RICOCHET OF 9 MM PISTOL BULLETS ON GLAZED CERAMIC TILES: AN EMPIRICAL STUDY IN SUPPORT OF SHOOTING INCIDENT RECONSTRUCTION

1. INTRODUCTION

Bullet ricochet is a common occurrence in shooting incidents. It can be explained as a glancing rebound of fired projectiles off surfaces and is affected by various factors [1], including the ricochet surface type and its reaction, bullet angle of incidence, bullet type, shape and construction, and impact velocity are some of the main factors responsible for the ricochet behaviours of bullets [2]. Although existing literature presents theoretical explanations of how a bullet is generally expected to behave when ricocheting off different surface types [2, 3], recent studies have highlighted empirical results as the most viable source to understand the ricochet behaviour and surface evidence of different bullet target combinations [4 -11]. Further, these studies have reported novel findings related to ricochet angles and ricochet evidence of commonly reported bullet target combinations. The influence of single and multi-layered structures and surface finishes on the ricochet angles of bullets [8], how different failure mechanisms of target surfaces result in diverse ricochet trends [10], and post-ricochet behaviours of bullets [11] are some of the interesting findings which significantly highlight the complexity of bullet target interactions during ricochet events. Moreover, these studies have presented novel ricochet marks on different surfaces with potential forensic value. ‘Double-headed ricochet marks’ on sheet metal [4] and ‘nucleus bullet impact marks’ on ceramic tiles [10] are some of the interesting highlights of these studies, demonstrating the significant variability of ricochet evidence on different surface types.

In practice, these empirical findings are regularly used for ricochet-related scene reconstructions by shooting investigators. Ricochet analyses are performed for this purpose during shooting reconstructions to understand the pre-and post-trajectories of ricocheted bullets or even the possibility of bullets ricocheting during a shooting incident, alongside analysis of the available physical evidence [10]. As most bullet ricochet incidents occur rapidly during shooting incidents (unexpectedly or unintentionally), eyewitnesses usually have different accounts of such incidents, depending on their observations and overall understanding [2]. Therefore, ricochet analyses are critical as they provide the most precise and scientific explanation of what happened during a bullet ricochet incident, and can also assess the reliability of eyewitness accounts. Nevertheless, there is a significant lack of experimental ricochet data on even the most commonly found bullet-target combinations in shooting incidents. Therefore, empirical data of the most commonly found bullet–target combinations are in a great demand for use in ricochet-related scene reconstructions and findings of empirical studies are frequently referred to during firearms expert testimonies and attorneys during ricochet-related trials [4, 8, 12]. They are also used to aid in the design of new bullets and protective equipment and in the planning of defence constructions for military use [13,14].

This study provides an empirical investigation on the ricochet behaviour of pistol bullets (9 mm x 19 mm Luger) on glazed ceramic wall and floor tiles. These 9 mm bullets are the world's most popular handgun and submachine gun ammunition [15] and one of the most commonly reported handgun bullet types in recent crime scenes [16]. Ceramic tile is a common surface type, regularly found in urban environments with a high possibility of impact during bullet ricochet incidents. Their ricochet behaviour has been examined only in a single study with rifle bullets (7.62 mm × 39 mm) [10], and no study has attempted to explore the ricochet behaviour and surface evidence of pistol bullets. While exploring and presenting the ricochet behaviour of pistol bullets (9 mm × 19 mm) on glazed ceramic floor and wall tiles, this study compares its findings with the previous ricochet study conducted using 7.62 mm × 39 mm rifle ammunition [10] and other empirical ricochet studies.

2. METHODOLOGY

The methodology used in many other recent ricochet studies was adopted for this study [8-10]. Accordingly, a FN 9 mm Browning High Power (HP) pistol was used to fire at glazed ceramic wall and floor tiles placed at different angles to the bullet's path. The experiment was designed to be as realistic as possible, so a Browning HP pistol was used instead of a 9 mm test barrel. Similar to a previous study [10], the tile samples used for the experiments were securely fixed onto concrete blocks using the standard masonry practice to give the bullets a more realistic impact.

2.1 The gun mount and target holder

A gun mount was designed to firmly hold the Browning HP pistol with the gun barrel parallel to the ground. The mount was fixed on a stable iron frame on a cement base with its horizontal frames parallel to the ground. The level of the gun barrel was set precisely parallel to the ground, and a custom-made muzzle insertion with a bubble level was used to check the level of the barrel before each shot. The height from the ground level to the muzzle end of the gun was 1.6 m.

A target mount with a steel box frame was designed to mount a 300 mm × 300 mm × 300 mm (L × W × H) steel target tray. The target tray could hold the targets at different angles as it was pivoted at the far end of the steel base using two hinges. A digital inclinometer [17] with ± 0.2 degrees accuracy was was placed on the flat target surfaces to accurately set the angles. Once an angle was set, the target tray could be locked so it would not change from shot to shot during data collection repeats, however the angles were further checked between shots. The same height (1.6 m) was set from the ground level to the targets' impact points, and the expected points of impact on targets were identified using a 9 mm laser bullet inserted into the gun's chamber. The velocities of the shots were measured using a Doppler radar (Labradar v 1.3 [18]) which was set 30 cm from the muzzle end of the pistol. The distance from the muzzle end of the pistol to the impact points of the targets was 10 m.

A paper screen was fixed at the far edge of the target frame to capture ‘silhouettes’ of the ricocheting bullets. The ricochet angles were calculated using basic trigonometry as done in most other ricochet experiments [8-10]. Cumulative failure plot analysis of the MINITAB software [19] was employed to estimate the critical angles and ricochet probability of the bullets. The same method has also been used in previous research [8-10]. To estimate the critical angles, first, the total number of true ricochets and instances where bullets fragmented upon impact from the 10 shots performed at each angle were recorded. Then, the probability of the ricochet was modelled as a function of incident angles, with a true ricochet event given a value of “1” and a fragmentation event given “0”. The transitional area where the bullets changed from ricochet to fragmentation in the cumulative failure plot graph was decided as the critical angle of the bullets with a 50 percent probability. A one way ANOVA [20] using the SPSS statistical software platform [21] was performed to analyse the statistical significance of the results. The method is used when there is one independent variable (angle of incidence) affecting a dependent variable (ricochet angles), to decide whether any statistically significant differences between the means of three or more independent groups exist [22]. One way ANOVA post-hoc tests were also conducted to determine which of the means ricochet angles differed [23] and the partial eta squared method was used to measure the ‘effect sizes’ between reported mean ricochet angles [24].

The ammunition used for this experiment was standard 9 mm × 19 mm 124 grain RN Luger FMJ bullets (manufactured in 2016 in China) with a lead core and a copper alloy jacket. The thickness of the jacket was 0.5 mm ± 1 mm, and the jacket was confirmed to be a copper-zinc alloy with approximately 70 % copper and 30% zinc, following x-ray fluorescence (XRF) analysis. Images of the ammunition used can be seen in Figure 1. The critical angle of the bullets in this study was defined as when the bullets fragmented upon impact [2]. To decide a true ricochet event or bullet fragmentation event on impact, a box filled with Kevlar cloth pieces was kept behind the target tray and soft captured the bullets and fragments that ricocheted. After each shot, the bullet capture box was cleared of all ricocheted bullets and fragments. All ricochet marks were then numbered and photographed for analysis. A schematic of the experimental setup is shown in Figure 2 along with photos of key aspects in Figure 3.

The glazed ceramic floor and wall tile samples used in this study were purchased from a reputed supplier. As per the tiles used in a previous study [10], these floor and wall tiles were also produced in compliance with the ISO standards [25] for the manufacturing of ceramic tiles. The tile sizes were 600 mm × 300 mm × 9 mm (L × W × H), and a glaze had been added to the surface of the ceramic tiles. Glazed tiles are coated with a layer of liquid glass before going through the firing process at a high temperature [26]. The wall and floor tile samples used in this study were fixed onto concrete blocks using standard masonry practice. A standard M 15 grade concrete mixture [27] with a 1:2:4 ratio of cement: sand: gravel with water was poured into wooden moulds of 300 mm × 600 mm × 50 mm (L × W × H) to make concrete blocks upon which the tiles were mounted. After two weeks, the blocks were taken out of the moulds, and the tiles were laid on top of a 50 mm thick cement layer and a 20 mm thick tile mortar layer. The methods used were based on standard masonry tile-laying processes [28]. The technical specifications of both ceramic tile types used in this study are given in Table 1.

Two weeks after the tiles were laid, the targets were taken to the range for testing. The samples were inserted into the target tray, and ten shots were fired at each incident angle, starting from 5 degrees and increasing in 2-degree increments. This was repeated for both tile types. The data collection process continued a few incident angle increments beyond the estimated critical angles to observe any additional surfaces features for these angles.

3. RESULTS AND DISCUSSION

3.1 Ricochet angles for floor tiles

The critical angle for the floor tiles was calculated to be 14.8 degrees, at which the bullet fragments on impact. The critical angle observed was slightly higher than the critical angle of 7.62 mm × 39 mm rifle bullets (10 degrees) on floor tiles in a previous ricochet study [10]. The ricochet angles generally complied with the current understanding of bullet ricochet on frangible and non-yielding surfaces, where the ricochet angle tends to be less than the angle of incidence [2]. The average measured velocity of the bullets fired was 296 $m.s^{-1}$ ± 5 $m.s^{-1}$ with no lateral deviation of the ricocheted bullets observed due to the short distance from the ricochet point to the paper screens. The Cumulative Failure Plot Analysis for predicting the critical angle with 50 percent probability and the mean ricochet angles reported are given in Figures 4 and 5 respectively.

The ricochet angles reported for 5 and 7-degree incident angles (1.3 to 3.1 degrees) differed greatly from those reported for 9 to 13 degrees, the latter being around a whole degree lower. This suggests the possible occurrence of two different phenomena with two incident angle groups. Ricochet angles reported for incident angles from 9 to 13 degrees complied with the current theoretical understanding of bullet ricochet angles from hard, unyielding surfaces, i.e., ricochet angles remain low and close to the plane of the struck surface for all incident angles until the critical angle is achieved [2]. However, the different trend observed here with comparatively high ricochet angles at 5 and 7 degrees, and lower ricochet angles at the higher angles of incidence have not been reported in any literature source or empirical studies describing the ricochet behaviour of bullets off frangible or unyielding surfaces. Therefore, this is believed to be a phenomenon specific to this bullet-target combination.

A one-way ANOVA was performed to compare the effect of angle of incidence on ricochet angles. The results revealed that there is a statistically significant difference in the mean value of post-ricochet angles between at least two ricochet angle groups (F (4, 45) = [48.08], p =< 0.001). Post-hoc tests performed to compare the mean ricochet angles using Tukey HSD indicated that the mean scores for 5 and 7 degrees (5-degree mean = 1.96, SD = 0.68, 7-degree mean = 2.34, SD = 0.72) were significantly different from the mean scores for higher incident angles (9 to 13 degrees) which ranged between 1 to 0.6 degrees and a low associated standard deviation from 0.04 to 0.06. Effect size calculated through the Partial Eta Squared method indicated a large effect size of 0.85 between groups (Standard range - small effect = 0.01, medium effect = 0.06 large effect = 0.14 [24]. The statistical analyses for floor tile data from the ANOVA tests are given in Table 2.

During ballistic ricochet events, the impact pressure compresses and deforms both the projectile and target with deformation of both the projectile and surface being partially permanent (plastic) and partially elastic. The subsequent recovery of the stored elastic energy will change the motion of the bullets, resulting in ricochets [6]. The ricochet angles reported at 5 and 7 degrees could be related to the degree of recovery of the bullets' stored elastic energy. No deformation of the tiles was visually observed at these angles due to the hard unyielding nature of the floor tile surfaces. The bullets recovered from these angles were, however, slightly deformed. At lower angles of incidence, a short bullet-target interaction time and less resultant frictional forces experienced by the ricocheting bullets can also reduce both bullet and target deformation [8].

From 9 degrees upwards, the ricochet angles were extremely close to the struck plane due to the greater transfer of energy into the surface at higher angles of incidence and a more significant amount of energy contributing to the permanent deformation of bullets. At this stage, the bullet's recovery of stored elastic energy was less compared to impacts on lower incident angles as they exceed the elastic limit of the bullet components, leading to more deformation. When a projectile strikes an unyielding surface, it sustains a flattening of its bearing surface that will extend outward into the ogive as the incident angle increases [2]. The velocity of the bullets is also significantly reduced due to the transfer of kinetic energy discussed above along with the increase in frictional forces acting on the bullets. Due to this, the ricocheting bullet's momentum is significantly reduced, and ricochet angles become low and almost close to the struck plane. The surface characteristics, including surface properties and geometry, material properties, material interfaces and its subsequent deformation, also govern the direction and magnitude of the resultant resisting force, all affecting the bullet [6]. This was observed here and further confirmed through the ricocheted bullets fired at 9 to 13 degrees which became considerably deformed with increasing severity in line with an increasing incident angle. In contrast, the bullets ricocheting at 5 and 7 degrees experienced more minor deformation. To better exemplify this, two bullets recovered from the bullet capture box at 5 and 11 degrees are shown in Figure 6.

When high-velocity rifle bullets (7.62 mm × 39 mm) ricocheted off the floor tile samples (manufactured to the same ISO standards) in a previous ricochet study [10], all average ricochet angles (including at 5 degrees) consistently reported close to the struck plane (1.0 to 1.4 degrees). The existing literature also highlights that bullets with low velocities usually record higher ricochet angles than high-velocity bullets [30] and the same is witnessed here in the 5 to 9 degrees. However, when the incident angle is further increased, more factors come into play and a different phenomenon was observed as explained above. Furthermore, different effects from the bullet geometries and construction can also contribute to these variations from the previous study.

3.2 Ricochet angles for wall tiles

The critical angle of wall tiles was calculated to be 16.6 degrees, suggesting this to be the minimum angle at which bullet fragmentation occurs upon impact. The critical angle observed was similar to the critical angle for 7.62 mm × 39 mm rifle bullets (16.0 degrees) on floor tiles in the previous ricochet study [10]. No craters on the wall tile surfaces were observed from 5 to 11 degrees. Craters were observed for all shots with incident angles at 13 degrees and higher. The ricochet angles generally complied with the current understanding of bullet ricochet on frangible and unyielding surfaces, that ricochet angles tend to be less than incident angles [2]. The Cumulative Failure Plot Analysis for predicting the critical angle of wall tiles with 50 percent probability is given in Figure 7.

The ricochet angles reported with wall tiles ranged between 0.4 and 5.6 degrees, and the trend observed was different and opposite to the ricochet angles reported with the floor tile samples. More consistent ricochet angles (below 2 degrees) were reported from 5 to 11-degree incident angles with more significant data variation at higher angles (13 to 15 degrees). Similar to the floor tiles, the severity of the deformation to the bullets increased when the angle of incidences increased, and the jacket and cores were found intact until the critical angle was reached. The summary of ricochet angles reported with wall tiles is given in Figure 8.

When bullets ricochet off frangible surface types at low angles, the surface usually behaves like an unyielding surface, producing low ricochet angles [2, 10] with no cratering in general. This may have resulted due to the additional strength provided to the wall tiles by the multi-layered structure with tile mortar, cement, and concrete base. However, craters are produced when the failure point of the material is achieved, typically when bullets ricochet off at higher angles of incidence. The wall tiles in this experiment reached their failure point at around 13 degrees, before the bullets reached their critical angle. Therefore, craters were produced on the wall tile surfaces upon impact with the shattering of the subsurface as explained in the existing literature [2]. These craters were irregular in shape due to the typical failure mechanism that takes place when bullets impact frangible surfaces at high angles [2, 10]. The general structure of these irregular craters provides a 'ramp' with which the bullets can then engage with when ricocheting off of the surface, resulting in ricochet angles that are higher than when the ramp does not exist. The extent of this effect can vary from shot to shot [10]. This characteristic was observed for bullets that ricocheted from the 13-degree angle of incidence upwards, producing clear craters. A significant inconsistency of the ricochet angles was observed above 13 degrees with high associated standard deviations, suggesting a strong frangible surface ricochet mechanism. However, it is significant to note that the same inconsistency was not observed when high-velocity rifle bullets ricocheted off wall tiles in the previous study [10]. Instead, a positive, linear trend with a significant coefficient correlation value was reported ($R^2 = 0.99$). The cratering effect was observed in the previous study with rifle bullets [10] from 5 degrees onwards (due to the higher velocity and energy of rifle bullets), whereas a different trend was observed here with comparatively lower velocity pistol bullets, no cratering phase for 5 to 11 degrees and then a cratering phase for 13 degrees and above. The energy differences may be a major reason for the differences observed.

Similar to the results of the analysis on floor tiles, the results of the one-way ANOVA revealed that there is a statistically significant difference in the mean ricochet angles between at least two groups ($F (5, 54) = [4.5]$, $p = < 0.002$). Post-hoc tests performed to compare the mean ricochet angles using Tukey HSD indicated that the mean scores for 5, 7 and 9 degrees (at 5 degrees the mean = 1.7 and SD = 0.16, at 7 degrees the mean = 1.6 and SD = 0.13, at 9 degrees the mean = 1.6 and SD = 0.2) were significantly close and consistent while the mean scores for higher angles have a notable difference in ricochet angles and associated high standard deviation values (at 11 degrees the mean

= 0.73 and SD 0.10, at 13 degrees the mean = 2.5 and SD = 1.9, at 15 degrees the mean = 2.7 and SD = 1.6). The results strongly support the above explanation of the different trends. Partial Eta Squared value also indicated a larger effect size 0.30 between the group means (Standard range, small effect = 0.01, medium effect = 0.06 large effect = 0.14 [24]. A summary of the the statistical analysis results for wall tiles from the ANOVA test can be seen in Table 3.

3.3 Ricochet marks on wall and floor tile samples

3.3.1 Novel 'caterpillar' ricochet mark

Before the surface cratering phase, a novel ricochet mark on wall tile samples was observed for shots fired at 5 to 11 degree incident angles. These marks were similar in shape and size for a particular incident angle. This impact feature has not been described in any of the ricochet-related literature sources and is henceforth referred to as the 'caterpillar effect' or 'caterpillar ricochet mark' on wall tiles. Some images of the caterpillar effect observed on wall tile samples at each angle of incidence are given in Figure 9. The curved semi-circle crack marks are believed to be stress fractures produced due to the bullet impacts on wall tiles. The cracks have been produced only on the this glazed glass surface without extending to the ceramic layers underneath. A scanning electron microscopy (SEM) image of typical tile layers can be seen in Figure 10 [31]. A standard glazed ceramic tile will usually have a layered structure consisting of glaze, engobe and ceramic biscuit [31]. The explanation for these caterpillar marks only being observed for the wall tiles could be due to structural differences in the layers of glaze, engobe and main ceramic body (biscuit), reacting differently to the ricocheting bullets. Although it is difficult to separate the effects of the surface alone from the underlying layered structures, the evidence highlights that a complex bullet and surface interaction has taken place, resulting in the observed caterpillar ricochet mark. A similar phenomenon has previously been explained when AK bullets separately ricocheted off both rough and intermediate layered concrete samples [8]. There were significant differences in the observed ricochet angles purely due to the addition of an extra 20 mm layer on the intermediate cement samples. A similarly sensitive surface effect may be causing the caterpillar ricochet marks solely for the wall tiles.

When a bullet impacts the wall tile surface, an oval-shaped crack is produced at the first contact point due to the round nose profile of 9 mm bullets [32]. These round-shaped cracks could be seen at the beginning of each impact mark (Figure 9), produced from 5 to 11-degree incident angles. When the bullet continues to slide after impact, the surface experiences more deformation; and the more the bullet deforms, the greater the interaction surface and a greater energy transfer occurs. This phenomenon is evident from the variation in stress fractures. Stress fracture sizes increase as the D profile of deforming projectiles increases along the V profile [33] of the ricochet marks observed from left to right along the ricochet creases (These D and V profiles are explained in in Figure 11). When the bullet starts to ricochet, the bullet-target interaction and energy transmission to the surface become less as the bullet disengages from the surface. Therefore, the stress fracture lines towards the end of the ricochet marks become smaller. Similar stress wave fractures observed on painted sheet metal in a previous ricochet study [34] illustrated stress fractures being produced on either side of the forward-moving bullet but this current study shows stress fractures being produced across the whole ricochet mark for the first time.

In addition to the fracture lines, small streaked depositions from the bullet's structure (lead and copper alloy) are visible across the fracture lines in the direction of the bullet's travel. These can be seen in the high-resolution picture taken of a ricochet mark in Figure 12. Stress fracture lines are sequentially produced in front of the bullets when they slide along the wall tile surface. Due to the deformation, the copper alloy bullet jacket is damaged, and the bullet lead core is exposed to the impact surface underneath. As the bullet slides across the stress fractures, these lead and copper particles get deposited in the thin fracture lines. These depositions could provide important information about bullet type and construction as part of a real-life investigation.

However, it is significant to note that the caterpillar effect was not reported when rifle bullets ricochet off wall tiles [10], given they had been manufactured according to the same ISO standards. The comparatively high velocity and energy of the 7.62 mm × 39 mm bullets (approximately 727 $m.s^{-1}$) produced craters upon impact with the wall tiles from 5 degrees onwards as the failure point of the target surface had been achieved. The comparison also suggests that the ability to observe these stress wave fractures on surfaces may depend on a certain velocity level at which sufficient energy is delivered to the surface, producing stress fractures, but without achieving total material failure of the underlying tile layers, leading to craters. The observations associated with the caterpillar effect currently demonstrates a novel ricochet profile specific to pistol bullets ricocheting off wall tiles. It is also suggested that the caterpillar ricochet mark is likely to be observed on surfaces with layered structures, similar to glazed ceramic tiles and painted sheet metal. Further studies are suggested to explore other mark variations related to other commonly available surface types with layered and non-layered structures.

3.3.2 Nucleus impact mark and pinch points during bullet fragmentation

The bullet impacts on floor tile surfaces have produced dark bullet impact marks with all shots fired up until an incident angle of 17 degrees (passing the critical angle at 14.8 degrees). At 19 to 23 degrees, the ‘nucleus’ bullet ricochet mark appeared. Nucleus bullet ricochet marks had been reported in a previous ricochet study [10] on floor tiles using AK rifle bullets from 7 and 9 degree incident angles. These impact marks consisted of clear imprints from the AK bullet’s (M 43) copper alloy jacket and steel core [10], occurring at incident angles where following impact, the mild steel core of the AK bullets protruded through the copper jackets to interact with the floor tile surface. This feature is now observed for 9 mm Luger pistol bullets for all shots fired at 19 to 23 degrees, where the bullets fragmented on impact. Figure 13 depicts nucleus ricochet marks observed when a rifle bullet (7.62 mm × 39 mm) ricocheted off floor tiles [10] and the similar marks produced from the pistol bullets in this study.

A similar feature to the ‘pinch point’ reported for floor tiles in a previous ricochet study [10] at 9 degrees incident angle was also reported for 19 to 23 degrees in this work. However, the pinch points from pistol bullets were relatively larger in diameter (approximately 9 to 10 mm) compared to the pinch points reported with rifle bullets (5 to 6 mm) [10]. The observed size differences are mainly due to the diameter and velocity (and thus energy) differences between 7.62 mm and 9 mm bullets, with the pinch poing diameters being very close to the bullet calibres. Differences may also be partly due to the differing nose profiles of the bullets [32]. Although the findings with regards to the nucleus impact mark and pinch points in this study were reported when the bullets fragmented upon impact, the features emphasise the wide variation in evidential markings on impact surfaces under different terminal ballistic conditions and their potential evidential value when used during shooting reconstructions.

4. CONCLUSION

The ricochet behaviour of pistol bullets (9 mm Luger with copper alloy jackets and lead cores) was explored in this study. The critical angles reported for floor tiles and wall tiles were 14.8 degrees and 16.6 degrees respectively. In comparison, from a previous study, the values for the critical angle of floor and wall tiles with rifle bullets (7.62 mm × 39 mm) were 10 degrees for floor tiles and 16 degrees for wall tiles [10], suggesting that the critical angle of bullets ricocheting off glazed floor and wall tiles generally falls approximately between 10 and 17 degrees.

The ricochet angles reported for both tile types generally complied with the current understanding of bullet ricochet on frangible and unyielding surfaces that ricochet angles are typically less than incident angles. However, wall and floor tile groups reported two different ricochet trends. At 5 and 7 degree incident angles, high ricochet angles (1.5 to 3.1 degrees) were reported compared to those reported from 9 to 15 degree incident angles (below 1 degree). The ricochet angles reported on wall tiles ranged between 0.4 to 5.6 degrees, and the trend observed was different and contradictory to the ricochet angles reported on the floor tile samples. More consistent ricochet angles were reported from 5 to 11 degrees, with more significant variations and high associated standard deviations observed at higher degrees. Compared to a previous ricochet study conducted with rifle bullets [10], the results highlighted a significant difference in ricochet angle trends for each velocity group and bullet type. The highlighted differences could be explained by the velocity (and energy) difference and the complex surface reaction to ricocheting bullets from layered surfaces. These are further affected by other bullet-related factors such as the profile, size and construction of the different bullet types. The results of the one-way ANOVA for floor and wall tiles revealed a statistically significant difference in the mean value of ricochet angles between at least two incident angle groups. Estimated Partial Eta Squared results also indicate a significant effect size between the mean values of incident angle groups of both the surface types.

This study has introduced the first observations of a ‘caterpillar effect’ or ‘caterpillar ricochet mark’ on wall tiles during a ricochet event (5 to 11-degree incident angles), highlighting how bullet-target combinations propagate stress-induced fractures on wall tiles with a glazed layer. Thus, the novel caterpillar ricochet mark introduces a new ricochet profile specific to pistol bullets and wall tiles. This seems to appear for ricochet events on the wall tile surfaces up until the point that craters are produced and energy transfer is sufficient to take the surface past its failure point. Nucleus ricochet marks were observed on floor tiles at 19 to 21-degree incident angles, where the 9 mm bullets fragmented on impact. These had also been observed in a previous study for rifle bullets on the same surface at 7 to 9-degree angles of incidence. The velocity differences, bullet construction, shape, mass, and the nature of the bullet-target interaction could all be contributing causes for the differences observed.

In particular, the critical angles, ricochet angles and ricochet marks presented in this study could be effectively used for practical scene reconstructions. However, investigators must make sure that the tiles found on a scene have complied with the general standards indicated. While presenting important and novel findings concerning bullet-target combinations with a high probability of undergoing bullet ricochets, this paper also highlights the challenges and uncertainties that continue to persist in predicting the ricochet behaviour of bullets. It still holds true that a strong understanding of specific projectile-surface combinations is essential for the most accurate shooting scene reconstructions.

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TABLES

Table 1: Technical specifications for the ceramic tiles used in this study.

Physical properties	**Wall tiles**	**Floor tiles**
Size / Thickness	30 cm × 60 cm / 6.4 mm	30 cm × 60 cm / 12.7 mm
Material	Ceramic clay	Ceramic clay
Glazed	Yes	Yes
Water absorption	12 % - 18 %	3 % - 6 %
Breaking strength (min.)*	500 N	1000 N
Modulus of rupture (min.)**	22 $N.mm^{-2}$	13 $N.mm^{-2}$
Compliance with ISO (International Organization for Standards (ISO, 2021)	ISO 13006:2102 (E)	ISO 13006:218 (J)
* The breaking strength is the force obtained by multiplying the breaking load by the ratio (span between the support rods/width of the test specimen). ** Modulus of rupture measures the bond strength of the tile specimen. It is calculated by dividing the breaking strength by the square of the minimum thickness along the broken edge [29].		

Table 2: Statistical analyses, including ANOVA results, for floor tile data.

Descriptive Statistics - ANOVA								
Angle of incidence (degrees)	N	Mean ricochet angle	Standard deviation	Standard error	95% Confidence interval for mean		Minimum ricochet angle value	Maximum ricochet angle value
					Lower bound	Upper bound		
5	10	1.9	0.6	0.22	1.4	2.4	1.1	3.2
7	10	2.3	0.7	0.23	1.8	2.8	1.7	3.7
9	10	0.6	0.2	0.07	0.4	0.7	0.3	0.9
11	10	0.3	<0.1	0.02	0.2	0.3	0.2	0.4
13	10	0.1	<0.1	0.01	0.1	0.2	0.1	0.2

Table 3: Statistical analyses, including ANOVA results for wall tile data.

Descriptive Statistics - ANOVA								
Angle of incidence (degrees)	N	Mean ricochet angles	Standard deviation	Standard Error	95% Confidence interval for mean		Minimum value	Maximum value
					Lower bound	Upper bound		
5	10	1.6	0.1	0.05	1.5	1.8	1.5	2.1
7	10	1.6	0.1	0.04	1.5	1.7	1.4	1.8
9	10	1.5	0.2	0.06	1.4	1.7	1.2	1.8
11	10	0.7	0.1	0.03	0.6	0.8	0.6	0.9
13	10	2.5	2.0	0.63	1.0	3.9	0.4	5.6
15	10	2.6	1.5	0.49	1.5	3.8	0.6	4.8

FIGURE LEGENDS

Figure 1: The lead core, a removed copper-zinc alloy jacket portion and the headstamp for the 9 mm Luger ammunition used in this study.

Figure 2: The experimental arrangement for this study.

Figure 3: Photographs detailing the angled target position (left) and measurement systems used at the firing position (Doppler radar top right and barrel level, bottom right).

Figure 4: Cumulative Failure Plot Analysis, predicting the critical angle of floor tiles with 50 percent probability.

Figure 5: Mean ricochet angles with standard deviations for the floor tiles used in this study. The data points on the graph represent instances where true ricochets were reported for all 10 shots.

Figure 6: Photographs of the recovered bullets following impacts at incident angles of 5 and 11 degrees on floor tiles. The bullet at 11 degrees shows more severe deformation.

Figure 7: Cumulative Failure Plot Analysis, predicting the critical angle with 50 percent probability.

Figure 8: Mean ricochet angles with standard deviations for the wall tiles used in this study. The data points on the graph represent instances where true ricochets were reported for all 10 shots.

Figure 9: A range of ‘caterpillar effect’ ricochet marks on the wall tiles at different angles of incidence.

Figure 10: A scanning electron microscopy (SEM) image of a cross-section through a standard wall tile, highlighting the layers (from [31]).

Figure 11: Explanation of the caterpillar ricochet mark’s main features and how it is produced on wall tiles. The black arrow indicates the direction of the bullet’s travel. The V profile of the ricochet mark [33] is shown by the dashed lines, and D profile of the deforming projectile is also shown from the perspective of the base of the bullet along the impact surface. The D profile size varies depending on the degree of bullet deformation caused from interacting with the target surface.

Figure 12: Lead and copper alloy deposits amongst the stress fracture lines on a wall tile impacted by a 9 mm Luger bullet at a 9-degree angle of incidence. The black arrow indicates the direction of the shot from left to right.

Figure 13: A ‘nucleus’ ricochet mark left by rifle bullets (7.62 mm x 39 mm / M 43) following a ricochet event at a 9-degree angle of incidence (Left, [10]) and 9 mm bullets in this study (Right) during bullet ricochet at 19 degrees. White arrows indicate the direction of the bullets. Pinch points are circled in red.