COMPUTATIONAL BALLISTIC IMPACT ANALYSIS OF AIRCRAFT ARMORS

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ABSTRACT
Lightweight and ballistic resistance are significant parameters in the design of aircraft armors. Aircraft should not compromise the payload or its maneuverability due to the armors added to the system. In addition to this, the aircraft has to sustain high ballistic resistance under enemy fire. In the design of aircraft armors choosing light and high strength materials that respond to these demands ballistic impact resistant concepts are being developed.

In this study numerical simulation of ballistic impact is carried out for the aircraft armors. The ballistic impact response of the fiber reinforced composite armor is computed using forward finite difference method. Cylindrical rigid projectile hitting the woven crimp composite fabric at an angle 90° is analyzed. The yarn segments between hinged joints at crossovers are modeled using discrete mass-spring-damper in pin-joint systems consisting of planar square lattices. After a certain time of impact: displacement of the fabric, change in the velocities and the failure in the material is computed and depicted graphically. The effect of crimp and slip viscosity on the ballistic performance of the fabric is examined and discussed.

Keywords: Aircraft armors, fiber reinforced composite armors, cylindrical projectile, ballistic performance, forward finite difference method.

1. INTRODUCTION
Combat and transportation vehicles that operate in land and air are commonly ballistic resistant under the enemy fire to protect the personnel inside and/or the payload. The armors in these vehicles offer protection with modular, flexible, lightweight and durable designs. When the aircraft armors are taken into consideration, weight becomes a very important factor such that aircrafts should not compromise the payload or its maneuverability due to the armors added to the system. Depending on recent progress in material sciences, particularly by the invention of synthetic fiber, aircraft armors are now being developed lighter and stronger than they ever were before.

In the beginning of 1970s, a strong synthetic fiber is introduced under the trade name Kevlar® by DuPont. Due to high tenacity and elastic modulus; Kevlar® has found widely used application in ballistic protection, aerospace and military. The aramid fibers for ballistic protection is not limited to Kevlar®, similar fibers having roughly the same chemical structure as Kevlar® are also developed namely, Technora®, Twaron®, Nomex® and Teijinconex® [1, 2]. There are also recently developed high performance fibers, namely Dyneema®, Zylon® and etc. that are being used in ballistic protection and defense applications. Since the start of commercial production, the performance of these fibers has been improved considerably, still holding a significant potential for further improvements.

Even though, fabrics made of high performance fibers are being increasingly utilized in the manufacture of aircraft armors, modelling and simulation of ballistic impact into fabrics has

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always been a very challenging task due to the complexity of the problem that incorporates both micro and macrostructural aspects. Thus, analytical and numerical models that accurately predict ballistic behavior have been slow to evolve.

The development of an analytical model requires thorough understanding of the physical phenomena taking place during ballistic impact. A very early analytical model is proposed by Rakhmatulin and Dem’yanov [3-6]. Following to this work, in the middle of 1950s Smith et al. [7] developed an analytical model that correlates velocity of transverse wave front with the longitudinal wave velocity and yarn strain, and using this model they studied the response of a single-yarn to transverse impact. Recently, Phoenix and Porwal [8-10] developed a model to solve the problem of transverse impact on an un-tensioned 2-D membrane by a blunt-nosed projectile and then revised it to include multiple bi-axial layers.

Nonetheless, research on simulation methods for modelling ballistic impact into fabric-based has also been very challenging. There are several proposed numerical simulation models that have been used so far, known as pin-joint models. Some of the earliest, seminal work was due to Roylance et al. [11, 12] who developed an elementary pin-joint model for ballistic impact into a single fabric layer. These early models consisted of laminar square lattices of interconnected massless elastic rods representing the yarn segments between crossovers and with all the yarn element mass associated with yarn segments concentrated at yarn crossover points. In the late 1990’s these models had evolved to include simple warp and weft yarn interlacing and crimp [13, 14], and some were said to manage multiple layers and yarn slip [15], though few results, if any, appear to have been published. Similar pin-jointed models and plotted results were also introduced by others [16-19] and some workers developed FEM models in an effort to capture more realism [20, 21], though at greatly increased computational cost.

We lastly give a brief review of the relevant literature developed in Turkey. For instance, Özşahin and Tolun [22, 23] conducted ballistic impact tests of aluminum alloys as lightweight armors. They have investigated impacts of surface coating and adding supporting layers on high velocity normal impact resistance of aluminum plates. Moreover, Bozdoğan and his team [24, 25] studied the mechanical hazard resistance properties of high performance fabrics.

We, in this study, carried out the computational ballistic impact analysis of the aircraft armors. The proposed numerical model is based on authors’ previous works [26-29] and simulates the ballistic impact of a cylindrical (RCC) rigid projectile into a plain weave fabric target. After providing some details on the finite difference formulation of the model, we present a sampling of results obtained at various times after impact. The results include contour plots of out-of-plane displacements, out-of-plane and in-plane velocities and yarn strain distributions at a given time, as well as plots, over time, of maximum local strain level, and out-of-plane velocities and displacements in the contact region of the projectile. Some parameters will be varied to provide insight into the rich behavior possible. The influences of varying crimp factor and slip viscosity on the ballistic performance of the armor are further studied and discussed.

2. PROBLEM DEFINITION

In this section we will present our model developed for the numerical simulation of the ballistic impact onto aircraft armors and we will explain the elements used in both modelling of the projectile and fabric. This model is developed at Cornell University over the past few years [29] and was programmed on MATLAB platform considering the following assumptions:

- A flat-nosed, right circular cylinder (RCC) projectile with a radius of \( r_{proj} \), mass of \( m_{proj} \) and initial velocity of \( v_{proj} \) is assumed to impact a bi-axial composite panel from a 90° perpendicular angle. Besides, the projectile is rigid, its shape, \( i.e. r_{proj} \) does not change during the impact and deceleration process.

- The armor material is chosen as a ballistic resistant fabric made of fiber reinforced composite. The fabric is structured as an over-under interlacing of yarns to form a plain weave fabric layer. Also, the fabric surface is defined such that it is large enough so that interference from wave reflections at the boundaries plays no role.

- At the moment of impact, the instantaneous velocity drop is calculated using conservation of momentum between the projectile and the square patch of fabric material it contacts, resulting in a new velocity of \( v_{proj} \).

- To reduce the computational cost we only model the quarter domain and calculate results to represent the entire piece of fabric. To do this we impose boundary conditions to describe and account for the \( x- \) and \( y- \) axial symmetries.

A forward finite-difference (FD) method is applied to numerically solve the problem of transverse
ballistic impact on a woven crimp model for biaxial fabrics fabric. The computational domain can be seen in Figure 1(a). The impact process has been started by assigning relevant masses and velocities to all the red nodes covered within quarter-circle area.

The fabric structure is constructed using square lattice system of pin-joint models. This layout is shown in Figure 1(b), in which the discrete masses represent the masses of yarns that are interconnected by elastic spring elements representing the elastic properties, or stiffness of the yarns and lastly, the dampers represent the viscoelastic properties of the yarns.

The woven model is presented with the fabric panel in its unperturbed crimped state in Figure 2(a). As seen from this figure, crimp factors are equal in both horizontal and vertical yarn directions. The blue lines represent the horizontal, red lines represent the vertical yarns; while the circles in red/blue show the cross-over nodes.

The cross-over nodes at which the horizontal and vertical yarns coincide is modeled as shown in Figure 2(b). Once the deformation begins, the yarns will start to move relative to each other that will result in the cross-over nodes to alter their position and velocities. Depending on this relative motion, the out-of-plane tension and/or compression, as well as in-plane sliding forces start to occur. These forces with the parameters used to model them are also shown in Figure 2(b).
2.1 Numerical Model

As mentioned before, the numerical solution is handled by forward-finite difference method.

The Newtonian equation of motion in all three Cartesian coordinates are solved for the current nodal velocities [17, 29, 30].

\[ f = m \frac{dv}{dt} \]  \hfill (1)

Equation (1) can be written in impulse-momentum format for a given time \( t \) and in the all directions:

\[ \frac{m_{\text{hori}}}{\Delta t} (v_{\text{hori},x} - v_{\text{hori},x}^{t-\Delta t}) = \sum f_{\text{hori},x}^{t-\Delta t} \]  \hfill (2a)

Figure 2. (a) Pin-jointed network representing the fabric panel with out-of-plane crimp in an initial unperturbed state, (b) The inner-forces in horizontal and vertical yarns.
where $v^t_{\text{hori},x}$, $v^t_{\text{hori},y}$ and $v^t_{\text{hori},z}$ represent the velocity components of horizontal yarns, while $v^t_{\text{vert},x}$, $v^t_{\text{vert},y}$ and $v^t_{\text{vert},z}$ represent the ones of vertical yarns at time $t$. Also, $f^t_{\text{hori},x}$, $f^t_{\text{hori},y}$ and $f^t_{\text{vert},x}$, $f^t_{\text{vert},y}$, $f^t_{\text{vert},z}$ denote the projections of tension forces of horizontal and vertical yarns, respectively, in the directions of $x$-, $y$- and $z$-directions at time $t$. 

Once the velocity field has been determined, these values are used to solve for the nodal positions in all directions at time $t$.

Lastly, the spring element lengths $L'$ are determined and then used to solve for updated strains within the springs as given in the following:

$$
\varepsilon^t = \varepsilon^{t-\Delta t} + \frac{L' - L^{t-\Delta t}}{L^{t-\Delta t}}
$$

### 2.2 Input Parameters and Variables

This section deals with the physical and simulation parameters that are necessary to execute our numerical code of the woven crimp model for biaxial fabrics. These parameters and variables are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definitions</th>
</tr>
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<tbody>
<tr>
<td>$E_x$</td>
<td>Young's modulus in the x-axis</td>
</tr>
<tr>
<td>$E_y$</td>
<td>Young's modulus in the y-axis</td>
</tr>
<tr>
<td>$\rho_{\text{fabric}}$</td>
<td>Density of fabric material</td>
</tr>
<tr>
<td>$AD$</td>
<td>Areal density of fabric material</td>
</tr>
<tr>
<td>$v_{\text{proj}}$</td>
<td>Projectile velocity right before impact</td>
</tr>
<tr>
<td>$v_{\text{proj},0}$</td>
<td>$\frac{R_{\text{proj}}}{\pi R_{\text{proj}}^2 AD + m_{\text{proj}}}$</td>
</tr>
<tr>
<td>$m_{\text{proj}}$</td>
<td>Projectile mass</td>
</tr>
<tr>
<td>$R_{\text{proj}}$</td>
<td>Projectile radius</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Crimp factor</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Rocking viscosity</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Slip viscosity underneath projectile</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>Slip viscosity</td>
</tr>
<tr>
<td>$\tau = \frac{R_{\text{proj}} t}{a_0}$</td>
<td>Dimensionless time</td>
</tr>
<tr>
<td>$a_0 = \sqrt{\frac{E_x}{\rho_{\text{fabric}}}}$</td>
<td>Tension wave speed</td>
</tr>
<tr>
<td>$d = AD / \rho_{\text{fabric}}$</td>
<td>Thickness of the fabric</td>
</tr>
<tr>
<td>$m_y = \frac{AD L^2}{2}$</td>
<td>Fabric mass per node</td>
</tr>
<tr>
<td>$n_{\text{steps}}$</td>
<td>Actual number of time steps</td>
</tr>
<tr>
<td>$n_{\text{elem}}$</td>
<td>Number of element spacing in the entire fabric square</td>
</tr>
<tr>
<td>$dL$</td>
<td>Grid size</td>
</tr>
<tr>
<td>$dt$</td>
<td>Time step size</td>
</tr>
</tbody>
</table>

Table 1. A list of physical and simulation parameters used in the code
2.3 Crimp Factor

For the interlaced yarns in the fabric, crimp is defined as the out-of-plane undulation or waviness of a yarn. In the international standard ISO 7211-3 [29, 31] the crimp factor is expressed as follows:

\[ k = \% \frac{P - L}{L} \]  

Here, P represents the actual length of the yarn while L is the projected length in the plane measured from both ends, see Figure 3.

In this study we have used the crimp factor as \( \alpha = \tan(\varphi) \). For the forthcoming simulations, the values of crimp used and their comparisons with the ones in ISO standards are given in Table 2.

As depicted in Table 3, \( \alpha = 0.0 \) shows the case of straight yarn, while crimp factor \( \alpha = 0.4 \) stands for a yarn which is stretched to its 7.70 % length.

<table>
<thead>
<tr>
<th>Table 2. Comparison of crimp factors</th>
</tr>
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<tbody>
<tr>
<td>( \alpha )</td>
</tr>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
</tr>
</tbody>
</table>

3. NUMERICAL SIMULATIONS AND DISCUSSIONS

Analysis and simulations are carried out for the fabric made of high performance ballistic-resistant polyethylene fiber, namely Dyneema®. The material properties of Dyneema® can be found in Table 3. As mentioned before, the impactor is chosen as a rigid RCC (right circular cylinder) projectile with a mass of 8 gr and a diameter of 9 mm. The initial velocity of projectile is set to 406 m/s.

As we carefully investigate the displacement plot given in Figure 4, for an elapsed time of 24.71 µs (\( \tau=60 \)) we see that the fabric deforms about 9 mm. We particularly observe that the yarns in contact with the projectile become straightened and flattened, in other words yarns change from crimped state to un-crimped state (de-crimp). This process provides the projectile an additional space for its transverse motion. Whereas, the yarns that are not in contact with projectile preserve their crimped state.

Table 3. Material properties of Dyneema®

| \( E_x \) | Young's modulus in the x-axis | 117 GPa |
| \( E_y \) | Young's modulus in the y-axis | 117 GPa |
| \( \rho \) | Density | 980 kg/m³ |
| \( \varepsilon_{max} \) | Failure strain | 2.81 % |

The ballistic impact simulation onto woven crimped (\( \alpha = 0.15 \)) fabric is performed for dimensionless time \( \tau=60 \) which corresponds to \( t=24.71 \) µs. The results to predict the ballistic performance of the fabric are plotted in several figures. First result is the deformation of the fabric after the impact, shown in Figure 4. Other quantities for ballistic performance prediction are the out-of-plane velocity, in-plane velocity, strain profiles and vertical forces in the yarns. The views of these results from top-, side- and 3-D views are demonstrated in Figure 5, Figure 6, Figure 7 and Figure 8, respectively.

Next, we plot Figure 5 to show slowdown of the vertical velocity of the projectile. Recalling that the initial velocity was set to 406 m/s, we find in this figure that the projectile is decelerated to approximately 300 m/s in 24.71 µs (\( \tau=60 \)).

Figure 6 plots the in-plane velocity distribution and illustrates material flow in the fabric. This inflow of yarn material is necessary for the deformation cone to form. As seen from this figure, the in-plane velocities take higher values in the impact cone due to sliding yarns over each other.

Another important result is the strain profiles that are demonstrated in Figure 7. By the help of this figure, we point out that the highest strains, approximately 0.9 %, are obtained at the contact zone in 24.71 µs time. The strain profiles are of great importance in the ballistic design process, because the decision on whether the failure of the yarn occurs or not is made according to strains. In our simulation, since highest strains are read lower
than 2.81 %, which is the failure strain of Dyneema yarns, we directly conclude that no failure occurs due to not exceeding the maximum strain. Additionally, from the top view of this figure we see the position of which the tension wave reaches. For this purpose, the patch size of the computational domain is taken as $K_{\text{patch}}=0.4$. Note that the rest of the figures are plotted for a patch size of $K_{\text{patch}}=0.1$.

Lastly, Figure 8 is plotted to show the contours of vertical force in the fabric. The force in the edge yarns of contact zone have very large values, while the ones that are not in contact with projectile are calculated nearly zero.
Figure 4. Out-of plane (vertical) displacements of yarns (a) top-view, (b) side-view (c) 3-D view, 
$\alpha=0.15$, $\tau=60$, $K_{patch}=0.1$
Figure 5. Out-of-plane (vertical) velocities of yarns (a) top-view, (b) side-view (c) 3-D view, 
\( \alpha=0.15, \tau=60, K_{\text{patch}}=0.1 \)
Figure 6. In-plane (horizontal) velocities of yarns (a) top-view, (b) side-view (c) 3-D view, $\alpha=0.15$, $\tau=60$, $K_{patch}=0.1$
Figure 7. Horizontal strain profiles (a) top-view, (b) side-view (c) 3-D view, 
\( \alpha=0.15, \tau=60, K_{patch}=0.4 \)
Figure 8. Yarn forces in z-direction (a) top-view, (b) side-view (c) 3-D view, \( \alpha=0.15, \tau=60, K_{patch}=0.1 \)
3.1 Effect of Crimp on Ballistic Performance

Crimp is one of the very important factors that affects the ballistic performance. Recent studies show that intentionally introducing crimp in a controlled way can improve ballistic performance. In order to investigate this effect we plot Figures 9(a) and 9(b). Figure 9(a) shows the variation of horizontal strains with respect to dimensionless time for selected values of crimp factors. At first we see that the strain ratio $\varepsilon_{\text{hori}}/\varepsilon_{\text{max}}$ is not reached to 1, which means that no failure has been occurred in the yarns. Another point is as the crimp factor is increased, we observe that the strains tend to decrease. For example, the lowest strains are measured for the case with the highest crimp factor $\alpha = 0.4$. Discussing this result, we can conclude that the crimp factor appears to play a beneficial role to enhance the ballistic behavior of the yarns. Woven fabrics made with higher crimp will have lower strains and higher V50, which is an important parameter in the ballistic fabric making process, than fabrics with lesser and/or no crimp in the yarns.

Figure 9(b) shows the variation of the deceleration of vertical velocity over the dimensionless time for selected values of crimp factors. We see in this figure that deceleration of the projectile is slower for the fabrics made with higher crimp in the yarns than the ones with lesser and/or no crimp. Therefore we can conclude that, on the contrary to the result found in previous figure, the crimp in the deceleration of the projectile has a negative role on ballistic performance of fabrics.

![Figure 9](image_url)

**Figure 9.** Variations of (a) horizontal strains and (b) vertical velocities with respect to dimensionless time for selected values of crimp factors.

3.2 Effect of Slip Viscosity on Ballistic Performance

Similar to previous subsection, we plot Figures 10(a)-(c) to investigate the role of inter-yarn slip viscosity on the strains, vertical displacements and vertical velocities, respectively. To do this, the viscosity values in both $x$- and $y$- directions are taken as equal. Slip viscosity is a parameter that controls how much viscous slip occurs between yarns due to yarn force imbalance at the nodes driving shear effects at the yarn crossovers [29]. Figure 10(a) reveals the slip viscosity has a beneficial role in reducing the strains. On the other hand, Figures 10(b) and 10(c) show a negative role of slip viscosity on the deformations of fabric and the deceleration of the projectile. In detail, lower slip viscosity causes a lower deceleration of the projectile and higher deformations of the fabric.
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Figure 10. Variations of (a) horizontal strains, (b) vertical velocities and (c) vertical displacements with respect to dimensionless time for selected values of slip viscosities, $\alpha=0.15$

4. CONCLUSION

Within this study we have performed the computational ballistic impact analysis of aircraft armors. For this purpose, we used our code to simulate the impact into a woven fabric target by a rigid RCC projectile. This model allows us to vary projectile radius, mass and velocity, and various parameters characterizing yarn spacing, stiffness and linear density, non-linear viscoelastic slip at yarn crossovers and between fabric and projectile, non-linear contact compressibility of yarns at crossovers, and degree of yarn crimp. As we run cases, the code produces several results plots such as projectile displacement over time, out-of-plane fabric displacement, and projectile velocity decay over time. Using the woven crimp model we have presented the effect of varying crimp on strains, out-of-plane displacements and out-of-plane velocity and have observed that higher crimp causes lower strain and slower velocity deceleration. Also, when we investigated the varying slip, we have found that higher crimp can result in lower strain but milder reduction in projectile velocity.

In the future, the numerical simulation model presented here can be extended to handle performing a wide variety of armor constructions and bullet scenarios.

REFERENCES

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