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Experimental study of bullet-proofing capabilities of Kevlar, of different weights and number of layers, with 9 mm projectiles

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A B S T R A C T

Kevlar is the most commonly used material as armour for protection against bullets used in hand guns because of its impact resistance, high strength and low weight. These properties make Kevlar an ideal material to be used in bullet-proof vests as compared to other materials. In the present study, different numbers of layers of Kevlar with different weights are tested to determine the weights and the number of layers needed to design a safe bullet-proof vest. For this purpose, several ballistic tests were performed on combinations of ballistic gel and Kevlar layers of different weights. Ballistic impacts are generated by 9 mm Parabellum ammunition. The objective is to assess the characteristics of high-speed ballistic penetration into a combination of a gel and Kevlar and determine the number of layers needed to safely stop the 9 mm bullet and thereby contribute to the design of safe bullet-proof vests. The tests provide information on the distances the bullets can travel in a gel/Kevlar medium before they are stopped and to identify the resistance capabilities of Kevlar of different grams per square meter (GSM). The tests were conducted with the use of a chronograph in a controlled test environment. Specifically, results identify the number of layers of Kevlar required to stop a 9 mm Parabellum projectile, and the effectiveness of using different number of layers of GSM Kevlar material.

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1. Introduction

The concept of body armour was developed in 1538 and comprised of steel plates. Fully steel bullet proof vests were progressively used and improved up until the 20th century [1]. Today's body armour systems may still incorporate steel (but at a minimal amount), but consist mostly of Kevlar [2]. The use of Kevlar was integrated into vests in the mid-1970's and a fully developed vest was produced in 1976 after the discovery of Kevlar by Stephanie Kwolek in 1971 [3]. This new material greatly reduced the overall weight of the body armour system and drastically improved the mobility of the person wearing the vest, resulting in the modern bulletproof vests utilised today.

Kevlar used in the vests is comprised of a woven fabric consisting of synthetic fibres made through polymerisation. It is a high strength material known for its high strength to weight ratio, and in comparison to the strength to weight ratio of steel, Kevlar is five times stronger [4]. The lightweight property of Kevlar in conjunction with its high tensile strength (3620 MPa) [5] and its capacity for energy absorption [6] in comparison to other materials, makes it an ideal material for use in body armours. Ballistic applications of Kevlar based composites mostly include protective clothing [7,8]. The effect of ballistic impact on Kevlar and other composites, and the mechanical properties of the material, have been investigated in several studies [9–18] with a view towards assessing its characteristics and effectiveness under impact loading. These studies involved both experimental testing [9–18] and numerical modelling [19–21] and established the effectiveness of Kevlar as an impact resistance material. Experimental ballistic tests performed with the samples of the Kevlar-Phenolic composite, used in Ref. 18, showed that the results did not correlate with the ones given in current publications, and they therefore indicated that further controlled experiments were needed. In the previous experimental studies, various methods of impact were used including gas guns [9,12], 9 mm bullets [10,14] and armour piercing projectiles [11]. An active area of research concerning the impact resistance of Kevlar materials involved the study of the effect of shear thickening fluids

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on the ballistic performance of Kevlar reinforced composites [22–25]. Reviews on shear thickening fluids and their applications were given in a number of publications [26–28]. A number of high velocity projectile tests have been performed before as noted above, but in many cases, different methods of inducing motion, such as compressed air, or dropped weight [29] were implemented. These motion induction methods do not correlate with the uncertainty characteristics of ammunition, the explosion of gun powder, and the rifling used in the firearm barrels.

The present study aims at investigating the ability of Kevlar fabric of different weights to stop a projectile of common calibre, and the distance the projectile can travel through a gel/Kevlar combination to prevent life-threatening incidents. The contributions of this paper can be summarized as follows:

1) Identify the effectiveness of different layers of three grades of Kevlar layered, namely 160 GSM, 200 GSM and 400 GSM Kevlar fabrics.
2) Investigate the relationship of GSM with the number of layers needed to stop a 9 mm bullet.
3) Investigate the relationship of the type of ammunition with its penetration depth
4) Assess the number of Kevlar layers needed to stop a projectile.

In the tests, the layers of Kevlar that a projectile can penetrate are considered as the layers that are damaged. The calibre of the ammunition used is 9 mm Parabellum ammunition as they are used extensively. The tests were performed with a Glock 17 handgun inside a Roni carbine conversion kit. It is noted that the authors are not associated with the companies manufacturing the ammunition and obtained no financial gain for performing the tests. The results given are unbiased, and are purely as observed in the tests conducted. Due to many uncertainties in ballistic tests, many of the tests conducted in the present study had to be repeated numerous times, for example, when the projectiles deviated out of the ballistic gel, or external interference was observed that might have an effect on the results.

2. Ballistic gel and Kevlar samples

The description of how the ballistic gel and the Kevlar samples were constructed are described below.

2.1. Ballistic gel

The ballistic gel was made from unflavoured gelatine. The density and consistency of the gel have to be the same as that used by the Federal Bureau of Investigation (FBI). To achieve the same consistency, instructions given in Ref. [30] were followed and it has been tested against the standards described in Ref. [31].

8 cups (250 ml) of unflavoured gelatine powder (approximately 1.25 kg) is mixed with 8 L of water (1 part gelatine for every 4 parts of water) until all the powder is dissolved. After the solution was poured into the containers (2×5 L containers were used for the above mixture), 5 drops of essential oil (cinnamon leaf essential oil) was poured over the solution and gently stirred into it. The reason for the essential oil is to allow for the bubbles in the solution to dissipate, and to give the ballistic gel an improved smell. The solution is set in the containers placed in a fridge. The ballistic gel was ready to be used 36 h after it was made and then it was wrapped in cellophane wrapping. A video showing the details to make the ballistic gel is available from https://www.youtube.com/watch?v=0nLWqJauFEw.

Density of the ballistic gel was calculated as 996 km/m^3 (99.6% of water density). The average density of human blood, fat and muscle [32], which is the consistency of the human flesh, is 1004 kg/m^3. A 0.8% difference in the densities is considered as acceptable for the ballistic gel to replicate the flesh of a human body.

2.2. Kevlar samples

Three weights of Kevlar fabric were used in the tests, namely, 160 GSM, 200 GSM and 400 GSM. Since Kevlar can be used as a woven material, the highest strength of the material could be utilised in a 0–90 orientation. The samples were stacked with a −45/+45 (quasi-isotropic) orientation which absorbs more energy upon impact than 0–90 orientations stacked on each other [33]. The samples that were used in the tests were made in multiples of 3 layers where each sample was layered in the order of 90/±45/90. When two or three samples were placed on top of each other, it was done such that the last layer of one sample was placed at 45° to the next layer of the next sample.

The Kevlar sheets were divided and cut into A4 size sheets to prepare them to be bound together using the recommended epoxy resin and hardener. The samples were left to dry. The samples were cut after the resin had set and bolted to each other and were placed into position for the tests to be conducted.

3. Tests and experiments

The experimental setup and ammunition used are discussed next followed by the experimental results that were obtained.

3.1. Experimental setup

Ballistic tests were carried out using two different kinds of ammunition, namely, full metal jacket (FMJ) and jacketed hollow point (JHP) of the 9 mm Parabellum (P or Para for short) calibre. The method used to test the samples is described next:

1) A firearm chronograph was set up to measure bullet speeds. The chronograph was placed 2 m from the muzzle of the firearms to prevent the muzzle flame to give inaccurate readings.
2) A baseline test was performed to determine the bullet velocity directly into the ballistic gel. The kinetic energy equation $E = (1/2)mv^2$ was used to determine the energy and distance of penetration into the ballistic gel.
3) The Kevlar samples were then placed in front of the ballistic gel and this was placed 1 m away from the chronograph. The reason for the distance of 1 m is to replicate the worst case scenario where a person or object is shot at a close distance.
4) The sample was shot with the projectile going through the chronograph to determine its initial speed. After this, the sample is penetrated and the projectile is lodged in the ballistic gel. The velocities of the tests were used to obtain an average velocity reading which was used to update the values in step 2.
5) The distance of penetration into the ballistic gel was measured and recorded.
6) Step 2 was repeated for each type of ammunition used in the tests. Step 3 to step 5 was repeated for each Kevlar sample. A test with specific ammunition was repeated if the projectile did not travel straight within the ballistic gel, or if it penetrated the Kevlar sample in an area that was considered not to be structurally sound.

The setup configuration is shown in Fig. 1.

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