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Experimental and numerical investigation of fabric impact behavior

Piotr Kędzierski *, Arkadiusz Popławski, Roman Gieleta, Andrzej Morka, Grzegorz Sławiński

Military University of Technology, Department of Mechanics and Applied Computer Science, Gen. Sylwestra Kaliskiego Street 2, 00-908 Warsaw, Poland

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ABSTRACT

This paper presents experimental and numerical research regarding blunt trauma resistance of ten fabrics made of high strength fibers. Fabrics of various architecture were examined, including plain woven fabrics, unidirectional laminates and multiaxial fabrics. The fabrics were compared with respect to the depth of the depression formed and the amount of energy transferred to the backing during projectile impact. Absolute values of mentioned parameters were compared, as well as their values after normalization with respect to thickness and areal density of the fabrics. A numerical method for estimating the amount of energy transferred to the backing was proposed.

Normalized results, obtained experimentally and numerically, proved that most of the analyzed fabrics provide a similar level of protection, but the best blunt trauma resistance is given by multiaxial fabrics and the least by plain woven fabrics. This study has also shown that the depth of the depression in the backing material is an insufficient parameter in describing protective properties of fabric against blunt trauma. It is possible that impacts into ballistic packages composed of different fabrics with the same depth of depression may cause completely dissimilar injuries because of the amount of energy transferred to the backing material.

1. Introduction

Fabrics and flexible laminates comprised of high performance polymer fibers possess superior strength, stiffness and impact resistance. The best known and most widely used are fabrics based on para-aramid fibers (e.g. Kevlar from DuPont, Twaron from Teijin) and ultra high molecular weight polyethylene fibers (e.g. Dyneema from DSM) [1]. In today's practice, fiber compositions are extensively employed in flexible armor applications such as bulletproof vests. The primary role of body armor is to stop a projectile. During a ballistic impact, kinetic energy from the projectile is absorbed by several layers of fabric and the projectile is prevented from completely penetrating the system. Apart from stopping bullets, the deflection of the body armor is supposed to be as small as possible to reduce the non-penetrating injuries of the internal organs, otherwise known as blunt trauma. Protection against blunt trauma is measured by the depth of depression in the backing material which supports a bulletproof vest during impact tests. The ballistic performances of body armor are regulated and codified. US standards implemented by the National Institute of Justice are the most commonly used in industry. As specified by NIJ Standard-0101.06, depressions in backing material should not exceed 44 mm.

Ballistic behavior of fabrics produced from high-tenacity fibers has been investigated by both experimental and numerical methods [2–11]. However, a significant deficiency of these studies is that they do not take into account the protective properties of fabrics against blunt trauma with respect to perforation resistance. Cork and Foster [12] examined the ballistic performance of various narrow fabrics and compared these results to the performance of wider ones made of Kevlar and nylon. They studied, among other parameters, the shape and depth of deformation in the backing clay, while Park et al. [13] considered the effect of the layering sequence of unidirectional/woven fabric hybrid packages in regards to perforation resistance against a 5.56 mm fragment-simulating projectile as well as the blunt trauma resistance represented by the backface signature caused by a projectile of a 0.44 Magnum cartridge. Chen et al. [14] also conducted an analysis concerning the effectiveness of hybrid panels composed of unidirectional (Dyneema SB21) and woven (Dyneema SK75) fabrics. One of the criteria used to estimate their usefulness was the form of the depression in the backing material. The most attention to blunt trauma was paid by Karahan et al. [15]. They investigated the effect of fabric ply number, stitching type and conditioning on the diameter and depth of the signature in the backing material as well as the amount of energy transferred to the backing. Energy

* Corresponding author. Tel.: +48 22 6837610; fax: +48 22 6839355.
E-mail address: p_kedzierski@wat.edu.pl (P. Kędzierski).

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transferred to the backing material was estimated based on the volume of the depression and energy required per unit volume, which was previously determined by dropping an iron bar of known mass from a known height into the backing material. Plain woven fabric Twaron CT710 was used in this research.

This paper presents experimental and numerical research regarding blunt trauma resistance of ten fabrics made of high strength fibers. Fabrics of various architecture were analyzed, including plain woven fabrics, unidirectional laminates, and multi-axial fabrics. The selected fabrics are well-known and commonly used in bulletproof vest design. Investigations concentrated on the depression that formed in backing material after impact. Apart from the depth of depression, energy transferred to the backing was also taken into account. Absolute values of the mentioned parameters were compared, as well as their values after normalization with respect to thickness and the areal density of the fabrics. The aim of study was to identify the most effective type of fabrics, resulting in the smallest injuries during bullet impact. Additionally, a numerical method for estimating the amount of energy transferred to the backing was proposed by the authors.

2. Investigation procedure

Packages including ten plies made of one type of fabric were subjected to the impact of a cylinder. In this study, the ten different fabrics listed in Table 1 were investigated. Fig. 1 shows samples of the analyzed fabrics. Packages have the shape of a square with 200 mm long sides. Unclamped samples were supported by a box filled with plasticine sold under the trade name Roma No. 1. Before each trial, the backing material and box were conditioned in a heated chamber at 40 °C.

The diameter of the bearing steel cylinder was 6 mm with a height of 23 mm. The cylinder was placed in a foam sabot and accelerated by a gas gun. The pressure in the gas gun was carefully selected so as to not perforate any of the ply. The average of three velocities measured with the use of laser gates was taken as the muzzle velocity of the projectile. During impact, the cylinder did not deform plastically. Three packages were tested for each fabric type. The test stand with an installed sample made of Twaron T750 and the projectile with foam sabot are shown in Figs. 2 and 3.

2.1. Depth of depression

After impact, the surface of the backing was digitalized with the use of a hand-held laser scanner. Scanning was conducted with a resolution of 0.05 mm in the direction of the *x*, *y* and *z* axes. The size of the depression was determined during processing of the scanned surface. The backing, prepared for scanning with adhesive markers, is depicted in Fig. 4.

Table 1
Fabrics selected to studies and their properties.

Fabric	Thickness g (mm)	Areal density ρ (g/m^2)
Dyneema HB26	0.35	264
Dyneema HB50	0.29	233
Dyneema SB21	0.19	145
Dyneema SB51	0.28	253
Dyneema SB71	0.22	190
Twaron T750	0.65	460
Twaron UD41	0.25	238
Twaron Microflex	0.35	220
Kevlar XP S102	0.46	510
Kevlar XP S307	0.29	300

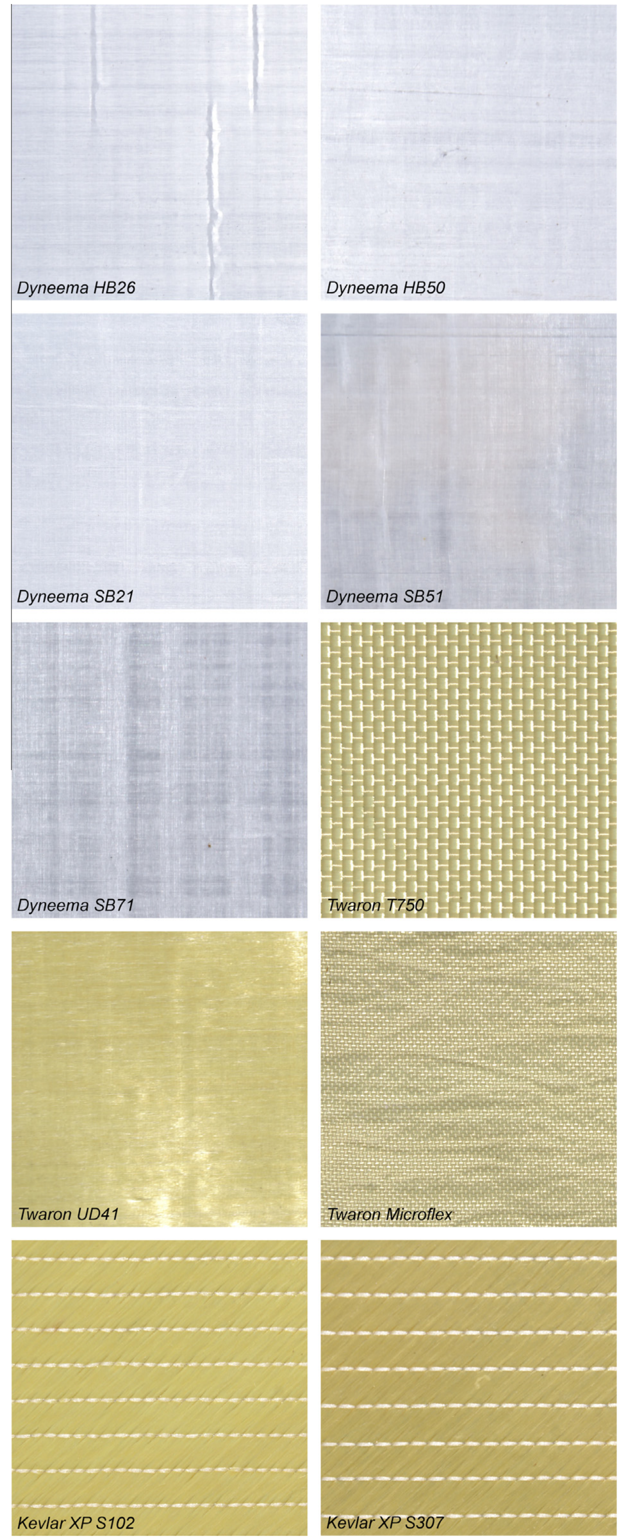

Fig. 1. Samples of analyzed fabrics.

2.2. Energy transferred to backing

The amount of energy absorbed by the ballistic backing was numerically estimated. For each impact a numerical model was built in which the scanned depression was used as a numerical stamp. During the simulation, the stamp extruded cavity in the backing directly corresponded to that of the experimentally