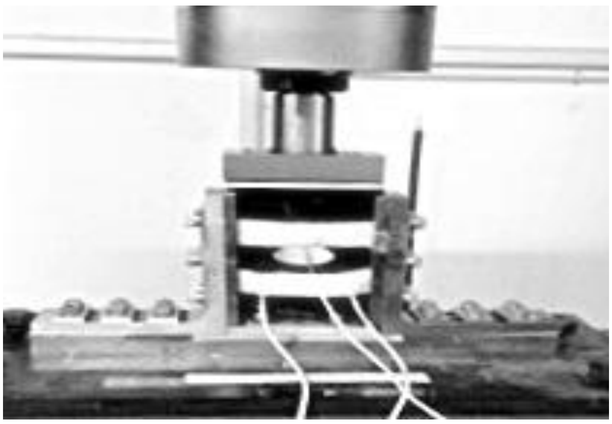

Fig. 2: Experimental setup of compression test

3. Results and discussions

3.1. Compression test results

Compression test specimens have been tested in a Tinus Olsen 100 kN (servo) UTM under controlled condition to obtain the material properties. The test load is indicated on the screen of the data acquisition system. The ultimate compression load of no hole and cut out specimens are shown in Fig. 3. Pristine Specimen resist more load when compared to other specimens where the ultimate load for failure was 35.75 kN. Among the specimens with cut-outs, the circular cut-out specimen sustained more load, 30.85 kN, which is 13.7% less when compared to pristine specimen. The ultimate load for failure for horizontal elliptical specimen is 22.75 kN which is relatively lower than pristine specimen by 36.36%.

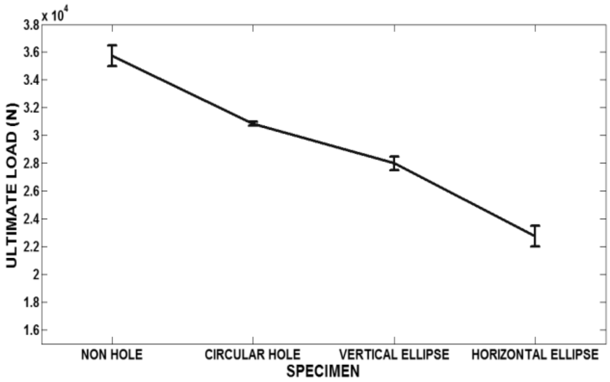

Fig. 3: Ultimate compression load form test of composite specimens

The visual observations (see Figs. 4(a) to (d)) during testing shows that a primary buckling is present in pristine specimen but absent in case of cut out specimens. In specimen with cut-out local buckling takes place in the fibers next to free edge of the hole and in region where internal defects are present. The primary buckling causes initiation of delamination and the delamination get propagated on further loading [20]. This local buckling is found to be more in horizontal and vertical elliptical specimens. This may be the reason for less load carrying capacity of elliptical specimens when compared to other specimens. The horizontal elliptical specimen sustained very less load when compared to other specimen. This may be due to the presence of delamination along with local buckling of the adjacent fiber near the free edge of the hole in addition to matrix cracking when compared to other specimen.

For pristine specimen the event location is distributed evenly throughout the specimen. The failure takes place at the top and bottom edges near the clamping ends as confirmed from the visual inspection of the damaged specimen after testing. The damaged portion near the clamping area is marked and shown in Fig. 4(a). From the acoustic emission failure location plot of circular cut-out specimen it is confirmed that events are distributed evenly around the hole where the stress concentration raises leading to failure of the laminate as shown in Fig 4(b). The effect of stress concentration near the clamping ends is less dominated in case of specimens with cut-out.

For horizontal and vertical elliptic hole specimen, more events are concentrated near the free edge of elliptic hole region as shown in Fig 4(c) and Fig 4(d).The failure location distributions for the specimens with and without cut-outs are entirely different. From this it can be confirmed that geometry of the cut-outs in composite laminates affects the strength to a maximum extend. The visual inspection of specimen with horizontal and vertical elliptical cut-out damaged extremely due to severe matrix cracking at failure load. Finally failure occurs in the minimum cross section.

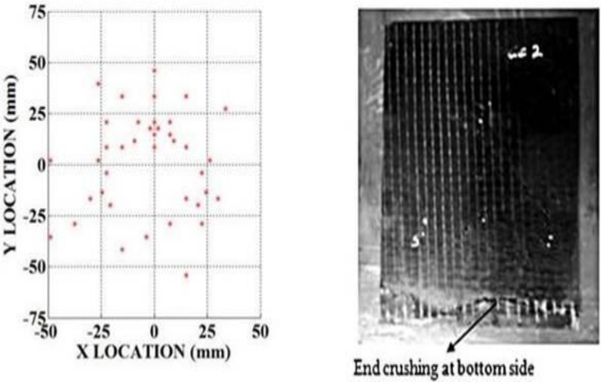

Fig. 4(a): Event location for pristine specimen

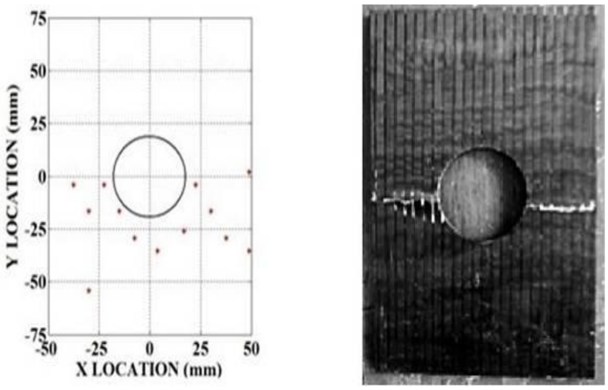

Fig. 4(b): Event location for circular hole specimen

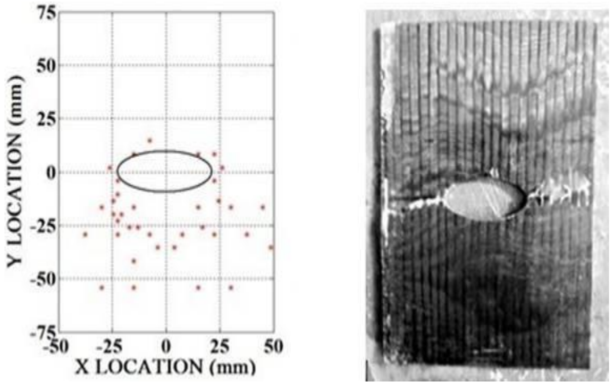

Fig. 4(c): Event location for horizontal elliptical specimen

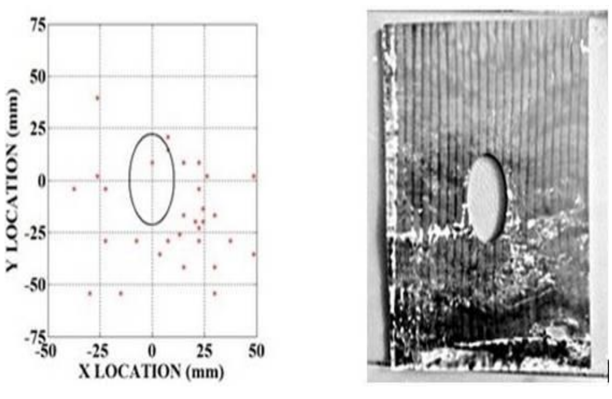

Fig. 4(d): Event location for vertical elliptical specimen

3.2. AE monitoring results

The stress wave signals corresponding to different failure modes obtained during the compression testing of specimens with and without cut outs is recorded in AE data acquisition system to perform frequency and parametric analysis. AE data obtained during compression testing has been used to an effective separation of failure modes in these specimens. During the compression testing three different range of frequency are obtained. In all literatures related to AE the frequency ranges for matrix cracking, delamination and fiber breakage shows an increasing pattern for the respective failure modes.

Peak frequency versus time plots for specimens with and without cut-outs are depicted in Figs. 5(a) to (d). The AE signals are captured by the white band sensors once the laminate under testing starts to emit damage signals under the application of the compressive load. For both specimens with and without cut-outs three ranges of frequency such as 0-140 kHz, 140-200 kHz and 200-375 kHz are observed. The lowest frequency range 0-140 kHz obtained during the initial stage of loading which may correspond to matrix cracking [21]. According to the hierarchy in frequency ranges, the 2nd frequency range 140-200 kHz is related to delamination [21], the 3rd frequency range 200-375 kHz is related to fiber breakage [21].

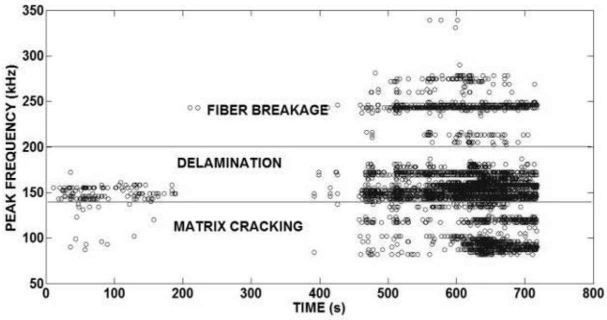

Fig. 5(a): Peak frequency vs. Time for pristine specimen

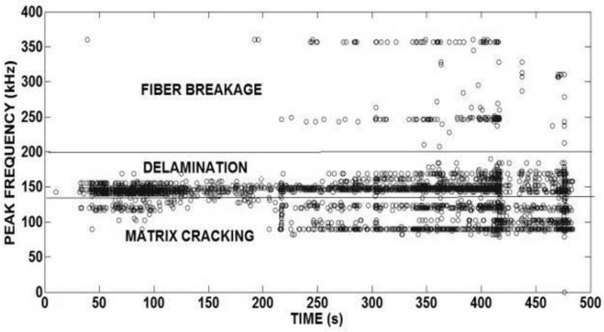

Fig. 5(b): Peak frequency vs. Time for circular hole specimen

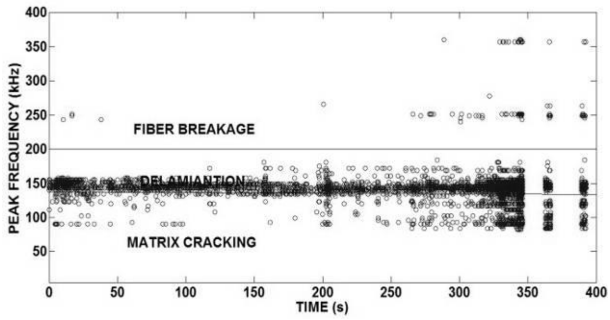

Fig. 5(c): Peak frequency vs. Time for vertical elliptical cut-out specimen

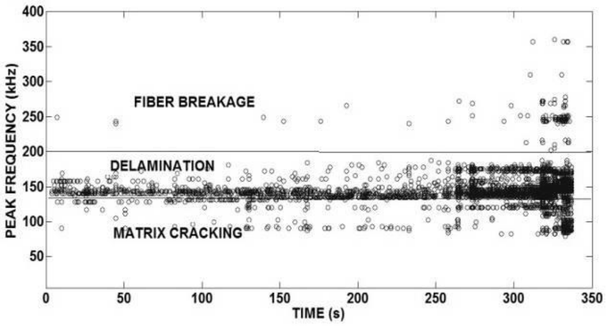

Fig. 5(d): Peak frequency vs. Time for horizontal elliptical cut-out specimen

From Fig. 6, the percentage of failure mode plot obtained from the peak frequency corresponding to different failure modes, the delamination is predominant in the whole of the compression tests performed for each samples. It states that the peak frequencies range 140 kHz to 200 kHz corresponding to delamination is dominating in case of all specimens.

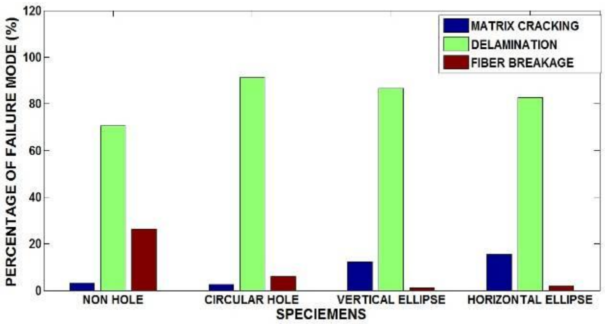

Fig. 6: Percentage of failure mode for composite specimens

From visual inspection, primary buckling is observed during static compression test of specimen without cut out. This is confirmed by a fiber failure and delamination in large amount in the pristine specimen confirming the end of crushing failure. In case of specimen with circular cut-out the failure is mainly due to delamination. In case of specimen with vertical and horizontal ellipse cut-out the matrix cracking dominates after delamination. From the percentage of failure plot it is confirmed that the delamination is a dominating failure mode. This fiber breakage is not dominant in horizontal ellipse specimen due to the unstable short length of the fibers near to the cut-out leading to more delamination. In all cut out specimens the fiber breakage is noticeable in a negligible amount.

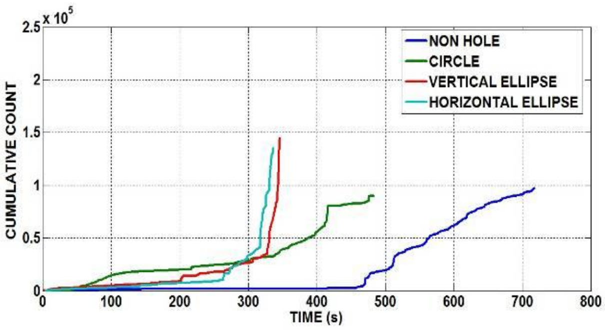

Fig. 7: Cumulative count vs. Time for composite specimens

Fig. 7 provides the information on the initiation of damage and the ultimate failure of the material. Where the slope of the curve is almost zero being damage initiation, very less AE activity is present. As time progresses, the counts increase and damage accumulates. Hence, this region with higher slope is called damage propagation. The final region where the slope is highly steep is called failure region. Using the above concept, the initiation and failure times for different specimens with and without cut-outs are given in Fig. 8 (a) & (b). The pristine specimen is hardly resisting the compression load. The vertical and horizontal ellipse cut-out specimens are easily susceptible to the damage initiation at the very beginning of the test. In case of specimen with circular cut-out the damage initiation is intermediate between specimen with elliptical cut-out and specimen without cut-out. This AE results confirm the results obtained from static compression test and the parametric analysis.

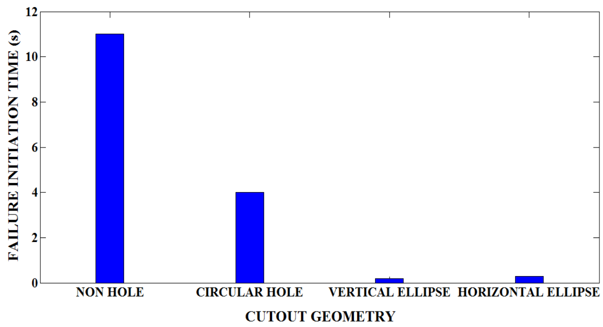

Fig. 8 (a): Time for damage initiation for composite specimens

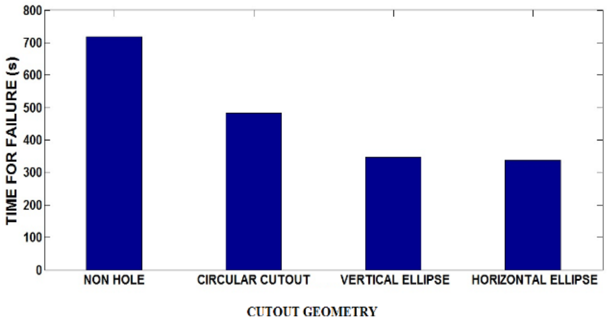

Fig. 8 (b): Time for failure plot for composite specimens

In order to study different failure modes that arise at various locations during the testing, peak frequency vs. location (x, y) were plotted for four categories of specimens at three time intervals of testing such as damage initiation, damage propagation and failure. The event location corresponding to each time interval was sorted according to the slope of the cumulative curve and plotted. For the non hole specimen from fig. 9 (a), it could be observed that peak frequency corresponding matrix failure and little delamination are scattered during damage initiation and propagation. But during the failure time, frequency hits corresponding to delamination and fiber failure modes value are present throughout the specimen, especially near the ends. For specimens with circular cut-outs, the hits corresponding to matrix failure are concentrated near the circular hole, indicating the onset of damage due to stress concentration. So, the dominance of matrix failure which is initially present is replaced by hits corresponding to delamination during damage propagation. At the time of failure, majority of hits corresponding to fiber failure and delamination are observed from Fig. 9(b). Similar trend is observed in Fig. 9 (c) and (d), the initial hits are corresponding to matrix failure. They are found lying near the cut out region. As time progress, hits corresponding to delamination could be observed.

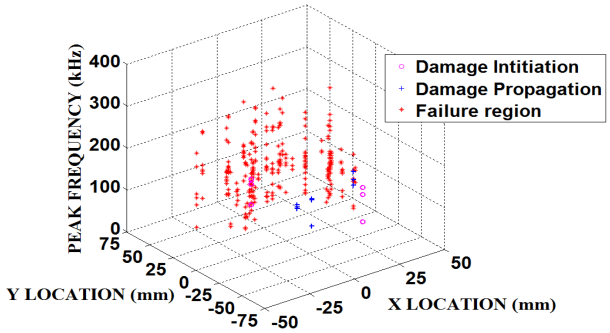

Fig. 9 (a): Peak frequency (kHz) vs. Location (X, Y) mm for pristine specimen

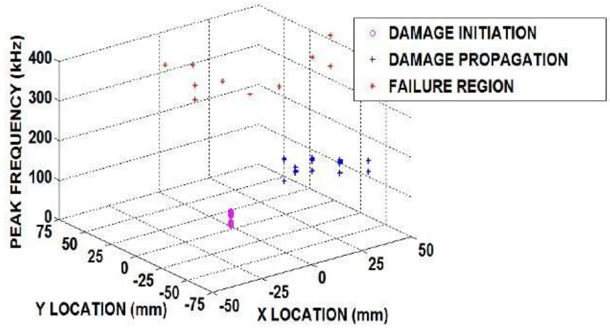

Fig. 9 (b): Peak frequency (kHz) vs. Location (X, Y) mm for circular cut-out specimen

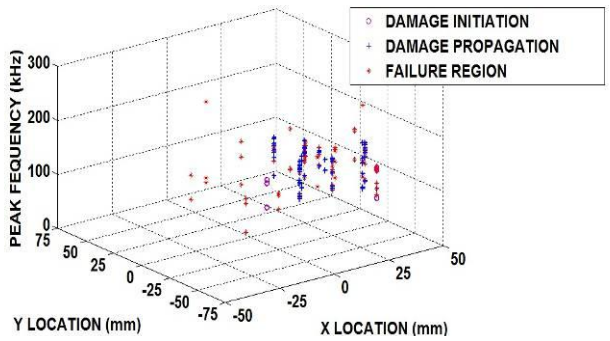

Fig. 9 (c): Peak frequency (kHz) vs. Location (X, Y) mm for vertical elliptical cut-out specimen

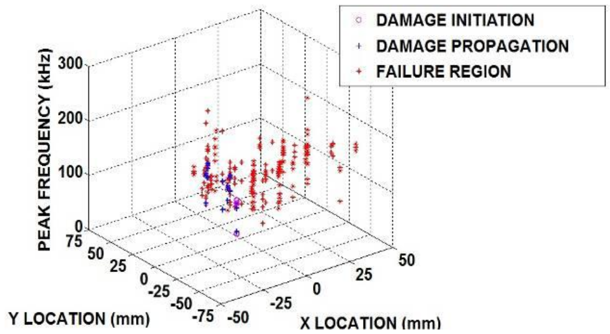

Fig. 9 (d): Peak frequency (kHz) vs. Location (X, Y) mm for horizontal elliptical cut-out specimen

4. Conclusions

The effects of CFRP specimen with and without cut-outs subjected to static compression load were studied. The compression tests were performed on pristine specimen and specimens with circular, horizontal elliptical and vertical elliptical cut-outs at cross head speed of 0.5 mm/min. The ultimate load, maximum stress and maximum displacement for failure is recorded in data acquisition system and compared. The stress concentration region of the specimen with and without cut-outs was determined from failure location plot. The specimen with horizontally elliptical cut-out resists very less load due to the delamination of adjacent fibers near the free edge of the hole and it is 1.59 times less than maximum load bearing capacity of pristine specimen.

The AE technique is used to characterize different failure modes and to pick out the dominating failure mode leading to the material failure during compression test. Three distinct ranges of frequencies are noted from frequency analysis. The time required for initiation damage and ultimate failure of the specimen were determined from cumulative count plot. The peak frequency of hits during damage initiation were associated to matrix failure where as during damage propagation and failure, peak frequency corresponding to delamination and fibre failure were predominant.

REFERENCES:

[1] A.M. Waas, W.G. Knauss and C.D. Babcock. 1991. Damage progression in compressively loaded laminates containing a circular cut-out, *AIAA J.*, 29(3), 436-443. http://dx.doi.org/10.2514/3.10597.

[2] C. Pein and R. Zahari. 2007. Experimental investigation of the damage behaviour of woven fabric glass/epoxy laminated plates with circular cut-outs subjected to compressive force, *Int. J. Engg. & Tech.*, 4(2), 260-265.

[3] H. Al Qablan, H. Katkhuda and H. Dwairi. 2009. Assessment of buckling behaviour of square composite plates with circular cut-out subjected to in-plane shear, *Jordan J. Civ. Engg.*, 3(2), 184-195.

[4] Y. Liu, F. Jin and Q. Li. 2006. A strength-based multiple cut-out optimization in composite plates using fixed grid finite element method, *Compos. Struct*, 73(4), 403-412. http://dx.doi.org/10.1016/j.compstruct.2005.02.014.

[5] S. Ghannadpour, A. Najafi and B. Mohammadi. 2006. On the buckling behaviour of cross-ply laminated composite plates due to circular/elliptical cut-outs, *Compos. Struct.*, 75(1), 3-6. http://dx.doi.org/10.1016/j.compstruct.2006.04.071.

[6] D.R. Ambur, N. Jaunky, M. Hilburger and C.G. Dávila. 2004. Progressive failure analyses of compression-loaded composite curved panels with and without cut-outs, *Compos.Struct*. 65(2), 143-155. http://dx.doi.org/10.1016/S0263-8223(03)00184-3.

[7] A. Khamseh and A. Waas. 1997. Failure mechanisms of composite plates with a circular hole under remote biaxial planar compressive loads, *Indian J. Eng. Mater. Sci.*, 119(1), 56-64.

[8] A. Abu Talib, A. Ramadhan, A. Mohd Rafie and R. Zahari. 2013. Influence of cut-out hole on multi-layer Kevlar/epoxy composite laminated plates, *Mater. Des.*, 43(1), 89-98. http://dx.doi.org/10.1016/j.matdes.2012.06.001.

[9] H.M. Arslan, M.Y. Kaltakci and H.R. Yerli. 2009. Effect of circular holes on cross-ply laminated composite plates, *Arab J. Sci. Engg*., 34(2B), 302-312.

[10] M.Y.H. Arslan. 2006. Stress concentrations of symmetrically laminated composite plates containing circular holes, *Iran. J. Sci. Tech.,* 30(B4), 447-460.

[11] C. Lopes, Z. Gürdal and P. Camanho. 2010. Tailoring for strength of composite steered-fibre panels with cut-outs, *Composites Part A*, 41(12), 1760-1767. http://dx.doi.org/10.1016/j.compositesa.2010.08.011.

[12] S. Eslami, R.A. Esmaeel and F. Taheri. 2013. Experimental investigation of the effect of aging on perforated composite tubes under axial compressive loading, *Adv. Compos. Mater*, 22(3), 151-164. http://dx.doi.org/10.1080/09243046.2013.782806.

[13] E. Sadeghpour, M. Sadighi and S. Dariushi. 2013. An investigation on blunt notch behaviour of fiber metal laminates containing notch with different shapes, *J. Reinf. Plast. Compos*., 32(15), 1143-1152. http://dx.doi.org/10.1177/0731684413484817.

[14] H. Suemasu, H. Takahashi and T. Ishikawa. 2006. On failure mechanisms of composite laminates with an open hole subjected to compressive load, *Compos. Sci. Tech*., 66(5), 634-641. http://dx.doi.org/10.1016/j.compscitech.2005.07.042.

[15] J. Fazilati and H.R. Ovesy. 2013. Parametric instability of laminated longitudinally stiffened curved panels with cut-out using higher order FSM, *Comp. Struct*., 95(1), 691-696. http://dx.doi.org/10.1016/j.compstruct.2012.08.034.

[16] D. Aggelis, N.M. Barkoula, T. Matikas and A. Paipetis. 2013. Acoustic emission as a tool for damage identification and characterization in glass reinforced cross ply laminates, *Appl. Compos. Mater*, 20(4), 489-503. http://dx.doi.org/10.1007/s10443-012-9283-6.

[17] V. Arumugam, C.S. Kumar, C. Santulli, F. Sarasini and A. J. Stanley. 2011. A global method for the identification of failure modes in fiberglass using acoustic emission, *J. Test. Eval*., 39(5), 1-13.

[18] J. Berthelot and J. Rhazi. 1990. Acoustic emission in carbon fibre composites, *Compos. Sci. Tech.*, 37(4), 411-428. http://dx.doi.org/10.1016/0266-3538(90)90012-T.

[19] V. Arumugam, A.A.P. Sidharth and C. Santulli. 2014. Failure modes characterization of impacted carbon fibre reinforced plastics laminates under compression loading using acoustic emission, *J. Compos. Mater*., 48(28), 3457-3458. http://dx.doi.org/10.1177/0021998313509504.

[20] C. Soutis, N. Fleck and P. Curtis. 1991. Hole-hole interaction in carbon fibre/epoxy laminates under uniaxial compression, *Composites*, 22(1), 31-38. http://dx.doi.org/10.1016/0010-4361(91)90100-U.

[21] R. Asokan, V. Arumugam, C. Santulli and A.J. Stanley. 2012. Acoustic emission monitoring of repaired composite laminates, *J. Reinf. Plast. Compos*, 31(18), 1226-1235. http://dx.doi.org/10.1177/0731684412455957.