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Enchanching Body Armor: Evaluating UHMWPE with Contoured Surfaces for Improved Anti-Ballistic Performance using Finite Element Methods

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Abstract. Anti-ballistic is an indispensable personal protective equipment such as body armour for military and police personnel. This tool has received a lot of attention in recent decades due to increasing threats and insurgencies. Several studies have reviewed the development of anti-ballistic technology. However, there still needs to be discussion related to the development of anti-ballistics using UHMWPE (Ultra High Molecular Weight Polyethylene) and the contours of the surface of the UHMWPE. In addition, anti-ballistic studies are rarely carried out compared to other fields. This is because discussions or research related to weapons are still sensitive discussions. This study aims to determine whether the quality of body armour made using UHMWPE which one of the surfaces is given a specific profile, is better when compared to UHMWPE, which has no contours on all surfaces. UHMWPE material that is given a certain profile is one of the ideas chosen because it has high strength and aesthetic value, so it is expected to withstand bullet impact, comfortable and attractive when used. The antiballistic properties of UHMWPE given the diamond contour were obtained from numerical simulations using the finite element model (explicit dynamics) of ANSYS Workbench software. The two UHMWPE variants used in the multiplelayered configuration consist of UD UHMWPE sheets. Ballistic testing used a 7,62 mm calibre lead bullet with a velocity of 720 m/s. The material model of the bullet and UHMWPE plate used the Johnson-Cook plasticity model.

1 Introduction

Weapon technology has advanced significantly in recent years. As a result, the required performance of protective equipment is also higher. However, the manufacture of more advanced personal protective equipment means that it becomes heavier and cumbersome, which can affect the mobility of defence personnel [1]. Today, protective equipment based on various polymer composite materials offers excellent ballistic protection. In addition, the use of composite materials in the manufacture of military equipment makes military equipment lighter, which can improve the mobility of defence personnel and defence vehicles [2].

The two most common fibres with high performance are para-aramide and (UHMWPE) ultra-high molecular weight polyethylene [3]. The registered trademarks Twaron, Kevlar, Dyneema, and Spectra are the most common highperformance fibres used widely in the manufacture of flexible ballistic body armour for humans, characterised by highly desirable properties such as high strength, high durability, good chemical properties, high durability, and low density properties [4]. In addition, Zylon, Spectra, M5 Vectran, Technora and Nextel are also well-known fibres used for high performance, which are different from traditional fibres.

Unlike metals, polymers are generally amorphous, not crystalline or ordered over a long range. However, polymers can be engineered so that their structure has crystalline regions, either in the process of synthesis or deformation. The amount of crystalline area in a polymer is expressed as the degree of crystallinity of the polymer. The degree of crystallinity of polymers can for example be engineered by controlling the solidification rate and chain structure, although it is very difficult to obtain 100% crystallinity as is the case with metals. Polymers with branched chain structures for example will have a lower degree of crystallinity when compared to structures without branches. The mechanical and physical properties of polymers are strongly influenced by the degree of crystallization. Mechanical properties that are affected by the degree of crystallization include stiffness, hardness, and ductility. While the physical properties associated with the degree of crystallization, for example, are the optical properties and density of the polymer.

UHMWPE is a fibre commonly used in high-quality high modulus ballistic plate materials which is a polymer. The term polymer is used to describe giant molecular shapes or very long chains composed of

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repeating smaller units or mer or meros as building blocks. Its flexible, lightweight, waterproof, and impact-resistant properties make this material one of the options in the selection of materials for making body armour. Based on the properties of UHMWPE, it is possible to vary the surface contour of the material in order to produce characteristics that can change the direction of the bullet and also reduce bullet energy.

2 State of the art

Fibre-based composites are playing an increasingly important role as body armour materials, military vehicles, and aircraft. This approach to designing ballistic materials attracts much consideration when various fibre-based materials have been developed in recent times, for example, aramids (e.g., Kevlar and Twaron), UHMWPE (Dyneema and Spectra), poly-phenylene benzobisoxazole (PBO) fibres (e.g., Zylon), and PIPD (e.g., M5). However, Zylon is considered susceptible to hydrolytic and photolytic damage, and consequently is not proposed for use in ballistic protection [5]. M5 fibre has less degradation than PBO from exposure to radiation and increased humidity, although it may show weaknesses at ballistic build-up levels [6]. In addition, Zylon, Spectra, M5 Vectran, Technora and Nextel are also known as high-performance fibres. These fibres exhibit unique behaviour and performance that sets them apart from natural fibres. Likewise the situation, fibres for ballistic protection are mostly aramid and UHMWPE fibres.

The current trend is the demand for obtaining armoured lining plates made of low-density multilayer composite materials, which ensure against piercing protection and combined ammunition impact, for example, reducing overpressure and blast abundance [7]. Fibre engineering in composites used for anti-ballistics has been influenced by the design of the material structure of the body armour layer. Correspondingly, many composites used for ballistic protection contain woven textures comparable to those used in body armour.

UHMWPE (aramid) fibre has high strength properties and good damping (vibration damping) when hitting the bullet's impact. The bullet's kinetic energy will be dampened and distributed to a wide cross-section of kevlar through many deformations. This inward-pressing deformation (shock wave) in the direction of the bullet's penetration will cause a large strain to a certain extent before failure [9].

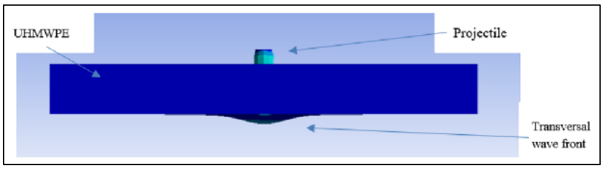


Fig. 1. Projectile impact into body armor

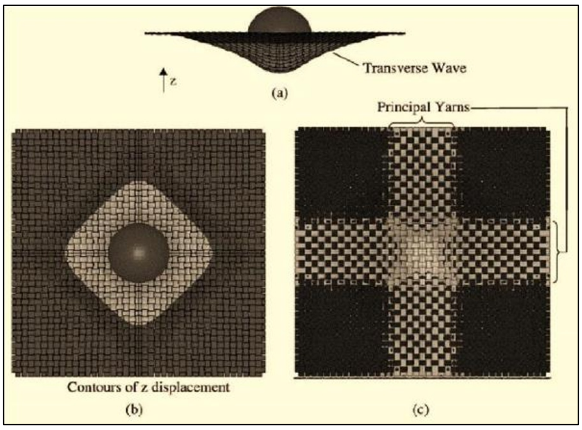


Fig. 2. Sphere impacting single ply of fabric (a) side view, (b) top view of z displacement contours and (c) bottom viewshow ing principal yarns under high stress [9].

The impact of high ballistic velocity causes the target material to behave like a liquid and generates wave propagation in the structure, as shown in Figure 1 and Figure 2. The impact response of single-layer fabrics and single fibres show similarities in generating transverse and longitudinal waves in direct contact with the bullet. The bullet momentum transferred in the main fibre causes strain and failure due to stresses exceeding the maximum strain limit. Ballistic protection against high-speed bullets is more effective using laminated materials than single materials [10]. Combining the given contour on UHMWPE can produce high strength and impact resistance on the anti-ballistic. UHMWPE material with a low density, a strong structure, good damping properties (vibration damping), and high resistance to dynamic loads in the form of laminates and giving contour can be used as an alternative to making bullet-resistant materials.

3 Governing equation

The anti-ballistic properties of UHMWPE given the diamond contour were obtained from numerical simulations using the finite element model (explicit dynamics) of ANSYS Workbench software. The UHMWPE used in the multiplelayered configuration consists of UD UHMWPE sheets 20mm. Ballistic testing used a 7,62 mm calibre lead bullet with a velocity of 720 m/s. The material model of the bullet and UHMWPE plate used the Johnson-Cook plasticity model in equation (1).

$$\sigma_{\mathrm{eq}} = [A + B(\varepsilon)^n][1 + C \ln \dot{\varepsilon}^{p*}][1 - T^{*m}] \quad (1)$$

where σeq is the equivalent stress (MPa), A is the yield stress (MPa), B is the hardening constant (MPa), ε is the equivalent strain, n is the hardening exponent, C is the strain rate constant and m is the softening temperature parameter. temperature is determined from equation (2):

$$T^* = \frac{T-}{(T_m - Tr)} \quad (2)$$

where T is the test temperature, Tr is the room temperature and Tm is the melting temperature of the material. The strain rate is given in equation (3):

$$\dot{\varepsilon}^{*} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \quad (3)$$

where ε is the test strain rate and εo is the reference strain rate. Design and material properties on which the simulation computations are based are shown in Figure 3 and Tables 1.

Table 1. Bullet material properties[12], and UHMWPE plate material properties[11]

Parameter	Symbol	Unit	Bullet [12]		Plate
			Tin	Brass	UHMWPE [11]
Density	ρ	kg/m3	10660	8520	945
Elastic modulus	E	MPa	1000	115000	575
Poisson's rasio	ν	-	0,42	0,31	0,43
Specific heat	Cp	J/kg-K	124	385	195
Parameter model plastisitas Johnson-Cook					
Yield stress constant	A	MPa	24	206	230
Hardening constant	B	MPa	300	505	120
Hardening exponent	n	-	1	0,42	0,8
Strain rate constant	C	-	0,1	0,01	0,1
Melting temperature	Tm	K	760	1189	413
Room temperature	Tr	K	293	293	293

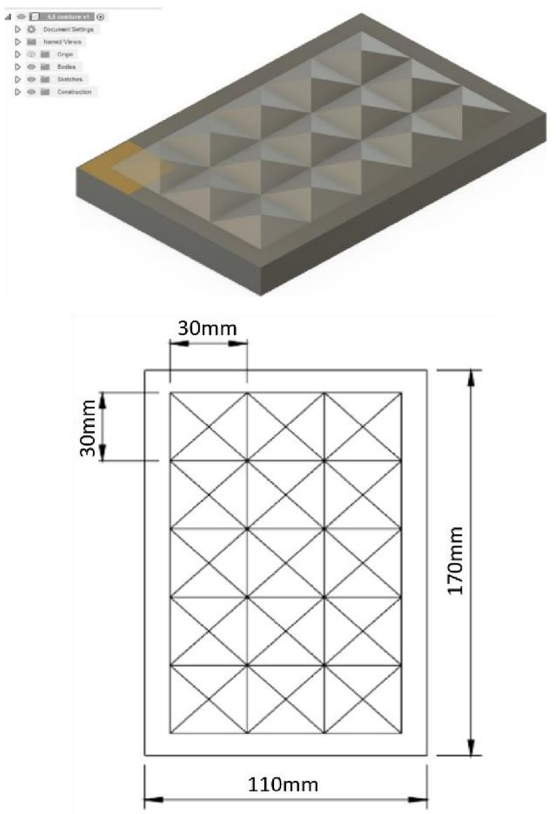


Fig. 3. Design prototipe body armor

The target plate was divided into two zones, namely, contact and non-contact zone. In the non-contact zone ratio, the meshing size is the same on the distance from the centre of the target plate. In the contact zone, the mesh size was 3 mm × 3 mm × 3 mm. The contact zone was part of the target plate in direct contact with the bullet, so the numerical analysis focused on this part. Furthermore, the non-contact zone was part of the target plate that was not in direct contact with the projectile, so the mesh size could be larger or the same to minimize analysis computational time (Figure 4.a). Using partitions on components aims to maintain accuracy, on the other hand, it can also reduce computation time so that the simulation becomes more efficient. If not using partitions, the computation time will be longer. In this analysis, only use four faces on geometry selection fixed support. To make it easier, see the boundary conditions in this case shown in Figure 4. b.

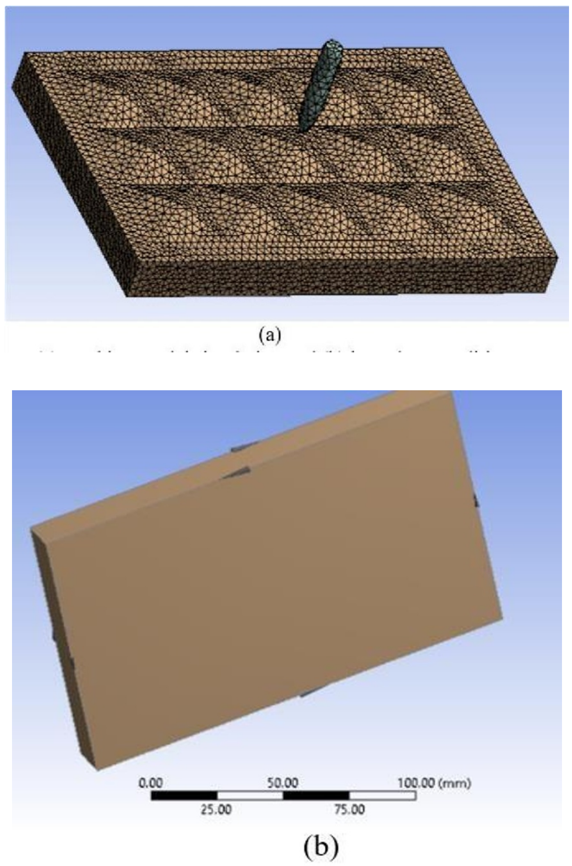
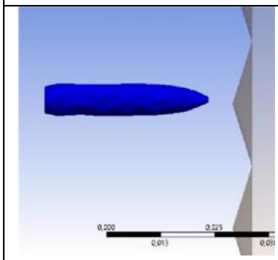
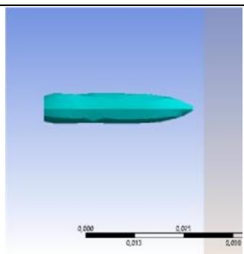
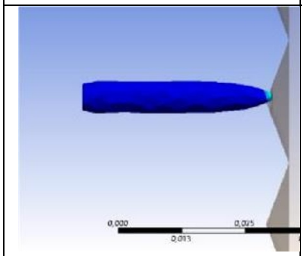
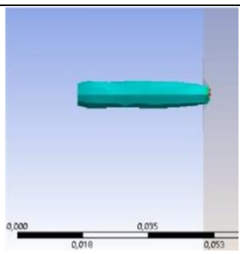
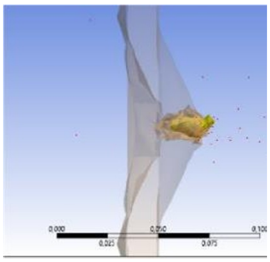
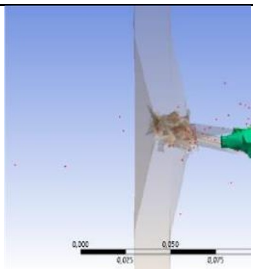
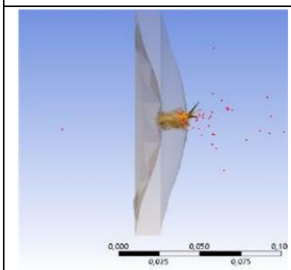
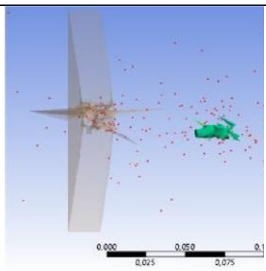
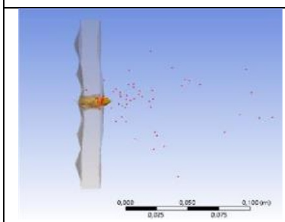
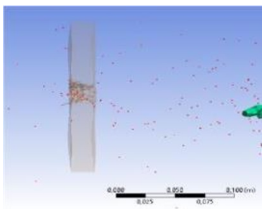
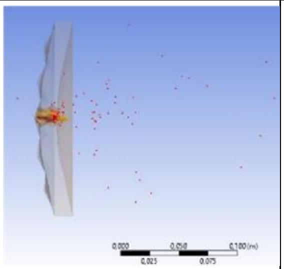
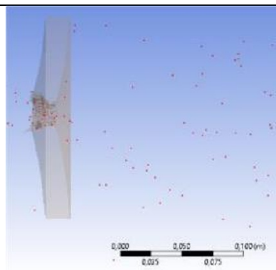
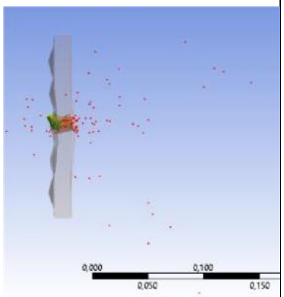
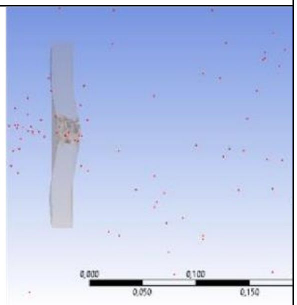
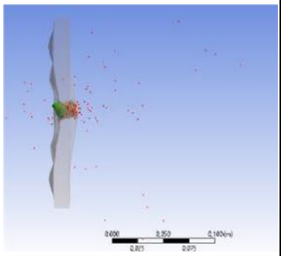
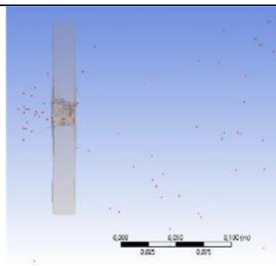


Fig. 4. (a) meshing model simulation and (b) boundary condition.

4 Results

The ballistic impact is observed using numerical simulation the decelaration process of the bullet caused by the UHMWPE target. The deceleration and residual velocity of the bullet at a certain time are shown in Table 2. The equivalent stress distribution with different colours shows the stress distribution that occurs on the target. The redder the colour on the target, the greater the stress, and vice versa; the stress decreases, marked by a change in colour on the target to blue which indicates lower stress. The equivalent stress distribution is shown in Table 3.

Table 2. Deceleration and residuall velocity of a bullet at a given time

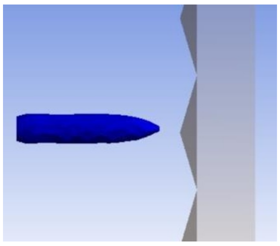
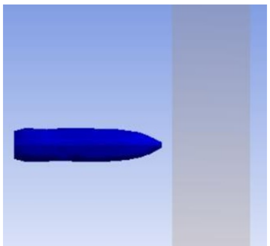
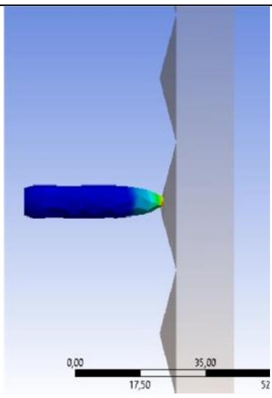
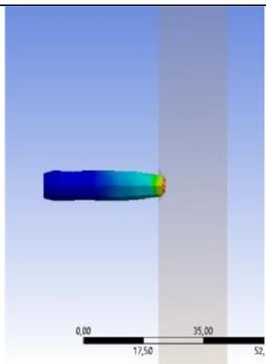
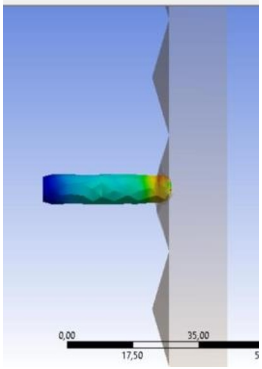
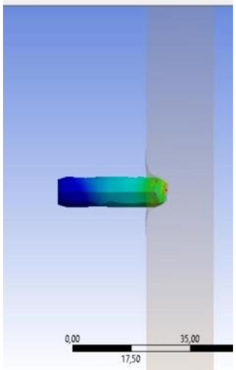
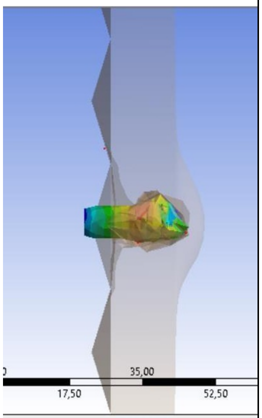
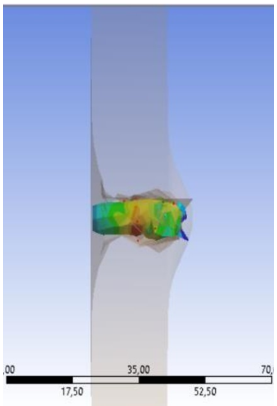
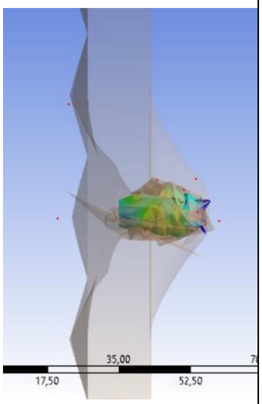
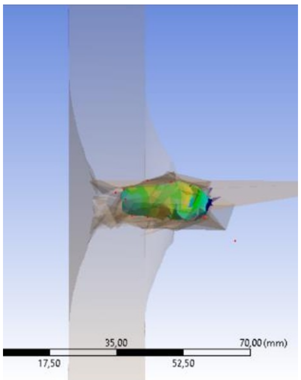
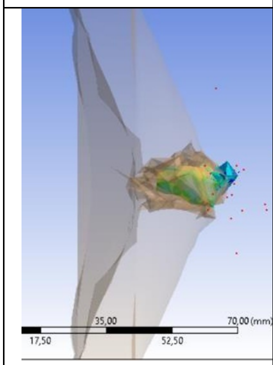
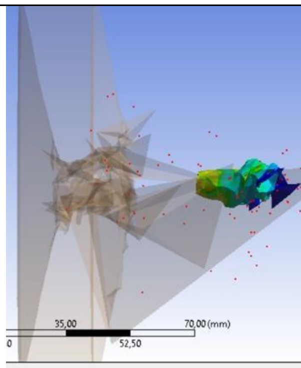
With Contour	Without Contour
 Time = 0 Bullet belocity = 720 m/s	 Time = 0 Bullet belocity = 720 m/s
 Time = 1,0012e-005 Bullet belocity = 711,01 m/s	 Time = 1,0012e-005 Bullet belocity = 694,22 m/s
 Time = 1,9001e-004 Bullet belocity = 7,5569 m/s	 Time = 1,9001e-004 Bullet belocity = 306,53 m/s
 Time = 3,0004e-004 Bullet belocity = -35,175 m/s	 Time = 3,0004e-004 Bullet belocity = 298,7 m/s
 Time = 5,0002e-004 Bullet belocity = -77,247 m/s	 Time = 5,0002e-004 Bullet belocity = -297,96 m/s
 Time = 7,0002e-004 Bullet belocity = -89,397 m/s	 Time = 7,0002e-004 Bullet belocity = 297,23 m/s
 Time = 9,7003e-004 Bullet belocity = 159,61 m/s	 Time = 9,7003e-004 Bullet belocity = 296,95 m/s
 Time = 1,0001e-003 Bullet belocity = 146,63 m/s	 Time = 1,0001e-003 Bullet belocity = 296,8 m/s

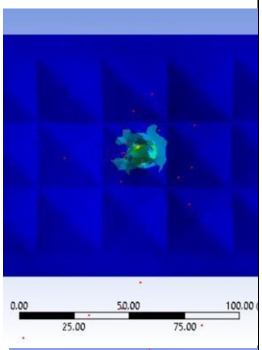
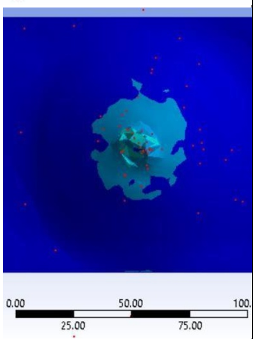
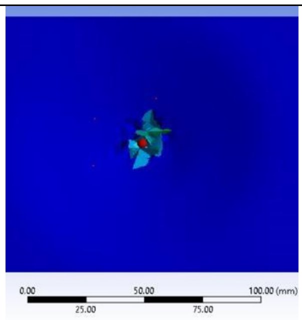
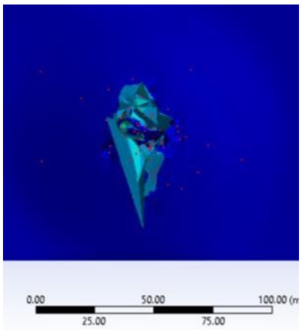
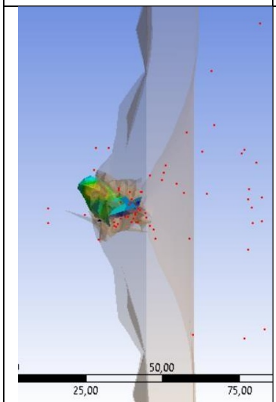
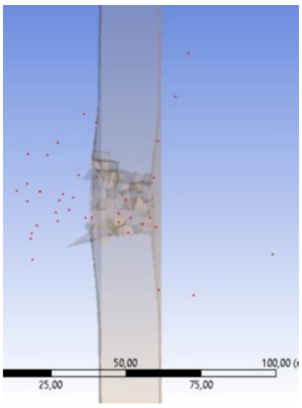
Based on the observations presented in Table 4, a notable difference in the deceleration of the 7.62 bullet with a velocity of 720 m/s was observed. The implementation of a contoured plate design contributed to an increased elasticity, resulting in improved bullet deceleration compared to the flat plate design.

Of particular note is the striking difference in bullet velocities at the point of impact. At the time of 1.9001e-004 seconds, the bullet's speed was recorded as 7.5569 m/s for the contoured plate and 306.53 m/s for the flat plate, and it had already penetrated the body armor. At the time of 3.0004e-004 seconds, the bullet's speed was recorded as -35,175 m/s for the contoured plate and 298.7 m/s for the flat plate. By the time of 1.0001e-003 seconds, the bullet came to a complete stop inside the body armor. This significant variation in bullet velocity highlights the superior performance of the contoured plate in slowing down the projectile.

These findings suggest that the contoured material exhibits enhanced bullet deceleration capabilities and can even cause the direction of motion of the bullet to reverse. Contoure plat it a promising option for effective projectile-resistant panels. Further investigation and analysis of the contoured plate's performance at different velocities could provide valuable insights for optimizing ballistic protection systems. The next observation is Equivalent (von-Mises) that shown in table IV.

Table 3. Equivalent (Von-Mises) stress at any given time

With Contour	Without Contour
 Time = 0 Equivalent (von-Mises) Stress = 0 MPa	 Time = 0 Equivalent (von-Mises) Stress = 0 Mpa
 Time = 1,0004e-005 Equivalent (von-Mises) Stress = 745,56 Mpa	 Time = 1,0004e-005 Equivalent (von-Mises) Stress = 750,05 Mpa
 Time = 2,0016e-005 Equivalent (von-Mises) Stress = 591,29 MPa	 Time = 2,0016e-005 Equivalent (von-Mises) Stress = 861,53 Mpa
 Time = 6,0061e-005 Equivalent (von-Mises) Stress = 698,43 Mpa	 Time = 6,0061e-005 Equivalent (von-Mises) Stress = 724,1 MPa
 Time = 9,0014e-005 Equivalent (von-Mises) Stress = 721,84 Mpa	 Time = 9,0014e-005 Equivalent (von-Mises) Stress = 687,93 MPa
 Time = 1,9001e-004 Equivalent (von-Mises) Stress = 568,77 MPa	 Time = 1,9001e-004 Equivalent (von-Mises) Stress = 664,81 Mpa

  Time = 1,9001e-004 Equivalent (von-Mises) Stress = 568,77 MPa	  Time = 1,9001e-004 Equivalent (von-Mises) Stress = 664,81 Mpa
 Time = 8,7001e-004 Equivalent (von-Mises) Stress = 495,19 MPa	 Time = 8,7001e-004 Equivalent (von-Mises) Stress = 283,08 MPa

Based on the findings presented in Table 3, a distinct disparity in deformation between the contoured plate and the plain plate upon bullet impact becomes evident. This disparity is intriguing and has been thoroughly analyzed. Examining Time 1 (1.0004e-005 seconds), the contoured plate exhibited an Equivalent (von-Mises) Stress of 745.56 MPa, while the plain plate registered 750.05 MPa. Transitioning to Time 2 (2.0016e-005 seconds), the Equivalent (von-Mises) Stress recorded for the contoured plate was 591.29 MPa, whereas the flat plate showcased a significantly higher stress value of 861.53 MPa. This trend continued into Time 3 (9.0014e-005 seconds), with the contoured plate revealing an Equivalent (von-Mises) Stress of 721.84 MPa, juxtaposed with the flat plate's lower 697.93 MPa.

The remarkable occurrence where the bullet nears a complete halt upon striking the contoured plate transpires at an intriguing juncture - 1.9001e-004 seconds. This event is accompanied by a velocity of 7.5569 m/s and an equivalent (von-Mises) stress of 568.77 MPa.

The distinctive shape of the contoured plate inherently influences the bullet's trajectory, compelling it to undergo alterations that inherently curtail its energy during rotation. Furthermore, this contour-induced trajectory adjustment induces a gradual energy dissipation due to the material's inherent elasticity and shape configuration, ultimately facilitating the bullet's cessation.

The deformation values, meticulously outlined in Table 3, conspicuously illustrate an inherent correlation between greater deformation and an increased cross-sectional area of the bullet. Consequently, this engenders a heightened level of resistance that the bullet encounters during impact. The most important to underscore the significance of the unique attributes possessed by the contoured plate.

5 Discussion

The observed slight difference in the results presented compared to the experiment conducted by Li Chen et al. [13] raises interesting points for discussion. In Li Chen's experiment, plain UHMWPE with a thickness of 20mm demonstrated the ability to withstand a 7.62 bullet traveling at a speed of 720m/s. The variance in the outcomes could be attributed to the distinct material properties employed in the two studies. Materials with different characteristics may exhibit varying behaviors when subjected to ballistic impact. However, it is crucial to highlight that in this paper, efforts were made to ensure comparability by equalizing the material properties, bullet model, and bullet velocity between the contoured plate and the one without contour; the primary distinction being solely in the design of the material surface shape.

The discrepancy in results may stem from several factors. First, the contoured plate's surface shape introduces variations in the way the impacting bullet interacts with the material during the test. This alteration in the geometric design might lead to different stress distribution and energy dissipation within the plate upon impact, consequently affecting the bullet's ability to penetrate or be stopped. Moreover, the contoured surface might influence the bullet's trajectory and stability during its trajectory, potentially leading to deviations in the bullet's impact characteristics compared to a flat plate.

Additionally, the choice of material properties and their mechanical behavior plays a significant role in determining the bullet's resistance capability. UHMWPE's properties, such as its density, hardness, and flexibility, are vital factors in determining its ballistic performance. Similarly, other material properties, such as Young's modulus, Poisson's ratio, and yield strength, significantly impact the energy absorption and dissipation characteristics of the material upon impact. Even subtle variations in material properties can lead to notable differences in the outcome of ballistic tests.

Furthermore, the experimental setup and testing conditions might also contribute to the observed differences. Factors like the mounting of the contoured plate, the orientation of the bullet's impact, and the position of the plate during the test could all affect the results. The use of different testing equipment or variations in the setup procedures could introduce discrepancies in the obtained data. The generally recognized determinants of the wounding intensity of a projectile are the velocity and mass of the shot, along these lines, its momentum, but the energy delivered in a shot depends on the size of the explosive material touched to fire the projectile and the distance from the gun gag [14].

To address these discrepancies and gain a comprehensive understanding of the contoured plate's ballistic performance, further investigations are warranted. Conducting a series of systematic experiments with varying material properties, different contour designs, and bullet impact velocities would allow for a more in-depth analysis of the factors influencing the plate's resistance to ballistic impact. Moreover, employing advanced numerical simulations, such as finite element analysis, in conjunction with experimental data could provide valuable insights into the underlying mechanisms at play during the ballistic impact process.

6 Conlusion

The observed slight difference in the results between this paper and Li Chen et al.'s experiment highlights the need for further exploration and study. The impact of the contoured plate's surface design on the bullet's behavior warrants deeper investigation, considering various material properties and testing conditions. Advancing our understanding of the factors influencing the plate's ballistic performance will facilitate the enhancement and optimization of protective materials for diverse applications, including body armor, vehicle armor, and other ballistic protection systems.

The results presented demonstrate that the bulletproof plate's effectiveness is strongly influenced by material properties, material design, and the direction of fire. While the material properties used in this analysis are commonly employed, the simulation's material design has a significant impact by altering the bullet's motion direction, thereby affecting the energy imparted to the plate. This finding unveils a novel perspective that merits thorough investigation through real-world experiments for validation.

To gain a comprehensive understanding of the contoured plate's performance, conducting further research and realworld experiments would be essential. This would involve evaluating different material designs, exploring additional material properties, and conducting tests with varying directions of fire to ascertain their collective impact on the bulletproof plate's performance. By delving deeper into these factors, we can devise improved and tailored solutions for ballistic protection, ultimately enhancing the safety and security of individuals in hazardous environments.

The slight disparity between the results presented here and Li Chen et al.'s experiment serves as a catalyst for future inquiries. The contoured plate's surface design, along with material properties and testing conditions, plays a crucial role in its ballistic performance. By advancing our understanding of these factors, we can pave the way for more effective and specialized protective materials that can safeguard against ballistic threats across a range of critical applications.

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