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Mechanical behavior of Kevlar/basalt reinforced polypropylene composites

Aswani Kumar Bandaru [a,*], Shivdayal Patel [a], Yogesh Sachan [b], Suhail Ahmad [a], R. Alagirusamy [b], Naresh Bhatnagar [c]

[a] *Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi, India*
[b] *Department of Textile Technology, Indian Institute of Technology Delhi, New Delhi, India*
[c] *Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi, India*

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ABSTRACT

In this study, mechanical behavior of thermoplastic composites reinforced with two-dimensional plain woven homogeneous and hybrid fabrics of Kevlar/basalt yarns was studied. Five types (two homogeneous and three hybrids) of composite laminates were manufactured using compression molding technique with polypropylene (PP) resin. Static tensile and in-plane compression tests were carried out to evaluate the mechanical properties of the laminates. The tension and in-plane compression tests had shown that the composites with the combination of Kevlar and basalt yarns present better tensile and in-plane compressive behavior as compared to their base composites. Improvement in the properties such as elastic modulus, strength and failure strain in both tension and in-plane compression was observed due to the hybridization. Numerical simulations were performed in ABAQUS/Standard by implementing a user-defined material subroutine (VUMAT) based on Chang-Chang criteria. Good agreement between the experimental and numerical simulations was achieved in terms of damage patterns.

1. Introduction

During the last few years, substantial use of polymer composites reinforced with organic (Kevlar, Spectra) and inorganic fibers (basalt, hemp, flax) has been increased in the aviation, defense and sports sectors due to the combination of properties like low density, high strength and high stiffness. The performance can be optimized and the behavior of composites can be enhanced using hybrid composites [1]. Wide varieties of materials and formats are available to develop tailor-made composite materials. For a specific application, an engineer must be aware of the influence of the selected materials over the required properties. After developing a novel material, designers must perform experimental or numerical campaigns to know the basic mechanical behavior of the material [2].

The constituents of a composite, such as fibers and matrix, influence the mechanisms operating in the composites during loading, damage progression, failure modes and eventually the strength. Mostly, characterization of polymer composites reinforced with carbon, Kevlar, glass and natural fibers was reported in the literature [3]. There are several studies available on the characterization of hybrid composites with the combination of carbon/-glass [1], Kevlar/glass [3], carbon/flax [4], PLA/hemp [5], carbon/aramid [6], jute/glass and jute/carbon [7] fibers. The performance of these composites has been discussed in terms of modulus of elasticity, strength and failure mechanisms depending on the loading direction (tension/compression/shear). All these studies investigated the mechanical characterization of thermoset composites. Implementation of thermoset composites is limited due to their long shelf life, low-temperature storage and long curing process [8]. Thermoplastics are generally less stiff, but more damage tolerant and can alleviate these drawbacks providing increased stiffness, better impact strength and lower density [8–11].

From the literature, it was observed that in hybrid combination either glass or carbon fibers were used with Kevlar fiber. Recently, basalt fibers gained attention as a possible alternative for glass and carbon fibers [12,13], due to their increased advantages in terms of physical properties and environmental cost. Basalt fibers were also used as a partial replacement for carbon or glass in the low velocity impact studies [14–16].

The previous studies carried out so far concerned with the tensile and compressive properties of thermoset composites. Moreover, few works discussed the influence of hybridization on the

* Corresponding author.
E-mail address: aswani006@gmail.com (A.K. Bandaru).

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mechanical properties of polymer composites. The lack of research on the characterization of PP composites reinforced with Kevlar and basalt fabrics led us towards the present investigation.

Development of a novel material system for a particular application must always followed by its mechanical characterization. In this prospective, the present study was focused to study the influence of hybridization on the tensile and in-plane compression behavior of PP composites reinforced with Kevlar and basalt fabrics. Homogeneous fabrics were woven with Kevlar or basalt yarns while hybrid fabrics were woven with the combination of Kevlar and basalt yarns. The architecture of all the fabrics was two-dimensional plain woven (2D-P). Five types (two homogeneous and three hybrid) of composites with eight layers in each laminate were manufactured using vacuum assisted compression molding technique. To evaluate the influence of hybridization on the mechanical behavior, static tensile and in-plane compression tests on homogeneous and hybrid composites were carried out. Further, the comparison was made between the different composites using composite stiffness and strength (tensile and in-plane compression). Numerical simulations were performed using ABAQUS/Standard to validate the material constants measured from experiments. A VUMAT subroutine based on Chang-Chang failure criteria [17], was developed and implemented into the numerical simulations to compare the damage patterns with the experiments.

2. Materials and manufacturing

Basalt yarns of 2700 denier and aramid (Kevlar) yarns of 1000 denier were used to weave 2D-P using the CCI sample weaving machine [11]. Four different types of fabric (Fig. 1); two homogeneous and two hybrid fabrics were woven into a 2D-P structure. Two homogeneous fabrics were produced with Kevlar (KPL) and basalt (BPL) yarns and two hybrid fabrics were produced by the combination of Kevlar and basalt yarns. In hybrid-1 (HP-1) fabric, Kevlar and basalt yarns were woven alternately and in hybrid-2 (HP-2) fabric, basalt yarns were woven in the warp direction and Kevlar yarns were woven in the weft direction. All the fabrics were produced with balanced 2D-P structure. Detailed description on the weaving of fabrics was described clearly in Refs. [9–11]. The constructional and measured parameters of different fabrics are provided in Table 1.

Five different types of composite laminates with eight layers in each laminate were manufactured using vacuum assisted compression molding method with PP as resin. The PP sheets were produced using in-house extrusion facility. Four laminates were manufactured with the KPL, BPL, HP-1 and HP-2 fabrics and the fifth laminate (HPLL) was manufactured by stacking alternate layers of BPL and KPL fabrics. The specimens were cured at a temperature of 195 °C under 10 bar pressure for 2 h. Vacuum at 550 mm of Hg was maintained to avoid voids and air entrapment. Volume fraction and density of the new composites were measured using methods described in ASTM D2584 [18] and ASTM D792 [19] standards, respectively. Specimens for tensile and in-plane compression tests were prepared using computer aided laser cutting machine. All the physical parameters of the manufactured composite laminates are given in Table 2.

3. Mechanical characterization

The mechanical characterization of the composite laminates in tension and in-plane compression directions was carried out using a Zwick-Roell Universal Testing Machine (UTM), equipped with a load cell of 100 kN. The test setups are discussed in the following sections.

3.1. Tensile test setup

The tensile tests were performed following ASTM D3039 [20] test standard. Five samples of each composite were tested in each direction. The tensile tests were performed in both the warp and weft directions. The dimensions of the tensile test specimens were 160 mm × 25 mm × t (thickness of the laminate), with a gauge length of 60 mm. Tests were performed at a speed of 2 mm/min. The instantaneous longitudinal and transverse strains were measured using an extensometer (biaxial model) of 25 mm gage length. The model of the extensometer is 3560-BIA-025M-010-ST (Epsilon Technology Corp, Jackson, WY, USA) with a resolution of 0.10 mm for all measuring ranges. An extensometer was arranged in different positions to measure the instantaneous strain in various directions. Using instantaneous strain measurements, Poisson's ratio was measured. The UTM and arrangement of an extensometer in different positions are shown in Fig. 2. The properties measured from tensile tests were Young's modulus, Poisson's ratio, tensile strength and failure strain.

1- represents the longitudinal direction, 2- represents the transverse direction and 3- represents the in-plane direction. When extensometer is positioned in 1–2 direction, it measures the instantaneous longitudinal and transverse strain. When extensometer is placed in 1–3 direction, it measures the instantaneous longitudinal and in-plane strain.

3.2. In-plane compression test setup

In-plane compression (1–3 direction) tests were carried out similarly to ASTM D695 [21] standard. Modifications were made in the UTM machine to mount the specimen for the compression test. Flat plates were placed between the crossheads and the specimen was kept between the surfaces of the plates, taking care that the ends of the specimen were parallel to the compression tool

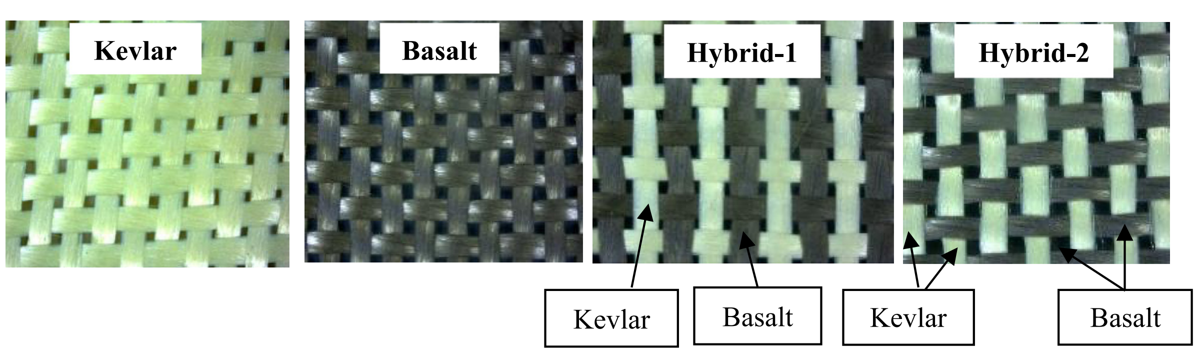

Fig. 1. Surface photographs of fabrics.