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Influence of laminate lay-up, hole size and coupling agent on the open hole tensile properties of flax yarn reinforced polypropylene laminates

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ABSTRACT

The effect of laminate lay-up, open hole size and coupling agent on the open hole tensile properties of flax yarn reinforced polypropylene (PP) laminates were studied in this work. Unidirectional flax/PP laminates were prepared using a stacking technique, where newly developed interwoven fabric (flax/PP) and maleic anhydride grafted polypropylene (MAPP) copolymer film were used as a raw material and coupling agent respectively. The cross ply laminates $(0/90/0)_S$ showed high strength retention (98%) which ensured less notch sensitivity to the open hole profile. MAPP treated open hole samples achieved a reasonable improvement in tensile strength for all kind of laminate lay-up. Undrilled laminates tensile strength was improved by 14–17% due to MAPP treatment. Highest strength retention in MAPP treated sample was observed for cross ply laminates with 4 mm hole size, which was noted as 92%. Fractography studies confirmed the tensile fracture of fiber across the hole and good interfacial adhesion between fiber and matrix for MAPP treated laminates.

1. Introduction

Natural fiber reinforcement is a new advent for replacing the conventional glass fiber based reinforcement product in the composites. It has gained in importance during the past few decades due to low cost, environmental friendliness, good mechanical properties and less skin irritability [1–3]. Natural fiber composites are used in the field of automotive applications, packaging industry and general appliance products [4,5].

It is inevitable to enable joints and bolts to be used during end applications, so drilling the holes in composite becomes unavoidable. Hence the holes in composites induce the discontinuity and strength reduction in the composite structure, which happens due to the stress concentration development around the notched area [6,7]. It is important to understand the sensitivity of laminates against the notches and geometrical discontinuities. Notch sensitivity has been influenced by many factors such as laminate (thickness, ply number, and lay-up), notch (dimension/diameter and shape), and material (thermal expansion, constituents, and interfacial strength) [8,9].

Flax fiber is one of the suitable natural fiber for the structural application because of its higher strength and stiffness compared to other natural fibers [10,11]. It is important to consider the interface bonding of fiber reinforced composites, which may have reasonable influence on the open hole strength of the composites. Some works related to the carbon fiber reinforced epoxy composites explained the effect of interface bonding on open hole tensile strength after fiber surface treatment [12,13]. The interface bonding between flax fiber and matrix can be enhanced by several surface treatment and coupling agents [14]. The surface treatment provides such benefits as cleaning the flax fiber surface, preventing the moisture absorption and increasing the surface roughness which tends to improve the interface bonding between fiber and matrix and mechanical properties of composites [15]. Most of the researchers have used MAPP as the coupling agent for natural fiber/PP composites [16–18].

Many scientists conducted their research on the open hole strength analysis of synthetic fiber reinforced laminates. But, no attempt has been made to investigate the damage behavior of natural fiber reinforced laminated composite with drilled hole. This study explains the effect of laminate lay-up, hole size and coupling agent on the open hole strength of the flax/PP laminates. This work has also made an attempt to reveal the damage behavior of natural fiber reinforced laminates by an experimental study.

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2. Experimental

2.1. Materials

Flax yarn with the fineness of 105.4 tex and polypropylene draw textured yarn (PP DTY) with the fineness of 72.2 tex were used in this work which were supplied by the Tai Yuang Textile Company and Tri Ocean Textile Company, Taiwan, respectively. Flax and PP yarn were used as weft and warp respectively for producing newly developed interwoven fabric in the Dornier rapier weaving machine. Newly developed interwoven fabric was constructed to obtain 40/60% (flax/PP) volume fraction in the final untreated laminates. The detailed specification of the interwoven fabric is given in Table 1.

The maleic anhydride grafted-polypropylene (MAPP) (Polybond 3002) copolymer was provided by the Chemtura Corporation, USA. MAPP was used to fabricate a thin film, which enables it to keep between the lamina in the laminate. The melt flow index (MFI) (at 230 °C and 2.16 kg load) of MAPP was 9.8 g/10 min, which was carried out as per ASTM D1238 standard.

2.2. Methods

The natural fiber reinforced composite fabrication comprised of two stages namely, lamina and laminate preparation.

2.2.1. Lamina preparation

Interwoven fabric was heat set in the oven at 160 °C for 30 min under fixed tension condition. This was purposefully done to retain dimensional stability by avoiding fabric shrinkage and to facilitate the placing of the fabric at the original position during lamina preparation. Preheating temperature and time has been optimized in our previous research work [19,20], which is adopted in this research. The pre heated fabric was hot pressed with the MAPP film on one side of the sample, where the previously prepared MAPP film 5% OWM (on the weight of materials) was spread over the fabric and the process was performed in a certain manner to keep the MAPP film between the lamina in the final composites. Single lamina was finally obtained by hot pressing at 170 °C for 1 min [21]. The detailed process of preparation of MAPP treated lamina and laminate is shown in Fig. 1. Untreated lamina was produced by following the similar condition to above without incorporation of MAPP film on the fabric.

2.2.2. Laminate preparation

Laminate was prepared by stacking technique, where the previously prepared MAPP treated or untreated laminas were stacked together and pressed by the hot pressing machine. This process was done at 190 °C for 3 min under the pressure of 10 MPa. The processing temperature of laminate was optimized from PP rheological test, where the huge viscosity drop found between 190 and 200 °C. Moreover, natural fibers start to degrade above 200 °C [2,10]. By considering all above factors including PP matrix flow rate and impregnation, the processing temperature was selected as 190 °C for laminate fabrication. After hot pressing of stacked laminate, the mold was cooled by the continuous water supply to reduce temperature to 50 °C. Untreated and MAPP treated laminate was produced with 40% and 37% fiber volume fraction respectively. The different stacking sequence was used to prepare the laminates including axial (0_6), cross ply $(0/90/0)_S$ and off-axial ($\pm 45_6$), which were found as a better stacking sequence than other combinations in our previous research work [20].

Table 1
Specification of flax/PP interwoven fabric.

	Weft direction	Warp direction
Material	Flax ring spun yarn	Polypropylene draw textured yarn (PP DTY)
Fabric density	13 Picks/cm	22 Ends/cm
Yarn count (tex)	105.4	72.2
Fabric breaking force (N)	532	970
Fabric elongation (%)	2	12

2.3. Tensile test of laminates

The tensile test sample was prepared as per ASTM D3039 standard. Samples were prepared with dimension of $250 \times 25 \times 2\ mm^3$. Undrilled laminate was used to obtain the tensile strength of the sample without a hole. It was used as reference sample for comparing the open hole tensile strength of different hole size samples. The drill machine was used to make an open hole at the middle of previously prepared tensile test samples with aluminum end tabs. A circular shape open hole was located at the middle surface of each sample. Circular holes with three different diameters, namely 4, 6 and 8 mm were prepared for the open hole tensile test. The tensile test was conducted for undrilled and open hole laminates by the universal testing machine (Trapezium X (AG-100 KNX)). Sample testing speed and gauge length was 5 mm/min and 180 mm respectively. An average of five readings was taken for each sample.

2.4. High quality digital camera and scanning electron microscope

High quality digital camera (Canon EOS 550D) was used to capture the tensile damage of flax/PP laminates. Platinum sputtered tensile test damaged samples were further examined by the scanning electron microscope (SEM-Hitachi S-3000 N) under a liquid nitrogen atmosphere. Platinum sputtering helps to enhance the conductivity of fibers and improves the quality of the image.

3. Results and discussion

3.1. Effect of laminate lay-up on the open hole tensile properties

Table 2 shows the comparison of strength retention of untreated flax/PP, carbon/epoxy and glass/epoxy laminates for different laminate lay-up. Axial flax/PP laminates experienced highest tensile strength for the undrilled and open hole sample than other lay-up. It is due to the presence of more fibers in the axial direction which allows carrying the high tensile load. The cross ply laminates achieved moderate open hole tensile strength, which is believed to be contributed by the combination of axial and transverse directional lamina, where the highest value was mainly contributed by axial (0°) lamina. The main reason for the intermediate strength of cross ply laminate is because of less contribution of transverse direction lamina up to the final damage of the sample. Lowest open hole tensile strength was observed for off-axial laminate because of the off-axial arrangement of unidirectional flax yarn, which may not contribute their intrinsic properties for tensile test.

Fig. 2 illustrates the damaged surface of the laminates for different laminate lay-up. Fractography showed a split and tensile fracture of fiber for the axial laminate. The sample failure for axial laminate initiated with fiber–matrix splitting at the open hole edge in the loading direction. The split widened the damage into the entire fiber bundle around the hole. The cross ply laminate failure started with the matrix crack at the edge of the hole boundary, which has been shown in Fig. 3. Finally the cross ply laminate ended with tensile fracture of fiber. The off-axial laminate