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Evaluation of Personal Body Armor Effectiveness Against Artillery Fires

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Abstract

Personal body armor has evolved to address threats typical of contemporary warfare. Artillery effects, particularly fragmentation, have become a significant threat to military personnel, increasing the demand for effective protective solutions. This paper proposes a combined analytical–experimental framework for evaluating the effectiveness of personal body armor against artillery fragmentation. Fragmentation characteristics are examined using mathematical modeling and analytical methods. Additionally, existing body armor evaluation standards and testing methods are reviewed. The results indicate that fragmentation represents the dominant lethal mechanism of artillery fire. Although the V50 ballistic test is commonly used to assess fragment resistance, it does not provide a comprehensive evaluation of real-world protection effectiveness. These findings highlight the need for more advanced and realistic assessment methods.

KEY WORDS: *personal body armor, artillery fire, fragmentation, ballistic materials.*

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1. Introduction

Recent developments in the war in Ukraine have demonstrated the growing importance of modern technologies in warfare, particularly unmanned aerial vehicles and electronic warfare systems [1]. Although these technologies existed prior to the conflict [2], their extensive and coordinated use has significantly transformed the battlefield environment [3]. At the same time, certain traditional elements of warfare, such as trench warfare, have re-emerged [4].

Despite these changes, artillery and fire support remain decisive components of conventional combat. The increasing availability of precision-guided munitions and advanced fire control systems has further enhanced the effectiveness of artillery by improving targeting accuracy and response time. As a result, the probability of successful target engagement has increased, leading to a greater need for effective countermeasures and personnel protection. Moreover, the ongoing development of autonomous weapon systems suggests that the role of artillery may become even more significant in future conflicts [5]. The effectiveness of modern artillery is increasingly influenced not only by munition characteristics, but also by the integration of fire control procedures, meteorological data, and decision-support systems, which together significantly affect target engagement accuracy and the resulting exposure of personnel to fragmentation effects [6-8].

In contemporary operations, artillery units must meet several key requirements, including accuracy, the ability to achieve surprise effects, and effective concealment [9,10]. However, these units are highly vulnerable to detection, particularly by unmanned aerial systems, which can enable rapid counter-battery fire. This vulnerability has increased the demand for integrated air defence measures, including both specialized systems and improvised solutions such as heavy machine guns or shotguns [11].

To enhance survivability and reduce the effects of enemy fire, personal body armor is widely employed. Modern body armor typically consists of a ballistic helmet and a vest combining hard and soft protective elements. Since the beginning of the conflict in Ukraine in 2014, body armor systems have undergone continuous development on both sides, including modifications in size, geometry, materials, and overall protection coverage [12]. Current approaches often treat these factors in isolation, and there remains a lack of integrated frameworks that link artillery effects, operational conditions, and the effectiveness of personal protective systems [13,14].

However, despite these advancements, the effectiveness of personal body armor against artillery effects-particularly fragmentation - remains insufficiently understood.

The aim of this paper is to analyze the relationship between artillery fire effects, with emphasis on fragmentation, and the protective capabilities of personal body armor, using a combination of analytical modeling and evaluation of existing testing standards.

2. Artillery Fires

Artillery units employ both direct and, more commonly, indirect fire to engage targets using artillery, rocket, and mortar ammunition. The most widely used type of artillery ammunition is high-explosive (HE) munition [15]. Such munitions affect targets through several mechanisms, primarily blast wave, fragmentation, thermal effects, and secondary fragmentation.

The blast wave, generated by the detonation of the explosive charge, produces a high overpressure that can cause severe injuries, particularly at close range. For example, a 155 mm M107 HE shell containing approximately 6.86 kg of TNT generates a critical overpressure of 138 kPa at a distance of 6.9 m from the point of detonation [16]. This indicates that blast effects are especially lethal at short distances, typically up to approximately 20 m, and are particularly dangerous in enclosed environments [17]. Standard personal body armor provides limited protection against blast overpressure, especially with respect to pulmonary injuries [17]. In addition to its direct effects on personnel, the blast wave can also alter terrain conditions, thereby affecting mobility. Such effects may also have potential applications in civilian contexts, for example in wildfire suppression [18,19].

Other effects of artillery detonation include thermal radiation and the release of toxic gases [20]. These effects are not further analyzed in this study, as standard personal body armor does not provide effective protection against them.

The most significant threat to personnel, however, is fragmentation. Fragments are generated by the rapid disintegration of the projectile casing during detonation. Their characteristics, including mass distribution and total number, are determined by the design of the munition. Denser casing materials or increased wall thickness typically result in fewer fragments with higher average mass. Conversely, increasing the explosive charge generally produces a larger number of smaller fragments.

Fragment size has a direct influence on their kinematic behavior. Larger fragments tend to have lower initial velocity but retain their velocity over longer distances, whereas smaller fragments exhibit higher initial velocities but experience more rapid deceleration. From a tactical perspective, a greater number of smaller fragments is generally more effective against exposed personnel, as lower kinetic energy is sufficient to cause injury. In contrast, heavier fragments are more relevant when engaging protected or armored targets. As a result, improvements in fire control accuracy may increase not only the probability of target engagement but also the likelihood of fragment exposure for personnel within the affected area [21].

3. Fragmentation

A fragment impact does not necessarily result in injury or fatality. Due to low mass or insufficient velocity, a fragment may possess inadequate kinetic energy to cause significant damage. The probability of injury or death decreases with increasing distance from the point of detonation. For example, for a 105 mm shell, beyond approximately 40 m from the explosion, the probability of injury exceeds that of fatality, while at distances around 97 m, the risk of severe injury becomes significantly reduced [22]. Nevertheless, there remains a non-zero probability of fatal injury even at distances of up to 200 m, while survival is still possible at much shorter distances.

In addition to distance, several other factors influence fragmentation effects, including the angle of impact, height of burst, residual velocity of the projectile at impact, and the orientation of the target relative to the detonation. Due to their typically steep angle of impact, mortar shells can produce fragmentation effects comparable to those of higher-calibre artillery shells with lower impact angles.

The projectile casing is generally divided into three structural components: the front ogive, the rear ogive, and the cylindrical section. The majority of fragments - up to approximately 75% - originate from the cylindrical section. When a projectile impacts the ground, its velocity is reduced and the surrounding medium absorbs part of the energy, thereby suppressing both blast and fragmentation effects [16].

Under optimal conditions, maximum fragmentation effectiveness is achieved when the projectile impacts at a steep angle and detonates upon or immediately before ground contact. In this context, “maximum effectiveness” refers to the utilization of the full fragmentation potential against the target.

Fragments can be characterized using several parameters, including average mass and spatial density, both of which influence the probability of target engagement. The most widely used model for fragment mass distribution is the Mott distribution, which describes an exponential decrease in fragment count with increasing mass. For 155 mm HE shells and similar calibres, approximately 60% of fragments have a mass below 5 g [16,22].

Another important parameter is the average fragment mass, which reflects the overall fragmentation character of the munition. A higher average fragment mass corresponds to a smaller number of heavier fragments, whereas a lower average mass indicates a larger number of lighter fragments. For instance, a projectile weighing 36.86 kg may produce approximately 2,835 fragments with an average mass of 6.5 g, or approximately 1,245 fragments with an average mass of 14.8 g. In the latter case, a higher proportion of heavy fragments is present, as illustrated in Figure 1.

In addition to mass, fragment shape plays a significant role. Lighter fragments tend to exhibit more regular shapes, such as square or near-spherical forms with aspect ratios of approximately 1:1 or 1:2. In contrast, heavier fragments are typically more elongated, often with aspect ratios of 1:3 or greater [23].

Fragments differ fundamentally from small-arms projectiles in their injury mechanism. Bullets concentrate kinetic energy at a single point of impact, whereas fragments often cause damage through cutting and tearing due to their irregular shapes and sharp edges. Heavier fragments with sufficient velocity can also induce blunt trauma and internal bleeding shapes and sharp edges. Heavier fragments with sufficient velocity can also induce blunt trauma and internal bleeding.

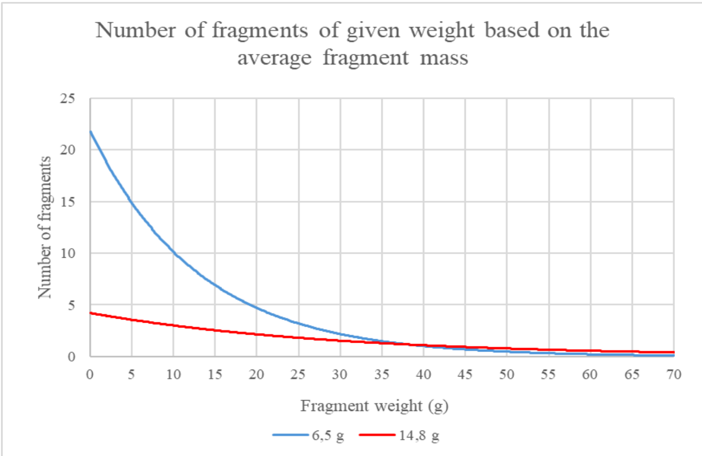

Fig. 1. Number of fragments of given weight based on the average fragment mass

A key advantage of fragmentation compared to small-arms fire is its area coverage. Even when individual fragments are not lethal, their cumulative effect can incapacitate personnel due to multiple simultaneous impacts [17]. Additionally, a high density of small fragments may contribute to secondary effects, such as sympathetic detonation of nearby munitions [24].

Overall, fragmentation effects are governed by a complex combination of factors, including munition design, detonation conditions, and environmental interactions. This complexity highlights the importance of comprehensive analysis when evaluating their impact on personnel and protective systems.

3.1. Fragmentation characterization

All these parameters must be combined to create a comprehensive representation. Based on data from [26] and using computational tools, the following procedure was applied:

1. For cylindrical part of 155mm M107 He shell, parameters were: 2030 fragments with average fragment mass of 14,34 grams and initial velocity 1030 m/s. Fragment distribution was calculated using Mott´s distribution.

$$N(m) = N_0 \cdot e^{-(\frac{m}{\mu})^{1/3}} \mu \tag{1}$$

Where: N(m) - number of fragments wight bigger weight than m; N_0 – total number of fragments; m – fragment weight; μ - average fragment mass

2. Initial weight was calculated using Gurney equation.

$$v_M = \frac{\sqrt{2E}}{\sqrt{(\frac{M}{C} + \frac{1}{2})}} \tag{2}$$

Where: v_M – initial velocity; 2E – Gurney constant; M/C - metal to explosive mass ratio

3. For each fragment weight, its kinetic energy based on distance was calculated using the formula for aerodynamic drag.

$$E_{mx} = \frac{1}{2} m \cdot (v_0 \cdot e(-\frac{kx}{\sqrt[3]{m}})^2 \quad (3)$$

Where: x – distance from detonation point; m – fragment weight; k – drag coefficient; v_0 – initial velocity

4. Lightest effective fragment calculation (effective fragment has kinetic energy higher than 79 Joules [25]). In combination with Mott´s distribution, number of all effective fragments for given distance is calculated. Results showed that 250 metres from the point of detonation, 500 out of 2030 fragments would still have enough kinetic energy.
5. Fragment density based on distance was calculated, based on spherical zone for the cylindrical part of shell. With increasing distance, number of fragments per square metre dropped significantly. Important fact to note is that fragments do not cover the entire sphere, rather just a given zone of sphere based on shell velocity, angle of impact and the initial velocity of fragments [26].
6. Using these results, probability of hit can by calculated. Assume that average standing person has area of 0,56 m^2 and is in the way of fragment zone.

$$P = \rho(s) \cdot S(c) \quad (4)$$

Where: P – probability of hit; p(s) – number of fragments per 1 m^2; S(c)- target area

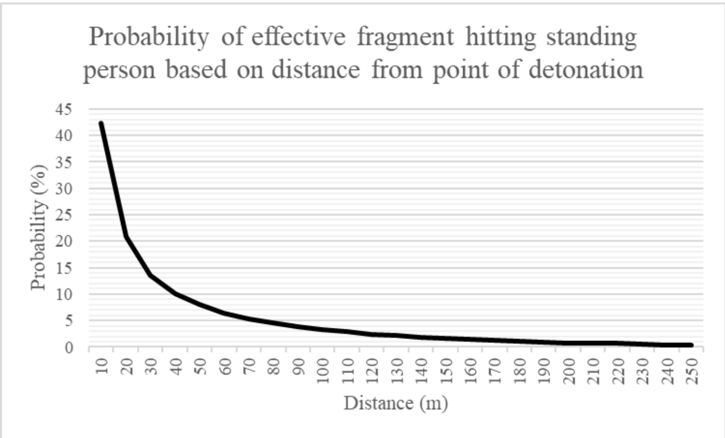

Fig. 2. Probability of effective fragment hitting standing person based on distance from the point of detonation (source own)

Results indicate that even 80 metres away from the point of detonation, there is 5% chance of being hit by fragment with enough kinetic energy. This shows the importance of factors such as impact angle or height of initiation from the ground, otherwise portion of the fragmentation effect would be suppressed.

4. Personal body armor

Personal body armor has evolved significantly over time, evolving from early materials such as leather and metal to modern composite and synthetic solutions [2]. It has been demonstrated that in contemporary conflicts, where threats from artillery, air power, and small arms fire are prevalent, the use of body armor significantly reduces thoracic injury rates compared to conflicts in which such protection was not widely employed [27,17].

However, recent observations from the war in Ukraine indicate an increase in thoracic injury rates compared to previous conflicts such as Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF). One of the primary reasons for this trend is the widespread use of modern technologies that enhance the accuracy of fire, including improved meteorological data for fire control [28,29]. Additionally, the diversity of threats has increased, as conventional armed forces employ a broader spectrum of weapon systems compared to irregular forces primarily equipped with improvised explosive devices and mortars [30].

Modern personal body armor typically consists of a ballistic helmet and a protective vest. The vest can be divided into several components, although not all configurations include the same elements. Hard armor plates, usually made of steel or advanced composite materials, are designed to protect vital organs against small arms projectiles. Depending on their classification, these plates can provide protection against threats ranging from handgun rounds to rifle ammunition. Due to their high resistance, they also offer significant protection against fragments.

To maintain mobility and reduce physical burden, hard armor plates are typically limited in size and positioned to cover critical areas such as the heart and lungs, both on the front and back of the torso. Additional protection can be provided by soft armor components, including cummerbund systems.

Soft armor is typically composed of high-performance synthetic fibers such as Kevlar, Twaron, or Dyneema. Although it provides a lower level of ballistic resistance compared to hard armor, it offers advantages in terms of weight, flexibility, and coverage. However, its effectiveness against fragmentation is limited. Unlike bullets, which concentrate kinetic energy at a single point, fragments often cause damage through cutting and tearing mechanisms due to their irregular shapes and sharp edges. As a result, soft armor is generally more vulnerable to fragmentation than hard armor of comparable protection rating.

4.1. Body armor protection area

The concept of ideal personal body armor assumes the existence of an ultralight, flexible material capable of providing full-body protection without restricting mobility. However, such material is not currently available, and therefore a compromise between protection level and weight must be achieved.

In addition to ballistic helmets and vests, supplementary protective elements such as groin, shoulder, and neck protection can be employed. However, increasing the total weight of the protective system negatively affects soldier mobility and endurance, and prolonged use may lead to musculoskeletal strain, including spinal stress [17].

Extremities present a particular challenge, as they must remain mobile and unencumbered. As a result, they cannot be effectively protected using conventional armor systems. Nevertheless, advances in battlefield medicine, particularly the widespread use of tourniquets and improved trauma care, have significantly reduced mortality rates associated with extremity injuries in recent decades [17].

From a survivability perspective, the protection of vital organs, especially the heart and lungs, is of primary importance. These areas are typically covered by hard armor plates. Due to weight constraints, however, these plates provide only limited coverage. Typical dimensions of hard armor plates are approximately 25 cm × 25 cm, focusing on the central torso region.

For example, the NPP 2006 size L plate, with dimensions of 22.5 × 27.5 cm, covers approximately 11% of the projected surface area of an average standing human body, estimated at 0.56 m². This limited coverage highlights a critical vulnerability: while body armor can effectively protect vital organs, a significant portion of the body remains exposed to fragmentation effects.

4.2. Body armor classification

Numerous national and international standards define the evaluation and classification of personal body armor. One of the most widely recognized standards is the American NIJ 0101 standard, which is commonly used by manufacturers to demonstrate the ballistic performance of their products. This standard classifies protective equipment based on its ability to resist specific ballistic threats. For example, Level IIIA armor is designed to provide protection against handgun projectiles such as 9 mm rounds or .44 Magnum ammunition.

However, ballistic protection against fragments differs fundamentally from protection against bullets. Fragment impacts involve different physical mechanisms, including irregular geometry and cutting effects, which are not adequately represented in standard ballistic classifications.

To address this limitation, specialized standards such as the Czech ČOS 130027 have been developed, based on NATO standards STANAG 2920 and AEP-2920. These standards evaluate fragment resistance using the ballistic limit velocity, denoted as V50. This parameter represents the velocity at which 50% of impacting projectiles are expected to perforate the armor [31].

Fragment resistance testing is typically conducted using Fragment Simulating Projectiles (FSPs), which are standardized projectiles with defined shapes, materials, and masses. These projectiles are designed to approximate the effects of fragmentation in a controlled manner. For example, a designation such as F5 [V50 = 650 m/s] indicates that the armor is expected to stop 50% of impacts from F5-type projectiles at a velocity of 650 m/s. Current evaluation methods are typically based on controlled conditions and predefined parameters, which may not adequately reflect the variability and uncertainty present in real combat environments.[32]

4.3. FSP vs fragments

The primary difference between FSPs and real fragments lies in their geometry and variability. While FSPs have standardized shapes and predictable behavior, real fragments exhibit irregular shapes, varying mass distributions, and diverse impact orientations. As a result, their penetration characteristics may differ significantly.

Experimental studies indicate that standardized fragment simulators, including FSPs, may in some cases exhibit higher penetration efficiency than real fragments of comparable mass [34]. This suggests that V50 values derived from FSP testing may provide a conservative estimate of protection performance. However, this relationship is not consistent across all fragment types and impact conditions.

An important question is whether V50 values can be generalized to different fragment sizes and types, for example through kinetic energy equivalence. For instance, a 1.1 g FSP with a V50 velocity of 650 m/s corresponds to a kinetic energy of approximately 232 J. Nevertheless, experimental results demonstrate that kinetic energy alone is insufficient to fully describe fragment penetration behavior, as factors such as shape, orientation, and energy distribution also play critical roles [35].

These findings indicate that there is currently no universally accepted method for accurately classifying body armor performance against fragmentation threats. Although the V50 parameter provides a useful reference, it does not fully capture real-world conditions.

One possible approach is to develop scaling relationships based on fragmentation physics, such as power-law distributions, to relate FSP results to real fragment behavior [36]. Another approach is to introduce alternative evaluation criteria, such as energy density, which has been shown to better correlate with penetration mechanisms in some experimental studies [33].

5. Field testing

An alternative approach to laboratory-based evaluation is the use of field testing under realistic operational conditions. Standardized tests are typically conducted in controlled environments, where fragment–armor interactions are isolated from external influences. However, real battlefield conditions introduce additional variables that significantly affect fragmentation behavior.

The tactical environment plays a crucial role in determining the effects of artillery fire. In urban areas, the presence of structures increases the likelihood of secondary fragmentation, while also requiring higher precision to minimize collateral damage [37]. In contrast, open terrain typically results in a wider fragmentation distribution and greater overall area coverage, although with reduced secondary effects. Other important factors include target type, formation, and level of protection. For example, engagements against exposed personnel differ significantly from those involving fortified or entrenched units, requiring different fuze settings and ammunition types.

To better evaluate the effectiveness of personal body armor under realistic conditions, two field experiments are proposed. These experiments aim to assess armor performance in representative scenarios and to compare the results with analytical models and numerical simulations. Such an approach may provide a more accurate understanding of protection effectiveness than conventional laboratory testing alone.

5.1. Field test 1

The objective of the first test is to evaluate the effectiveness of personal body armor against the effects of artillery fire. To simulate engagement against protective field fortifications, particularly trenches, mortar fire is selected as the most appropriate means. Compared to howitzers, mortars employ a high angle of impact, which is suitable for this scenario. Therefore, an 81 mm high-explosive mortar round will be used.

This experiment represents a worst-case scenario in which the projectile detonates directly within a trench. The test subject consists of standard-issue body armor used by the Army of the Czech Republic. The armor will be positioned at a height corresponding to an average standing soldier, approximately 1.5 m above ground level. To ensure realistic conditions, the mortar round will be initiated using a standard fuze. To minimize the influence of blast overpressure and focus on fragmentation effects, the distance between the point of detonation and the body armor will be set to 5 m, corresponding to a probability of lethal overpressure effects of approximately 1% or less [38]. The experiment will be conducted five times, each using a new body armor vest. The primary evaluation metrics will be the number of fragment impacts and their size distribution. The results will be expressed as mean values to ensure statistical reliability.

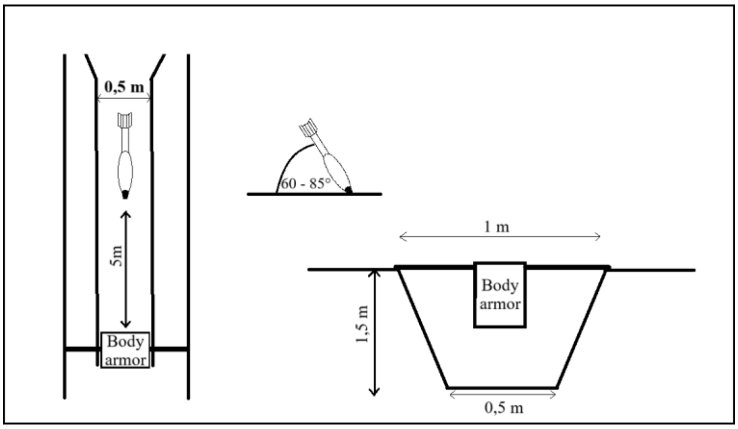

Fig. 3. Layout of the field test 1

5.2. Field test 2

The second test is designed to evaluate the effectiveness of artillery fire in open terrain, considering the increased accuracy of modern fire control systems, which enable a high probability of first-round target engagement. Given that contemporary combat operations often involve small, dispersed units, the experiment simulates an artillery strike against an infantry section in column formation [39]. Armor racks representing individual soldiers will be deployed with realistic spacing, as illustrated in Figure 4.

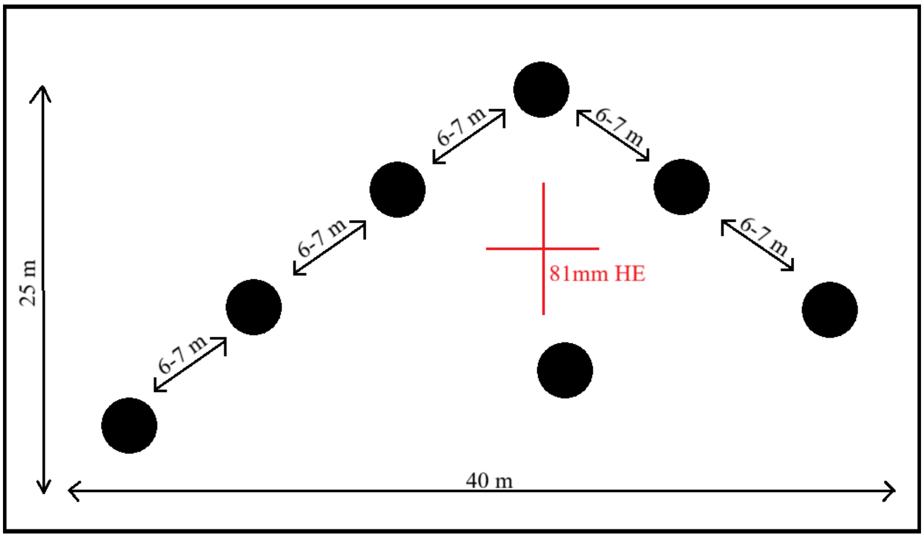

Fig. 4. Field test 2 layout

To replicate real operational conditions and account for variability in the point of impact, the projectile will not be statically initiated. Instead, an 81 mm mortar crew will conduct fire adjustment from an auxiliary target, thereby simulating first-round accuracy under realistic firing conditions.

Furthermore, the scenario will simulate an artillery ambush conducted by a platoon-sized mortar unit, in which a total of 12 mortar rounds are fired into the center of a defined target area measuring 25 × 40 m. This setup reflects realistic engagement conditions and allows for the assessment of fragment distribution and hit probability across the formation.

5.3. Field tests summary

The evaluation of both experiments will be based on the analysis of fragment interactions with the body armor. Individual fragment impacts will be categorized into three groups according to their effect: non-penetrating, partially penetrating, and fully perforating impacts. In addition, backface deformation will be assessed for all impacts to evaluate potential blunt trauma effects. For Field Test 2, the performance of individual body armor samples will be compared to analyze the relationship between distance from the point of detonation and the resulting fragmentation effects. The experimental results will be further compared with the outcomes of the mathematical model described earlier. This comparison will allow for the assessment of the model's applicability and its ability to predict real-world fragmentation effects.

6. Conclusions

The results confirm that fragmentation is the dominant lethal mechanism of artillery munitions. While personal body armor provides effective protection for vital organs, it cannot mitigate all effects associated with artillery fire. In particular blast overpressure affects personnel regardless of protective equipment, and thermal effects remain largely unaddressed by standard armor systems.

Fragmentation poses the greatest threat due to its wide spatial distribution and the large number of high-velocity projectiles generated during detonation. Even at considerable distances from the point of impact, a significant number of fragments retain sufficient kinetic energy to cause injury. Although hard armor plates provide effective protection of critical areas, their limited coverage leaves a substantial portion of the body exposed. As a result, extremities and unprotected regions of the torso remain vulnerable. It should also be noted that even low-energy fragments can cause injury, as penetration of human skin may occur at kinetic energies as low as 1 J [33].

The study further highlights that body armor cannot prevent fragment impacts but can significantly reduce the probability of fatal injury by protecting vital organs. In addition to protective equipment, tactical measures such as reducing the exposed silhouette play an important role. For example, a prone soldier presents a significantly smaller target area compared to a standing individual, thereby reducing the probability of being hit [26].

Finally, the findings indicate that current testing methods do not fully capture the complexity of real-world fragmentation effects. Future research should focus on more realistic testing approaches, including field-based experiments and advanced numerical simulations. In particular, further investigation of urban environments and secondary fragmentation effects would provide valuable insights into the effectiveness of personal protective equipment. This study contributes by combining analytical modeling with experimentally designed field testing, providing a more comprehensive understanding of fragmentation effects and the real-world effectiveness of personal body armor.

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