NUMERICAL INVESTIGATION ON THE IMPACT OF VARIOUS CONSTRUCTION DESIGNS OF CERAMIC MOSAIC ARMOUR ON BALLISTIC RESISTANCE

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The ballistic resistance of hexagonal mosaic ceramic tiles (Al_2O_3) has been investigated by conducting three-dimensional finite element simulations on LS-DYNA. The aim of the present work is to offer an overview of the potential energy absorption and dissipation mechanisms and advantages of ceramic mosaic tiles construction designs against projectile impact. The ceramic tile configurations examined for the study have two different head shapes, namely semi-spherical nose (SCH) and pyramidal nose (PH) with a flat hexagonal base. In the numerical simulation of the ballistic impact, a 5.56x45 mm M855 bullet was launched at 900 m/s. Numerical predictions demonstrated that PH ceramic tiles outperform SCH ceramic tiles in terms of energy absorption. It was found that the residual velocity of the projectile decreases with increasing base thickness.

Keywords: hexagonal ceramic mosaic tiles, semi-spherical nose, pyramidal nose, projectile, numerical simulation

1. Introduction

The battlefield of the future is largely characterized by lethal autonomous weapons systems, full coordination of all categories of forces and the use of cyber-physical systems to complement the physiological limits of the fighters. In this context, the role of personal protective equipment (PPE) is essential in protecting the safety of soldiers and improving combat effectiveness [1].

As a result of these new threats and risks on the battlefield, there are more and more situations where the traditional materials from which the body armour is made cannot fully satisfy the multitude of restrictions imposed, and how the geometric configuration of hard ballistic plates are generally imposed, the only level at which it can act, remains the use of new materials with special qualities. Ceramic is one of the widely used armouring materials.

The ceramics used in ballistic applications are either monolithic plates or multi-layer composites (a hard ceramic plate as the front face and high strength and high modulus fibres as the back face). The role of the ceramic tile is to cause fragmentation of the bullet or to produce erosion, by redirecting and spreading

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kinetic energy. When a projectile strikes and perforates the ceramic tile, a fragile damage develops which results in widespread tile fragmentation. The kinetic energy of the remaining projectile fragment and ceramic is absorbed by the high strength and high modulus fibres layer through plastic deformation, Fig. 1.

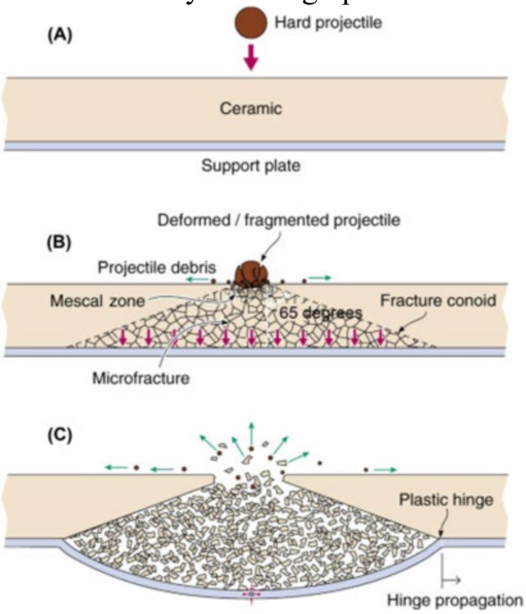

Fig. 1. The ceramic penetration mechanism [2]

Ceramic tiles are usually not as durable as metal tiles and can easily crack or break, especially in the event of multiple impacts. They are therefore usually only intended to be used for a limited number of strikes before being replaced. To improve the situation, one way is to reduce the size of the tiles so that if a single tile has been damaged, the surface exposed to any further impact is minimized. This design is called “mosaic armour”.

The effect of the boundary conditions by changing the shape of a ceramic tile has been investigated by Nadda [3] who impacted two different shapes of ceramic/ metal tile (hexagonal and square) by a 7.62 mm AP projectile. He showed that the hexagonal shape can reduce the back face deformation compared to the square shape.

The design of the interface between adjacent ceramic tiles is also important for the ballistic testing of ceramics. Guodong et al. performed ABAQUS/Explicit simulations using a 7.62 mm AP projectile and impacting ceramic mosaic/ composite plates with different interface designs [4]. They showed that interface design affects the ballistic resistance of armour.

In the most cost-effective models of mosaic armour, head shapes are most important for ballistic resistance. Wu et al. [5] conducted ballistic tests of a spherical cylindrical ceramic armour by firing a 14.5 mm AP projectile. Hu et al [6] directed ballistic tests by striking ceramic columns with different head shapes (flat and spherical) by a fragment simulator projectile (FSP). Wang et al. [7] impacted different metal matrix ceramic composite plates that were manufactured using ceramic balls of different diameters. Luo et al. [8] also conducted tests on metal matrix ceramic composite plates with varying arrangements of ceramic balls. Jiang et al. [9] showed ballistic tests of a semi-spherical ceramic armour by firing a 12.7 mm API projectile. Yang et al. [10] studied the impact resistance of two types of nacre-like composites of different tablet arrangements. Jiang et al. [11] investigated the ballistic performance of columnar ceramic/interlayer hybrid fibre composites. Their research has shown that ceramic plate design has significantly improved the protective capabilities of armour against ballistic threats.

The effect of the angle of incidence has been studied by Jitarasu [12] who subjected a multi-layer armour by a 7.62 mm projectile. Depending on the angle slope, better ballistic protection is achieved.

In this research, a finite element model of the ceramic mosaic tile is developed to investigate its ballistic performance against ballistic penetration. In contrast to the classical flat-sided designs, two different novel head shapes of hexagonal ceramic mosaic designs are proposed. The main focus is on the effect of the shape of the hexagonal ceramic tile head. The typical failure mode and penetration process of the mosaic tile are also analysed. Finally, the energy absorption capacity of mosaic tile is discussed.

2. The theoretical approach

2.1 Structural design of mosaic ceramic tiles and projectile

The mosaic ceramic tiles (Al_2O_3) have two different head shapes, namely semi-spherical nose (SCH) and pyramidal nose (PH), as shown in Fig. 2, with a flat hexagonal base.

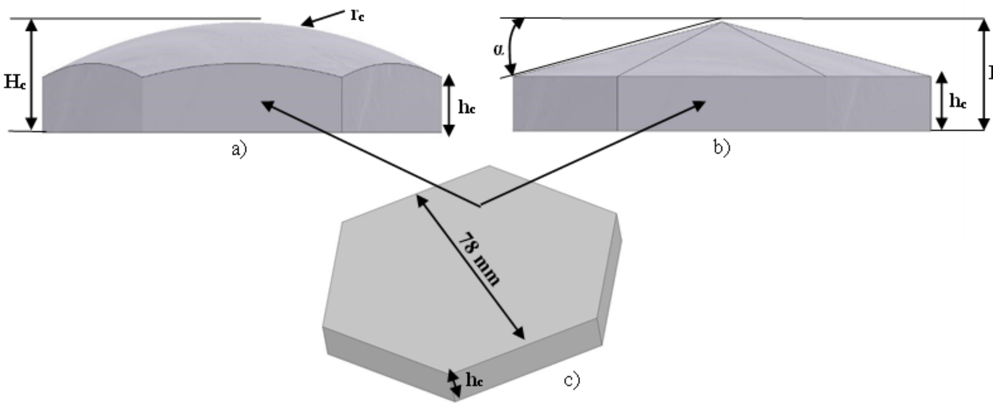

Fig. 2. The geometries of ceramic tiles: a) semi-spherical nose; b) pyramidal nose; c) base

Seven types of hexagonal ceramic mosaic tiles have been developed to evaluate ballistic resistance to projectile penetration. These ballistic tile configurations from the research are shown in Table 1.

Table 1

Configuration of the hexagonal ceramic mosaic tiles

Configuration code	H_c [mm]	h_c [mm]	r_c [mm]	α [°]	m [g]
SCH1	15	4	97.68	-	96
SCH2	15	7.5	138.95	-	108
SCH3	15	11	255.5	-	120
PH1	15	4	-	13.73	69
PH2	15	7.5	-	9.46	90
PH3	15	11	-	5.08	111
PHF	15	15	-	0	135

A 5.56 × 45 mm (M855) projectile, made of a steel tip penetrator, a lead core and a copper jacket is used for impact analysis, Fig. 3.

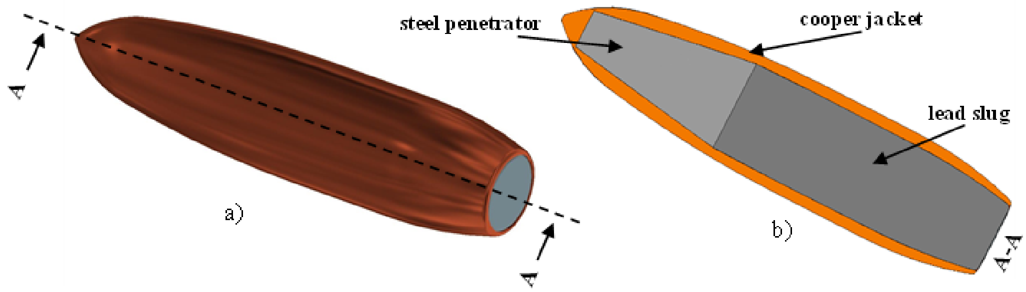

Fig. 3. The projectile used in analysis: a) lateral view; b) cross section view

2.2 Finite element modelling

The finite element method (LS-DYNA software) has been used to model and analyse the impact mechanism of the hexagonal ceramic mosaic tiles investigated. The finite element models of the ceramic tiles and the projectile have been developed using *Solid* elements, Fig. 4.

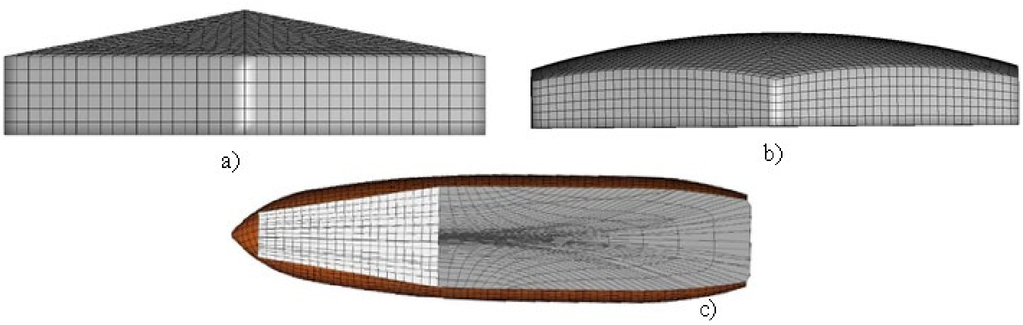

Fig. 4. Finite element model: a) PH ceramic tile; b) SCH ceramic tile; c) projectile

The sensitivity of the mesh was evaluated through the utilization of different element sizes: 0.5 mm for the hexagonal ceramic mosaic tiles and 0.2 mm for the projectile. The mesh of the projectile comprised a total of 15267 elements, distributed as follows: 8703 elements for the lead core, 2688 elements for the steel tip penetrator, and 3876 elements for the copper jacket. Additionally, the mesh configurations for the tiles varied between 10737 and 38858 elements, depending on the specific tile configurations.

In all numerical simulations, tests were performed on 8 processors, with completion times ranging from 3 to 7 hours, depending on the ceramic tiles' configurations analysed.

The interaction between the projectile parts and between the ceramic tiles and the projectile has been modelled using the CONTACT_ERODING_SURFACE_TO_SURFACE contact algorithm. The friction between the ceramic tiles and the projectile has been also included in the analysis. The value of the friction coefficient was set at 0.28 [13].

2.3 Constitutive modelling

The MAT_JOHNSON_COOK plasticity model (JC) has been used to define the material behaviour on impact for the projectile consisting of three distinct materials as mentioned above. It is one of the most widely adopted models for determining material characteristics and damage to initiate and describe material behaviour under the effect of strain rate, temperature and deformation. The JC constitutive model parameters for the steel tip penetrator, the lead core and the copper jacket are defined in Table 2 [14, 15, 16, 17].

Table 2

Projectile input parameters

Property	Symbol	Value (lead slug)	Value (steel penetrator)	Value (copper jacket)
Density	ρ	11340 kg/m^3	7850 kg/m^3	8940 kg/m^3
Poisson´s ratio	υ	0.3	0.33	0.35
Elastic modulus	E	16 GPa	210 GPa	124.9 GPa
Specific heat capacity	C_p	124 J/kg·K	452 J/kg·K	385 J/kg·K
Johnson-Cook plasticity constitutive model	A	0.024 GPa	1.6 GPa	0.5 GPa
	B	0.3 GPa	0.807 GPa	0 GPa
	n	1	0.1	1
	c	0.1	0.008	0.025
	m	1	1	1
	$\dot{\varepsilon}_0$	5e-4	5e-4	5e-4
	T_m	760 K	1800 K	1790 K

	T_{tr}	293 K	293 K	293 K
Johnson-Cook damage constitutive model	D_1	-	0.051	0
	D_2	-	0.018	2.65
	D_3	-	-2.44	-0.62
	D_4	-	0.0001	0.028
	D_5	-	0.55	0

The ceramic tile is modelled using the MAT_JOHNSON_HOLMQUIST_CERAMICS model (JH-2). This model is used to analyse brittle materials, such as ceramics, which are exposed to high pressures, shear strain and high strain rates. The JH-2 model parameters for alumina (Al_2O_3) are defined in Table 3 [18].

Table 3

Ceramic input parameters

Property	**Symbol**	**Value**
Density	ρ	3840 kg/m^3
Shear modulus	G	93 GPa
Intact normalized strength coefficient	A	0.93
Fractured normalized strength coefficient	B	0.31
Strain rate coefficient	C	0.007
Fractured strength exponent	M	0.6
Intact strength exponent	N	0.64
Normalized maximum fractured strength	ε^f_{max}	1 GPa
Hugoniot elastic limit	HEL	8 GPa GPa
Pressure at the Hugoniot elastic limit	P_{HEL}	1.46 GPa
Bulking factor	β	1
Damage coefficient	D_1	0.01
Damage exponent	D_2	0.7
First pressure coefficient	K_1	131 GPa
Second pressure coefficient	K_2	0 GPa
Third pressure coefficient	K_3	0 GPa

Also, other similar material parameter values for Al_2O_3 tiles and M855 projectile can be found in the literature [16]. The material parameters mention above were calibrated using dynamic tests. Since high-velocity impact is a phenomenon involving high strain rates, ballistic tests were performed for calibration and validation of numerical models. The prediction of the ballistic impact was made with high accuracy.

3. Results and discussion

3.1 Simulation of penetration

The ballistic impact on the hexagonal ceramic mosaic tiles is simulated with a striking velocity of 900 m/s. The numerical analysis focused on a geometrical configuration projected at an angle of 0° between the projectile and the tile, representing a frontal impact near the centre of the tile. Encased boundary conditions were imposed along the edges for consistency and stability in the simulation.

Fig. 5 displays the behaviour of the PH1 configuration in the event of a ballistic impact. Circumferential cracks in the ceramic tile can be seen around the projectile hole, forming circular rings and radial cracks appear on the rear face. A plug of material has been ejected, perforating the ceramic tile, Fig. 5d.

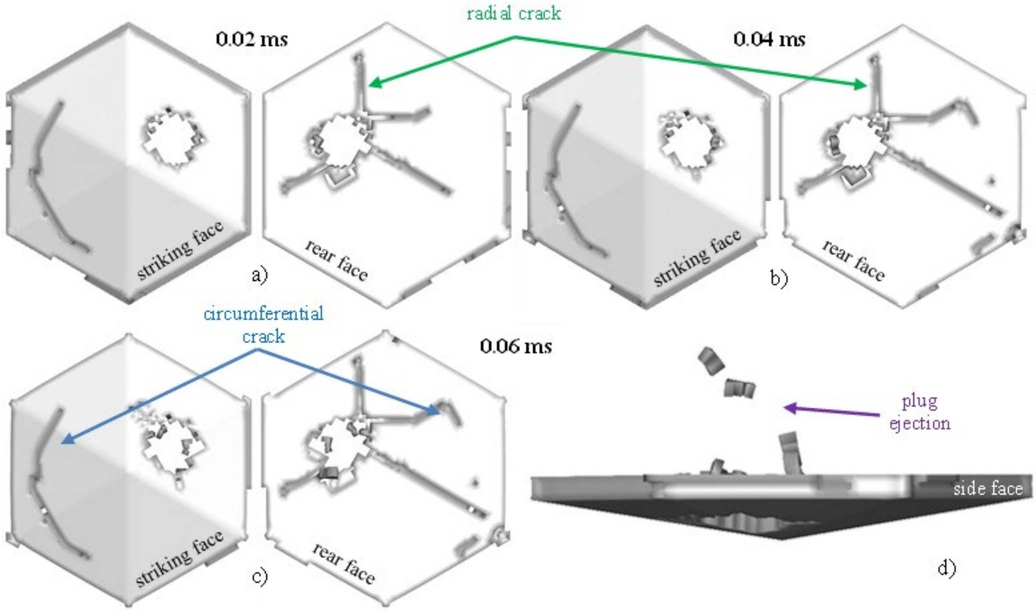

Fig. 5. Evolution of the impact process for the PH1 configuration

For the PH2 configuration, it was found that the ceramic tile shows better performance compared to PH1 configuration. However, the propagation of circular and radial cracks can be observed almost over the entire surface of the ceramic tile. Small fragments of the mosaic ceramic tile can be observed in the impact area, Fig. 6d.

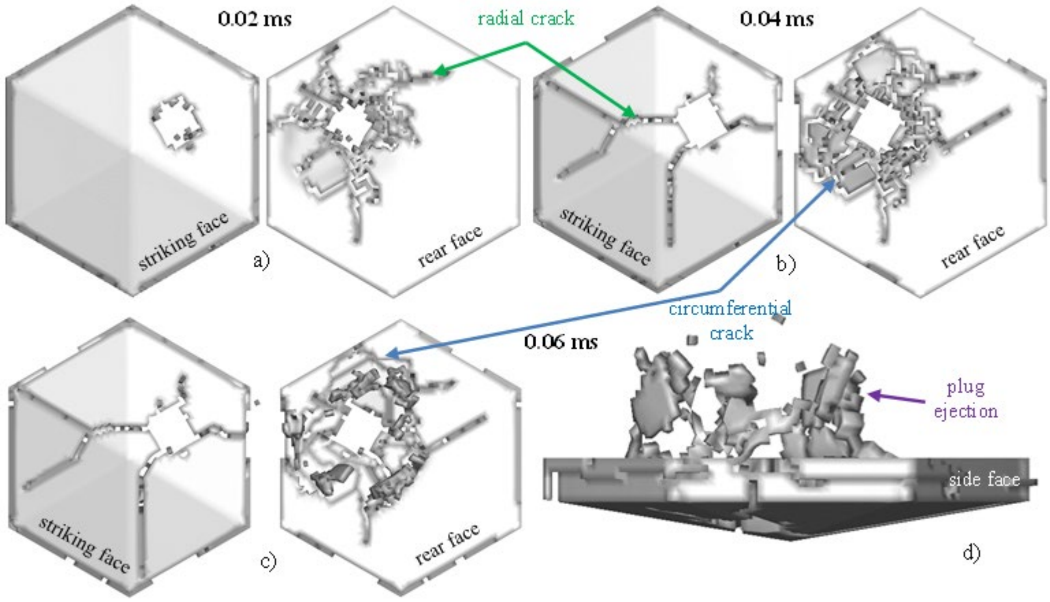

Fig. 6. Evolution of the impact process for the PH2 configuration

In the case of the PH3 configuration, it can be seen the initiation and development process of fracture in the ceramic tile, as well as the large, damaged area of the ceramic material in the impact zone and that the bullet was able to almost completely scatter the rear face of the tile into small fragments, Fig. 7d.

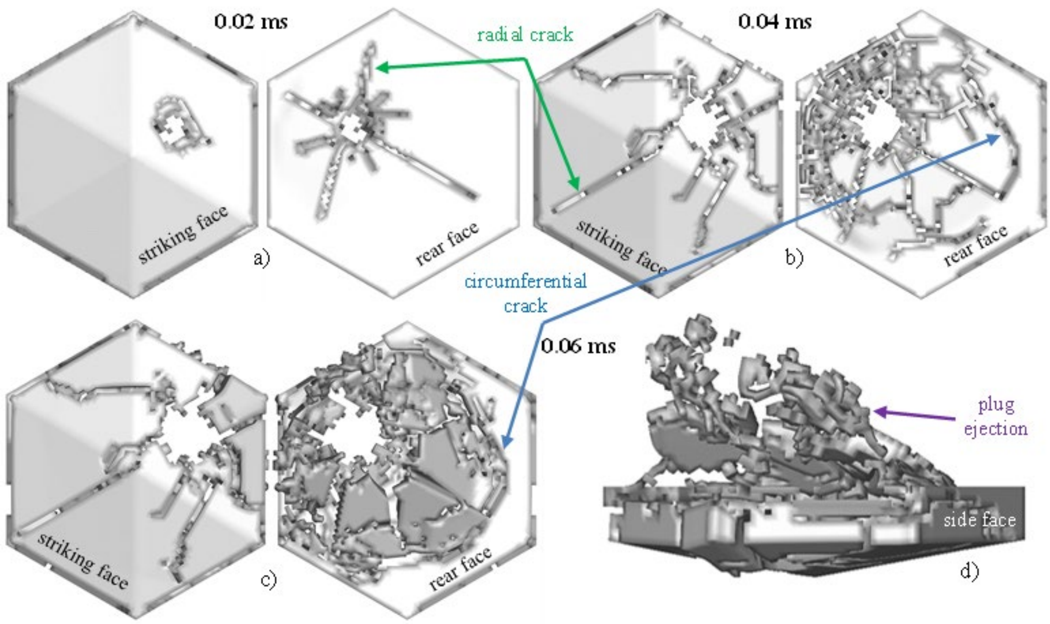

Fig. 7. Evolution of the impact process for the PH3 configuration

In the case of the PHF configuration, the ceramic tile has provided a significantly improved resistance compared to previous configurations. Considerable damage can be observed as the rear face of the tile is completely separated into tiny fragments, Fig. 8d.

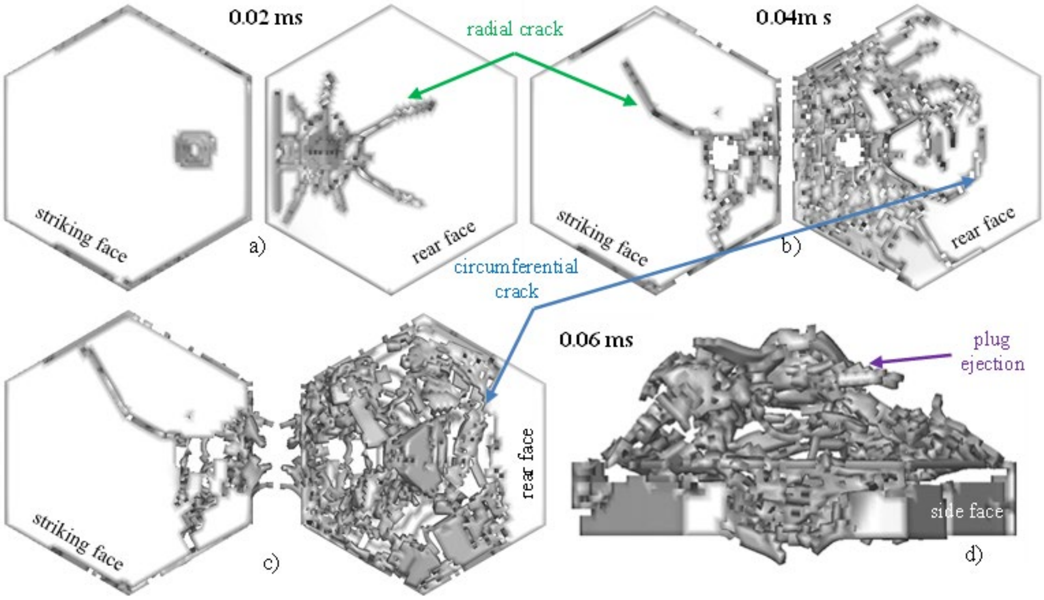

Fig. 8. Evolution of the impact process for the PHF configuration

Fig. 9 shows the behaviour of the SCH1 configuration during the ballistic impact. The ceramic tile failed to withstand the striking bullet and developed several significant cracks. The plug of material ejected from the tile is almost negligible, as shown in Fig. 9d.

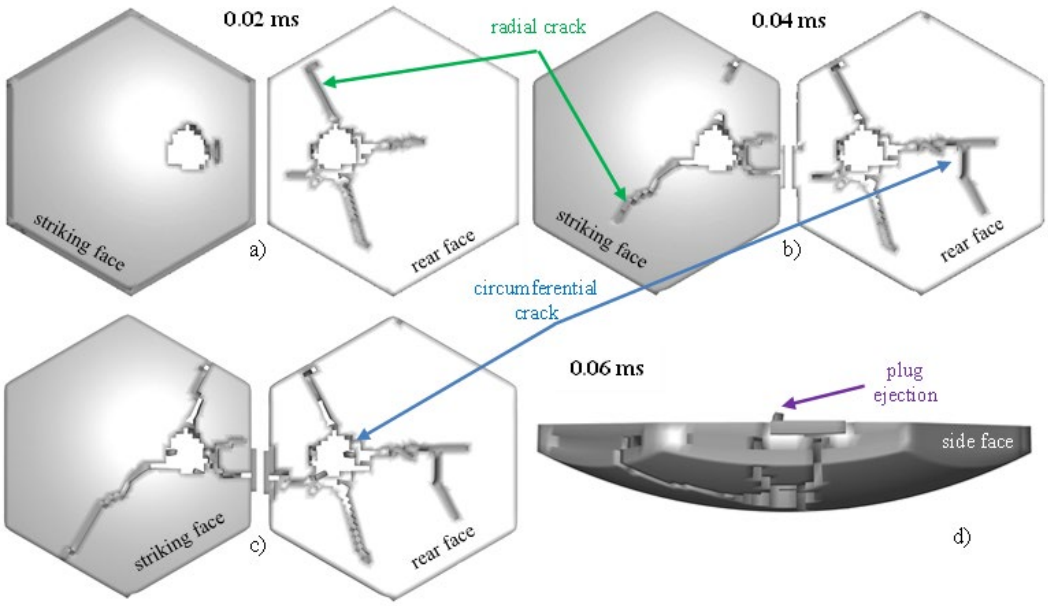

Fig. 9. Evolution of the impact process for the SCH1 configuration

For the SCH2 configuration, it was found that the propagation of circular and radial cracks can be observed almost over the entire surface of the ceramic tile. Small fragments of the mosaic ceramic tile have been ejected, perforating the ceramic tile, Fig. 10d.

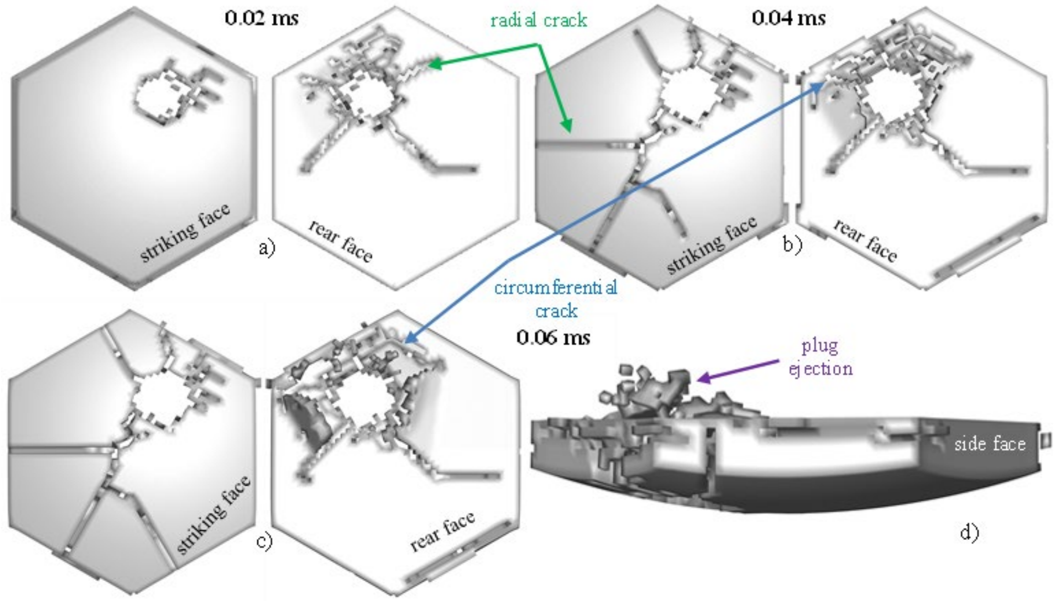

Fig. 10. Evolution of the impact process for the SCH2 configuration

In the case of the SCH3 configuration, it can be noticed that the ceramic tile developed major cracks and that the bullet was able to almost completely scatter the rear face of the tile into small fragments, Fig. 11d.

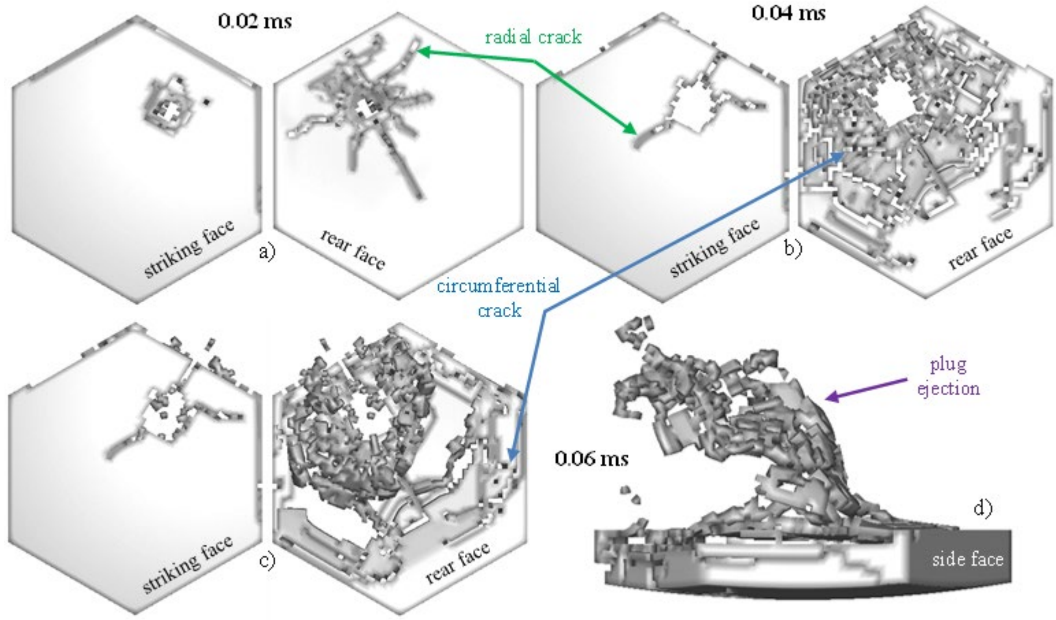

Fig. 11. Evolution of the impact process for the SCH3 configuration

3.2 Residual velocity

The research also compared the residual velocity of the bullet in case of ballistic penetration of ceramic tiles.

When the projectile strikes the ceramic tile with an impact velocity V_0, it is exposed to an almost stable deceleration in the ballistic process and the velocity of the projectile decreases as it penetrates the ceramic material. The residual velocity of the projectile after piercing the ceramic tile is defined by the relation:

$$V_r^2 = V_0^2 - V_p^2 \quad (1)$$

where:

- V_r is the residual velocity;
- V_0 is the striking velocity;
- V_p is the velocity necessary to perforate the ceramic tile.

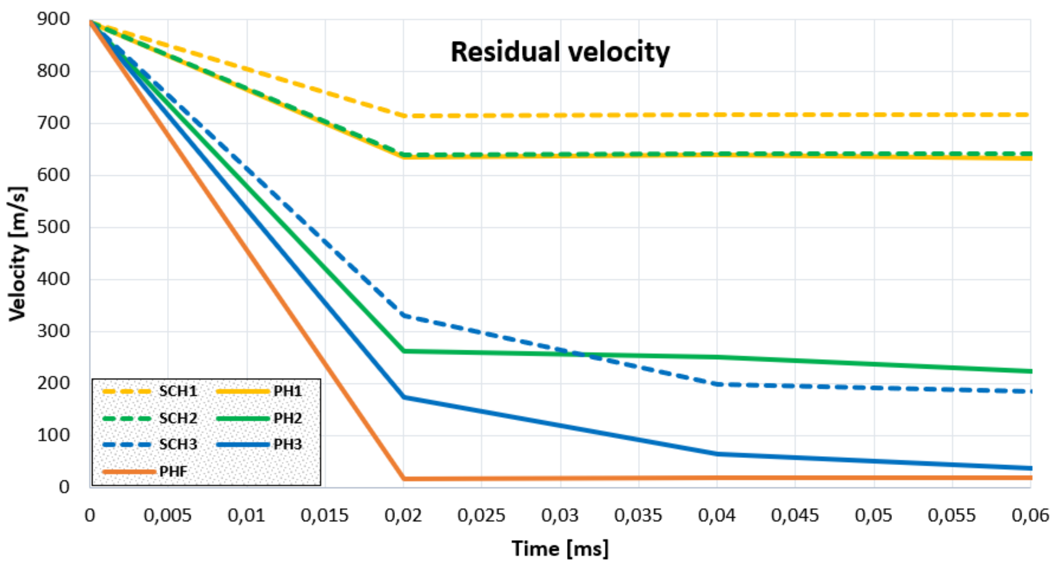

Fig. 12. Comparison of residual velocity for the hexagonal ceramic mosaic tiles

Fig. 12 illustrates the residual velocity of the projectile after piercing the ceramic tiles. Residual velocity results against mosaic ceramic tiles showed almost the same trend for the whole range of base thickness (h_c) of the two different head shape configurations. In both cases, the higher the h_c, the higher the level of protection and the more striking velocity is absorbed, Fig. 13. In the graph above it can be seen that the residual velocity in the case of the pyramidal nose is higher than in the case of the semi-spherical nose in all three cases. This can be attributed to the way the energy is dissipated on impact. A ceramic tile with a pyramidal nose configuration tends to spread the impact force over a larger area compared to a semi-spherical nose configuration. This spreading of the force can result in a larger area of the ceramic material being affected by the impact, which can cause more significant damage, leading to considerable damage to the bullet, resulting in reduced bullet velocity. On the other hand, a ceramic tile with a semi-spherical nose configuration concentrates the impact force on a smaller area due to the rounded shape. This concentrated impact results in less damage to the overall structure of the ceramic tile, resulting in a higher concentrated force in the striking area. However, the PH3 and PHF configurations reduced the projectile's strike velocity almost to a minimum.

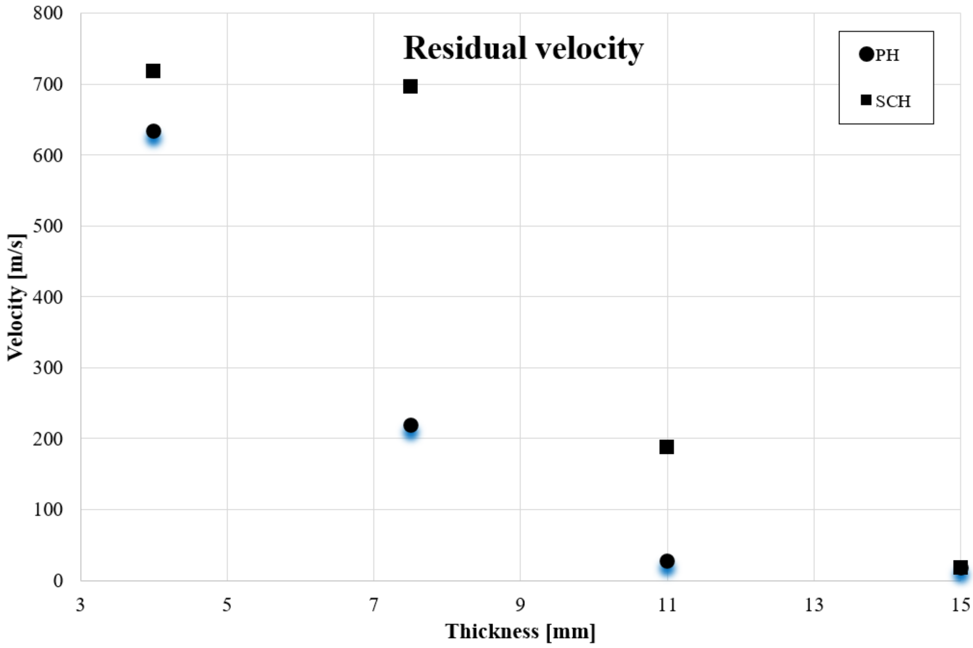

Fig. 13. Adjusting the residual velocity data of the projectile for various ceramic tile thickness configurations

The dependence between the residual projectile velocity and the tile thickness for the different configurations is presented in Fig. 13.

Fig. 14 illustrates the plot of the maximum stress in the impact zone of hexagonal ceramic mosaic tiles in relation to the residual velocity of the projectile. It can be noted that the stress level increases as the kinetic energy decreases. This observation has significant implication as it directly influences the ceramic tiles' ability to absorb more kinetic energy and enhance ballistic resistance.

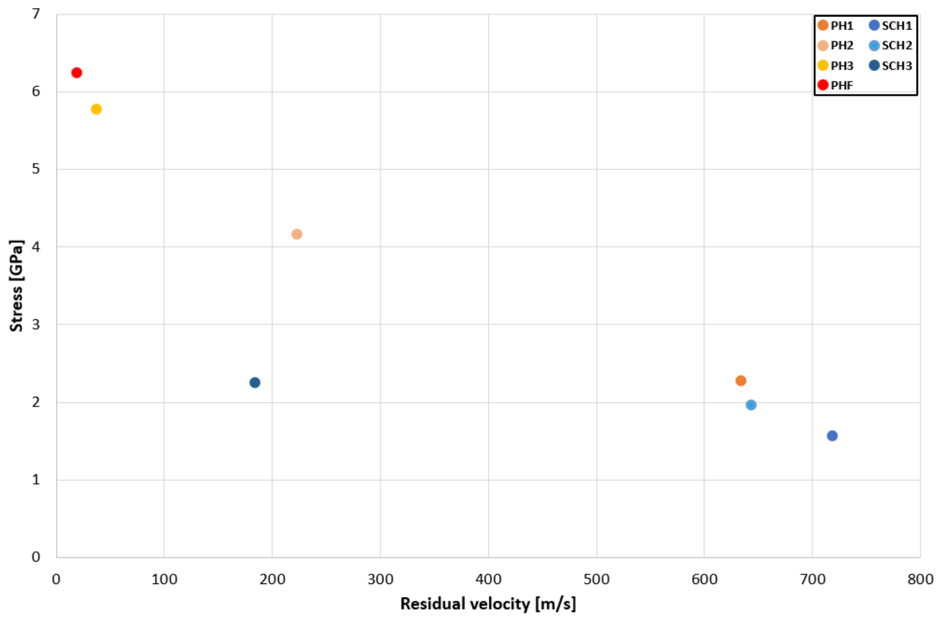

Fig. 14. The maximum stress identified in the impact zone versus residual velocity

4. Conclusions

Numerical simulations of the projectile's ballistic response to impact at high velocities with hexagonal ceramic mosaic tile configurations (Al_2O_3), consisting of two different head shapes, semi-spherical (SCH) and pyramidal (PH), were performed.

Numerical experiments were carried out at an impact velocity of 900 m/s to investigate the ballistic behaviour of the ceramic tiles in terms of considering the effect of boundary conditions by changing the shape of the ceramic tile head. The effects of base thickness, dissipated energy response and the failure mechanism of ceramic tiles were also examined.

PH ceramic tiles were found to be more resistant to penetration by a 5.56x45 mm M855 bullet and dissipated more energy than SCH ceramic tiles. The reason is due to its design, which allows for better distribution of impact forces and more efficient transfer of energy upon impact.

The efficiency of ceramic head shapes in ballistic protection can vary based on their ability to dissipate and redirect the energy of an impacting projectile. When a PH ceramic tile with a significant base thickness is hit by a bullet, the impact force is distributed over the entire surface of the plate. This allows the ceramic material to absorb and dissipate energy more efficiently. On the other hand, a SPH ceramic plate may not be able to distribute the impact force as effectively because of its shape. The curvature may concentrate the force in a smaller area, making it more vulnerable to being pierced by a projectile. Finally, the pyramidal shape of the ceramic tile can potentially provide better deflection properties compared to a round shape. The angled sides of the pyramid can help to redirect the energy of the bullet away from the impact point, reducing the likelihood of penetration.

In summary, the shape of the nose configuration plays a significant role in how the ceramic tile responds to impact forces, with the pyramidal nose configuration generally offering better resistance due to its ability to concentrate and distribute the energy more effectively compared to a semi-spherical configuration.

Also, the base thickness of a ceramic tile is very important in the penetration process as it determines the amount of material the projectile has to penetrate before passing through. A thicker ceramic tile provides more material for the projectile to penetrate, increasing the chances of the tile successfully reducing the projectile's striking velocity. In contrast, a thinner ceramic tile may not provide enough resistance to fully dissipate the projectile's kinetic energy, which could lead to potential penetration.

The improved ballistic performance of these types of hexagonal ceramic mosaic tile configurations can be easily implemented by following these conclusions.

As a possible continuation of the research, exploring different shapes and compositions of ceramic tiles could further optimize their performance in providing protection against impacts, leading to advancements in the development of more effective and efficient protective materials for a wide range of applications.

It is intended to perform impact experiments on tile configurations to analyse their ballistic capabilities, validate numerical simulations and provide improved technical understanding of ceramic materials as protective layers for structures used in various impact or ballistic applications.

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