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Damage characterization of stiffened glass-epoxy laminates under tensile loading with acoustic emission monitoring

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ABSTRACT

The design of composite components in the aerospace industry often includes structural discontinuities, such as cutouts, for functional requirements like ventilation, tunnel passage, maintenance and repair. The presence of cutout holes leads to complicated stress concentrations with a substantial reduction in structural stability and strength of the resulting composites. It is known that reinforcing with additional material at the cutout zones can extend the damage tolerance of a structure, therefore maintaining structural integrity and load carrying capacity. This study focuses on the experimental investigation of the tensile behavior and failure characteristics of stiffened glass/epoxy composite laminates, with cutouts, under acoustic emission monitoring. The progressive failure mechanisms of laminates with cutouts and the potential benefits of additionally dropped reinforcements are evaluated under tensile loading. The additional reinforcements were provided in either a step-like or as a simultaneous drop-off sequence between adjacent continuous plies. Results showed that adding ply drop reinforcements at the location of the cutout hole improves the stiffness, strength, and also prolongs the life of the composite laminates. It is also observed that step-like ply drop arrangements performed more effectively than simultaneously dropped configurations. The location and extent of damage identified by microscopic images correlated well with the acoustic emission results.

1. Introduction

The evolution of fiber reinforced plastic (FRP) composites has developed new vistas in aerospace industries. Primary structural components, such as wings, fins, helicopter rotor blades, stiffened structures with joints and access holes, etc., are fabricated by the termination of internal ply-drop off to enhance weight reduction, cost effectiveness, and obtain tailored stiffness values. The mechanical behavior of the composite structure is drastically affected due to the presence of cutouts, such as access holes for hydraulic piping, electrical wiring and fastener holes, which become critical during loading conditions [1]. It is crucial to have a sound and complete idea of the intricate behavior around notched areas, connecting the bolts and rivets [2]. High stresses are produced around holes because of material discontinuities causing a relatively larger reduction in strength than unnotched laminate [3–6]. Takeda et al. studied the tensile behavior of glass/epoxy plain weave fabric-reinforced laminates under cryogenic temperatures investigating the progressive failure methodology [7]. Kaltakci [8] studied the effects of fiber orientation and stress concentration on single-layered anisotropic plates with/without holes, revealing significant influence on the fracture behavior based on 3D weaving of different bundle size of the yarns. Aljibori et al. [9] investigated the compressive behavior of woven glass fiber/epoxy composite laminate plates with and without a cutout. The effect of cutout size and fiber orientation angle has also been considered, in models predicting strength and damage accumulation in open hole composite laminates with different failure criteria [10–12]. Observations unveiled the fact that cross-ply orientation possesses higher strength than other fiber orientations. Also, as the cutout size increases, load bearing capacity decreases due to the effect of material discontinuities.

Murat Arslan et al. investigated the stress analysis of isotropic and orthotropic plates with and without cutout hole using finite element methods [13]. Camanho et al. proposed a fracture mechanics model based on unnotched specimen strength and fracture toughness, for predicting open hole tensile (OHT) strength of composite laminates [14]. Lee and Kim studied compressive response and damage evolution in laminated plates with cutouts based on a micromechanical constitutive model [15]. The damage was found to be controlled by the interfacial fiber debonding and nucleation of microcracks in the matrix. The employed model predicted accurately results for cross-ply, while it

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overestimated stiffness and failure load for angle-ply and quasi isotropic plates. Several studies employed computational FEM models for predicting tensile strength and progressive damage in notched composite laminates [16–20]. Chen et al. [16] employed smeared crack model using cohesive element to investigate the scaling effects on open hole tension testing on composite laminates which correlated well with the experimental results by Wisnom et al. and Hallett et al. [17,18]. Ridha et al. studied the prediction of ultimate open hole (OHT) strength and failure progression of notched laminates with various size and stacking sequence based on progressive damage model with initial in-plane damage and delamination [19]. Maa and Cheng were able to predict failure strength and load–deflection relations of notched laminated composites, again discussing the effects of hole size and specimen width [20].

Ersin et al. studied the effect of circular hole location on lateral buckling of woven composite laminates [21]. Predominant failure mode, i.e., delamination, grows significantly because of interlaminar stress at the free edges [22]. To prevent such stress concentrations around the cutout holes and to avoid strength reduction, suitable reinforcements must be installed around the cutout regions to improve sufficient load bearing capacity of laminates [23]. Being a damage prone region, it is advisable to monitor the progression of failure and onset location of delamination to forecast the damage.

Acoustic emission, as a structural monitoring technique, proved able to detect microscopic failure events under loading conditions. A number of studies have been carried out for the identification of the failure modes in damaged composite materials e.g., post-impact loading, using parametric-based approach and signal-based approach [24–26]. In particular, several studies utilized AE parametric approach to characterize the damage mechanism based on AE parameters, such as amplitude, counts, duration, energy and rise time, to determine the nature of failure and the location of emission source [27–29]. Berthelot et al. employed AE parametric approach to discriminate failure modes in different stacking sequences (0°, 0°/90°, 0°/45°, 90°/45°) [30]. Different failure modes encountered in composites are matrix cracking, fiber-matrix debonding, delamination and fiber breakage [31–33]. These failure events cause transient, elastic stress waves, which can be detected by piezoelectric sensors attached to the composite structure using suitable couplant. The damage mechanisms of self-reinforced polyethylene (SRPE) during tensile loading have been investigated by Zhuang et al. [34], in which case acoustic emission signals and amplitude histogram plots were associated with SEM images depicting the nature of damage. Ramirez-Jimenez et al. [35] and Arumugam et al. [36] investigated the classification of failure modes based on the primary frequency content of AE signals. They also discussed the discrimination of failure modes based on signals' amplitude, concluding that the AE signals associated with low amplitudes and low duration are related to matrix cracking, those with moderate amplitude and duration are related to fiber-matrix interface debonding and those with medium to high amplitude are associated with fiber breakage. Similarly, Kotsikos et al. investigated the different failure mechanisms in glass/epoxy laminates under fatigue loading. They reported that the low amplitude signal range (from 40 to 55 dB) is related to matrix cracking, the medium range (from 55 to 70 dB) is associated with interfacial debonding and high amplitude signals (> 70 dB) belong to fiber breakage [37].

This study focuses on the uni-axial tensile behavior and failure characteristics of GFRP laminates with cut-outs. Its aim is particularly linked to the fact that the effectiveness of cutouts, not leading to extensive damage, which can also be applied when repair is needed since the procedure is basically the same, has been only limitedly investigated with acoustic emission. What is suggested is that the remediation after the creation of cut-outs may change the mode of damage in the composites. More specifically, acoustic emission can offer indications in cases where two different repair modes are possible on the respective suitability for mechanical remediation of the composites, of course till the extent this is possible. Since repair enhances and extends the life of composites, this is a crucial topic very limitedly studied so far with acoustic emission, as suggested from literature.

The influence of additional reinforcements at the location of cut-out has also been discussed. It is observed that reinforcing with additional material at cut-out zones can extend the damage tolerance of structure, maintaining on the other side structural integrity and load carrying capacity. The mechanism of damage progression and various failure modes during loading have been investigated using acoustic emission monitoring.

2. Materials and methods

2.1. Fabrication of conventional E-glass/epoxy laminates

The laminate consists of 12 layers of unidirectional E-glass fiber mat with an areal weight of 220 g/m^2 and epoxy resin (Araldite LY556) at a ratio of 1:1 by weight. The resin was mixed with the hardener (HY951) at a ratio of 10:1 by weight, to accelerate the curing process. The resin was allowed to impregnate the reinforcement with the aid of rollers. The fabricated laminate has a stacking sequence $[0°]_{12}$ yielding a nominal thickness of 3.5 (± 0.15) mm. The laminate was fabricated by hand lay-up technique. ASTM D3039 tensile test specimens of dimension 280 mm long, 30 mm wide were cut from the laminates using abrasive water jet cutting.

2.2. Fabrication of laminates with submerged plies as cutout reinforcement

These laminates were fabricated with the experimental procedure similar to that of conventional laminates, exposed in Section 2.1. Additional ply reinforcements were dropped off at the center during the hand layup process, which were supposed to enhance the strength and integrity of the cutout hole. The plies were dropped off in different stacking arrangements, namely step-like and simultaneous between adjacent covering continuous plies, as shown in Fig. 1. Both the step-like and the simultaneous configuration have the same ply arrangement as $\mathbf{[0°_2/\underline{0°}/0°/\underline{0°}/0°/\underline{0°}/0°_2]_S}$ within which the underlined plies indicate the dropped submerged reinforcements. In the step-like arrangement, the plies were dropped with a stagger distance of 5 (± 0.5) mm. In contrast, in the simultaneous arrangement, the plies were dropped instantaneously at the same station between the adjacent covering plies, as suggested in Ref. [38]. As a whole, six additional reinforcement plies were introduced between adjacent plies. A total of 18 plies were used therefore for fabricating cutout reinforced laminates. Only [0°] plies were used for all the dropped and covering ply configurations. The fabricated laminate has a nominal thickness of 3.5 (± 0.15) mm and 4.5 (± 0.25) mm in thin and thick section, respectively. Initially, the plies were marked for placement of additional reinforcement to avoid misalignment. Also in this case, ASTM D3039 tensile test specimens of dimension 280 mm long, 30 mm wide were cut from the laminates using abrasive water jet cutting.

In particular, some guidelines from Varughese et al. [38] were followed, such as:

- Dropping only one single ply at each station
- Plies must be dropped with stagger distance
- Each dropped ply must be covered with adjacent continuous/belt plies to minimize the delamination at the junction of terminated ply drop. This has been followed to reduce stress concentration to a great extent by distributing dropped plies over a region at specific locations. Severe geometric profile change can also be avoided by dropping plies gradually.