Comparison of penetration process of 2-layer elastomeric composite with thermoset composite using energy absorption equations

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ABSTRACT

The purpose of this paper is to present an analytical model for analyzing the penetration process by a spherical nose shape cylindrical on the kevlar/elastomer and the kevlar/epoxy composites and comparing them with each other using the energy method. To investigate this issue, energy absorption equations for linear and nonlinear materials are analyzed as a criterion for the performance of matrix-reinforced fabric. In this predicted model, the dependence of the ballistic behavior of the first and second layers of the composites on each other during the impact is considered. In this presented model, the components of energy absorption include the initial kinetic energy of the projectile, the kinetic energy of the projectile, the kinetic energy of the composite cone ahead the tip of the projectile, the energies absorbed by primary and secondary yarns, the energies absorbed by the delamination among the layers and the cracking of the matrix, the energy dissipated by plugging of the layers is calculated during impact. The results of this study show a positive effect of elastomer use on thermoset matrix in composite. Also, analytical results are validated with the experimental results of previous studies and the perturbation analysis is done to examine the reason of error.

KEYWORDS

Theoretical analysis, absorbed energy, rubber, kevlar fabric, elastomeric composite.

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1. Introduction

One of the critical requirements for various structural elements is protection against external high-velocity projectiles. Incident ballistic impact velocity effect on residual velocity, projectile diameter and on velocity of ballistic limit and contact duration are studied [1]. The main soft armor materials were made by high-strength fibers. Among the polymer fibers, high-performance fibers such as Kevlar, Twaron and Dynama fibers are used as body armor[2]. A comparison of behavior and energy absorption of neat kevlar fabric and polymer matrix composites studied under high velocity impact loading [3]. Two types of matrices including rubber and thermoset (epoxy) matrices were used in order to study the effect of a hard and brittle matrix compared with the soft and flexible matrix on energy absorption of the composite. Results show that the matrix affects the composites ballistic performance considerably. In previous studies, analytical models were predicted for behavior and energy absorption of under ballistic impact loading on the single-layer composites. Hence, these models for multi-layer composites were extended according to the main guess at the base of them was yarns/fibres in every layer act independently. As a result, energy absorption of layers is considered independent of each other. Therefore, the analytical predictions have remarkably been differed from the experimental results. But in this paper, layers are considered to be dependent which makes the energy absorption of layers is completely considered dependent on each other. Consequently, the predicted analytical is more noticeably correlated with the experimental results than the previous models. In this paper, the focus of the present study is on a generalized analytical formulation based on the energy balance equation for ballistic impact behavior of kevlar/elastomer and kevlar/epoxy composites impacted by a spherical ended cylindrical projectile. The formulation presented is valid for 2-layer laminate to predict the residual velocity and ballistic limit. The energy is absorbed by the most energy-absorbing mechanisms on the composite target which is discussed upon. Theoretical validation is performed on the ballistic impact behavior of composites to explain the error between the results of calculation and experiment.

2. Analytical formulation

The analytical model is based on the energy balance equation. The main consideration of the model are:

The maximum strain of a layer in the longitudinal direction is the initial strain for the next layer, energy absorption due to primary yarn/fibre breakage and deformation of the secondary yarns are treated independently, during any time interval, the velocity of the projectile remains constant, the yarns are stretched in one direction ($\sigma_{11}= \sigma$) while is stress-free in other directions ($\sigma22 = \sigma33 = 0$). So, it can be shown that the nonzero Cauchy stress component is $\sigma_{11} = E\varepsilon_{11}$ for Elastic model (linear) and for hyperelastic model (nonlinear), the Neo-Hookean constitutive model is initially adopted for the function of energy density, and for an incompressible material is given by [4]:

$$W = C_1(I_1 - 3) \tag{1}$$

Where C_1 is a material parameter. The relation between stretch λ and engineering strain ε_{11} in the direction of the practical load is $\lambda = 1 + \varepsilon_{11}$. If $\sigma_{22} = \sigma_{33} = 0$, Show that the nonzero Cauchy stress component is:

$$\sigma_{11} = 2C_1(\lambda^2 - (1/\lambda) = 2C_1\left((3\varepsilon_{11} + 3\varepsilon_{11}{}^2 + \varepsilon_{11}{}^3)/(1+\varepsilon_{11})\right) \tag{2}$$

The ballistic-resistance armour system principally helps to stop the projectile from penetrating, and absorbed its kinetic energy by transforming it into the different forms of the ballistic absorbing mechanisms. It can be presented in the following equation:

$$E_{Kp,0} = E_{Kp,i} + E_{KE,i} + E_{Py,i} + E_{Sy,i} + E_{Dl,i} + E_{Mc,i} + E_{Sp,i} \tag{3}$$

Where $E_{Kp,0}$ is the initial kinetic energy of the projectile, $E_{Kp,i}$ is the kinetic energy of the projectile at every time step, $E_{KE,i}$ is the kinetic energy of the composite cone ahead the tip of the projectile, $E_{Py,i}$ and $E_{Sy,i}$ are the energies absorbed by primary and secondary yarns, $E_{Dl,i}$ and $E_{Mc,i}$ are the energies absorbed by the delamination among the layers and the cracking of the matrix and $E_{Sp,i}$ is the energy dissipated by plugging of the layers. The total energy absorbed by the target is calculated by $E_{L,i} = E_{Py,i} + E_{Sy,i} + E_{Dl,i} + E_{Mc,i} + E_{Sp,i}$.

Hence, the correlation between the projectile velocity and the velocity of the projectile at any instant during the ballistic impact event can be obtained in the following:

$$V_i = \sqrt{(0.5m_pV_0^2 - E_{L,i})/(0.5\left(m_p + m_{c,i}\right))} \tag{4}$$

3. Energy-absorbing mechanisms

3.1.Kinetic energy of the moving cone formed

The velocity of the cone formed is V_i, equal to the velocity of the projectile at the end of i_{th} time interval. Thus, the energy of the cone shaped is:

$$E_{KE,i} = \sum_{i=0}^{i=n} 0.5\pi r_{t,i}^2 t\rho V_i^2 \tag{5}$$

3.2. Energy absorbed due to tensile failure of primary yarns

The primary yarns resist the penetration of projectile into the fabric target. Hence, the general equation is as follows:

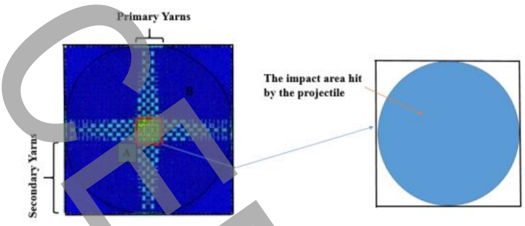
$$E_{py,i} = \sum_{i=0}^{i=n} A\int_0^{r_{p,i}} \left(\sum_{i=0}^{i=n} \int_{\varepsilon_i^* = i\varepsilon_0 b^{\frac{x}{a}}}^{\varepsilon_{i+1} = (i+1)\varepsilon_0 b^{\frac{x}{a}}} \sigma_{11}(\varepsilon)\, d\varepsilon \right) dx \tag{6}$$

Where ε_0 is the ultimate strain limit and $A = 4d_p h_1$.

3.3. Energy absorbed due to the deformation of secondary yarns

The planar view can be subdivided into two regions when the projectile strikes onto a composite target as shown in Figs 1. The variation of boundary conditions on the strain can be expressed by the following equation:

$$\varepsilon_{Sy} = \varepsilon_{Py} = \varepsilon_0 b^{\frac{x}{a}} \quad at \quad r = d/2, \qquad i.e.,\ at\ \text{point}\ A,$$
$$\varepsilon_{Sy} = 0 \quad at\ r = r_{t,i}, \qquad i.e.,\ at\ \text{point}\ B \tag{7}$$



(a)

Fig. 1. **(a)** Modelling energy absorption of secondary yarns deformation

The general equation of absorbed energy is as follows:

$$E_{sy,i} = \sum_{i=0}^{i=n} \int_{0.5d_p}^{x_{t,i}} \left(\sum_{i=0}^{i=n} \int_{\varepsilon_i^* = i\varepsilon_0 b^{\frac{x}{a}}}^{\varepsilon_{i+1} = (i+1)\varepsilon_0 b^{\frac{x}{a}}} \sigma_{11}(\varepsilon)\, d\varepsilon \right) h_1 \left\{ 2\pi x - 4d_p \right\} dx \tag{8}$$

3.4. Energy absorbed due to delamination and matrix cracking

The respective energies absorbed by delamination and matrix cracking during this time interval are expressed as below:

$$E_{Mc,i} = \sum_{i=0}^{i=n} P_m \pi A_{ql} h V_m r_{Dl,i}^2 E_{m,i}, \quad E_{Dl,i} = \sum_{i=0}^{i=n} P_d\, \pi\, A_{ql}\, r_{Dl,i}^2\, G_{IIcd} \tag{9}$$

3.5. Energy absorbed due to shear plugging

Shear plugging absorbs in the first few layers. It leads to a sharp decrease in the projectile kinetic energy and total contact force. Energy absorbed by shear plugging is given by:

$$E_{Sp,i} = \sum_{i=0}^{i=n} N\pi d_p h S_{Sp} h_{1,i} \tag{10}$$

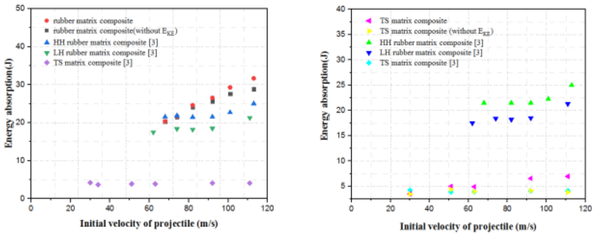
Properties are summarised in the following Table 1.

Table 1. Input parameters required for the analytical predictions of ballistic impact behavior [3,8] and [5-7]

Projectile details	
Mass(gr)	9.32
Diameter(mm)	10
Target details	
Material	Kevlar/elastomer
Thickness(mm)	0.5
No. of layers	2
Density(kg/m^3)	1175.4
Tensile failure strain (%)	5.5
Material constant C_1(Mpa)	0.99
Quasi-lemniscate area reduction factor	0.4
transmission factor	0.85
Delamination percent(%)	40
Matrix crack percent(%)	40
Mode II dynamic critical strain energy release rate(J/m^2)	3850
Matrix cracking energy(MJ/m^3)	0.4
Shear plugging strength,S_{sp}(Gpa)	0.8
Matrix cracking energy(MJ/m^3)	0.9
Target details	
Material	Kevlar/Epoxy
Thickness(mm)	0.5
No. of layers	2
Density(kg/m^3)	1230
Tensile failure strain (%)	1.68
Young's modulus(Gpa)	20.41
Quasi-lemniscate area reduction factor	0.9
Stress wave transmission factor	0.85
Delamination percent(%)	90
Matrix crack percent(%)	90
Mode II dynamic critical strain energy relea rate(J/m^2)	2856
shear plugging (Mpa)	9
Matrix cracking energy(MJ/m^3)	0.9

4. Results and Discussion

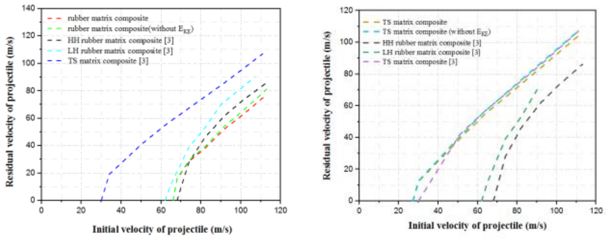
Energy absorption is predicted for various velocities on the kevlar/elastomer composite and the kevlar/epoxy composite comparing energy absorption between analytical and experimental results [3]. during a velocity, penetration model are presented in Fig. 2. It can be found that the agreement between the analytical model and experimental results is good.



(a) (b)

Fig. 2. Comparison energy absorption between analytical and experimental model during ballistic impact with different velocities a) on the kevlar/elastomer composite with a thickness of 1 mm, b) on the kevlar/epoxy composite with a thickness of 1 mm.

A function of the velocity of the event of ballistic impact as the projectile remaining velocity (V_R) is shown in Fig. 3. The results for the projectile remaining velocity of the kevlar/ elastomer composite of 2-layer, in the case of impact with an initial velocity of 74 m/s shows that the projectile remaining velocity is 38.66% lower than the initial velocity of impact and goes out of the goal, while in the case of impact velocity of 113 m/s shows that the projectile remaining velocity is 68.38% lower than the initial velocity of impact and goes out of the goal. Also, the results for the projectile remaining velocity of the kevlar/ epoxy composite of 2-layer, in the case of impact with an initial velocity of 51 m/s displays that the projectile remaining velocity is 76.84% lower than the initial velocity of impact and goes out of the goal.Accurately in the projectile remaining velocity plot against the incident velocity of ballistic impact, it can be seen that when the velocity of the incident ballistic impact increases above the ballistic limit velocity, similarly, the remaining velocity is also increased. But this increase has a higher slope just above the ballistic limit. For this instance, whole perforation for the kevlar/ elastomer composite of 2-layer does not happen with a ballistic impact velocity event of 66.06 m/s. But with the velocity event of a ballistic impact of 68 m/s, whole perforation takes place with the remaining velocity of 15.78 m/s and the whole perforation for the kevlar/epoxy composite of 2-layer does not happen with velocity event of ballistic impact of 27.20 m/s. But with the velocity event of ballistic impact of 30 m/s, the whole perforation is accomplished with the remaining velocity of 12.27 m/s.



(a) (b)

Fig. 3. Comparison of residual velocities between analytical and experimental model a) on the kevlar/elastomer composite with a thickness of 1 mm, b) on the kevlar/epoxy composite with a thickness of 1 mm.

5. Conclusions

This analytical study investigated the process for modeling the penetration of spherical ended cylindrical projectile in the target of the the kevlar/elastomer and the kevlar/epoxy composite. This study can be represent a comprehensive model which based on the total amount of energy absorbed from the projectile and the importance of energy absorbing by primary and secondary yarns. The kinetic energy of the composite cone ahead, shear plugging will change by altering of the initial velocity of projectile. It was observed the energy absorption of the kevlar/elastomer 2-layer composite is higher than the kevlar/epoxy 2-layer composite. The verification of this analytical model has been done with experimental results[3], which are in good agreement with each other.

6. References

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