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Product Performance

Impact behaviour of Dyneema® fabric-reinforced composites with different resin matrices

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A B S T R A C T

This paper presents an experimental study on the impact behaviour of composite laminates made of a Dyneema® woven fabric and four different resin matrices. Three thicknesses of each kind of resin laminate were subjected to impact by a spherical steel projectile in a velocity regime ranging from 100 to 200 m/s. The results revealed that the laminates having flexible matrices performed much better in perforation resistance and energy absorption, but had a greater extent of deformation and damage than the counterparts with rigid matrices. It was found that the matrix rigidity played a crucial role in controlling the propagation of transverse deformation, and thereby the local strain and perforation resistance of laminates. The more rigid matrix restrained the laminate's transverse deformation to a smaller area at a given time, which led to higher local strain and lower perforation resistance. Fibre failure in tension was identified as the dominant failure mechanism for the tested laminates.

1. Introduction

Since the invention of high-performance polymeric fibres in the 1960s [1], lightweight composites have been increasingly employed in military and law-enforcement applications to protect personnel and vehicles against high-velocity impact threats from bullets and fragments of exploding munitions. These fibres have high specific toughness along with high modulus and low density, which are excellent material properties for dissipating impact energy [2]. Ultra-high molecular weight polyethylene (UHMWPE) fibres (e.g., Dyneema® and Spectra®), being 10 times stronger than steel but lighter than water [3], are one of the most advanced and commonly used fibres in impact protection. In composite laminates, these fibres are usually used in two structural forms, collimated continuous fibres and woven fabrics, which are embedded in a matrix as the reinforcements. Generally, the fibre reinforcements are the principal load bearing constituents and largely determine the properties of composites, while the matrix keeps the fibres in the designed position and orientation and acts as a load transfer medium between the fibres.

The impact behaviour of non-woven composite laminates comprising UHMWPE unidirectional (UD) plies orientated in an alternating 0°/90° stacking sequence has been extensively investigated [4–21], and most of these studies were based on the commercially available products such as Dyneema® HB26 and Spectra Shield®. In comparison, woven fabric-reinforced composites have been given much less attention. Some recent studies have focused on the effects of reinforcement parameters, including ply orientation [22,23], weave structure [24,25], reinforcement continuity [26] and fibre surface treatment [27] on the impact behaviour of fabric-reinforced laminates. When it comes to the effect of matrix properties, however, there is a paucity of data on how the matrix influences the impact behaviour of fabric-reinforced laminates. Lee et al. [28,29] found the Spectra® fabric-reinforced laminates with a stiff vinyl ester resin had higher ballistic limit than those with a flexible polyurethane resin, and it was deduced that the stiffer resin prevented the yarn movement to a greater degree and, thereby, forced the projectile to engage and break more yarns. In somewhat of a contradiction to the work of Lee et al., Gopinath et al. [30] found the aramid fabric-reinforced laminates having a flexible matrix performed better in energy absorption and perforation resistance than the counterparts having a stiff matrix when the thickness ranged from 1 to 5.4 mm (1–5 layers). However, when the thickness increased to 7.6 mm (7 layers), the laminate with the stiffer matrix was more effective in absorbing the projectile's kinetic energy. Therefore, the effect of matrix properties on the impact behaviour of woven fabric-reinforced laminates has not been fully understood. Moreover, the matrix's influence seems to

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change with the laminate thickness.

Motivated by the current uncertainty of the role of matrix properties and the paucity of existing data, this paper works on the impact testing of composite laminates consisting of Dyneema® 4-harness satin weave fabrics and four different resin matrices. The main purpose of this experimental study is to evaluate the effect of matrix properties on the perforation resistance, energy absorption, failure process, deformation and damage extent of woven fabric-reinforced laminates subjected to impact loading. Three thicknesses of each kind of resin laminate have been tested with the aim of interrogating the thickness effect.

2. Laminate fabrication and experimental methodology

2.1. Woven fabric and resin matrices

A 4-harness satin weave fabric made of Dyneema® SK75 fibres supplied by PRF Composite Materials was selected as the reinforcement material of laminate specimens. Table 1 summarises the basic parameters of the fabric and the mechanical properties of the constituent fibres [31]. The fabric weave structure and the yarn paths and cross-sections are shown in Fig. 1.

Four thermoset resins were used as the matrices for manufacturing laminate specimens. These were a rigid epoxy resin (West System® 105), a nano-reinforcement toughened epoxy resin (West System® 105 with the addition of acrylate triblock copolymer Nanostrength® M52N), a flexible epoxy resin (Epopol® 7320), and a flexible polyurethane resin (Eracast XPE15-1957). The addition of triblock copolymer to the epoxy resin (weight ratio 1:10) was carried out by mixing them at 290 revolutions-per-minute at 90 °C for 2 h using a magnetic stirrer. Then, the mixed solution was degassed and allowed to cool to room temperature. The required amount of hardener was added to the mixed solution just before making the laminates. This triblock copolymer could improve the toughness of epoxy resin with little loss of its elastic modulus [32]. Table 2 lists the constituents of these resin matrices and their cured mechanical properties obtained from manufacturers and suppliers. The Young's modulus of nano-particle reinforced epoxy resin is measured from compression test. All these resins had low viscosity and long gel time at room temperature which allowed the use of wet lay-up method for laminate making. We use ‘Epoxy’, ‘Nano’, ‘Epopol’, and ‘PU’ here to represent these four resins, respectively, for easy reference in the following discussion of test results.

2.2. Laminate fabrication

The laminate specimens were fabricated using a traditional wet lay-up method. Firstly, the raw fabric material was cut into plies with a size of 600 mm × 400 mm. Then the cut fabrics were impregnated with the prepared resins and hand-stacked layer by layer to the designed number of plies. In this study, laminate specimens consisting of 2, 4, and 8 plies of reinforcing fabrics were made with all four resins. All the fabric layers were laid up in aligned orientation. The impregnated fabrics were placed in a vacuum bag with an applied pressure of 90 kPa to reduce porosity and absorb excess resin, as illustrated in Fig. 2. All the laminates were cured at room temperature and the curing time was carried out as per the specification of each resin. After the resins were fully cured, the laminates were cut to rectangle targets with dimensions of 250 mm × 150 mm for impact tests. Table 3 lists the reinforcement weight fraction, areal density and thickness of all the laminate specimens. It can be seen that there were only slight differences in these values among the laminates with the same number of plies except those made of Nano resin that had a higher viscosity than the other resins. This table also gives the nomenclature used for the laminate specimens. The first digit indicates the number of plies, the letter in the second place denotes the used Dyneema® fabric, and the word after the slash represents the used resin. For example, 8D/Nano corresponds to a laminate specimen made of 8 plies of Dyneema® fabric and nano-reinforcement toughened epoxy resin.

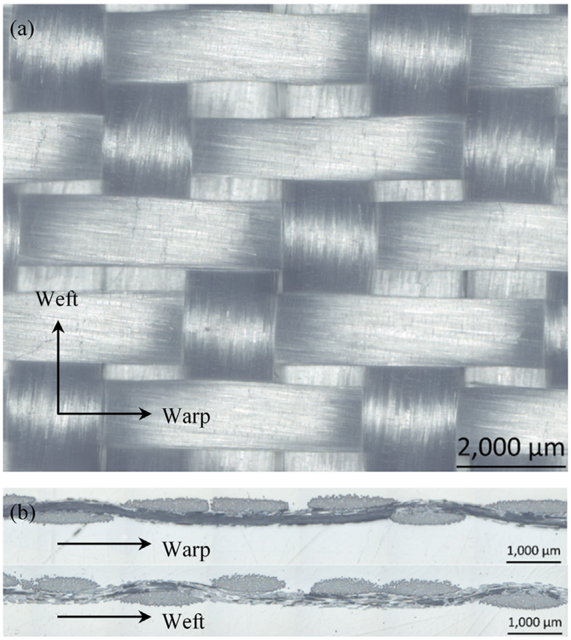

Fig. 1. Optical microscopy images showing (a) the 4-harness satin weave structure and (b) the yarn paths and cross-sections of the used Dyneema® fabric.

2.3. Experimentation

In the impact testing, the laminate target was clamped along their upper and lower sides, while the left and right edges were unrestrained. The clamping area was 50 mm × 150 mm on either side, which left an exposed area of 150 mm × 150 mm subjected to impact. A spherical steel projectile, having a diameter of 12 mm and a mass of 7.05 g, was propelled by a single-stage gas gun to impact the target centre at normal incidence. Two pairs of photoelectric sensors were sited just in front of the target to measure the projectile's impact velocity. The impact tests were conducted at three breech pressures, which produced nominal impact velocities of 112, 152, and 194 m/s (or nominal impact energies of 44, 82, and 133 J). The impact velocities were slightly different from test to test conducted at the same breech pressure. Under each impact velocity

Table 1
Properties of Dyneema® fabric.

Fibre	Tensile strength (GPa)	Tensile modulus (GPa)	Elongation to break (%)	Number of fibres in a yarn	Yarn denier (warp&weft)	Weave style	Areal weight (g/m^2)
Dyneema® SK75	3.3–3.9	109–132	3–4	780	1350	4-harness satin	180