Impact Modeling of Bio-Textile Composite from Agave and Pineapple Leaf Fibers with Sandwich Structure

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Abstract. The objective of this research is a comprehensive model is presented to study the deformation and damage to bio-textile composite from agave and pineapple leaves fibers under small projectile impacts. The approach dynamically follows the strain wave propagation along each individual yarn away from the impact point. As in previous work the mechanics of wave propagation is formulated in terms of impulse-momentum balance equations, which are solved at each fiber crosser using a finite different technique. Our approach explicitly considers the various projectile characteristics namely; mass, velocity and shape, as well as all fiber properties such as denier, modulus, and tenacity. Even more importantly the model allow to account for slippage of yarn at crossovers and within the clamps. In previous work, slippage of yarn and fracture processes are described with a kinetic approach, which explicitly accounts for their dependence on impact rate. Results of model are in good quantitative agreement with published experimental data on a single ply and several plies biotextile composite. They also clearly indicate that yarn slippage through clamps often seen experimentally is responsible for some salient features observed in ballistic.

1. Introduction

Amour body design has now involved, with the use of hard body amour using metal until soft body amour. Research on bullet-proof vests have been done by some previous researchers. Research using material from the three components of 5086-H32 aluminum alloy, epoxy and Kevlar fabrics impregnated with shear thickening fluid is able to withstand projectile 9 mm pistol [4,14]. While research using ramie-epoxy composites can lower the cost of 95% compared with Kevlar [5]. Research using bullet-resistant vest panel bio textile been done with a sandwich structure [12], while make composites for bullet-resistant fabric with silk thread [6,11]. Research bulletproof vest manufacture of polyester fibers have been made [12]

The impact resistance of bio-textile composite is a subject of considerable experimental interest. The response of bio-textile to ballistic impact is very complex problem solving the interplay of a large number of variables, not the least of which relates to the dependence of bio-textile composite behavior on the size and shape of the projectile. Because of that complexity and the need to identify controlling variables, several models have been proposed to describe ballistic impact. The problem of single yarn impact from agave and pineapple at short times has been described analytically. The case of bio-textile
composite cannot, however, be solved exactly because the resolution of stress wave interactions and reflections at yarn crossovers is intractable. As a result, one has to resort to approximate analytical techniques or to numerical simulation models. An analytical solution based on the equations has been derived, but the solution focuses entirely on the impact zone and avoids consideration of boundary conditions. Other mathematical model descriptions based on more semi empirical approaches have been proposed [1] and [3].

In alternative model developed [13]. This approach, however, predicts that the deformation region has a conical shape, which is unrealistic [7].

A finite element model in incorporating viscoelasticity and a stain-rate sensitifity criterion has been proposed [5] but the description is unable to address issue of yarn slippage and again leads to the prediction that the area affected by the projectile is circular[13].

In a more refined approach pioneered [8,9]a single-ply fabric is represented by two-dimensional array form of nodes representing yarn crossover point [10]. Furthermore, finite difference methods are then used to solve the impulse-momentum balance equations at each crossover. For simplicity, all these models assumed the fibers to pin-jointed at their crossovers, and the influence of fiber slippage often observed experimentally could not be asssed. Some numerical results detailing the importance of slippage have been reported for the case of a single crossover [10,15].

The purpose of this is to develop Roylance’s model to multi-ply bio-textile composite and to fully consider the effects of yarn slippage at bio-textile composite at crossover points as well as within the clamps[9]. However, in contrast to the original model and describe yarn fracture using kinetic approach, which explicitly accounts for the dependence of yarn strength on impact velocity.

2. Model Representation

The description that follows is for a plain weave pattern for bio-textile, but approach can be easily extended to other structure designs. The contrast to previous work, however, single yarns are not pin-jointed but, rather, allowed to slip over each other as well as within the clamp as see the section on yarn slippage. Furthermore, in accordance with typical experimental setups the structure is clamped between thick plates with opening (L) and impacted in the center of the aperture. The projectile is assumed to have a spherical shape with radius (r_p) and mass (m_p).

As we now proceed to describe our computational algorithm for a single ply. Extension to systems of several plies will be the subject of separate publication. At time where t = 0, and is than the initial projectile velocity (v_p) is imposed along the z-direction on the central crossover of the ply, thereby creating a strain in the neighboring crossovers. The strain propagates outward along individual yarns at the velocity of sound, with the equations as follow.

\[ C = \left(\frac{E}{\rho}\right)^{1/2} \tag{1} \]

Where E is the yarn’s tensile moduls and \(\rho\) its density. Thus, in computational scheme, the strain propagation is followed in a series of incremental times steps, namely;

\[ \Delta t = \frac{l}{c} \tag{2} \]

Where \(l\) denotes the unit segment length between adjacent crossovers. At each step, all the crossover points at the current wave front are being visited and their velocities ad positions are continuously updated. These updates are made in a Lagrangian reference frame attached and extending with the fiber. Vectors components with respect to the laboratory coordinator are then calculated using the corresponding inclination angles, and than algorithm proceeds as follows; crossover with coordinate indexes \((i, j)\) in the ply of yarn. Its velocity at time \(t\) is recalulate from that at time \(t - \delta t\) an impulse-momentum balance equation [5].

\[ V(i, j, t) = v(i,j,t - \delta t) + F(i,j,t) \delta t/m \tag{3} \]
Where $V$ is three dimensional vectors, $m$ is mass of a crossover and $F(i, j, t)$ denotes the net force from all yarn segments connected to the crossover $(i, j)$. Simplicity in all simulations, we assume a linear Hookean behavior for each segment, $F - \varepsilon$, in which $\varepsilon$ is the local strain. The strain value on the yarn segment connecting crossover $(i, j)$ to crossover $(i - 1, j)$ is calculated from:

$$\varepsilon(i, j, t) = \varepsilon(i, j, t - \delta t) + \frac{[s(i, j, t - \delta t) + v(i, j, t)\delta t] - [s(i-1, j, t - \delta t) + v(i-1, j, t)\delta t]}{[s(i, j, t - \delta t) - s(i-1, j, t - \delta t)] - 1} \tag{4}$$

Where $s$ denotes the position vector for a crossover. Having determined its velocity from equation (3) and (4), the new position vector for crossover $(i, j)$ is then obtained from:

$$s(i, j, t) = s(i, j, t - \delta t) + v(i, j, t)\delta t \tag{5}$$

The boundary conditions at the clamped edges require that:

$$V(i_{\text{edge}}, j_{\text{edge}}, t) = 0 \tag{6}$$

Where after each time increment $\delta t$, the position of the projectile is updated to:

$$S_p(t) = s_p(t) + v_p(t)\delta t \tag{7}$$

As the projectile follows its path along the $z$-direction and the crossovers in the ply are deflected along that same direction, adjustments must be made to prevent penetration between a ply and the projectile. This is performed using the velocity corrections be described below. In order to ensure stability of the numerical algorithms, we recommend that these corrections be performed immediately after the velocities (Equation 3) of all crossovers have been calculated and before their new positions are updated. The corrections for the exclusion between a crossover $(i, j)$ and the projectile closely follow those described [9]

$$s'(i, j, t) = s(i, j, t - \delta t) + v(i, j, t)\delta t \tag{8}$$

Denote the temporary position of that crossover at time $t$ and $R_{\text{cross}}$ denote the distance between that new position and the center of the projectile. Clearly, interpretation occurs when $R_{\text{cross}} < R_{\text{proj}}$ in that case, the correction is made [2] and [10]

$$V(i, j, t) \rightarrow v(i, j, t) + [s''(i, j, t) - s'(i, j, t)]/\delta t \tag{9}$$

In which

$$s''(i, j, t) = s_p(t) + [s'(i, j, t) - s_p(t)]R_p/R_{\text{cross}} \tag{10}$$

Where $s_p(t)$ denotes the position vector of the center of the projectile. The gain in momentum for crossover $(i, j)$ equation (9) must be compensated by a corresponding loss for the projectile as follows:[1]

$$V_p(t) \rightarrow v_p(t) - [s''(i, j, t) - s'(i, j, t)][m/m_p]\delta t \tag{11}$$

Equation 11 effectively describes the slowing down of the projectile due to its contact with the crossovers in the ply.
3. Yarn Fracture and Slippage

As the plies are being deformed, our approach also allows for breakage of yarn segments between crossover. Following is previous work on the ultimate tensile strength of polyethylene and polyphenylene-terephthalamide fibers, assume that a yarn segment $i$ breaks through a kinetic process at a rate:

$$V_i = \tau \exp[-(U - \beta \sigma_i)/kT]$$  (12)

Where $\tau$ is the thermal vibration frequency, $U$ and $\beta$ are the activation energy and volume for covalent bond breakage, and $\sigma_i$ is the local stress acting on segment $i$. Typical value of $\tau$, $U$ and $\beta$ for high strength of fiber in these case agave canala fibers and pineapple leaf fibers. As note that in this research, we neglect the contributions of non-covalent (van der waals or hydrogen) bond to the yarn breaking process. This is a reasonable approximation in view of the high strain rates experienced by the fibers during ballistic testing.

In our approach, yarn slippage is assumed to set in at a rate that has the same functional form as that yarn fracture (equation 12) but with different values for the activation energy $U$ and volume $\beta$. On the order hand, $\sigma$ now denotes the different in stress in two consecutive yarn segments that are separated by a crossover.

Upon slippage, the unit length of the strained segment is increased, increment $\delta l_{slip} (<< l)$ within the time interval $\delta t$, whereas that of its less strained counterpart is decreased by the same amount. These changes in unit length for a segment must be properly accounted for when calculating its strain value.

Thus for a segment connecting crossover $(i,j)$ to crossover $(i-j)$, this is obtained by multiplying the term in parenthesis in equation (4) by $l_i - \delta l_i$ where $l_i$, $\delta l_i$ and $l_i$ denotes the unit lengths of the segment at time $t - \delta t$ and $t$ respectively. In addition slippage at a crossover point, also allow for yarn slippage at the clamps. The process is similar to that described above expect for the fact that it is initiated at a higher value of activation energy.

Currently discuss about parameter values for describing the experimental data of on the ballistics performance of a single-ply blended bio-textile composite (agave fiber and pineapple leaf fiber) clamped at two opposite sides only. The other two sides remain unrestrained. In this research value of the basis weight (bio-textile composite) $\omega$ of bio-textile composite are readily available from experiment. In typical weaving techniques, the yarn are woven into a very tight construction so that value of $\omega$ and of the yarn denier are not independent. Thus, for plain weave $\omega$ as follows;

$$\omega = 0.088 + 0.00009*\text{denier} + 1.19.10^{-7}\text{denier}^2$$  (13)

which was obtained from a fit of experimental $\omega$ values (in kg/m$^2$) for yarn with $200 < \text{denier} < 1500$ as equations (5). Within the framework of square lattice representation and one also shows easily that the distance $l$ between successive crossovers is given by;

$$l = 2*(\text{denier} * 1.11 10^{-7})/\omega$$  (14)

where the term in parentheses represents the yarn denier expressed in kg/m$^2$, and the mass of a crossover is then obtained from

$$m = \omega * \bar{l}^2$$  (15)

All the results presented bellow are for a single plain weave blended bio-textile composite with $\omega = 180$ kg/m$^2$. In high velocity testing of the yarn, it is reasonable to assume that the impacted yarn should have a modulus value higher than its static value. As known that values parameters for yarn slippage at crossover more difficult to determine, because values of the normalized activation volumes $\beta E/kT$ for these processes are left as free parameters, denoted by $\beta_{cross}$ and $\beta_{clamp}$ respectively.
In accordance with the experimental set-up with views references, assume a spherical projectile with a radius of 3.5 mm and a mass equal to 4.6 gram.

The model description is in terms of only two free parameters, $\beta_{\text{cross}}$ and $\beta_{\text{clamp}}$ which describe the extent of yarn slippage through crossovers and within the clamps respectively. All other parameter values such as yarn modulus and strength are easily determined from experiment.

4. Discussion

Result for the dependence of residual velocity on impact velocity ($V_p$) are presented in Figure 1. Model predictions for a choice of $\beta_{\text{cross}} = 10^3$ and $\beta_{\text{clamp}} = 10^4$ are represented by symbol O and compared to experimental data of reference symbol*. The agreement is judged to be excellent, and calculated threshold perforation velocity observation. The discontinuity observed experimentally impact velocity around $V_p = 300$ m/sec, which is very well reproduced by the model, an even more stringent test of approach in Figure 2 for the dependence of the energy absorbed by the bio-textile composite on the impact energy. The former is simply given by the difference between the kinetic energy of the projectile before and after impact. As Figure 1, the experimental data of (*) shows a discontinuity at an impact energy of 157 joule, which corresponds to impact velocity $V_p = 300$ m/second. Inspection of Figure 2 again reveals an excellent agreement with model calculations.

![Figure 1. Relationship Impact Velocity (m/sec) with Residual Velocity (m/sec)](image)

Impact velocity results, for the dependence of residual velocity on impact for a single ply yarn of bio-textile composite with $\omega = 280 g/m^2$. The fabric has a square shape with $L = 100$ mm, and its clamped at two opposites sides and the other sides remain unrestrained. Model predictions for a choice $\beta_{\text{cross}} = 10^3$ and $\beta_{\text{clamp}} = 10^4$ are presented by symbol (*). Experimental data taken from reference are donated by symbol (0). The projectile characteristics are given in the section on the model. Symbol * denotes model values in the absence of yarn slippage through clamps.
Figure 2 illustrates the strong effect of impact speed $V_p$ on the deformation morphology of a single-ply bio-textile composite. The figure is for a time corresponding either to full arrest of the projectile ($V_p < 180 \text{ m/sec}$) or through perforation of the bio-textile composite ($V_p > 180 \text{ m/sec}$). The projectile radius equals three times the length of a yarn segment between two consecutive crossover points. Note the large amount of deformation and creasing at low velocity ($V_p < 300 \text{ m/sec}$), which see figure 1 and 2 is mainly driven by yarn slippage through clamps. These creases are consistent with the stretch marks observed experimentally at those impact speeds in the direction of clamped yarns. Also in support of model findings is the experimental observation of a substantial amount of yarn slippage at the clamp. Further inspection of model results Figure 2 reveals that above a critical impact speed of 300 m/sec, fabric penetration occurs before the transverse deflection of the fabric has reached the clamp edges. That sudden decrease in the extent of transverse deflection of the fabric fully explains the dramatic drop in absorbed energy observed in Figure 2–3 at $V_p > 300 \text{ m/sec}$. Similar conclusions have been reached from the model results.

Figure 3. Model Element for a Bio-textile composite panel

To study of the importance of yarn slippage through clamps, which is explicitly included in approach. The results are in poor agreement with the experimental data. Further investigation reveals that although calculated absorbed energy values could be increased through appropriate changes in yarn strength, and the process of yarn slippage through the clamps appears to be crucial for describing the discontinuities observed experimentally. In alternative model described, slippage was not considered, and part of those discontinuities could be ascribed to latent crimp present in the yarn. The importance of yarn slippage through crossovers has also been studied. Turning first to the data of figure 2–3, its found that model
results for a choice of $\beta_{\text{cross}} = 0$ and keeping $\beta_{\text{clamp}} = 10^4$ are almost identical to those obtained for $\beta_{\text{cross}} = 10^3$ (with symbol *). As far as could determine, a moderate amount of yarn slippage through crossover point has little effect on ballistic performance, at least until fiber fracture sets in. However, as already mentioned early, inclusion of that slippage process in a finite-difference model like this one appears to be crucial for ensuring stability and convergence of the numerical results.

5. Conclusions

To conclude, that have presented a comprehensive model for studying the deformation of damage to bio-textile composite under small projectile impact. The approach explicitly considers the various projectile characteristic such as; mass, shape and velocity as well as all fiber properties such as denier, modulus and tensile strength. Even more importantly the model allows for the first time to account for slippage of yarn over one another as well as within the clamps. Another essential feature of model resides in the fact that yarn slippage and fracture processes are described with a kinetic approach which explicitly accounts for their dependence on impact rate. Detailed results of model for bio-textile composite with sandwich structure will be presented in forthcoming publication.

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