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Innovative tailored fiber placement technique for enhanced damage resistance in notched composite laminate

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ABSTRACT

Composites have recently gained considerable acceptance in the transportation sector such as the aerospace and automotive industries, as these materials offer the ability to reduce weight, greenhouse gas emissions and associated fuel cost. Conversely, problems related to material behavior, cost, manufacturing process, assembly and choice of joining technique pose challenges that limit the wide acceptance and implementation of the composite materials. Specifically, a major problem related to joining is the use of mechanical/fastener joints with drilled holes that can damage the continuous fibers and cause considerable reduction in the load carrying capacity of resulting composite structures.

To address this issue, an innovative solution that manufactures fabric laminates using 'tailored placement' of fibers around the holes/notch was proposed. This eliminates the need for drilling and machining of holes thereby eliminating the sources of delamination. The tensile performance of notched composites from the novel tailored fiber placement (TFP) approach was compared to conventional notched composites. Additionally, the effect of various fiber placement patterns and machining processes on the strength, damage initiation and fracture mode of notched composite laminates were studied. Specifically, the stress and strain fields around the notch were thoroughly evaluated. The experimental results for notched specimens were compared with the damage initiation and strength predictions obtained from the Hashin failure criteria as available in commercially available FEA package (ABAQUS®). A good agreement between experimental results and numerical predictions was observed. Overall, the proposed approach shows great promise in the use of tailored fiber placement technique to eliminate delaminations, maintain continuous fiber alignments and reduce associated stress concentrations in a wide range of composite applications including but not limited to mechanical fastening.

1. Introduction

Recent advancements in novel materials, design for manufacturing (DFM), and computer-aided design (CAD) have enabled composite structural designs that offer more than 50% weight savings versus lightweight metals, as well as a threefold increase in specific strength and stiffness. However, joining of composites to other existing lightweight materials, such as magnesium, steel, aluminum, plastics, or glass fiber composites, to produce multi-material components has not fully advanced far enough to be used extensively in high volumes.

Both simple and complex composite structures utilize different joining techniques, such as mechanical fastening, adhesive joining, and combination of both mechanical and adhesive joining (hybrid joint). In applications with high level of safety requirements, e.g. in aerospace and ground vehicles, hybrid joint is the most commonly used joining technique, to achieve the desired performance requirements of high load carrying capacity and evenly distributed stress within the structure. Generally, mechanical fastening is not a preferred joining method, as drilling holes reduces the strength of composite structure through fiber breakage and delamination. However, it is inevitable, since some structural integrity cannot be obtained by other connection/joining technique. Therefore, in order to have firm structural integrity within the structural parts, appropriate safety factor is used to compensate the loss of strength caused by cutout and notches or holes [1].

Presently, a number of advanced hole making processes such as machining of composites using high performance tools, water jet cutting, laser cutting, electric discharge machining (EDM) and

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ultrasonic cutting are commonly available in the market. Nevertheless, conventional twist drill is widely used in industry to rapidly produce holes with relatively low cost. Different types of drills such as saw drill, candlestick drill, core drill, etc. have been used for drilling of composite structures [2]. As exhaustively reported in a vast number of publications, the quality of composite materials' cutting is strongly dependent on cutting parameters, such as feed rate, cutting speed and depth of cut [3,4]. It was found that higher feed rate, particularly at the end of the drilling process, will cause cracks around the exit edge of the hole [5]. It was also observed that the more the feeding rate, the more the crack severity [5]. In other cases, drilling at lower feeds and high speed leads to increased temperature generation due to low coefficient of thermal conduction and a lower transition temperature of resins. The accumulated heat around the tool edge tends to destroy the matrix stability and produces fuzzy and rough cuts.

Composite drilling usually results in both macro level damage, like delamination, and micro level damage, such as crack and fiber–matrix debonding. Delamination occurs both at the entrance and the exit planes of the work-piece. The types of delamination at the drill entrance and exit are peel-up delamination and push-down delamination, respectively. Experimental studies show that the degree of peel-up delamination depends on the feed rate and on the helix angle of the twist drift. Push-down delamination is mainly affected by the feed rate and the presence of support beneath the specimen [6,7]. A detailed analysis of delamination caused by various drill types and prediction of the critical thrust force at the onset of delamination is presented in [2,8].

Typically, the drilling of composites and resulting components is considered to be moderate solution from point of view of lightweight structural design that incurs additional cost and structural weight for reinforcement. On the other hand, the need to find a better solution to cope up with the existing bottlenecks of composite manufacturing and assembling is well recognized. Hence, several companies and researchers have proposed integrating approach that allows structural optimization through parts consolidation and "efficient" manufacturing and joining methods [9–11].

However, the question is how to affordably, reliably and quickly fabricate the resulting complex shapes that depend for their performance in the finished part on minimal quantities of precisely oriented fibers. Tailored fiber placement (TFP) is a unique stitched preforming process that has the potential to answer and eliminate most of the limitations of drilling/machining holes in composites.

TFP technology was originally developed by Institute of Polymer Research of Dresden [12–16]. The process is based on the well-known embroidery technique with enhanced tools and machining to layup structural fibers. By using CAD models the desired fiber direction is converted into a stitching pattern which is then fed to the embroidery fiber printing machine. The machine takes the reinforcement fibers, e.g. rovings, and stitches/places them on a base/carrier material. TFP technique provides an efficient method to arrange fibers in composite components in three ways: stretched (without waves and twists), aligned to the stress field and constantly stressed (local thickness of the component corresponds to the local load). The technique allows a near-net-shape production, which results in low waste and optimal fiber exploitation.

Gliesche et al. [17] studied the application of the tailored placement technique that combined the conventional textile reinforcements with TFP to relieve a stress concentration in a notched composite. In their work, an open hole tension plate was selected as a test component. The base material was a laminate made from a quasi multiaxial non woven carbon fiber fabric. The TFP-local reinforcements and the base material consist of carbon long fiber and epoxy resin. Results showed that the specific fracture load values for the reinforced plate reached 94% of that of the unnotched plate while the notched plate only reached 61%. As expected the fracture was outside of the reinforcement, hence the notch effect due to the hole was completely eliminated. On the open-hole plate without reinforcement the fracture was initiated from strain superelevations around the hole.

Mattheij et al. [18] investigated the effect of through-the-thickness reinforcing of TFP preforms on in-plane and out-of-plane mechanical properties. In their work, TFP preforms made of carbon fiber were 3D reinforced with aramid, polybenzoxazol (PBO), polyethylene and polyester fibers and vacuum injected with epoxy resin. Results showed that PBO fiber provided the most improvement in fracture toughness. 3D reinforcing with aramid fiber reduced tensile and flexural properties by 3–8%. Low velocity impact damage in TFP was larger than in fabric but smaller than in tape laminates. Compression-after-impact strength was partly increased by 3D reinforcing in some circumstances but no improvement was found under other conditions.

There are many approaches to predict the strength and stress field of a notched composite. These include the application of linear fracture mechanics, mechanics of materials analysis and detailed finite element analysis, which attempt to include micromechanical details and simulate individual damage modes [19–23]. The point-stress and average-stress criteria models described in [24,25] require the evaluation of "characteristics distance". In the case of point-stress criterion (PSC) the characteristic distance represents a physical length from the tip of a notch over which the local stress must exceed the un-notched strength; whereas in the case of the average stress criterion (ASC), the characteristic distance represents a physical length from the tip of the notch over which the averaged value of the stress equals the un-notched strength. Even though these models have the advantage of being easy to apply and providing good agreement with experimental data, their limitations are that they do not consider the physical damage mechanisms that occur prior to fracture, which in particular will modify, significantly, the assumed elastic stress distribution in the vicinity of the notch. In order to improve the agreement with experimental data, models incorporating additional fitting parameters [26,27] were proposed as an extension to approach described in [24,25].

The damage sequence and pattern observed in interrupted experimental tests by means of FE model was also predicted using interface element to model splitting and delamination propagation and a Weibull based statistical analysis for fiber failure [28]. In another related work, a comprehensive notch-edge damage analysis with help of recording test video, digital microscope, polariscope, and layer by layer SEM (Scanning Electron Microscope) analysis was performed in [1]. Tensile test results showed that the tensile strength, crack initiation and propagation around hole were influenced by the quality of notch. Experimental observations demonstrated that the effectiveness of finding of damaged zone was dependent on the damage observation techniques. Numerical predictions of the damaged zone and stress distribution illustrated good agreement with experimental observations [1].

In this paper, an innovative solution that manufactures fabric laminates by TFP technique around the notch/hole is presented. This method eliminates the sources of delamination such as drilling or machining of holes. Additionally, the effect of various fiber placement patterns and machining processes on the strength, damage initiation and fracture mode of notched composite laminate were studied. The tensile performance of notched composites from the novel TFP approach was compared with conventional notched composites. The experimental results for notched specimens were compared with the numerical predictions obtained from Hashin failure criteria in commercially available FEA package (ABAQUS®).