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A multicriteria experimental analysis of impact on fiber reinforced polymer composite laminates

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ABSTRACT

The use of fiber reinforced polymers (FRPs) is rapidly increasing in air, land, and marine manufacturing sectors. This is despite the fact that a universal methodology has not been yet developed to assist designers in selecting optimum reinforcing fiber architectures under different loading scenarios. The focus of the present article is to recommend a systematic approach for selecting the architecture of long-fiber fabric reinforcements in FRP composite structures under impact events. Namely, nine design criteria were selected and quantified for four types of PP/glass laminates through drop tower impact testing under 200 J energy, four-point flexural bending before and after impact, as well as microtomographic damage analysis of impacted samples. Subsequently, ranking of the candidate laminates was found using a multiple criteria decision making (MCDM) technique to aid in selecting the overall best performing fiber reinforcement option under the presence of *conflicting* and *inter-dependent* design attributes.

1. Introduction

It is no secret that today's modern industries aim at supplying premium quality products that offer added performance value, lower weight, less environmental impact, decreased manufacturing and maintenance costs, increased durability and safety, and eventually higher customer satisfaction and global market competitiveness. To achieve these milestones, new engineered materials such as fiber-reinforced polymers (FRPs) are rapidly replacing traditional monolithic materials. In particular, fabric-reinforced polymer composites have been receiving rapid attention in leading industries such as aerospace, marine, automotive and transportation. This interest is mainly driven by the ease of formability of these materials from original 2D shapes to 3D structures with complex geometrical features, along with a combination of light weight and superior mechanical properties.

During the last two decades, numerous investigations have been conducted on the material selection, design and optimization of FRP composites using different experimental, numerical and analytical methods. Among numerical methods, the finite element analysis (FEA) has been perhaps the most widely used technique [1–14]. In particular, the review articles by Ghiasi et al. [15,16] show how different FEA techniques have been applied to stacking sequence optimization, constant stiffness design [17–28], and variable stiffness design [29–35] of composites. Other investigations employed optimization methods along with FEA models to maximize stiffness [36], buckling capacity [37,38], post-buckling progressive damage [39], thermomechanical [40] and elastic response of FRPs [41]. Specifically regarding the impact design of composites, Yong et al. [42] used a genetic algorithm (GA) to choose optimal fiber directions that can minimize the central deflection of structure and the impactor's penetration.

In contrast to most of the above works that considered single objective optimization, in most practical applications, designers are often required to consider multiple (usually conflicting) criteria at the same time during their decision making. To address this issue, the present article was aimed to (a) identify a set of decision criteria that reveal multiple aspects of impact behavior of composites, (b) discuss a measurement methodology for each of these criteria, and (c) analyze impact and post-impact bending test results as well as micro-tomographic images of impacted samples. It should be noted that due to the large number of inter-correlated damage mechanisms and uncertainties in modeling impact response

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Abbreviations: AE, absorbed energy; EVD, exterior visible damage; FEA, finite element analysis; FT, flexural toughness (of healthy sample); GA, genetic algorithm; ID, interior damage; MCD, maximum central deflection; MCDM, multi-criteria decision making; PW, plain woven; RF, reaction force; RLFT, relative loss of flexural toughness due to impact; RLUFS, relative loss of ultimate flexural strength due to impact; TW, Twill woven; UD, unidirectional; UFS, ultimate flexural strength (of healthy sample); UW, unbalanced woven; XMT, X-ray microtomography technique.

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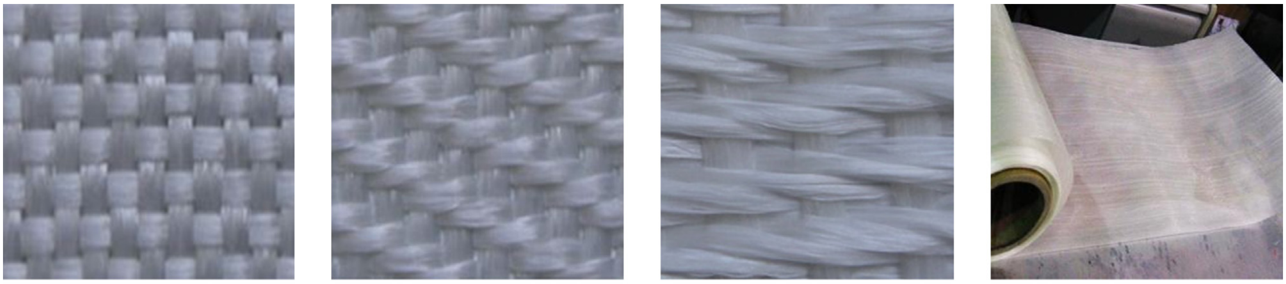
PW (11,11)
%60 glass fibers

TW (22,22)
%60 glass fibers

UW (22,11)
%60 glass fibers

UD (11,00)
%70 glass fibers

Fig. 1. Four different weave patterns examined in the case study for impact optimization; number of fibers in 22 bundles is twice the number of fibers in 11 bundles.

of fiber reinforced polymers (FRPs), the proposed methodology is merely based on experimental data (i.e., with no application of an FEA model/approximation). To exemplify the application of the approach, a case study is performed on the impact behavior of four different polypropylene/glass laminates with four different types of fiber architectures. The experimental methods are presented in Section 2, followed by discussions on the obtained test data and multiple criteria decision making (Section 3). Concluding remarks are included in Section 4.

2. Experimental procedure

2.1. Sample preparation and selecting the performance criteria

In this case study, test laminates were made of commingled polypropylene/glass fibers with four different weave patterns: (a) plain woven (PW), (b) twill woven (TW), (c) unbalanced twill woven (UW), and (d) unidirectional (UD) fiber tapes, as shown in Fig. 1. Under a multi-criteria decision making (MCDM) framework, these four groups of homogenous laminates constituted the decision ‘alternatives’. Each laminate was made by vacuum bagging at 200 °C and cut to a rectangular shape (150 mm × 100 mm) per ASTM D7136 [43]. In order to make a comparison between laminates in subsequent analyses, all laminates were fabricated at the same thickness (6 mm). Moreover, in order to attain a balanced layout, unidirectional (UD) plies and unbalanced woven fabrics (UW) were used in cross-ply configuration; i.e. $[\mathrm{UD}^{0/90}]_n$ and $[\mathrm{UW}^{0/90}]_n$, respectively.

The performance criteria selected for the evaluation of impact response of the four laminate types are: the reaction force during the dynamic impact event (RF), absorbed impact energy (AE), the maximum central deflection of the laminate (MCD), areal fraction of induced interior damage (ID), the exterior visible damage (EVD), ultimate flexural strength of the healthy/unimpacted sample (UFS), the relative loss of ultimate flexural strength due to impact (RLUFS), flexural toughness of healthy sample (FT), and the relative loss of flexural toughness due to impact (RLFT). Accordingly, three categories of experimentation were needed on each type of laminate to obtain the required performance values under each criterion. These experiments were comprised of (a) drop tower impact testing, (b) four-point flexural testing, and (c) non-destructive damage evaluation.

2.2. Drop tower impact testing

Drop-weight impact tests were carried similar to ASTM D7136 [43] using a Dynatub 8200 impact tester. The test machine was equipped with a mechanical mechanism to prevent impact repetitions due to the rebound. The only difference between these tests and the ASTM D7136 was the clamping system. Namely, because of the presence of relatively high impact energy, it was decided to clamp all sides of the specimens rather than clamping four corner points only. All tests were performed at the energy level of 200 J and repeated twice using two samples per laminate configuration. A hemispherical stainless steel projectile with the diameter of 1 in. and the mass of 12.35 kg struck each sample at a velocity of 5.69 m/s.

2.3. Pre- and post-impact flexural testing

Four-point flexural tests, with two repeats per laminate type, were performed on both impacted and non-impacted specimens according to ASTM D7264 [44]. The goal was to measure both the post-impact mechanical properties of the laminates as well as their mechanical performance loss due to impact. The latter can specially be important for specific applications where the structure (e.g., a composite barrier) may experience multiple impacts during its service life and/or maintenance/repair intervals. The support span and the loading span were set to be 100 mm and 50 mm, respectively.

2.4. Non-destructive damage evaluation

In order to assess the extent of damage in the impacted specimens, two different non-destructive techniques were employed as follows.

2.4.1. Visual inspection

Visual inspection with the aid of a digital camera and a ruler was implemented to quantify the exterior visible damage areas on the rear side of impacted samples. As shown in Fig. 2, a polygon was drawn around the boundary of each damaged zone and the corresponding area was calculated. Since the exact selection of the corner points of the polygon could be erroneous, the process was repeated six times and the data were averaged for each sample.

2.4.2. Microtomographic evaluation

The Xradia microXCT-400 machine was employed for the non-destructive evaluation (NDE) of the interior damage intensity in the impacted laminates. During the X-ray micro-tomography (XMT), the high power X-ray penetrates through the specimen mounted on the rotation stage and reaches to a scintillator detector. The adjusted lens magnifies the projected image obtained by the detector and the CCD camera records the enlarged image and transfers to a computer for further processing. In the performed XMT tests, the rotation stage was set to rotate between −110° to +110° and the detector was set to collect 630 images. The illumination time for each image was 1 second. The interior 3D microstructure of each sample was reconstructed from the 630 projections.