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Impact of a Projectile on Fabrics – An Experimental Test Method

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Article

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ABSTRACT

Fabric manufacturers are striving to produce value-added, high-end technical fabrics, such as smart textiles, protective clothing and accessories for sports, where the performance of the fabric has become a decisive factor. Fabric impact resistance is one such property of importance. Therefore the development of a suitable method to predict the impact on the fabric at the point of fabric development is of great importance. In this article, the authors have attempted to design and develop a test method to predict fabric impact more accurately. A mathematical model has been developed to show the relationship between impact force, impact velocity and the depth of penetration on impact. Finally, test equipment has been developed to measure the impact based on the developed model. The indentation depth on impact was measured against both impact velocity and kinetic energy, and the experimental impact force was calculated against the impact velocity. It was found that the impact velocity of the projectile affects both the impact on fabric and indentation into the backing material as well as the energy absorbed by the fabric. The energy absorption also increased with impact velocity and higher velocities caused greater damage. No great variation in temperature was detected.

KEYWORDS

projectile force, woven fabric, fabric impact resistance, impact velocity, penetration

INTRODUCTION

The resistance that fabrics show to an impact force is a property of great importance in many applications. These include products such as body armour, protective clothing in sports and boxing gloves. This necessitates a standard testing method to measure and grade the impact resistance force of a fabric. It is important to know how the impact force deforms the structure of the fabric. However, the problem becomes complex due to a large number of variables being involved. These variables include the fibre strength, fabric structure, and how the temperature, size, and shape of the impinging projectile affect the fabric behaviour. This complexity needs to identify controlling variables which led to the development of a model to measure the impact force. The goal of this manuscript is an attempt to analyse how the impact resistance force varies with velocity, mass and temperature at the point of impact with the projectile.

The ballistic performance of fabric armour depends on various mechanical properties of the fabric as well as the characteristics of the impinging projectile. Some mechanical properties of the fabric are the elastic modulus, tensile strength, bending rigidity, yarn count and the density and structure of the woven fabric. Projectile characteristics include mass, velocity, temperature, shape and surface finish. When making ballistic products, several fabric layers are laid one over the other to increase the areal density. Therefore it is necessary to optimize the ballistic behaviour of the assembled fabric layers. Hence, the development of a standard method to grade the fabric types before designing armour or a similar product will add value to the end product. Proper design of protective clothing is important to ensure optimum protection. In addition, proper knowledge of the impact force and its dispersion will help to design protective clothing better [1].

Strong fabrics need strong fibres and closely woven fabric structures. For many recent researches fibres such as Nylon, Kevlar, Twaron, Dyneema and plain woven structures were used.

In experiments done at Soochow University, finite element analysis has been used to investigate the effect of woven (plain weave, basket weave) and knitted fabric structures on the ballistic resistance of composite textile materials. When considering structures with similar areal density, it was found that knitted composite textiles showed very poor performance compared to others [2].

The term “aramid” is an acronym for aromatic polyamide [3]. Aramid fibres are organic fibres and their tensile modulus and strength are high enough to be used as reinforcement in advanced composites. Mechanical properties of aramids are 5-10% higher when compared to other synthetic fibres. Aramid fibres take the place of metal wires and inorganic fibres in high-performance end uses such as structural composites for ships, aircraft and automobiles, ropes used in offshore oil rigs and bulletproof vests [3]. Aramid polymers possess higher heat resistance and flame resistance which makes them eminently suitable for the above end uses.

When considering the chemical structure of aramids, at least 85% of amide linkages are directly attached to two aromatic rings. According to this definition Kevlar, Nomex, Technora, Teijinconex, Twaron, etc. belong to the aramid family. The discovery of lyotropic liquid crystalline aramids and the development of aromatic polyamides was revolutionised with DuPont Research Scientist Stephanie Kwolek inventing the first high molecular weight lyotropic aramid. She synthesized the rigid chain high molecular weight poly (p-benzamide). This synthesis was followed by that of many aromatic polyamide compositions and the development of several commercial aramid fibres. DuPont is the world's leading producer of aramid fibres, controlling about two-thirds of the world market [3].

Kevlar chains are comparatively rigid and, due to the para-orientation of the benzene rings, tend to form mostly planar sheets. When Kevlar is spun the chains lock together via H-bonds to form a sheet that has very high tensile strength. The sheets also stack radially, allowing additional interaction between neighbouring sheets to increase the strength of the overall fabric [4].

Dyneema is the brand name of an Ultra High Molecular Weight Polyethylene fibre (UHMW-PE). Dyneema is produced by a patented gel spinning process and has the chemical composition ~[C2H2]n~, where n is in the order of a million. As compared to this regular PE has n in the order of a few thousand [5].

Dyneema has the following characteristics.

- High specific stiffness (E/ρ) (~112 GPa cm^3 g^{-1})
- High specific strength (σ/ρ) (~3500 MPa cm^3 g^{-1})

While used in different applications, Dyneema armour panels can withstand the impact of projectiles travelling at velocities of hundreds of meters per second. This implies that Dyneema composite panels would be subjected to exceptionally dynamic impacts [5].

Nylon-6 is used in a wide range of engineering applications. It combines good mechanical properties with good processability. In addition, various fillers can be added to obtain composite polymers. Ballistic woven nylon has been developed to make protective wear [6]. Based on the original ballistic woven nylon developed for military body armour, CORDURA ballistic fabrics, which are based on the original ballistic woven nylon developed for military body armour, are made with high tenacity nylon 6-6 filament yarns. These fabrics possess enhanced tear and abrasion resistance. Characteristics of nylon that are concerned in this product are its high resistance to tearing, tight weave and high tenacity [7,8].

There are many factors which influence the impact force impinging on the fabric surface.

When considering fabric-related factors, fibre properties, fabric structure and the number of fabric layers play a role in the ballistic performance. Dimeski and associates have proposed that the impact and perforation of fabrics depend on many parameters, such as yarn properties, fabric structure, the interaction of multiple plies, the far-field boundary conditions and the friction between the yarns themselves and between yarns and the projectile [9]. Other factors are the mass, velocity and shape of the impinging projectile and the temperature of the projectile at the moment of impinging [10,11].

A study carried out by Abtew and colleagues reported on the influences of fabric construction of para-aramid fibrous products made of similar material and density on their ballistic behaviour when tested against different projectiles at a constant speed and deformation energy. Different fabric constructions such as plain weave, various twill weaves, 2×2 basket weave and satin constructions were tested. It was seen that at lower speeds a plain weave construction performed better against armour-piercing by full metal jacket rifle bullets than the other fabric constructions. However, at higher speeds, the 2×2 basket weave showed better ballistic resistance performance compared to the plain and twill weave constructions [2]. This could be explained by the fact that plain weave fabrics have greater stability than basket weaves. As a result, there is greater resistance to the projectile pushing through the fabric

[12]. At higher speeds, however, sufficient energy would be mustered to break through a plain weave, but due to the greater flexibility of the basket weave it shows a better performance.

The cover factor is another parameter that affects the impact force and ballistic performance. A loosely woven fabric will yield to the nose of the projectile more easily than a tightly woven fabric. However, if a fabric is very tightly woven its flexibility may not be sufficient to allow it to give way sufficiently to absorb and dissipate the impact force. Crimp is yet another factor that affects the impact force. If the crimp is high it will take longer to uncrimp and absorb the maximum energy, and therefore will break at a lower impact force [9].

When the shape of the projectile is conical or pointed the impact force on the fabric increases as compared to rounded shapes. The impact force increases with the mass of the projectile.

Many tests are available to measure the impact of various materials. These include the Charpy and Izod pendulum-type tests, the drop-weight test and the dynamic tear tests. However, these are developed mainly for metals and plastics and are generally not suitable for fabrics, which are more flexible and pliable than other materials.

Many different methods have been used to model the impact force on the fabric. Cavarallo came up with a method where the yarn strength, friction, fabric boundary condition and projectile impact location were considered [11]. A 5.556 mm diameter spherical steel projectile weighing 0.692 g was used, and the projectile location was randomly selected for each impact simulation. The method used single-layer fabric clamping and three major regions were identified. In Region 1 momentum transfer between fabric and projectile increased the fabric's kinetic energy. Simultaneously, the yarns started to decrimp and elongate as the longitudinal stress wave propagated along the yarn. This led to an increase in the strain energy. Region 2 was prominent for frictional yarn pull-out with a low deceleration rate. Region 3 is the post-impact region. The projectile velocity remains constant for the penetrating impact. When impact does not result in penetration the projectile can rebound backwards.

Randjbaran et al designed a drop-weight impact tester [14]. Such a tester with predefined impact energy is used for warp-knitted spacer fabrics. Both the acceleration and the force signals transmitted are measured and treated with a low-pass filter. A comparison is done of the peak contact force and transmitted force as a function of time. The velocity and displacement of the striker are also calculated. The contact force-displacement curves, energy absorbed-contact force curves, and transmitted-time curves are plotted and used to analyse the effects of different structural parameters such as the spacer monofilament yarn inclination, fibre fineness, fabric thickness and surface knitted structures on the impact compressive behaviour of the warp-knitted spacer fabrics. A relationship between the peak transmitted force and peak contact force was shown [14].

The velocity and displacement of the striker can be calculated by using the two equations below. According to these equations, the acceleration-time curve is integrated.

$$v = \sqrt{2gh} - adt \quad (1)$$

$$s = \sqrt{2gh}\, t - \int(adt)dt \quad (2)$$

Clay-Backed Ballistic Testing is another approach [15]. In this test, oil-based modelling clay is used because of its similarity to human flesh. Calibration is carried out to qualify the clay for ballistics testing. The clay is maintained at a controlled temperature to prevent changes in the properties. Five steel spheres are dropped from a height of 2 m onto the clay at a defined distance from the clay edges. The depth of the indentation in the clay is measured. The clay qualifies if the average depth is in the range of 17 mm to 21 mm, with no measurement less than 16 mm or greater than 22 mm.

When applying impact forces on fabrics initial stress waves occur in the longitudinal direction of yarns. Then in the initial shearing and shear jamming states, transverse waves will occur in the projectile direction. While pulling out the yarns from the woven structure the jamming process will occur.

It is important to determine the points of extension and shear-jamming points to ensure proper amounts of yarn mobility leading to optimized energy absorption levels. Pierce's Geometric Model for plain-woven fabrics may be used to calculate other fabric parameters relevant to jamming. The yarn crimp is directly relevant to the level the woven structures will absorb energy [14].

Impulse momentum and energy balance equations are used to determine impact force as well as the absorbed energy within the impact process of the fabric.

$$\int_{t_i}^{t_f} Fdt = m(V_i - V_f) \quad (3)$$

Here:

F = impact force

t =time

m= mass of the projectile

V_i= initial velocity of the projectile

V_f= final velocity of the projectile (V_f = 0 for non-penetrating impacts)

t_f=final time

t_i= initial time

The kinetic energy of moving objects may equal the sum up of damping energy, elastic and plastic strain energy of fabric layers, energy dissipated through friction at the yarn crossover regions and the kinetic energy of fabrics.
The stress wave propagation is also an important factor when following the impact force on fabrics. The stress wave velocity through the fibres can be calculated by using the following equation:

$$c = \sqrt{\frac{E(1-v)}{P(1+v)(1-2v)}} \tag{4}$$

where

C = stress wave velocity through the fibres

E = Young’s modulus of the fibres

v = velocity of the object

P = impact pressure.

The frictional characteristics of the fabric may be determined by the yarn pull-out test. This is performed by extracting a single yarn from a woven fabric and monitoring the force-displacement response using a fixture such as that developed by Kirkwood [16]. The initial extraction force produces a peak resistance. When yarn begins to slip the resistance force decreases.
Yet another method uses a gas gun tunnel, steel pallet and high-speed camera to assess the absorbed energy. Cylindrical pellets are used, and the pellet speed is calibrated by varying pressure of the Helium gas. The pellets are made of mild steel weighing 6.75 g, with a length of 13.07 mm and a diameter of 8.48 mm. It has a smooth surface to minimize friction factor. High-speed cameras are used here because they help to calculate the velocity of the moving pellets [17].
A strong linear relationship exists between the size of the damaged zones and the expended kinetic energy. The larger the area the higher amount of ballistic energy absorbed.Initial impact velocity and the velocity after impact of the moving pellets are measured. The absorbed energy of the fabric can be calculated by using a reduction of the above-mentioned velocities. However, this experiment does not measure the exact value of the impact forces on the fabrics. It gives only a rough idea that can be used to compare different fabrics.
Many shortcomings exist in the already developed test methods due to specific assumptions made in each test method to calculate the impact force. The drop-weight test used by Randjibaranis used for laminates, and not for pure woven fabrics. The Clay-Backed Ballistic Testing refers to Peirce’s model to determine the fabric parameters used in the equations of the method. However, this model is restricted to plain woven fabrics and is also constrained by many assumptions which are practically

not valid.

Therefore there exists a research niche for a unified scientific test method to calculate the impact force on the ballistic fabric. With the increase in the production of ballistic protective clothing due to the current situation in the world, it is important to reduce the lead time by avoiding a trial and error method as well as to produce high-quality lifesaving protective clothing. In this research paper, the authors attempt to develop a mathematical model to analyse the energy of the projectile and impact force on the fabric to derive a scientifically sound experimental test method to bridge the research gap in measuring the impact force on fabrics.

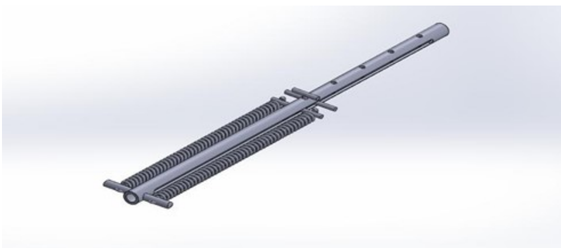
EXPERIMENTAL

Methodology

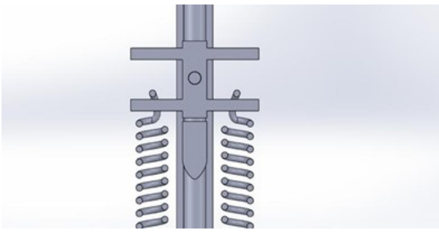
Mathematical expressions of energy, impact velocity and impact force generated by the projectile on the fabric were derived. Firstly the design of a suitable experimental method to calculate the impact force on the fabric was carried out. Secondly, the selection of suitable materials was done and methods to manufacture prototype experimental setup were developed. By using the said experimental method, variable speeds of projectiles were obtained with different extensions of springs. The other parameters such as the profile and mass of the projectile, the distance between the outlet and the fabric sample, the pipe length of the prototype, and fabric specifications are kept constant. An empirical method is used to determine the penetration depth for various speeds of the projectile and thereby calculate the energy and impact forces that have been carried out.

Materials and Methods

Initially, a mechanism was designed as a part of the test method to generate a high velocity for the projectile. This facility is required to vary the factors which affect the impact force on a fabric. By using Solid Works, a model was designed to achieve various speeds of the projectile. A bullet-shaped object was developed as the projectile.



(a)



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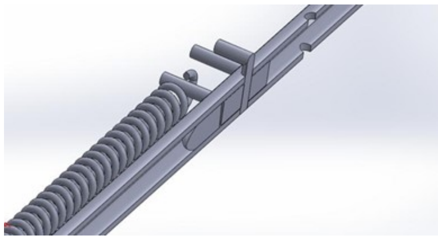

(c)

Figure 1. CAD model of velocity generator:(a) 3D view of the design;(b) Cross-Sectional top view; (c) Cross-sectional bottom view

Figure 1 shows the 3D view of the design of the velocity generator. By stretching the pin into the further away holes shown in the design, the elastic potential energy can be increased. This energy is converted to the kinetic energy of the moving projectile.

Figure 2. Prototype of the velocity generator

Figure 2 shows the prototype of the proposed velocity generator and how to load the instrument. The bullet-shaped projectile is inserted in front of the instrument which is rigidly fixed. By dragging the spring and holding the pin into the different positions various speeds can be generated. The pipe is made out of stainless steel with a length of 1.5 m and an internal diameter of 15 mm. The spring has a spring constant of 500 N/m is spiral in shape made out of steel.

By using a lathe machine the bullet-shaped projectile was made with standard measurements.

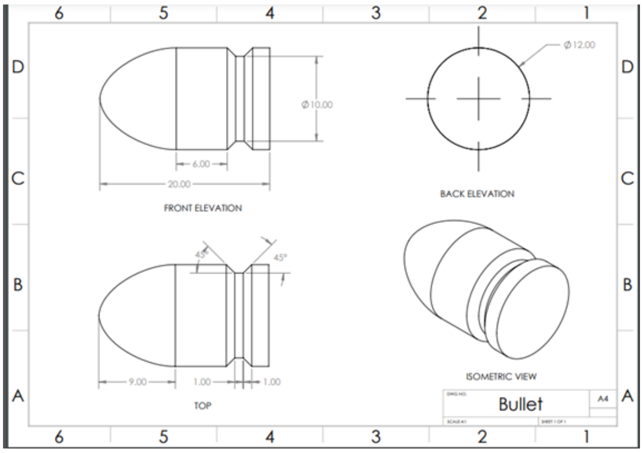

Figure 3. Design of the bullet-shaped projectile

Figure 4. Bullet-shaped projectile

A box was built, filled with clay to stop the moving projectile after penetrating a certain depth and measure the depth penetration.

Figure 5. The box filled with Clay

In the next phase, relevant equations were derived to determine the impact forces exerted by using the absorbed energy of fabric which will be described in the section of mathematical modelling. The variation of the impact forces on the fabric with variable weight, velocity, and temperature of the bullet-shaped projectile (the shape of a projectile is kept constant) needed to be studied. The impact forces are dependent on all these parameters, but only the velocity and temperature were considered in this study. The focus was on how to grade the fabrics based on the impact force acts on them.

Mathematical Modelling

The velocity of the bullet after being released from the barrel is calculated taking into account relevant assumptions. Using SUVAT equations, the velocity of the object just before striking against the fabric surface can be calculated under the following assumptions:

1. The bullet has a vector linear movement
2. The twist motion of the Bullet can be neglected (zero twist motion)
3. The spring force becomes zero after releasing from the pin

The development of the mathematical model was based on the parameters depicted in Figure 6.

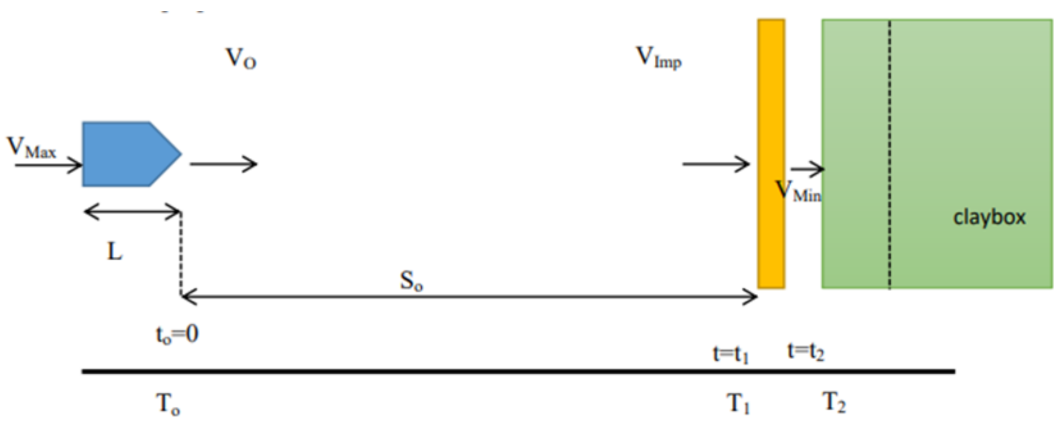

Figure 6. Mechanical diagram of equipment

Here we assume the following:

ρ- air density

A -cross-sectional area of the projectile

v -projectile velocity

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Cd - drag coefficient,

T – Surface temperature of the projectile

V_o- Velocity of the projectile when leaving the pipe

V_{max}-maximum velocity of the spring velocity generator

F-Friction force between the pipe and the projectile

m-mass of the projectile

L- displacement of the bullet inside the pipe

t-time

k-spring constant of each spring

Consider temperature and shape is constant during test 1. Assume that the conversion of energy into the sound is negligible and zero spring force for simplicity (as small extensions store small energies). Using the energy conservation law, kinetic energy generated on the projectile is equal to the potential energy stored in two springs with spring constant k each.

$$\frac{1}{2}(2k)x^2 = \frac{1}{2}mv_{max}^2 \tag{5}$$

$$v_{max} = \sqrt{\frac{2k}{m}}\,.x \tag{6}$$

Using SUVAT equations and F = ma,

$$V_o = \sqrt{v_{max}^2 - 2F\frac{L}{m}} \tag{7}$$

Due to the air drag force, the projectile is subjected to deceleration and it can be given as

$$\frac{1}{2}\rho A v^2 C_d = -\mathrm{m}\frac{\mathrm{dv}}{\mathrm{dt}} \tag{8}$$

It can be rewritten as

$$\frac{1}{2}\rho A v C_d = -\mathrm{m}\frac{\mathrm{dv}}{\mathrm{ds}} \tag{9}$$

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By integration of equation (9)

$$\frac{1}{2}\rho A C_d \int_0^{S_0} ds = -\mathrm{m} \int_{V_o}^{V_{Imp}} \frac{dv}{v} \quad (10)$$

The impact velocity can be expressed as

$$V_{imp} = V_o \times e^{\frac{-\rho A C_d S_o}{2m}} \quad (11)$$

The Ballistic Coefficient (BC) of a bullet quantifies the ability of a bullet to cut through the air. A bullet with a high BC has a better ability to slice through the atmosphere without being retarded by air particles. Bullets with higher BC have better resistance to drag than bullets with low BC [2,16].

$$Ballistic\ Coefficient = \frac{Mass}{drag\ coefficient \times Cross-sectional\ Area} \quad (12)$$

The mass of the bullet is kept constant, and the velocity varied by giving varying levels of kinetic energy to the bullet by pulling the spring to the various positions. The behaviour of the fabric can be checked for different velocities without changing the shape, temperature and mass. Likewise, the mass of the bullet can be changed without changing the shape, temperature and speed. This would help to get the behaviour of the fabric for different masses of the projectile.

However, the bullet has a twisted motion due to the nature of the barrel and the ballistic coefficient was derived to empirically model the combined motion of the bullet. Due to the nature of the pipe, no twisted motion is experienced and hence alternative simple alternative expression was derived in equation (11) to get the impact velocity considering the air drag.

Considering temperature changes: Inside the pipe, the projectile generates heat due to friction and this heating effect was considered. Considering the energy conservation law, initial kinetic energy is equal to the heat generated due to friction plus the velocity of the projectile at the outlet of the pipe. K1, K2 and K3 are the factors based on the units used for other variables. $(\Delta T)_0$ is the temperature difference created when travelling through the pipe and s is the specific heat coefficient of the projectile material.

$$\frac{1}{2}mv_{max}^2 = \frac{1}{2}mv_o^2 + \frac{(\Delta T)_0 ms}{K_1} \quad (13)$$

It can be expressed as

$$\frac{K_1}{2s}(v_{max}^2 - v_o^2) = (\Delta T)_o \tag{14}$$

Similarly, the temperature difference created due to the friction of the free air $(\Delta T)'$,

$$\frac{K_2}{2ms}(kx_{max}^2 - mv_{max}^2) = (\Delta T)' \tag{15}$$

If T_i=Temperature of the projectile before releasing the spring, the temperature of the projectile at the outlet of the pipe T_o can be given as

$$T_o = T_i + (\Delta T)_o + (\Delta T)' \tag{16}$$

Substituting for equation (16) from equations (14) and (15) the following expressions are yielded:

$$T_o = T_i + \frac{K_1}{2s}(v_{max}^2 - v_o^2) + \frac{K_2}{2ms}(kx_{max}^2 - mv_{max}^2) \tag{17}$$

The kinetic energy loss is assumed to cause an increment in the heat of the projectile. The following equation can be derived by applying energy conservation law:

$$\frac{K_3 m}{2}(v_{max}^2 - v_o^2) = (\Delta Q)_1 = ms(\Delta T)_1 \tag{18}$$

The loss in kinetic energy is converted to a rise in temperature and part of it is dissipated in the form of radiation.

$$\frac{m}{2}(v_o^2 - v_{imp}^2) = (\Delta Q)_2 = \varepsilon\sigma A(T_1^4 - T_{amb}^4) \tag{19}$$

Where ε is the surface emissivity and σ is the Stefan-Boltzmann constant

The loss in kinetic energy due to the impact of the projectile impinging on the fabric $(\Delta Q)_3$ is given by

$$\frac{m}{2}\left(v_{imp}^2 - v_{min}^2\right) = (\Delta Q)_3 \tag{20}$$

After the projectile has been stopped in the backing material inside the clay box, the energy conservation law can be applied to calculate the energy absorbed by the backing material (clay). The viscosity of the clay is assumed to be a constant.

To calculate the speed after the moment of impact, the following cases were considered:

Case 1 - temperature is constant:

$$\frac{1}{2}mv_{imp}^{2} = work\ done\ against\ the\ resistance\ force\ on\ fabric + energy\ absorbed\ by\ the\ backing\ material \tag{21}$$

The depth of the hole made inside the clay was measured and the energy absorbed by the backing material clay was empirically calculated.

However, if the projectile completely penetrates the fabric sample, the absorbed energy of the backing material (BM) should be measured. Then the impact energy of the fabric can be calculated by subtracting the energy absorbed by the backing material from the loss in the kinetic energy (KE) of bullet shaped projectile. The loss of kinetic energy due to impact against the fabric includes yarn elastic and plastic deformation energy plus heat energy dissipated. Heat can be neglected because temperature is assumed to be constant here.

The expression to measure the impact force on the fabric can be given as follows:

$$Impact\ Force\ \times t = Energy\ absorbed\ by\ the\ fabric \tag{22}$$

where t is the depth of deformation of the fabric before bursting into the backing material due to the bullet-shaped projectile.

Case 2 - Variable temperature:

For variable temperature heat energy (HE) of the bullet-shaped projectile and backing material were under consideration. In this case, the ultimate impact force can be expressed as follows:

$$I = \frac{(KE\ of\ projectile\ before\ impact) - (HE\ of\ projectile + KE\ loss\ of\ BM + HE\ of\ BM)}{t} \tag{23}$$

RESULTS AND DISCUSSION

Backing material calibration

Iron-moulded clay was used as the backing material. First, the backing material was calibrated and the Energy versus Indentation Depth graph was obtained. The bullet-shaped projectile (Diameter- 12 mm, mass- 7 g), equipment similar to firearms and Vernier callipers were used to get measurements. The length of the spring is 30 cm and the gap between two holes is 5.6 cm. The hole numbers and relevant extensions are given in Table 1 (when considering the hole numbers, the first two holes out of seven holes were not considered).

Table 1. Hole number vs. extension

Hole number of the pipe	Extension of the Spring(cm)
1	7+5.6*2 = 18.2
2	23.8
3	29.4
4	35

Equations 6, 7 and 11 above were used for calculations.

The parameters used for the experimental setup are mentioned below:

- F (Friction force between the tube and the pipe)- this was made negligible by applying grease and oil
- M (mass of bullet-shaped projectile)- 7 g
- ρ (Air density)- 1.225 kg/m^3
- A (cross-sectional area of projectile)- $A = \pi r^2$= 1.13 × 10^{-4}
- C_d (drag coefficient for projectile)- 0.295
- S (the gap between the outlet of the pipe and fabric sample)- 51.5 cm
- Spring constant k=500 N/m

By using equation (6) the maximum velocity V_max can be calculated. A negligible velocity drop is experienced due to the friction between the pipe and the projectile due to lubrication inside the pipe. Therefore V_0≈V_max The impact velocity of the projectile V_impact can be determined using equation (11). The kinetic energy possessed by the projectile E_imp at the point of striking can be calculated by the definition of kinetic energy. The indentation depth of the backing material due to the residual impact of the projectile was measured using physical testing procedures. The extension of spring, maximum velocity, velocity at the outlet of the pipe, impact velocity, impact kinetic energy and indentation depth through the backing materials are summarised in Table 2.

Table 2. Summary of details of velocity at different points, kinetic energy of projection and indentation depth for different extensions of springs

Hole No	Extension of springs (cm)	$V_{max}(\ ms^{-1})$	$V_0(\ ms^{-1})$	$V_{imp}(\ ms^{-1})$	E_{imp}(J)	Indentation Depth(cm)
1	18.2	68.78	68.78	68.677	16.504	0.72
2	23.8	89.95	89.95	89.77	28.205	0.95
3	29.4	111.12	111.12	110.89	43.03	1.25
4	35	132.28	132.28	132.015	60.99	1.59
5	40.6	153.45	153.45	153.143	82.084	1.96

The indentation depth vs. Impact velocity of the projectile graph is given in Fig. 7. Since the experimental indentation depth varied non-linearly with impact velocity, a second-order polynomial was fitted and its R-squared value was 0.9998. The empirical relationship between the indentation depth and impact velocity can be given as

$$d = 0.00005v_{imp}^2 + 0.0034v_{imp} + 0.2383 \tag{24}$$

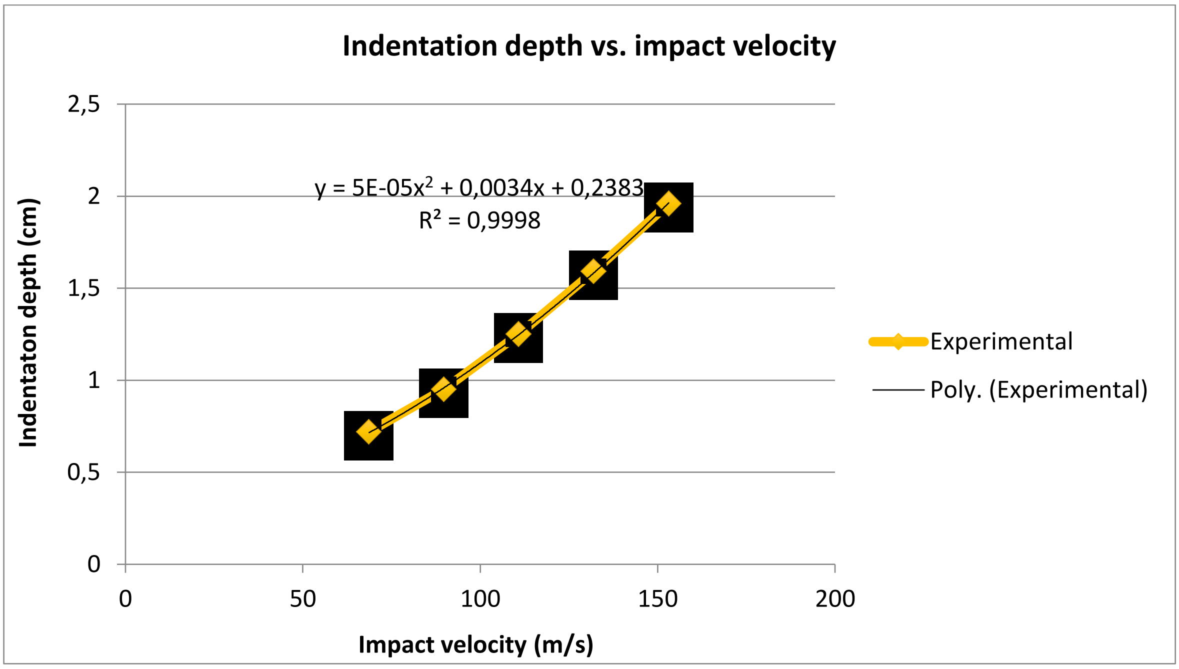

Figure 7. Indentation depth vs Impact velocity

Indentation depth was plotted against the impact energy absorbed by the backing material. A linear relationship could be noted in the graph and a linear model could be fitted with an R-squared value of 0.9992.

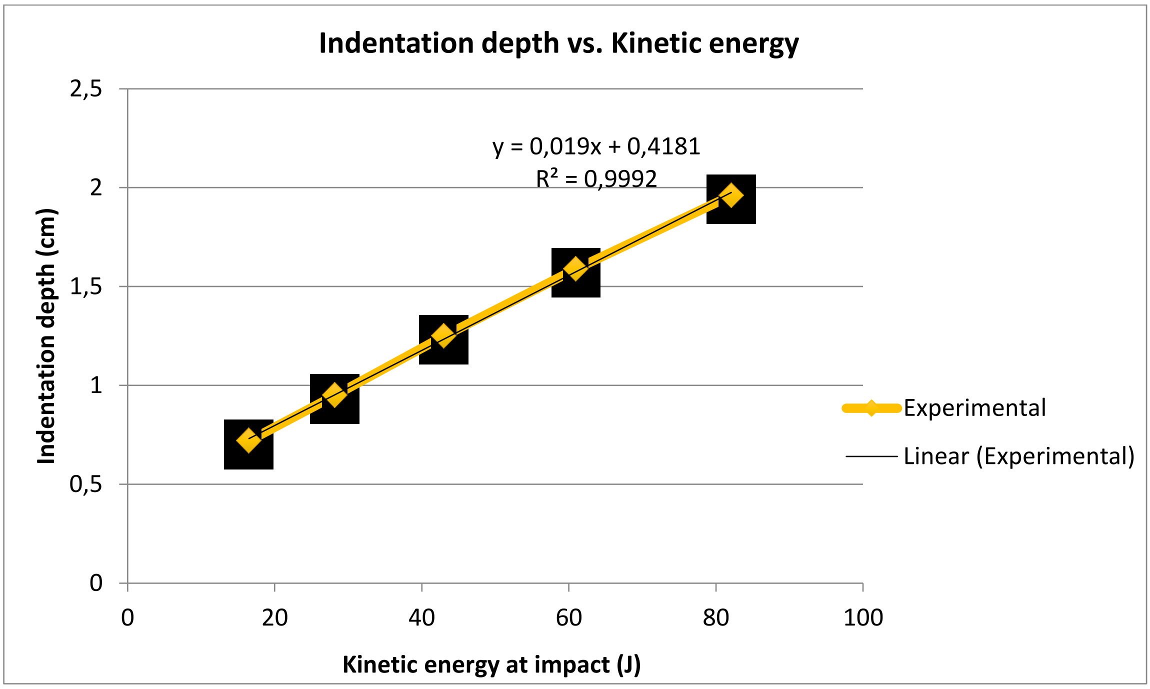

Figure 8. Indentation depth vs. energy absorbed by the Backing Material

The relationship between the experimental indentation depth and the energy absorbed by the backing material can be expressed as follows:

$$d = 0.019E_{imp} + 0.4181 \tag{25}$$

Rearranging the equation (25) the energy absorbed by the backing material for a given indentation depth can be expressed as

$$E_{imp} = 52.63d - 22.01 \tag{26}$$

The process of measuring impact forces on fabrics

The resistance force exerted by the fabric when the projectile hits the fabric sample is equal to the difference between the kinetic energy of the projectile just before striking and the energy absorbed by the backing material. So with the fabric sample, the indentation depth of backing material after penetration through the fabric was measured for various speeds as per the selected hole. For testing purposes the experiment was repeated ten times using the same extension of the spring and the average value of the indentation depth was calculated. Using the empirical calibration curve fitted for the absorbed energy by the backing material, the residual energy that remained in the projectile after penetration through the fabric sample was calculated. This equals the energy absorbed by the backing material after the projectile strikes the fabric.

Table 3. Average indentation depth with fabric sample and energy absorbed by backing material for different hole positions energy

Hole Number	Average indentation depth value (with fabric sample (cm)	Energy absorbed by backing material (J)
1	0.60	9.58
2	0.70	14.84
3	0.94	27.47
4	1.23	42.73
5	1.46	54.84

If the temperature variation is neglected, the heat energy increment of the projectile as well as the heat generated due to the resistance of the backing material will be equal to zero and equation (23) is reduced to

$$I = \frac{(KE\ of\ projectile\ before\ impact)-(KE\ loss\ due\ to\ the\ BM)}{t} \tag{27}$$

Using equation (27), the impact force exerted on the fabric for various initial extensions of the springs can be calculated and given in Table 4. The depth of deformation of the fabric t before bursting is measured experimentally using Vernier callipers considering the variation of diameter of the indentation hole in the backing material (before bursting it has a cone shape hole and then converted to the hole of constant diameter of the projectile).

Table 4. Impact force for different elongations of springs

Hole No	$V_{imp}(\ ms^{-1})$	E_{imp}(J)	Indentation Depth after bursting fabric (cm)	Energy absorbed by the backing material(J)	Energy absorbed by the fabric(J)	Impact force on fabric(N)
1	68.68	16.50	0.60	9.58	6.93	57.75
2	89.77	28.21	0.70	14.84	13.37	102.83
3	110.89	43.03	0.94	27.47	15.56	155.62
4	132.02	60.99	1.23	42.73	18.26	202.87
5	153.14	82.08	1.46	54.84	27.25	275.22

The experimental impact force exerted on the fabric is plotted against the impacted velocity of the projectile. The graph was curvilinear and hence a second-order polynomial was fitted. The R-squared value of the trend line was found to be 0.998 the empirically fitted polynomial can be expressed as

$$I = 0.0078v_{imp}^2 + 0.7973v_{imp} - 32.805 \quad (28)$$

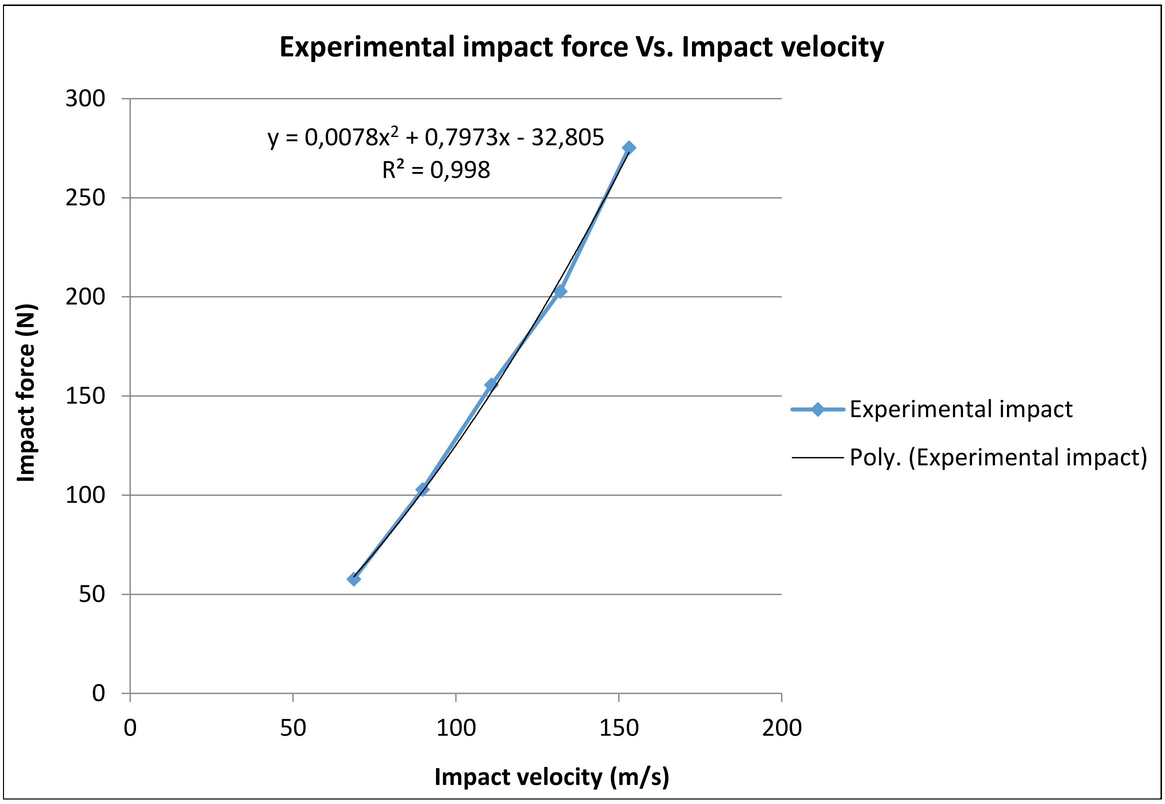

Figure 9. Experimental Impact Force vs Impact Velocity

The ultimate objective of the research was to calculate the impact force to develop a scientifically sound test method. Since this could not be directly calculated, the penetration depth of the backing material was measured with and without fabric and thereby difference in kinetic energy was calculated. According to the developed mathematical expressions, kinetic force is calculated by the impact energy absorbed by the material.

The experimental variation of temperature is insignificant at the speeds of the projectile that the acceleration head of the prototype can be exerted. Due to limitations in taking very accurate temperature measurements under very minimal temperature change, experimental results could not be achieved for case 2. This will be considered with a higher acceleration head of the prototype and an accurate measuring system to measure temperature variations in further studies.

CONCLUSION

Throughout the experiment, fabric parameters such as packing density, yarn density, etc. were not used in the calculations because the energy conservation law was used to calculate the impact forces.

The research aimed to develop a testing method to measure impact forces on fabrics. However, a proper calibration process of the backing material is necessary. It is more suitable to use "Roma plastilina number 1" clay. But, any type of constant Newtonian clay can be used for this. The indentation depth vs Energy absorption of the backing material graph should be drawn for relevant Newtonian clay. After attaching the fabric sample to the equipment the indentation depths were measured. In this experiment, the fabric sample was analysed for various velocities and the impact forces vs impact velocity graph for the fabric was plotted. The impact velocity of the projectile affects both the impact on the fabric and indentation into the backing material as well as the energy absorbed by the fabric. When increasing the velocity, there is a point that the impact force is at its maximum level. That is the breaking point. After this, the projectile (moving object) can penetrate the fabric. This is very suitable to check the strength of fabrics with external impact velocities.

It was noted that the energy absorbed by the fabric is increased as the impact force on the fabric is escalated. The higher the impact velocity, the more intensive the damage caused to the fabric which results in higher energy absorption. In the article, the authors describe the development of the prototype of a test instrument and a mathematical model developed for the prototype. Thereby a test method to calculate the impact force exerted on the fabric was developed and empirically validated. However, the temperature variation is insignificant at the operating speeds, so an accurate infrared temperature measurement system needs to be incorporated to measure the temperature for further studies.

Author Contributions

Conceptualization – Niles, Fernando and Jayawardene; methodology – Fernando, Nayanajith and Madushanka; formal analysis – Jayawardene; investigation – Nayanajith, Madushanka; resources – Fernando, Nayanajith, Madushanka; writing-original draft preparation – Niles, Nayanajith and Madushanka; writing-review and editing – Niles, Fernando, Jayawardene; visualization – Fernando; supervision – Niles, Fernando and Jayawardene. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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