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Numerical Analysis of the Ballistic Impact Behavior of 2D Woven Fabrics

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Abstract

Numerical simulations of the impact behavior of a single layer of 2D woven fabrics at low-velocity are presented. The configurations considered for the studies are three different architectures of 2D woven fabrics (plain weave, twill weave and satin weave) made of Kevlar and UHMWPE fibers. The numerical models are formulated and used to investigate the ballistic impact behavior of 2D woven fabrics when the fabrics are clamped along all four edges (4BC) or two edges (2BC). In this paper, the ballistic performance of 2D woven fabrics is first evaluated in terms of their structural integrity after impact, and the effect of boundary conditions by changing border constraints is investigated in numerical simulations. Subsequently, the effect of fracture behavior of primary and secondary yarns, energy absorption behavior and failure mechanism of 2D woven fabrics were discussed. It was found that the UHMWPE fabrics outperformed the Kevlar fabrics in terms of energy absorption. In addition, it was found that the fabrics with two fixed edges reduce the residual velocity of the bullet more and absorb more energy than fabrics with four fixed edges. Numerical predictions have shown that plain weaves are the most structurally stable fabrics. The ballistic performance, as well as the structural and mechanical properties of twill weaves, lie between the plain and satin weaves.

Subject Areas

Composite Material

Keywords

2D Woven Fabric, Pyramidal Deformation, Boundary Condition, Clamped Edge, Yarn Pullout, Yarn Slippage, Residual Velocity, Kevlar, UHMWPE

1. Introduction

With the invention of explosives, the dynamics of the battlefield took on different forms. Humanity was now exposed to ballistic threats from low and high-velocity projectiles such as bullets, shrapnel, fragments of hardened steel from a hand grenade or massive explosions from artillery shells or bombs. The lack of flexibility, mobility, safety and ergonomics, which until some time ago, was due to the use of mostly steel solutions in the manufacture of ballistic protective equipment, has meant that research has had to be carried out to overcome these shortcomings and to find ever more innovative solutions for the optimal protection of the human factor in the face of these deadly threats. The level of individual protection and protection performance against ballistic threats has evolved simultaneously with the progress of battlefield confrontations.

The bulletproof materials used in the manufacture of ballistic protective equipment have evolved from traditional materials such as metals to ceramics, aramid fibers (Kevlar and Tawron), ultra-high molecular weight fibers (UHMWPE-Dyneema and Spectra), polyphenylene benzoxazole fibers (PBO-Zylon) and polyhydroquinone di-imidazopyridine fibers (PIPD-M5). Aramid and ultra-high molecular weight polyethylene (UHMWPE) are the most commonly used materials for the manufacture of ballistic protective equipment. These bulletproof materials have a higher tensile strength and are lighter than other materials [1]-[6].

The current and future requirements for the manufacture of individual protective equipment such as bulletproof vests are to provide protection against projectiles and shrapnel using multi-layer aramid/UHMWPE fabrics. Flexible bulletproof vests (**Figure 1(a)**) are used to protect against fragments from explosions and small arms projectiles (low-velocity and low-energy bullets) in accordance with the test standards. In addition, it provides sufficient flexibility for body movement and offers maximum comfort. To achieve protection against rifle projectiles (high-velocity bullets), hard armor plates are manufactured to be inserted into bulletproof vests (**Figure 1(b)**) to prevent high-velocity threats [7]. Hard ballistic plates can be made of metal, ceramic and textile composites.

(a) (b)

Figure 1. Bullet stopping vests: (a) soft bulletproof vest; (b) hard bulletproof vest.

Ballistic fibers are currently produced in two-dimensional (2D) and three-dimensional (3D) arrangements. The fibers are either processed into woven fabrics, which are then assembled into a ballistic panel. Woven fabrics are typically made from aramid or UHMWPE fibers and are a very common type of 2D ballistic structure due to their good structural integrity and ability to propagate shock waves between the two sets of yarns arranged perpendicular to each other. The yarns in the longitudinal direction of the fabric are called warp yarns and the yarns placed in the traverse direction are called weft yarns (Figure 2).

Depending on the geometric configuration, 2D fabrics can be plain, twill and satin, each with different structural characteristics (Figure 3).

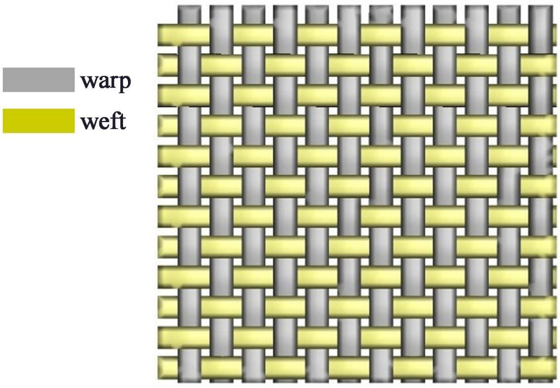


Figure 2. The warp and weft yarns in the fabric structure.

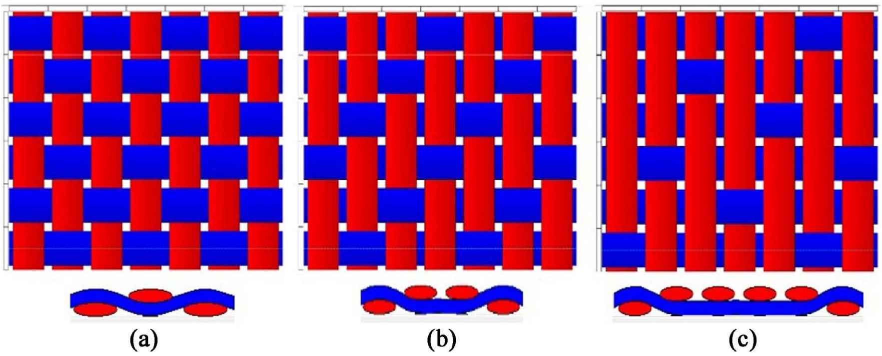


Figure 3. Geometric configuration of 2D fabrics: (a) plain; (b) twill; (c) satin.

A 3D fabric architecture is an integrated structure comprising conventional 2D fabrics and transverse yarns, connecting the yarns in the plane along the thickness direction (Figure 4). The relevant ballistic advantages of 3D fabrics include improved stiffness and strength in the transverse direction and increased resistance to fabric unfolding in the plane. The task of impacting a 3D fabric is solved in three orthogonal directions and not only in two in-plane directions, which improves the energy absorption capacity of the entire material.

In the present study, the ballistic impact behavior of a single layer of three different types of 2D woven fabrics (plain, twill and satin) made of Kevlar and UHMWPE fibers is first investigated using simulation methods. The 2D woven

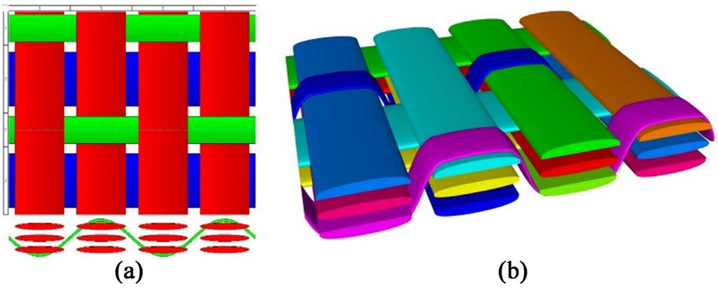


Figure 4. A geometrical model of a 3D orthogonal fabric of three layers: (a) geometric configuration; (b) 3D woven architecture.

fabrics are usually constrained, which must have certain effects on the ballistic performance. The numerical model is formulated and used to investigate the ballistic impact behavior of 2D woven fabrics when the fabric is clamped along all four edges (4BC) or two edges (2BC) with yarns aligned parallel to the edges. Thus, the study aims to investigate the effect of boundary conditions by changing border constraints in numerical simulations.

Finally, a comparative analysis between the three types of 2D woven fabrics made of Kevlar and UHMWPE fibers is presented, to evaluate the ballistic performance in conjunction with their structural integrity after impact.

2. The Theoretical Approach

2.1. CAD Model of 2D Woven Fabrics and Projectile

Three different types of 2D weaves are used in this study: plain weave, twill weave and satin weave (Figure 5).

TexGen software was used for the geometric modelling of the 2D woven fabrics. The number of yarns of the weft and warp in each system of 2D fabrics was 13, and the geometric structure of the yarn system is shown in Figure 6.

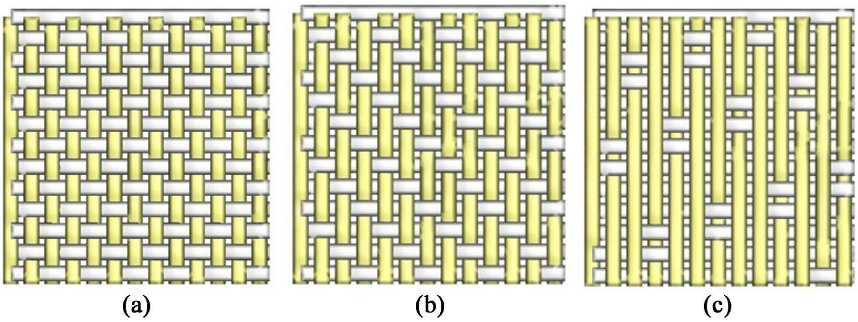


Figure 5. The weaving architectures used in analysis: (a) plain; (b) twill; (c) satin.

A 9 mm full metal jacket (FMJ) bullet is used for the impact analysis (Figure 7).

2.2. Finite Element Modeling

The finite element method (LS-DYNA software) has been used to model and analyze the impact behavior of the three investigated architectures. The finite element models of the three types of 2D woven fabrics and the projectile have been developed using *Solid* elements (**Figure 8**).

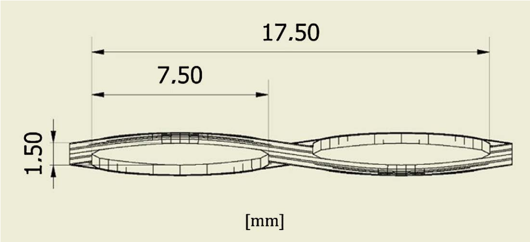


Figure 6. The cross-section of the yarns in the warp and weft system.

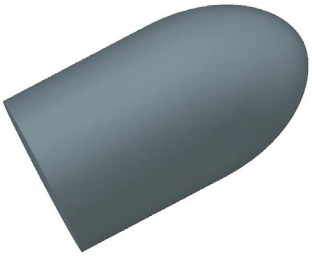


Figure 7. The projectile used in analysis.

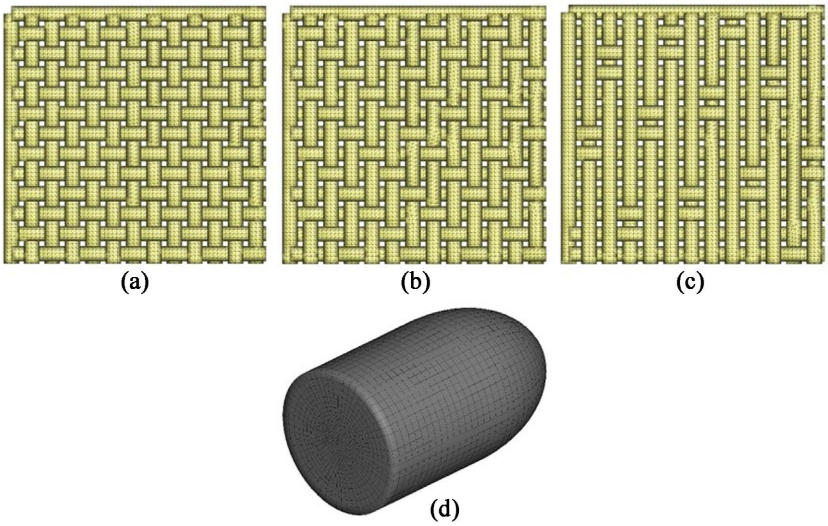


Figure 8. Finite element model: (a) plain weave; (b) twill weave; (c) satin weave; (d) projectile.

The sensitivity of the mesh was investigated by considering an element size of 2.5 mm for the weaving architectures, and 0.5 mm for the projectile.

The interaction between the yarns and between the yarns and the projectile has been modeled using the AUTOMATIC_SURFACE_TO_SURFACE contact algorithm. In the case of Kevlar fabrics, the friction coefficient (FS) is assumed to be 0.25 for the contact between the yarns, and 0.2 for the contact between the yarns and the projectile [8]. For UHMWPE fabric, however, FS is set at 0.11 for the contact between the yarns, and 0.2 for the contact between the yarns and the projectile [9].

The numerical model is formulated and used to study the ballistic impact behavior of 2D woven fabrics when the fabric is clamped along all four edges (4BC) or two edges (2BC) with yarns aligned parallel to the edges (**Figure 9**).

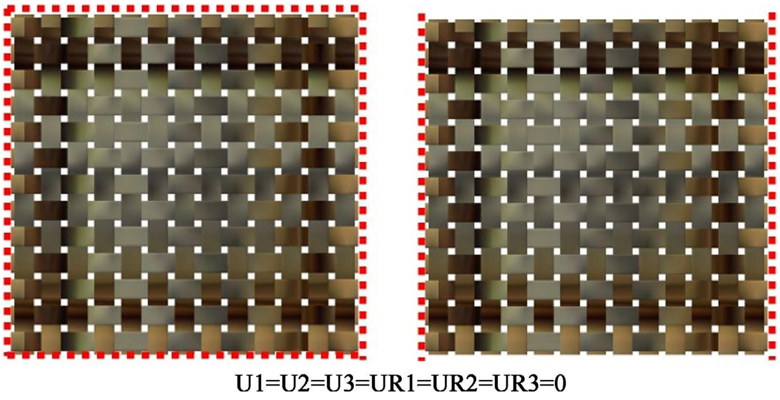


Figure 9. The boundary conditions and the constraints applied.

2.3. Constitutive Modeling

The MAT_PLASTIC_KINEMATIC constitutive model has been used to define the material behavior on impact for the bullet and the three types of 2D woven fabrics. This material model is used for isotropic and kinematic hardening plasticity with the option of including the rate effect according to the Cowper-Symonds strain rate model:

The model is expressed by the constitutive equation:

$$\sigma_Y = \sigma_{Y0}\left[1+\left(\dot{\varepsilon}/C\right)\wedge\left(1/P\right)\right] \tag{1}$$

where:

- σ_Y, σ_{Y0} represent the yield stress limits of the material;
- $\dot{\varepsilon}$ is the strain rate;
- p, C are material constants.

The basic properties of the bullet and weaving architectures are listed in **Table 1** [10]-[13].

2.4. Analysis and Results

The ballistic impact on the 2D woven fabrics is simulated with a striking velocity of 380 m/s. The geometric configuration, which was analyzed numerically, has been designed with an angle of incidence of 0˚, between the projectile and the 2D woven fabric, which coincides with a frontal impact (**Figure 10**).

Figure 11 shows the behavior of the 2BC plain woven fabric made of Kevlar in the event of a ballistic impact. It can be seen that a pyramidal deformation through-thickness occurs in the initial phase of the impact. The final breakage of the yarn occurs after 0.14 s, when the bullet perforates the fabric. The Kevlar 2BC plain weave retains good structural integrity after the impact with the projectile.

Figure 12 displays the development of the impact process of the 4BC plain

Table 1. Material parameters for the bullet and the 2D woven fabrics.

Parameter	Unit	Notation	Value (lead)	Value (Kevlar)	Value (UHMWPE)
Young's modulus	MPa	E	17,000	7500	21330
Poisson's ratio	-	PR	0.40	0.30	0.27
Density	kg/m^3	RO	11270	1440	962
Yield stress	MPa	SIGY	8	1240	320
Tangent modulus	MPa	ETAN	15	1500	7040
Hardening parameter	-	BETA	0.1	0	0
Strain rate parameter C	s^{-1}	SRC	600	0	0
Strain rate parameter P	-	SRP	3	1	1
Failure strain	%	FS	-	3.6	4.3
Formulation for rate effects	-	VP	-	1	1

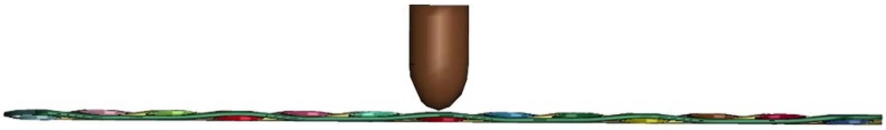


Figure 10. The impact angle.

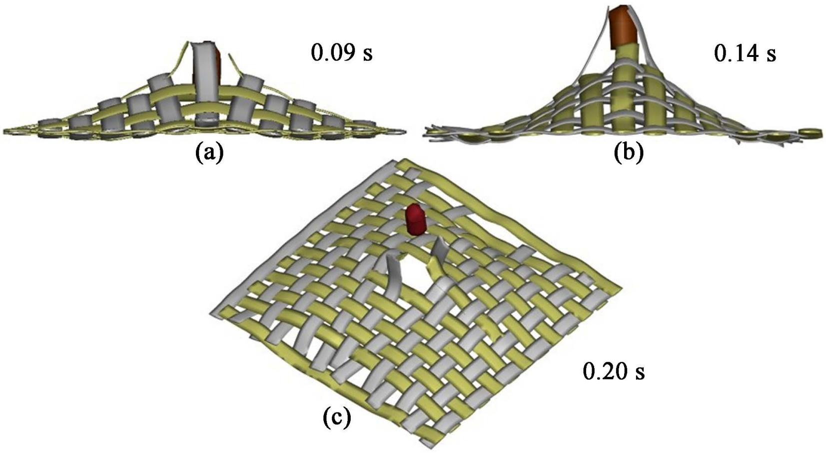


Figure 11. Evolution of the impact process for the Kevlar fabric—2BC plain weave.

woven fabric made of Kevlar during the ballistic impact. It can be noticed that a pyramidal deformation through-thickness occurs in the early stages of the impact. Yarn's final rupture occurs after 0.07 s when the bullet perforates the fabric, twice as fast as in the case of the 2BC plain woven fabric. The failure of the yarns occurs at almost the same time for the warp and weft yarns. In addition, the Kevlar 4BC plain weave maintains strong structural integrity after the impact of the projectile.

Figure 13 illustrates the behavior of the 2BC plain woven fabric made of UHMWPE during the ballistic impact. It can be seen that in the initial stages of impact, a large pyramidal-shaped through-thickness deformation occurs. The final breakage of the yarn occurs after 0.16 s when the bullet perforates the fabric. Also, the UHMWPE 2BC plain weave maintains good structural integrity after the impact of the projectile.

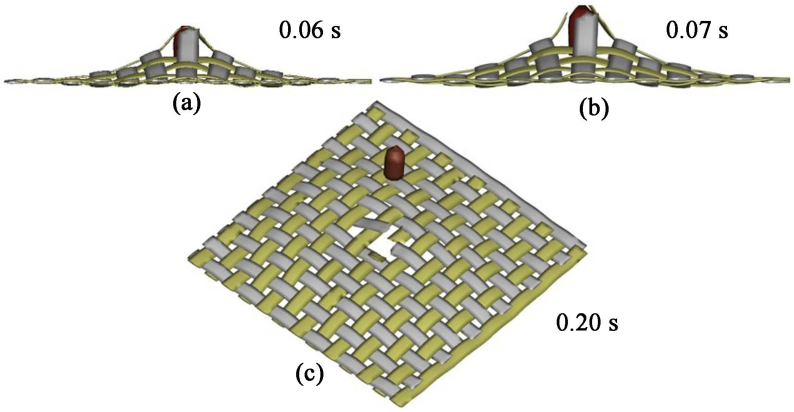


Figure 12. Evolution of the impact process for the Kevlar fabric—4BC plain weave.

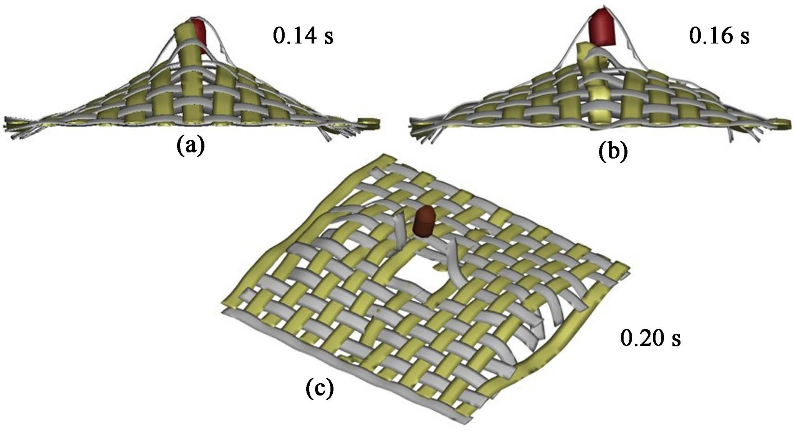


Figure 13. Evolution of the impact process for the UHMWPE fabric—2BC plain weave.

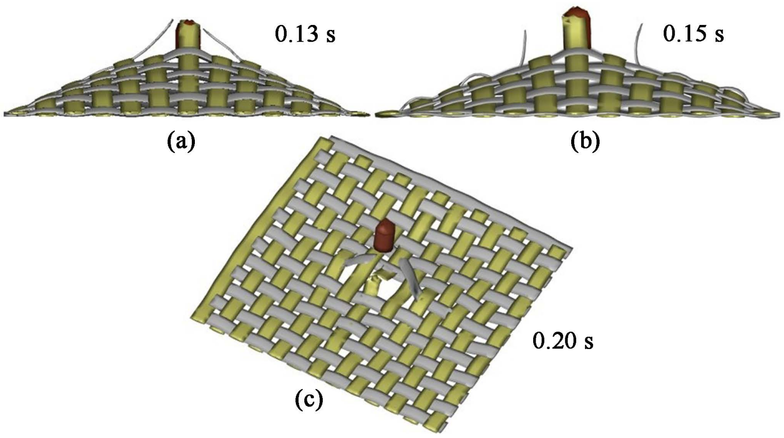


Figure 14. Evolution of the impact process for the UHMWPE fabric—4BC plain weave.

Figure 14 displays the evolution of the impact process of the 4BC plain woven fabric made of UHMWPE during the ballistic impact. It can be noticed that a large pyramidal deformation through-thickness occurs in the early stages of the impact. Yarn's final rupture occurs after 0.15 s, when the bullet perforates the fabric, almost at the same time as the 2BC plain woven fabric. In addition, the UHMWPE 4BC plain weave retains strong structural integrity after the impact of the projectile.

Figure 15 shows the behavior of the 2BC twill woven fabric made of Kevlar during the ballistic impact. It can be seen that a pyramidal-shaped through-thickness deformation occurs in the initial phase of impact. It can be noticed that the projectile pushes the central primary yarn to the side and slips through the architecture of the fabric (Figure 15(a)). The impact ends after a continuous development of slippage and the final breakage of the yarns occurs after 0.11 s, when the bullet perforates the fabric. Also, the Kevlar 2BC plain weave maintains good structural integrity after the impact of the projectile.

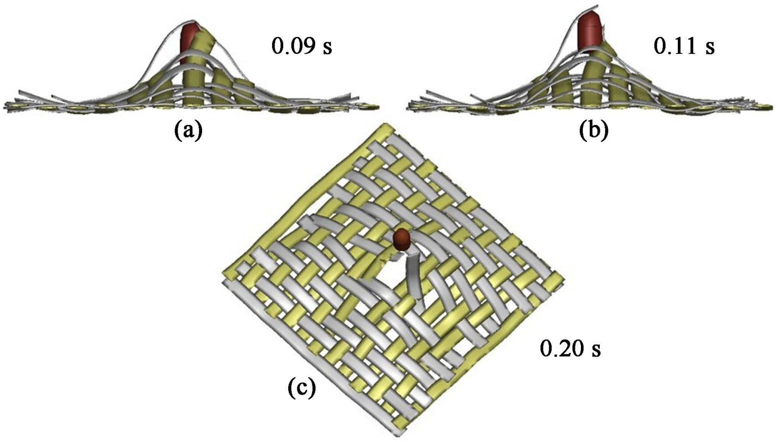


Figure 15. Evolution of the impact process for the Kevlar fabric—2BC twill weave.

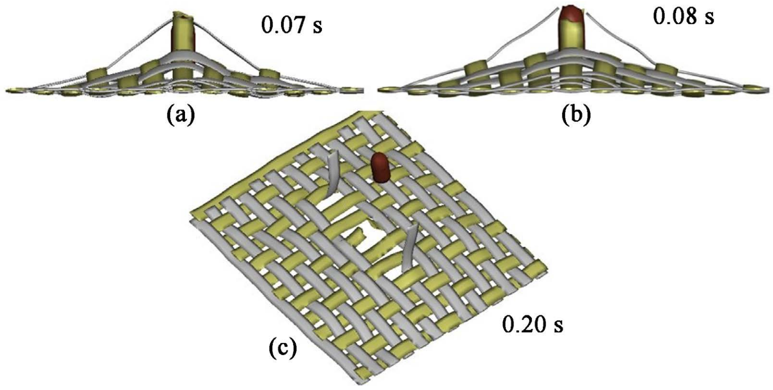


Figure 16. Evolution of the impact process for the Kevlar fabric—4BC twill weave.

Figure 16 displays the evolution of the impact process of the 4BC twill woven fabric made of UHMWPE during the ballistic impact. It can be noticed that a pyramidal-shaped through-thickness deformation occurs in the early stages of impact. Yarn's final rupture occurs after 0.08 s, when the bullet perforates the fabric. Yarn failure appears almost at the same time for the warp and weft yarns. Also, the Kevlar 4BC twill weave maintains a good structural integrity after the impact of the projectile.

Figure 17 shows the evolution of the impact process of the 2BC twill woven fabric made of UHMWPE during the ballistic impact. It can be noticed that a large pyramidal-shaped through-thickness deformation occurs in the early stages of impact. Yarn's final rupture occurs after 0.18 s, when the bullet perforates the fabric. Also, the UHMWPE 2BC twill weave maintains quite good structural integrity after the impact of the projectile.

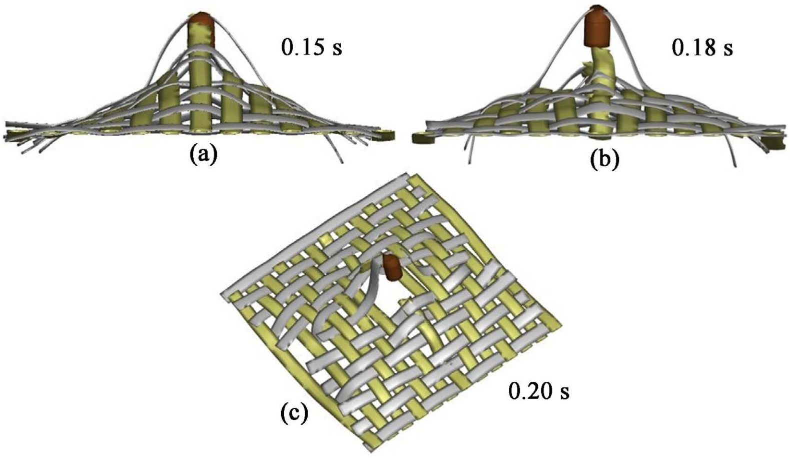


Figure 17. Evolution of the impact process for the UHMWPE fabric—2BC twill weave.

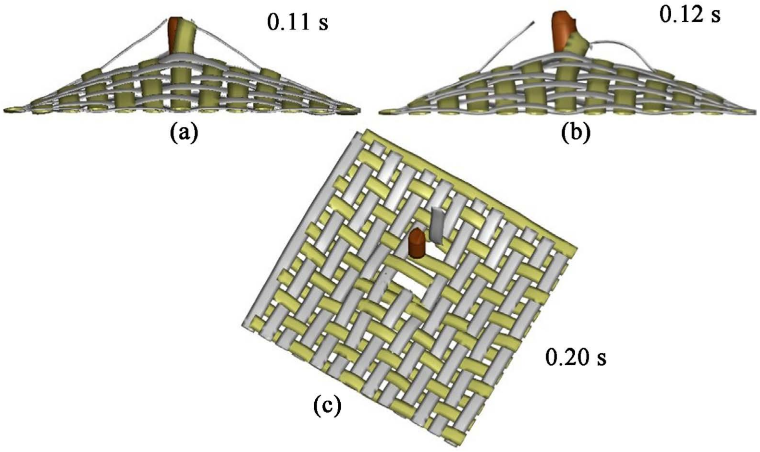


Figure 18. Evolution of the impact process for the UHMWPE fabric—4BC twill weave.

Figure 18 displays the behavior of the 4BC twill woven fabric made of UHMWPE during the ballistic impact. It can be seen that a pyramidal-shaped through-thickness deformation occurs in the initial stages of impact. It can be noticed that the projectile pushes the central primary yarn aside and slips through the fabric architecture (Figure 18(a)). The impact ends after continuous development of slippage and final rupture of yarns occurs after 0.12 s, when the bullet perforates the fabric. Also, the UHMWPE 4BC twill weave maintains strong structural integrity after the impact of the projectile.

Figure 19 illustrates the evolution of the impact process of 2BC satin woven fabric made of Kevlar during the ballistic impact. It can be seen that a pyramidal-shaped through-thickness deformation occurs in the initial stages of impact. It can be noticed that the central primary yarn has not slipped out of the impact area. However, due to bullet penetration, this yarn is pulled out from the fabric architecture, with advancing motion of the bullet (Figure 19(b)). This mechanism occurs due to the fact that the yarns are not firmly attached to the ends, and the ends are pulled out of the fabric mesh. In this case, yarn pullout occurs and none of the fibers within this zone of the yarn break. Also, the Kevlar 2BC satin weave possesses poor structural integrity after the impact of the projectile, having many yarns pulled out of the fabric architecture (Figure 19(c)).

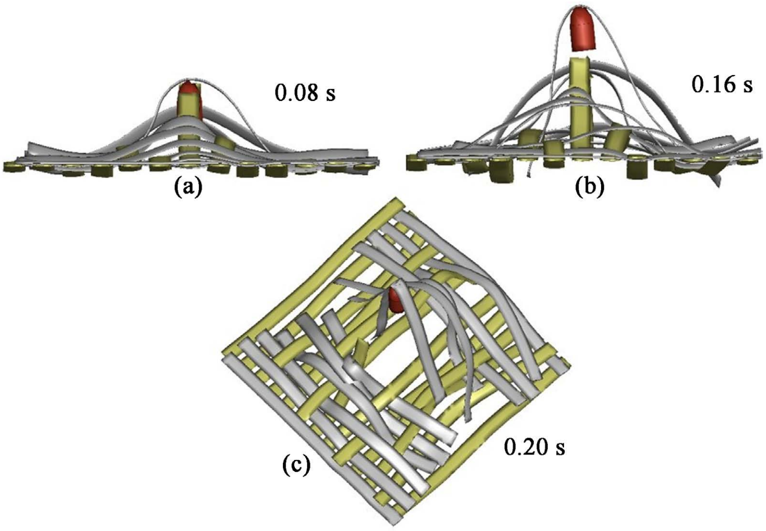


Figure 19. Evolution of the impact process for the Kevlar fabric—2BC satin weave.

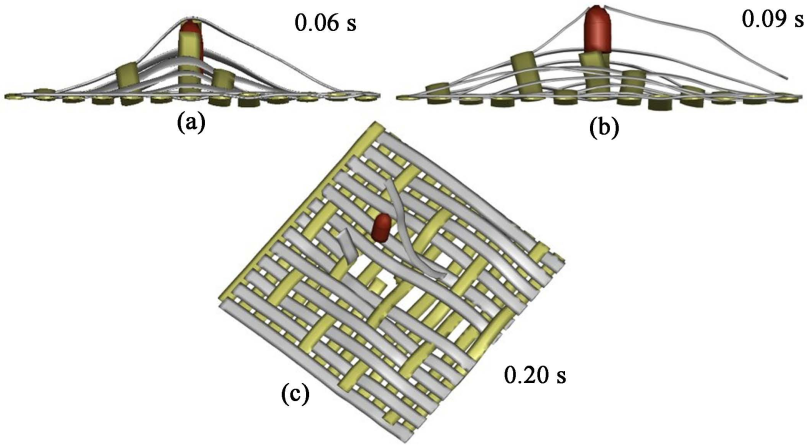


Figure 20. Evolution of the impact process for the Kevlar fabric—4BC satin weave.

Figure 20 displays the behavior of the 4BC satin woven fabric made of Kevlar during the ballistic impact. It can be seen that a pyramidal-shaped through-thickness deformation occurs in the initial stages of impact. Yarn's final rupture occurs after 0.09 s, when the projectile perforates the fabric. However, due to projectile penetration, part of the central primary yarn is pulled out from the fabric architecture (Figure 20(b)). Also, the Kevlar 4BC satin weave maintains agreeable structural integrity after the impact of the projectile.

Figure 21 illustrates the development of the impact process of 2BC satin woven fabric made of UHMWPE during the ballistic impact. It can be seen that a large pyramidal-shaped through-thickness deformation occurs in the initial stages of impact. It can be noticed that the central primary yarn has not slipped out of the impact area. However, due to bullet penetration, this yarn is pulled out from the fabric architecture, with the forward movement of the bullet (Figure 21(b)). This mechanism is caused by the fact that the yarns are not firmly attached to the ends, and the ends are pulled out of the fabric mesh. In this case, the yarn is pulled and none of the fibers in this area of the yarn break. The UHMWPE 2BC satin weave also exhibits poor structural integrity after the impact of the projectile, as many yarns have been pulled out of the fabric structure (Figure 21(c)).

Figure 22 displays the behavior of the 4BC satin woven fabric made of

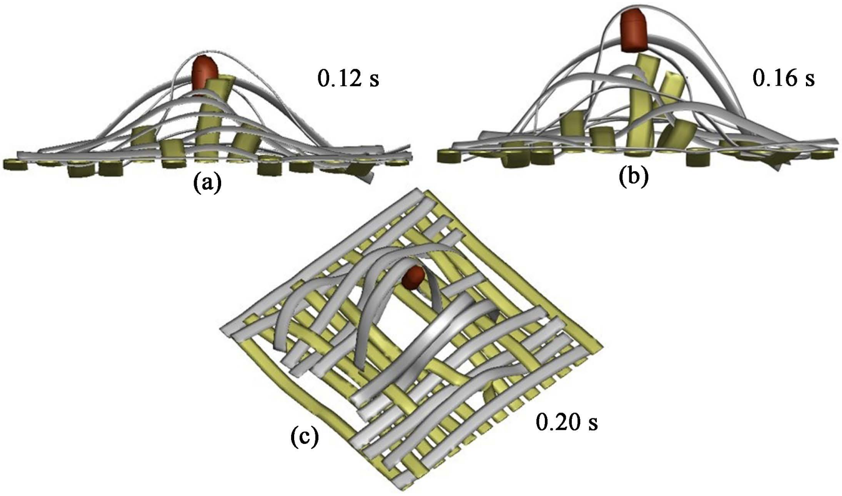


Figure 21. Evolution of the impact process for the UHMWPE fabric—2BC satin weave.

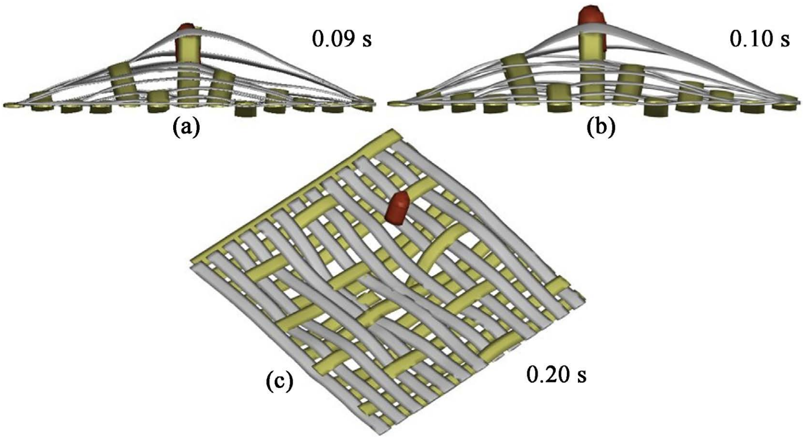


Figure 22. Evolution of the impact process for the UHMWPE fabric—4BC satin weave.

UHMWPE during the ballistic impact. It can be seen that a pyramidal-shaped through-thickness deformation occurs in the initial phase of the impact. It can be noticed that the projectile pushes the central primary yarn aside and slips through the fabric architecture (Figure 22(a)). The impact ends after continuous development of slippage and final rupture of yarns occurs after 0.09 s, when the bullet perforates the fabric. Also, the UHMWPE 4BC satin weave maintains fairly good structural integrity after the impact of the projectile.

3. Results and Discussion

3.1. Ballistic Behavior of 2D Woven Fabrics

Figures 11-14 show the image from the numerical simulation of the plain woven fabrics made of Kevlar and UHMWPE, respectively, when the fabric is clamped along all four edges or two edges. The kinetic energy of the bullet is dissipated by the deformation of the primary (yarn I) and secondary (yarn II) yarns, where the primary yarn is the one that passes through the impact region with the bullet, and the secondary yarn is the one beyond the impact region (Figure 23).

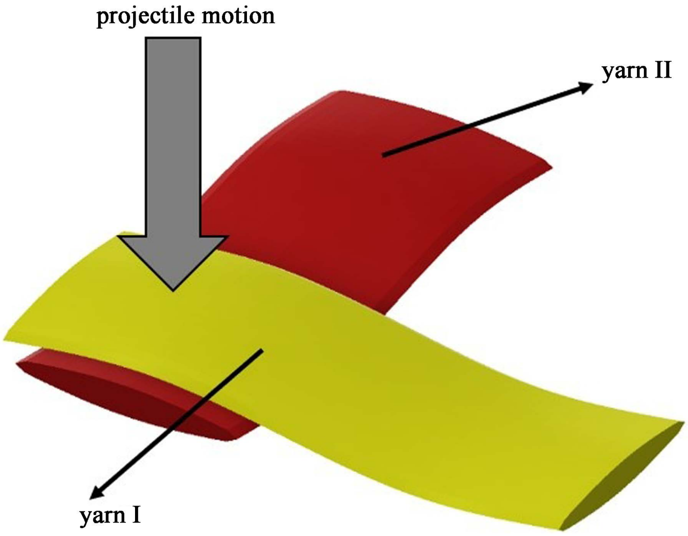


Figure 23. The schematic representation of primary and secondary yarns.

A comparison of Figure 11 and Figure 12 (for Kevlar material) shows that in the case of 4BC fabric, the final breakage of the yarn occurs after 0.07 s when the bullet perforates the fabric, *i.e.* twice as fast as in the case of the 2BC fabric. The reason for this is that the two-sided clamp provides the fabric more time to deform and the projectile has more time to penetrate the fabric. The failure of the primary and secondary yarns occurs almost at the same time in the 4BC configuration (yarn II broke 10 ms later than yarn I). In the 2BC configuration, the time difference between the two yarns is significant. Due to the clamping at the two edges, the yarn perpendicular to these edges is stretched and fails (yarn II in this numerical solution) (Figure 11(a)). When this yarn fails completely (after 0.09 s), its ballistic resistance becomes negligible and significantly affects the stress distribution and the transverse deformations of the yarn that is not fixed at both ends (yarn I). From this moment on, a larger part of the fabric is deformed before the projectile penetrates when yarn I finally fails (after 0.14 s).

In **Figure 13** and **Figure 14** (for UHMWPE material), it can be seen that the final yarn breakage occurs at almost the same time for both results of the numerical solution. As with the Kevlar 4BC configuration, the UHMWPE 4BC configuration also shows similar trend in the order of yarn breakage, *i.e.* yarn I fails before yarn II (yarn I fails after 0.13 s, while yarn II fails after 0.15 s). The same applies to the Kevlar 4BC and UHMWPE 4BC configurations, where due to the boundary conditions, yarn II breaks before yarn I (yarn II breaks after 0.14 s, while yarn I breaks after 0.16 s). It should be noted that in the case of UHMWPE structures, the projectile takes longer to penetrate the fabric. This indicates that pyramidal deformation is one of the main mechanisms for absorbing the kinetic energy of the projectile.

Figures 15-18 show the image from the numerical simulation of twill woven fabrics made of Kevlar and UHMWPE, respectively, when the fabric is clamped along all four edges or two edges. A comparison of **Figure 15** and **Figure 16** (for the Kevlar material) shows that the final yarn breakage occurs after 0.08 s in the case of the 4BC fabric while it occurs after 0.11 s in the case of the 2BC fabric when the bullet perforates the fabric. The difference is not as great as with plain woven fabrics. The reason for this is that in the 2BC configuration the breakage mechanism occurs mainly in yarn I (perpendicular to the two fixed edges), while the slippage is observed in yarn II (parallel to these edges). The impact ends after a continuous progression of the sliding of yarn II and the breakage of yarn I after 0.11 s (**Figure 15(b)**). The failure of the primary and secondary yarns occurs almost simultaneously in the 4BC configuration, as in the case of the plain fabric 4BC configuration (yarn II fails after 0.07 s, while yarn I fails after 0.08 s).

In **Figure 17** and **Figure 18** (for UHMWPE material), it can be seen that the final yarn breakage occurs after 0.11 s for the 4BC fabric, whereas it occurs after 0.18 s for the 2BC fabric when the bullet perforates the fabric. This large difference is due to the slippage of yarn II in the 4BC configuration (**Figure 18(b)**). In the 2BC configuration, the time difference between the two yarns is considerable (yarn I fails after 0.15 s, while yarn II fails after 0.18 s).

Figures 19-22 show the image from the numerical simulation of the satinized fabrics made of Kevlar and UHMWPE, respectively, when the fabric is clamped along all four edges or two edges. A comparison of **Figure 19** and **Figure 20** (for the Kevlar material) shows that the final yarn breakage occurs after 0.09 s in the case of 4BC fabric, while it occurs after 0.08 s in the case of 2BC fabric when the bullet perforates the fabric. At the same time, it can be seen that in the 4BC configuration yarn I breaks after 0.06 s and yarn II after 0.09 s, while in the 2BC configuration yarn I breaks after 0.08 s and the yarn II has not slipped out of the impact area as in the 2BC twill configuration. However, this yarn is pulled out of the fabric structure by the penetration of the bullet (Figure 19(b)). Pulling out the yarn can only be the most important mechanism for dissipating energy if the yarn is not clamped or is insufficiently clamped.

In Figure 21 and Figure 22 (for UHMWPE material), it can be seen that the final yarn breakage occurs after 0.09 s for the 4BC fabric, whereas it occurs after 0.12 s for the 2BC fabric when the bullet perforates the fabric. At the same time, it can be seen that in the 4BC configuration yarn I breaks after 0.09 s and yarn II is pushed aside (Figure 22(b)), whereas in the 2BC configuration yarn II breaks after 0.12 s and yarn I is neither pushed aside nor broken. However, the penetration of the bullet causes this yarn to be pulled out of the fabric structure (Figure 21(b)), as in the Kevlar 2BC configuration.

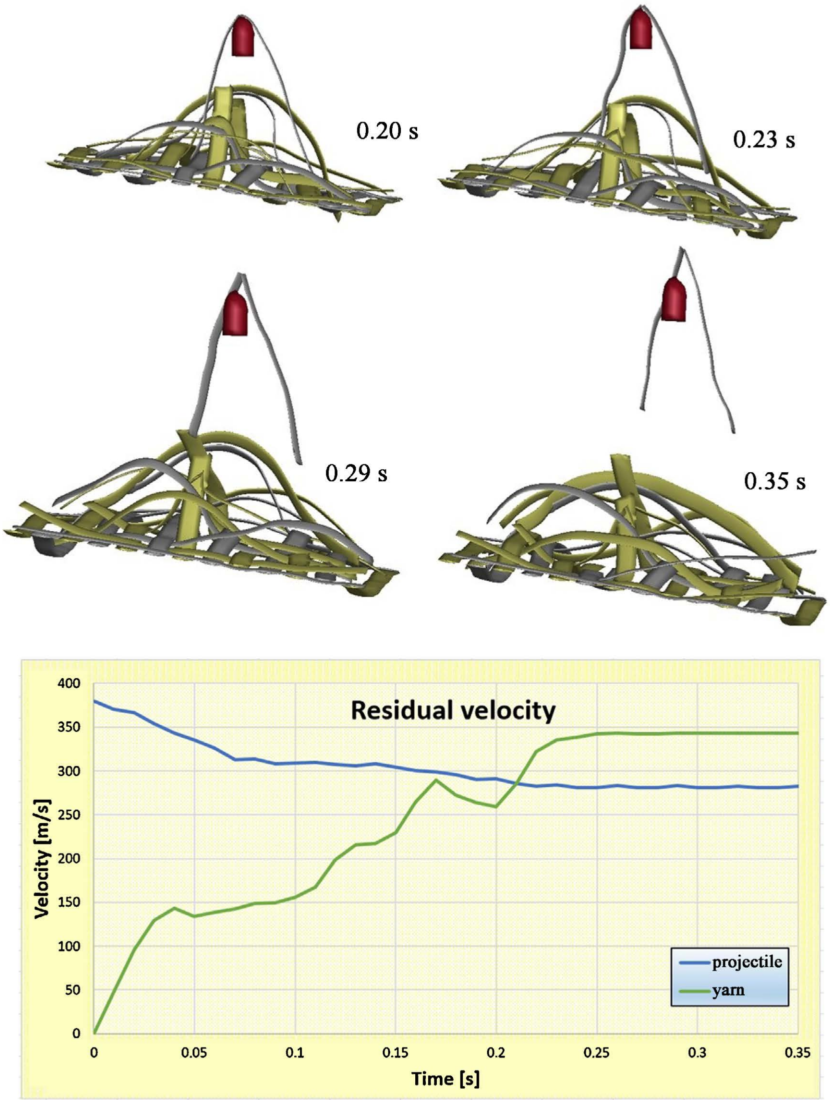
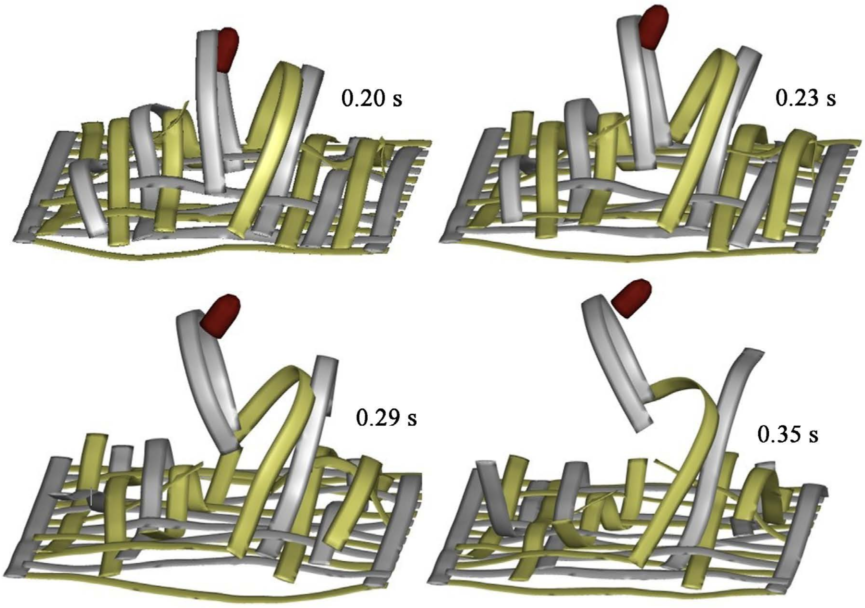


Figure 24. Velocity-time status for both the projectile and yarn pullout-Kevlar 2BC.

It is interesting to note that in the ballistic impact of Kevlar 2BC satin configuration, the yarn pullout has a higher velocity than the residual velocity of the bullet

(**Figure 24**). Due to this failure mode, the resistance force of the bullet is generally exerted by the yarn pullout. Zero resistance force indicates that the velocity of the yarn after it has been completely pulled out of the fabric structure is higher than the residual velocity of the bullet. The yarn therefore detaches from the bullet at this moment.



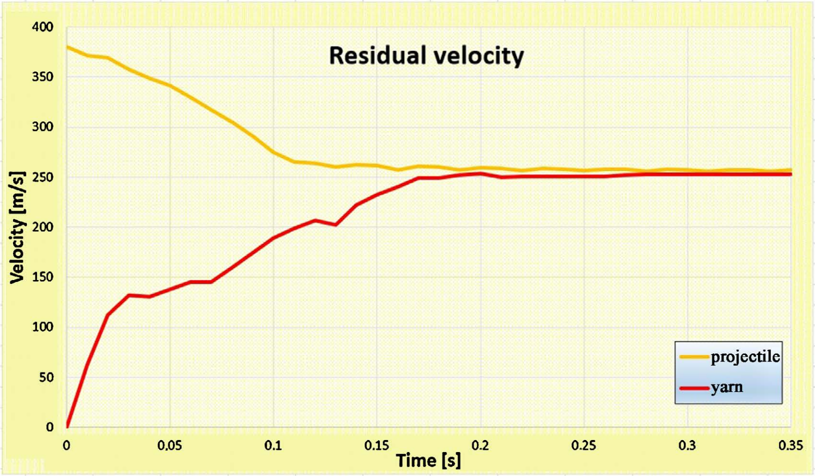


Figure 25. Velocity-time status for both the projectile and yarn pullout-UHMWPE 2BC.

In the case of the UHMWPE 2BC configuration, however, it can be seen that the residual projectile velocity is almost equal to the yarn pullout velocity (**Figure 25**). The reason for this is that after the yarn is pulled out of the fabric mesh, the yarn slips off without coming into contact with the bullet.

3.2. Residual Velocity

The study also includes a comparison between the residual velocity of the projectile in the event of ballistic impact on the 2D woven fabrics.

When the bullet penetrates the 2D woven fabric, it experiences a high acceleration and gradually discharges after penetrating the fabric. It is known that the striking velocity of the bullet hitting the fabric is V_0. Then the velocity of the bullet decreases as it penetrates the fabric and the residual velocity of the bullet after penetrating the fabric is defined by the relationship:

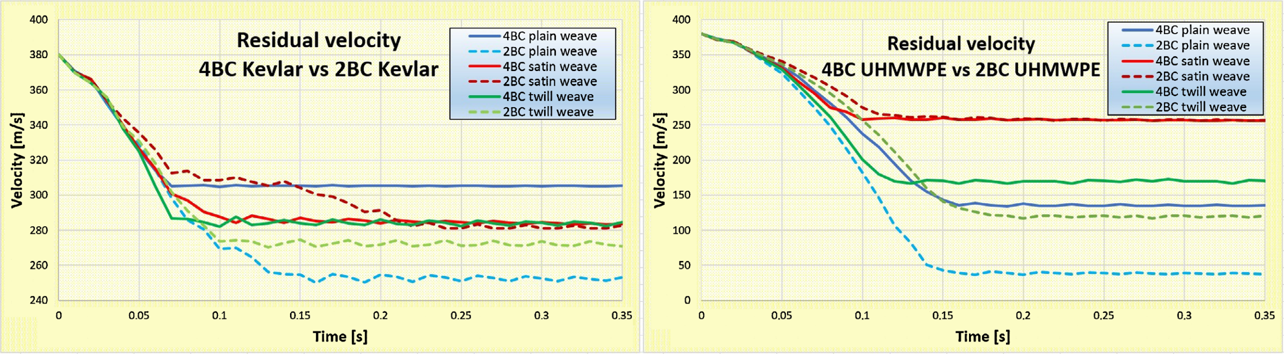
$$V_r^2 = V_0^2 - V_p^2 \tag{2}$$

where:

- V_r is the residual velocity;
- V_0 is the impact velocity;
- V_p represents the velocity required to perforate the thickness of the fabric.

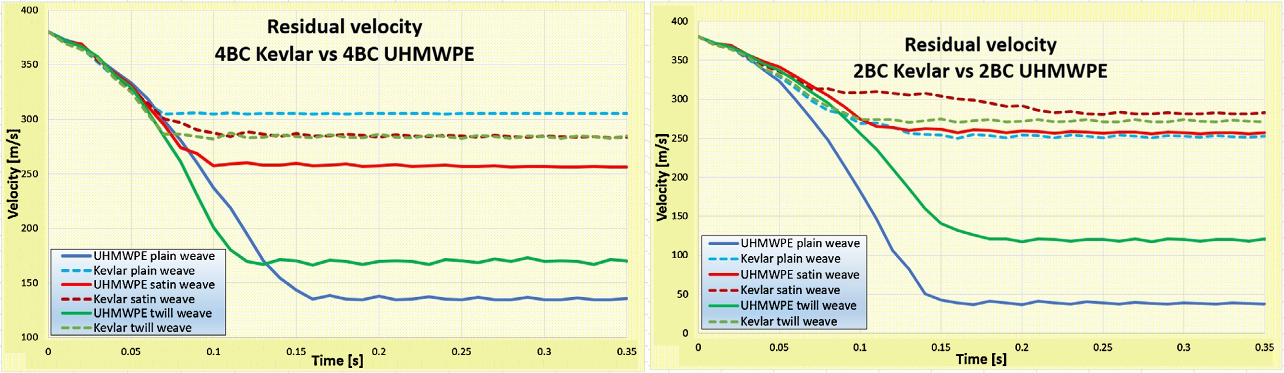
The development of the projectile velocity as a function of time after ballistic impact for 2D woven fabrics made of Kevlar and UHMWPE, respectively, when the fabric is clamped along all four edges or two edges, is shown in Figure 26 and Figure 27.

In Figure 26(a) (for Kevlar material), it can be seen that the fabrics with two fixed edges (2BC) reduce the residual velocity of the projectile more effectively than fabrics with four fixed edges (4BC). This is due to the fact that the time required for the perforation of the fabrics is much shorter for the fabrics with four fixed edges. Among the three types of fabrics, the plain fabric provides better



(a) (b)

Figure 26. Comparison of residual velocity for the 2D woven fabrics: (a) Kevlar fabrics; (b) UHMWPE fabrics.



(a) (b)

Figure 27. Comparison of residual velocity for the 2D woven fabrics: (a) 4BC constraints; (b) 2BC constraints.

ballistic performance when it is clamped at two edges. However, when it is fixed on all four edges, it is the least effective. The reason for this is seen in the reflection of stresses at the clamped edges and the number of crossover points in the fabrics. The 2BC plain weave has a 13.75 % better ballistic performance than the 4BC configuration. The satin fabric behaves approximately the same in both cases (difference of 0.27 %).

As expected, the results obtained show a lower value of residual projectile velocity in favor of the plain weave, followed by the twill weave. The highest value is found for the satin weave, which has the lowest ballistic performance.

In Figure 26(b) (for UHMWPE material), as with the Kevlar material, it can be seen that the 2BC configurations were more effective in reducing the residual velocity of the projectile than the 4BC configurations. Of the three fabric types, the plain weave offers better ballistic performance in both cases (2BC and 4BC). The 2BC plain weave has 25.87 % better ballistic performance than the 4BC configuration. The satin fabric performs approximately the same in both cases (difference of 0.26 %).

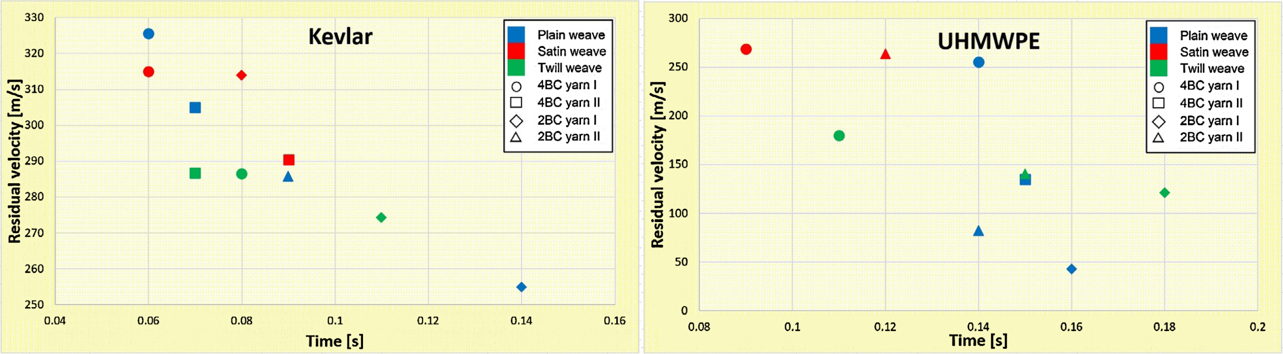
As with Kevlar fabrics, the ballistic performance of twill fabrics lies between plain and satin fabrics.

In Figure 27(a) (for the 4BC configuration), it can be seen that configurations made of UHMWPE reduce the residual velocity of the projectile more effectively than configurations made of Kevlar. The UHMWPE plain weave has a 44.62% better ballistic performance than the Kevlar plain weave.

In Figure 27(b) (for the 2BC configuration), it can be seen that the UHMWPE configurations reduce the residual velocity of the projectile more effectively than the Kevlar configurations, with the exception of the Kevlar plain weave, which are roughly on a par with the UHMPWE satin weave (difference of 0.77%). The UHMWPE plain weave has a 56.74% better ballistic performance than the Kevlar plain weave.

The development of the residual velocity of the projectile compared to the final breakage of the yarns during the ballistic impact is shown in Figure 28.

Figure 28(a) (for Kevlar material) shows that yarn I breaks before yarn II in the 4BC satin and plain weave configurations, while yarn II fails before yarn I in the 4BC twill configuration. The reason for this is attributed to the number of crossover points in the fabric configurations, whereby the freedom of movement of the yarn I in the twill configuration is greater than in the other two configurations. However, in the 4BC twill configuration, both yarns break at approximately the same residual projectile velocity of 314 m/s. It should be noted that in the 4BC plain configuration, the breakage of yarn I occurs in a relatively short period of time and at a higher residual projectile velocity compared to the other configurations. This can be explained by the fact that in plain weave, the crossover points between warp and weft yarns are the largest and the tensile wave propagating in the fabric is reflected at the crossover points, so that the yarns break long before the maximum amount of energy can be absorbed along their length. At the same



(a) (b)

Figure 28. Projectile residual velocity versus yarns final rupture: (a) Kevlar fabrics; (b) UHMWPE fabrics.

time, the breakage of the last yarn (yarn I, which is not fixed on the both sides) in the 2BC plain configuration occurs, as expected, at the later time and with the lowest residual velocity of 255 m/s compared to the other configurations.

In all three types of 2D weaves made of Kevlar, the yarns in 2BC configurations fail later and at lower residual velocities than in 4BC configurations.

In Figure 28(b) (for UHMWPE material), it can be seen that the breakage of the last yarns in both satin fabric configurations occurs in the earliest period and with the highest residual velocity (268 m/s for the 4BC configuration and 263 m/s for the 2BC configuration). This is due to the fact that yarn slippage and pullout are the main mechanisms for energy dissipation in this configuration due to the very low coefficient of friction between the UHMWPE yarns (0.11 compared to 0.25 for Kevlar). As with Kevlar, the breakage of the last yarn in the 2BC plain configuration occurs at the lowest residual velocity of 43 m/s. Compared to the other configurations and for all three types of 2D weaves, the yarns in 2BC configurations fail later and at lower residual velocities than in 4BC configurations.

From this, it can be concluded that the UHMWPE 2BC plain weave offers the highest level of protection in the event of an impact with a 9 mm bullet.

4. Conclusions

Numerical simulations were performed on the ballistic behavior of the projectile at low-velocity impact on a single layer of different 2D woven fabric configurations, including plain weave, twill weave and satin weave. Two different types of materials were selected for the 2D woven fabrics: Kevlar and UHMWPE. Quantitative data on the projectile impact behavior of six types of 2D woven fabric architectures studied at low-velocity impact are given. The numerical models are formulated and used to investigate the ballistic impact behavior of 2D woven fabrics when the fabrics are constrained along all four edges (4BC) or two edges (2BC) and the yarns are aligned parallel to the edges.

The numerical simulations were performed at an impact velocity of 380 m/s to evaluate the ballistic performance of 2D woven fabrics in terms of their structural integrity after impact and to examine the effect of boundary conditions by changing the border constraints in the numerical simulations. The effects of fracture behavior of primary and secondary yarns, energy absorption behavior and failure mechanism of 2D woven fabrics were also investigated.

It was found that the fabrics with two fixed edges reduced the residual velocity of the projectile better and absorbed more energy than the fabrics fixed at four edges. This was due to the fact that the time required to perforate the fabrics was much shorter for the casing with four fixed edges.

In all six types of 2D woven fabric architectures investigated, it can be seen that a pyramidal deformation through the thickness occurs in the initial phase of impact. This deformation reaches the limit of the fabric before it fails. There is evidence that the energy absorption of the fabrics is related to the pyramidal deformation zone.

Plain weaves are the most structurally stable fabrics. The ballistic performance, as well as structural and mechanical properties of twill weaves, lie between plain weaves and satin weaves. 2D satin fabrics may have limited application in the manufacture of protective equipment as their structural integrity is very low compared to the other two fabric types (they are unwoven after the ballistic impact).

UHMPWE fabrics have a very low coefficient of friction between the yarns. This property quickly leads to various problems that occur during a penetration process, such as yarn slippage and pullout. As a result, the friction between the yarns plays an important role in the ability of the fabrics to absorb the energy of the bullet. However, UHMWPE configurations offer higher ballistic protection and a better performance-to-weight ratio than Kevlar configurations, due to their combination of high strength, high modulus, high fracture strain and low density.

These conclusions can be easily implemented and lead to improved ballistic performance of these types of 2D fabric architectures.

Conflicts of Interest

The authors declare no conflicts of interest.

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