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Normal and Oblique Experimental Ballistic Impact on Bi Layered Metallic Configurations

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Abstract- Experimental ballistic investigations were carried out on 03 x groups of bi layered metallic target configurations by impacting ogive shaped 7.62 x 51 mm Tungsten Carbide (WC) core Armour Piercing (AP) projectiles at normal and target oblique angles ranging from 15°to 50°. The projectiles were fired using service rifle at a distance of 10 meters in the ordnance velocity range (800±20 m/s). The three groups ballistically tested consisted of 2 x basic protection shield layout each with applique, fixed space varying angles and fixed angle varying space arrangements respectively. Aluminum 5083 with thicknesses 12.7 mm, 19.65 mm, 31.75 mm and Miilux Pro 500 Steel armour with thickness 4.32 mm were utilized for 04 x configurations whereas 02 x configurations consisted of 4.32 mm Miilux Pro 500 and 6.60 mm Rukki, Raex 500 Steel armour. Non perforation of projectile at a particular angle was taken as the performance measure. It was observed that varying the inter layer space and oblique angle with optimized configuration was able to achieve higher ballistic performance with reduced areal density. The order of the orientation of layers with same material and different thicknesses has an effect on overall ballistic performance. A substantial 43 % weight saving was observed with the optimized configuration. The failure modes, deflection of the projectile, impact and exit side diameters of the configurations were also compared.

Keywords- Ballistic impact; layered multilayered configurations; ballistic efficiency; oblique impact; layered metallic configuration; spaced armour.

Abbreviations:

Stl	Steel
Al	Aluminum
SPH	Smoothed Particle Hydrodynamics
RHA	Rolled Homogenous Armour
AP	Armour Projectile

I. INTRODUCTION

Ballistic impact on metal armoured configurations represents a highly complicated penetration process which involves quite large forces in projectile target impact interactions occurring at a very short interval of time. J.A. Zukas and D.R. Scheffler (2001) [1] narrated that the layered armour configurations mostly consist of high strength metallic plates but since generally armour monolithic shields available have limited thickness therefore multilayered armour shields are used to achieve the desired thickness. Multilayered armour shield effectiveness has been studied by the researcher since many decades however due to complexities involved, more research is considered essential to further understand the ballistic configurations efficacy. As per X.Teng et al (2008) [2], D.W. Zhou and W.J. Stronge (2008) [3], the decisive results for the effectiveness of multilayered configurations against monolithic counterparts could not be obtained and the topic remains an open research area. Therefore, research is still required to arrive at the conclusive results. N.K. Gupta and V. Madhu (1997) [4] postulated that the protection effectiveness and weight reduction are the most important aspects while selecting materials for armour shields. The reduced weight is a very important design aspect particularly for aircraft and automotive structures. Backman and Goldsmith (1978) [5], Corbett et al (1996) [6] narrated that a significant effort has been made by the researchers in the past to understand the complex ballistic impact problems. Ben-Dor et al. (2017) [7] concluded that a lot of research has been carried out by the researchers in the ballistic impact phenomena through experimental, analytical and numerical methods but a universal close form analytical model encompassing all impact related aspects is however not available. Flores-Johnson et al. (2011) [8], Jena PK et al. (2009) [9], Rahman NA et al. (2016) [10] concluded that in order to achieve the goals of high mobility and increased pay load on mobile platforms, reduced weight armour protected solution is the main research motive without compromising the structural design integrity. Cantwell WJ et al. (1991) [11], Gama BA et al. (2001) [12] established that low weight nonmetallic materials like ceramics, composite etc. are being extensively researched in the last decades but they have limitations of reduced resistance towards moisture, high temperatures and have low multi hit capability due to brittle fracture behavior as compared to metallic materials. Çakır, Muhammed et al. (2015) [13] reported that metallic materials are still being used for the design and manufacturing of military vehicles due to their low manufacturing cost. Corbett et al. (1996) [14] performed experimental investigations to ascertain ballistic behavior at oblique angles. It was concluded that at oblique angles less than 30°, the behavior found was almost same as that impacted at normal angle. At high oblique angles greater than 45°, substantial increase in ballistic resistance was observed. Bokhari, Det al. (2016) [15] conducted experimental investigations on Rolled Homogenous Armour (RHA) plates with four thicknesses, 2.7 mm, 3.7 mm, 4.6 mm and 5.6 mm against 7.62x51 mm AP DAG 7.62x51 mm bullet. The authors concluded that the thin front plate with spacing no more than 10 calibers and obliquity no more than 45° provides optimum results. A ratio of front to rear thickness of 0.48:1 provides best results. It was also found that highest achievable mass efficiency was 2 with 400 mm air spacing which could be reduced to 50 mm with the reduction of 17% in ballistic efficiency. Iqbal, M.A et al. (2010) [16] carried out numerical study to ascertain the ballistic behavior of 1 mm thick 1100-H12 aluminum and 20 mm thick Weldox 460E Steel targets. The aluminum and Weldox plate targets were impacted by 19 mm ogive shaped and 20 mm diameter conical shaped projectile respectively. The plates were also impacted at oblique angles of 15°, 30°, 45° and 60° until ricochet occurred. It was found that the ballistic limit of Weldox at 30° oblique angle was same as if impacted at normal angle. The ballistic limit of aluminum however was found to consistently increase with each oblique angle. Shash, N. and Zuzov, V.N (2018) [17] investigated through numerical simulations by impacting 7.62 X 51mm AP M2 projectile with an initial velocity of 830 m/s at normal angle on monolithic, double layered and triple layered Stl plates with and without space. It was concluded that for bi layered configuration, the strike face with high strength and hardness exhibits better ballistic performance. Gürgen, S (2019) [18] conducted numerical investigations to assess the ballistic performance of 5083-H 116 aluminum plates when impacted by hardened steel projectiles of mass 197g, caliber 20 mm and length 95mm. It was concluded that the deformation mode changes from embedment at low angles to ricochet at high angles. The impact velocity was found to be the dominant factor even at 60° oblique angles. Although the performance of double layered and monolithic plate of 40 mm remains very close to each other, however, monolithic plate performance was better than layered configuration. Ehsan et al [19] [2018] carried out numerical study in which authors impacted 4340 steel projectiles on 6061-T651 aluminum target plate using SPH method. It was found by the authors that boundary condition and initial velocity are the dominating factors affecting residual velocity and penetration time of the projectile. Mehran Moradi et al [20] [2018] investigated through experimental and numerical study by impacting semi spherical silver steel projectiles of Rockwell hardness 50 on un alloyed cupper and Al 1100 plates with layered configurations. It was found that changing order of plates have significant effect on ballistic performance of the layered armored configurations. NA Rehman et al. [21] [2018] conducted experimental and numerical investigations by impacting NATO FMJ 7.62 X 51 mm ball ammunition on 7075-T6 Al and Ar 500 Stl plates. The depth of penetration was taken as performance measure. It was found that Ar 500 Stl at impact side and Al at non-impact side has less penetration depth than the vice versa. Han YOO et al [2019] [22] carried out numerical investigation on aluminum 6061-T6511 target material while impacting vacuum-arc-remelted 4340 steel. The depth of penetration of projectiles was determined. The authors inferred that penetration of ogive shaped projectiles with higher CRH is more both in normal and oblique impact. In a review by Ranaweera, P et al. (2020) [23], the authors concluded that most of the studies suggested that steel being hard plate when placed at impact side and aluminum being ductile metal at rear side improved ballistic performance. Tiwari, G et al [2020] [24] conducted numerical investigations by finding the energy absorption characteristics and ballistic resistance by impacting blunt and ogive nosed EN-24 Stl projectiles of Rockwell hardness 47 - 52 on 1 mm monolithic and equivalent thickness layered hemispherical shell manufactured using thin 1100-H12 Al sheets. The numerical results were compared with experimental investigation on monolithic shell. It was found that monolithic shell performed better against blunt projectile whereas layered showed improved performance against ogive shaped projectile. Mohammad, Z., et al. (2021) [25], conducted experimental and numerical investigations to determine the effect of nose shape of the projectile while impacting monolithic and bi layered configurations at normal and oblique angle on aluminum 1100-H12 targets. It was observed that highest ballistic resistance was found for both monolithic and layered shell targets against hemispherical nosed projectile. Furthermore, it was found that layered shell targets provided higher energy dissipation than monolithic targets for all the studied projectiles. Bekci, M.L. et al. (2021) [26] conducted experimental investigations on monolithic and bi layered configurations consisting of hardened steel plates Ramor 500 and Ramor 550 while impacting at normal and oblique angle using 7.62 ball ammunition. It was concluded that in bi layered configuration high hardness plate at strike end and low hardness at rear end provides better ballistic resistance. Scazzosi, R et al [27] [2021] postulated that only few experimental studies are available on the ballistic research. The authors conducted experimental and numerical study to determine the effect of layering by impacting 7.62 × 51 P80 steel AP rounds on monolithic and bi layered configurations using Ramor 500 steel plate and AA 6061-T6 Al plates having same areal densities. It was found that order of layering has an effect on the ballistic performance and a configuration with hard plate on impact side performs ballistically better than the opposite configuration. Scazzosi, R et al [28] [2021] postulated that different authors researching on comparison studies on layering of protection shields and monolithic armour shield have contradictory results. The authors conducted tests on monolithic and multilayered Stl and Al plates impacted by soft core projectiles and found that bi layered configuration of steel and aluminum exhibited less ballistic performance than the monolithic plate.

Numerical techniques are extensively used for ballistic reserach, however experimental techniques are still the most potent and viable option to determine the ballistic performance of the protective shields. Although conduct of ballistic experiments is a highly expensive option, yet it is the ultimate choice to arrive at logical conclusions [29]. A number of research studies are available in which researches have carried out research using analytical, numerical and experimental techniques to determine the effect of inter layer air gap (space) on ballistic performance of layered configuration using ogive shaped AP projectiles with projectile impacting at normal angles [7, 30-35]. It was generally concluded that space has detrimental effect on ballistic performance of the layered protective configuration for normal impact by ogive shaped projectile, however very limited literature is available for impact of the projectiles on inclined armour configurations.

Despite the fact that small caliber tungsten carbide (WC) core projectiles are the hardest and most lethal AP projectile available but it has been found through literature survey that most of the research in terminal ballistics has been carried out with hard Stl core AP projectile or with soft lead core ball projectiles. In this paper effort has been made to understand experimentally the ballistic research using WC core projectile on bi layered configuration especially with novel idea of fixed / varying angles /space configurations as discussed in paragraph 12.2 and 12.3. Moreover, a simple method has been used to determine the direction of deflection of the bullet on perforating through the armour system which will help in design decisions to enhance safety of the occupants. For instance, if layered armoued structure is designed in a way that it deflects the bullet in upward direction then crew can accordingly be instructed to take lower position which will enhance the occupant's safety levels. Keeping the advantages foreseen, an attempt has therefore been made in this paper to use both space and obliquity to determine the ballistic efficiency of armoured configurations with a view to achieve same level of protection with reduced weight configurations.

II. Aluminum (Al) and Steel (Stl) Armour

Al and Stl armours are widely used for manufacturing of protective structures. Al grade 5083, Stl armor Miilux Pro 500 and Rukki Raex 500 were selected for this research work. The mechanical tests including hardness and tensile tests were conducted using Brinell Hardness Test Machine HB 3000 and YEHHSIEN SHANTUNG and 30 Ton CHANGCHUN, model W3 510, universal hydraulic tensile testing machine respectively. The average tensile strength, hardiness of high strength low alloy Stl armour Miilux Pro 500 and Rukki Raex 500 were found as 1610 Mpa, 1630 Mpa and 490 BHN, 495 BHN respectively whereas average tensile strength for Al 5083 was found as 356.52 Mpa.

III. Ogive Shaped 7.62 x 51mm WC Core Projectile

The ogive shaped projectile consists of three parts namely coated Stl jacket, WC core and Al cup. The weight, length and diameter of the projectile were 8.2g, 28.45 mm and 7.82 mm respectively.

IV. Projectile Velocity Range

The impact velocities of the projectiles fired upon on the target configurations with service rifle were determined using chronographs placed at two meters from the target. The velocities obtained with particular barrel length using WC core ammunition fell in ordnance velocity range from 780 to 805 m/s.

V. Target Stand

A heavy rigid structured "target stand" was fabricated using high strength Al alloy of 5083 series. The stand was capable of withstanding high shocks experienced in a ballistic impact. The target stand comprised of three major parts namely, platform with provision of vertical and horizontal bars to fix the target configuration with the Stl bolts in Stl inserts. The second part of the target stand was the rigid base designed to support the platform. The third part was the attached mechanical manual mechanism with punched angle marks to alter and fix the target plate configurations at desired oblique angles. As an example, the target stand fixed at normal i.e., 0° and at oblique angle of 20° is shown in Fig. 1.

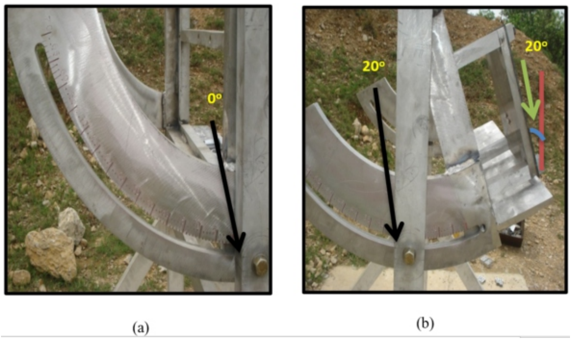


Fig. 1 Target Stand (a) 0° when fully retracted (b) 20° obliqe angle

VI. Bi Layered Ballistic Armour Protective Configurations

Stl and Al square plates of size 305 mm x 305 mm were cut utilizing Miller plasma cutter 875 and Cincinnati 3 axis spindle rail type vertical profiling machine 950 respectively. The Stl and Al armour plates used in ballistic layered configurations designated with codes along with areal density of individual plates are shown in Table 1. The details of target configurations along with related codes are given in Table 2. These codes will be used in the subsequent part of the paper.

Table 1. Designated codes for armour individual plates with areal density

Material	Plate thickness (mm)	Designation	Areal density (Kg/ ft^2)
Al	31.75	T1	7.84
Al	19.05	T2	4.70
Al	12.70	T3	3.13
Stl	4.32	T4	3.22
Stl	6.60	T5	4.85

Table 2. Target configurations with target configuration code

Target configuration	Target configuration codes
Applique Target "A"	T5+ T1
Applique Target "B"	T4+ T1
Spaced Target "C"	T4+ S (12.7mm) +T2
	T4+ S (25.4mm) +T2
Spaced Target "D"	T4+ S (25.4mm) +T3
Spaced Target "E"	T4 0°+S (38.1 – 167.39mm) +T5 23°
Spaced Target "F"	T5 23° +S (38.1 – 167.39mm) +T5 0°

The first letter as described in Target configuration codes in Table 2 represents the strike side plate whereas last letter indicates the rear side plate. The letter 'S' represents the space and the digits following in brackets show the air gap. The angles given for target configurations "E" and "F" show the orientation of the armour plates.

VII. Target Configuration Groups

The target configurations were grouped into three categories based on the layout pattern of the two plates constituting the ballistic configuration with the vertical plane.

7.1. Applique target configuration

The configurations "A" and "B" are applique configurations as the plates are fixed to each other without any air gap.

7.2. Spaced target configuration with fixed air gap and varying angle

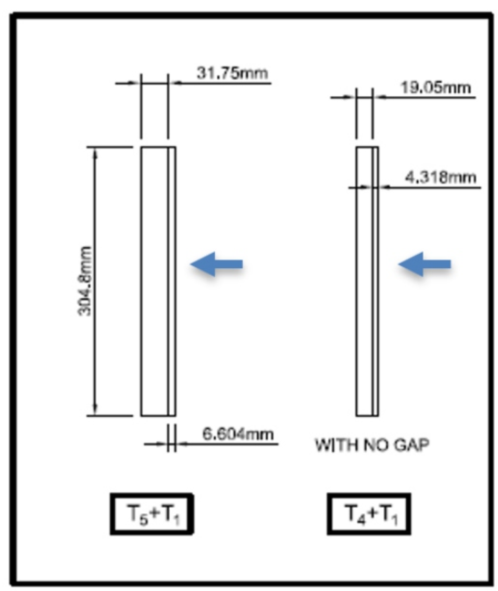
The configurations "C" and "D" are parallel plates with specified air gaps. The target oblique angles were varied during ballistic test till non perforation of the projectile was achieved.

7.3. Spaced target configuration with varying air gap

The configurations "E" and "F" are fixed angle plates with varying air gaps.

VIII. Target Configuration Layouts

The configuration layouts are shown in Fig. 2. The arrow at the side of the target configurations indicates the strike end.



(a)

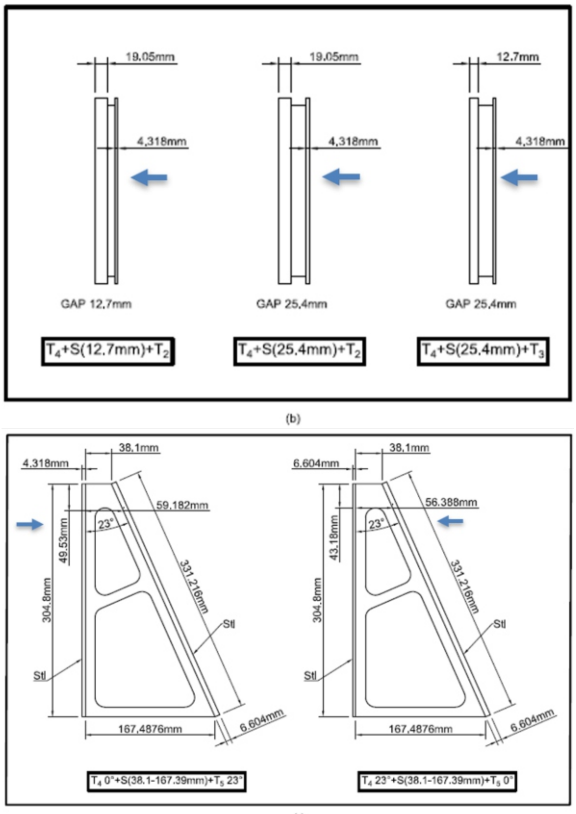


Fig. 2 Target configuration Layouts with groups (a) Applique target configurations (b) Spaced target configuration with fixed air gap and varying angle (c) Spaced target configuration with varying air gap

IX. Ballistic Experimental Setup

The ballistic tests were conducted using service rifle at the shooting distance of 10 meters to ascertain the ballistic properties of the target configurations tested in field environment as shown in Fig. 3.

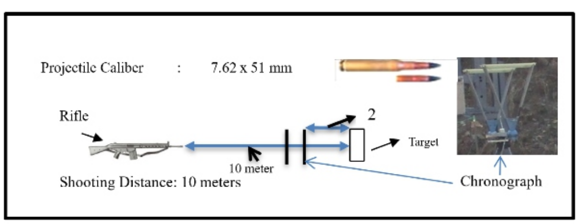


Fig. 3 Distance of 10 m between target and barrel end

X. Performance Measure

Non perforation of projectile using same weapon, environmental condition, ammunition and firer was taken as the performance measure.

XI. Conduct of Ballistic Experimental Investigations

Ballistic experimental investigations were conducted in a sequential manner to arrive at useful results. Initially the applique configurations with no air gap were tested which were followed by the tests on spaced configurations so that effect of space and obliquity could be gradually observed and recorded. In all the dual material configurations high hardness Stl plate was placed at the strike end due to the established fact that hard Stl at impact side and ductile Al plate at rear provides higher ballistic resistance [19]. Ballistic impact tests were carried out on the six target configurations during which applique target group configurations “A” and “B” were fired with one and seven bullets respectively as shown in Fig. 4. Four and two bullets were fired on target configuration “C” with 12.70 mm inter layer air gap and 25.4 mm gap respectively whereas 02 x bullets were fired on target configuration “D” of spaced target group with fixed air gap as shown in Fig. 5. One bullet each was fired on target configuration “E” and “F” of spaced target configuration with varying air gap. The impact and exit sides of the tested configurations are shown in Fig. 6.

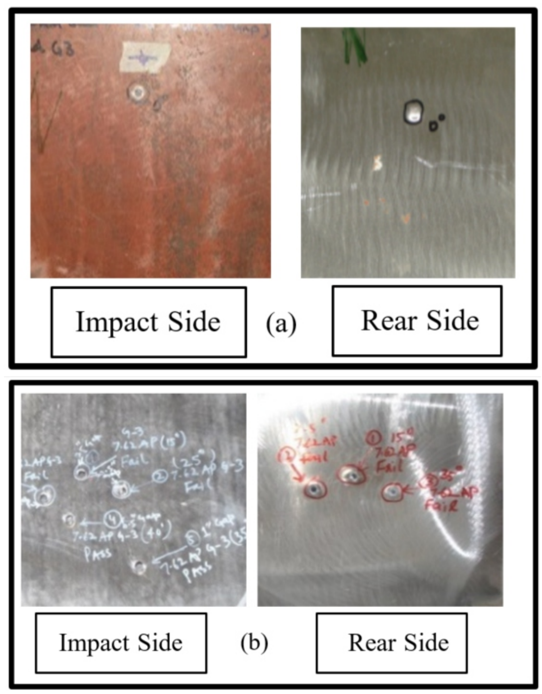
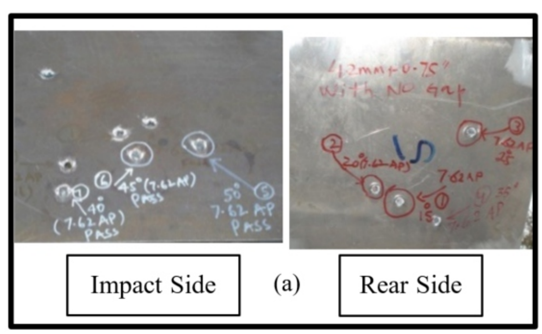


Fig.4 Applique target configuration (a) “A” (b) “B”



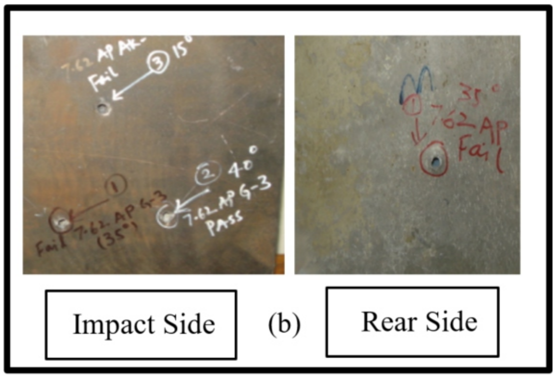


Fig. 5 Spaced target configuration with fixed air gap and varying angle (a) “C” (b) “D”

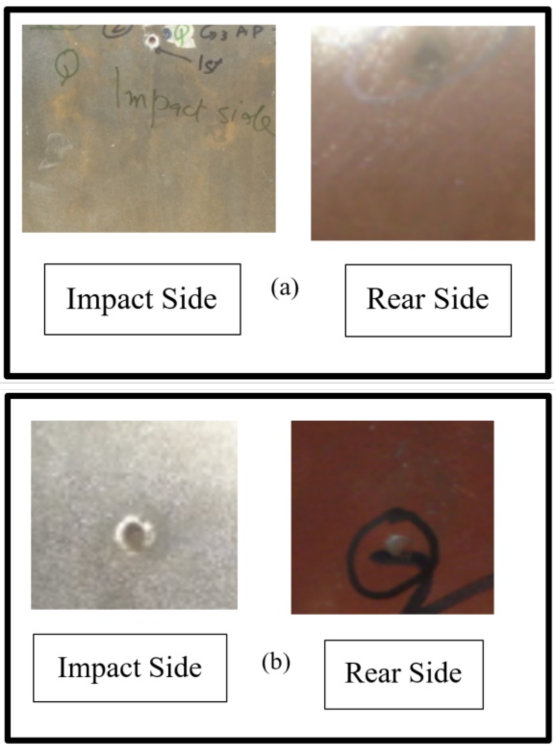


Fig. 6 Spaced target configuration with varying air gap (a) “E” (b) “F”

XII. Results and Discussions

12.1 Applique Target Group

12.1.1 Applique Target “A” (T_5+ T_1)

The projectile fired had hit the Stl plate at normal angle resulting in indentation and plastic flow of the Stl material while the backing applique ductile Al plate armour added in resistance to the impulsive piercing force of the projectile. Energy possessed by the projectile was capable to deform the Stl plate completely by creating a hole of diameter 6.1 mm which was approximately of same size as that of projectile core (5.6 mm). The indent produced on steel plate was less in diameter than when compared with overall diameter of the projectile i.e., 7.82 mm. It indicates that the jacket and Al cup were peeled off while interacting with the hard Stl plate. The flow of Stl material in the backward direction in the form of deformed lips can also be seen as shown in Fig.7. The strike end Stl armour appreciably reduced the kinetic energy of the bullet and back-end plate ductile Al plate was able to trap the bullet to its dead stop without perforation. The Al material failed by ductile hole growth. The projectile core created a small bulge of 2.8 mm amplitude at the back end as seen in Fig. 7. The studied configuration has the advantage in manufacturing of armour structure due to appliqué in nature; however, it has the disadvantage due to its relatively higher weight, which will be discussed subsequently in the results and discussions.

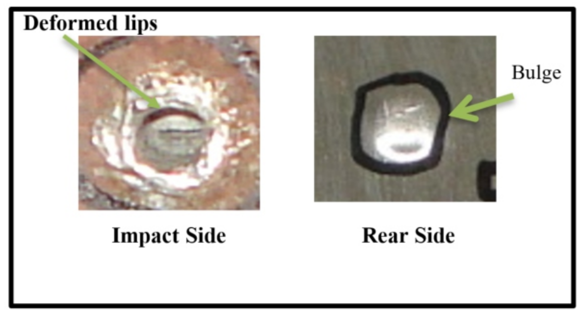


Fig. 7 Applique target configuration “A”

12.1.2 Target Configuration “B” (T_4+ T_1)

The projectiles impacted the applique target configuration inclined at 15°, 20°, 25°, 35°, 40°, 45° and 50°. The impacting projectile faces strong resistance due to high strength hard Stl plate at strike end. The jacket and Al cup of the projectile peels off and subsequently conical surface of the projectile core interacts with the hard target surface. It was concluded by Forrestal, M.J. et al. [36] that the projectile jacket and lead filler of 7.62 x 51 mm AP projectile when interacting with 6082-T651 Al armor plates peeled off at the surface and had little contribution in the overall penetration process. Since the target was inclined at an angle, therefore asymmetric forces act on the projectile core tip which causes its deflection, see reference [37]. The asymmetric indentation produced on impact side Stl plate as shown in Fig. 8 also suggests asymmetric forces acted upon the projectile by the target material during indentation process. The higher erosion at lower through thickness Stl surface in comparison to upper surface also suggest deflection of the projectile in the upward direction. The intense deformation activity with erosion of target and projectile material continues. The projectile core indents, pierces and deforms the Stl plate material in transverse direction. The deformation surpasses the elastic limit and enters into the plastic regime which ultimately results in failure of the Stl plate at local impact area. The rearward flow of the

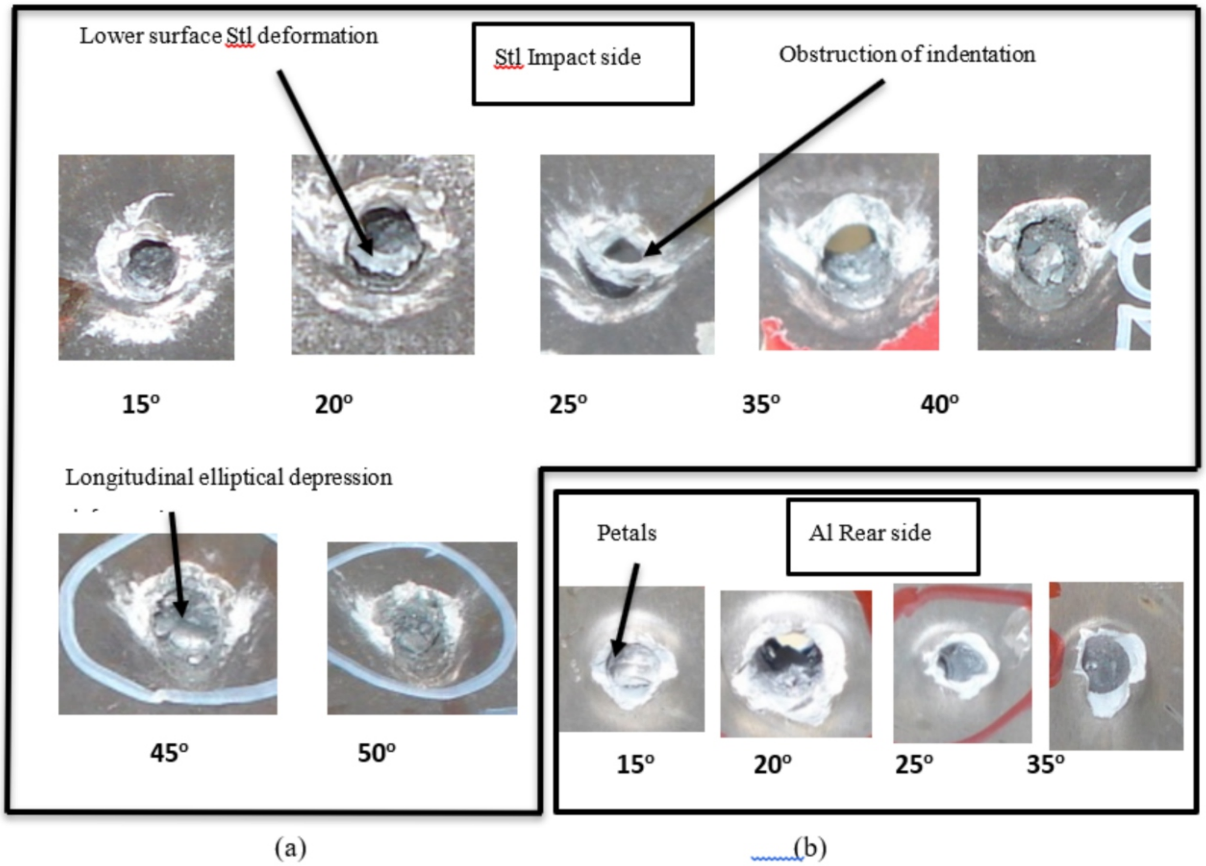


Fig. 8 Indentation geometry on target configuration "B" (a) Stl impact side (b) Al exit side

material in the form of deformed lips was also seen at the impact side. Concurrently, deformation of the in-contact Al plate also occurs. The energy of the projectile is still enough to overcome the resistance offered by the rearward Al plate. The deformation in Al plates ensues in the form of ductile hole growth until failure of the Al rear surface by petalling occurs for impacts at 15°, 20°, 25°and 35°. At 35° and higher angles, considerable deflection of projectile was observed which was due to change the point contact by the projectile to increased area contact. At 35° however, projectile still possessed substantial energy to perforate the target configuration. At 40° and beyond, significant flow of the Stl material in longitudinal direction was observed. The elliptical depression can be observed on the Stl surface which indicates change in direction of the projectile with its shank ultimately establishing contact with the Stl surface material with intense friction force. The projectile ricocheted with significant bending and possible shattering during the longitudinal slip on the surface of the hard Stl plate at higher angles.

In order to determine the deflection of the projectile during through thickness penetration, the linear distances of the projectile indentation on impact and exit side were measured from target lower edge and are presented in Table 3 and Fig. 9. Generally, an upward trend in projectile deflection was observed. At 20° however, downward deflection of the projectile along with rearward flow of the material resulting in obstruction of indenting geometry produced was observed as shown in in Fig. 8. This may be due to highly completed ballistic impact phenomena affected by many variables, see reference [38-40]. Up to 25°, no considerable deflection of the projectile and difference in impact, exit side diameters were observed. This is in agreement to the findings by [14 and 16] that up to 30° no noticeable effect of obliquity observed.

The diameters of geometry produced on impact and exit side were also measured and it was revealed that the diameters up to 25° were close to the projectile core diameter, thus affirming that jacket and Al cup were peeled off at the target surface and had little contribution in the overall penetration process. The details of diameters measured are given in Table 3 and Fig. 10.

Table 3. Measurement of linear distance and diameters of indented geometry

Oblique Angle	Impact Velocity (m/s)	Linear Distance from Stl plate lower edge to the edge of indentation on impact side in mm	Linear Distance from Al plate lower edge to the edge of indentation on exit side in mm	Diameter on Stl Impact side in mm	Diameter on Al exit side in mm	indented geometry produced
15°	782	93	98	6.35	6.75	Hole
20°	785	107	116	6.35	6.67	Hole
25°	802	168	183	5.16	6.67	Hole
35°	780	49	85	9.53	6.78	Elliptical
40°	792	37	Not perforated	11.11	Not perforated	Elliptical
45°	801	73	Not perforated	13.69	Not perforated	Elliptical
50°	795	78	Not perforated	14.29	Not perforated	Elliptical

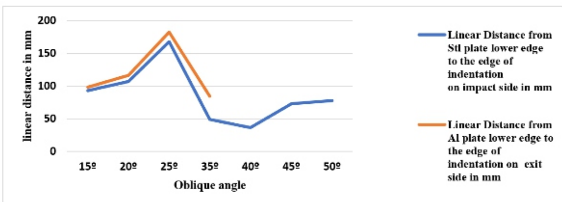


Fig. 9 Deflection of the projectile

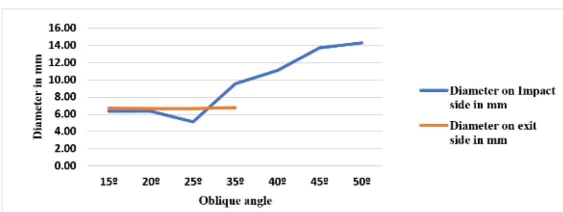


Fig. 10 Impact and exit side diameters of the indents

Thus, applique target configuration "B" was able to defeat the projectile at 40° oblique angle.

12.2 Fixed space varying oblique angle group

12.2.1 Target configuration "C" - (T_4+ S (12.7mm) +T_2 and T_4+ S (25.4mm) +T_2)

Target configuration "C" was essentially the same configuration as that of target "B" but was introduced with interlayer gap instead of applique. In terms of bending stiffness, the applique target had higher bending stiffness than the single plates separated by air gap due to reduced thickness. The purpose of ballistic experiments on target configuration "C" was to ascertain the effect of space and obliquity on ballistic performance and compare its performance with its applique counterpart. The configuration "C" was ballistically tested with 12.70 mm and 25.4 mm interlayer gaps. Mounting of the target on stand is shown in Fig. 11.

Four projectiles were impacted on target configuration with 12.70 mm air gap inclined at 15°, 25°, 35° and 40°.

Fig. 11 Target "D" mounted with 12.7 mm air gap

On impact, the jacket and Al cup peeled off as was in the case of target configuration "B". The asymmetric forces resulted in the deflection of the projectile. On impact at reduced bending stiffness plate, the high energy projectile indented, pierced and ultimately failure occurred through tensile stretching and tearing. The indentations produced on the impact side along with oblique angles are shown in Fig. 12.

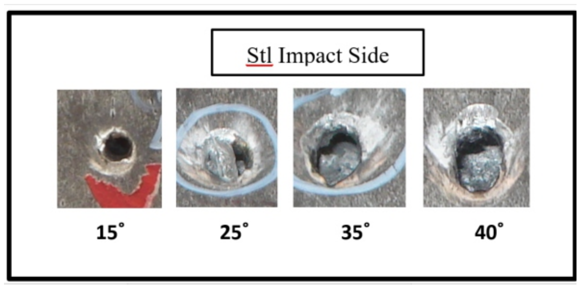


Fig. 12 Target "D" indents with 12.7 mm air gap - impact side

The projectile along with stl pieces in the form of deflected debris cloud were ejected from the exit side of the Stl plate. The cloud then travels through the air gap of 12.7 mm and finally impact the rearward Al plate. Till 35° obliquity, the cloud had sufficient energy to defeat the Al plate through ductile hole growth and pettaling. The petals formed can be seen in Fig. 13.

Table. 4 Measurement of linear distance and diameters of indented geometry – Target "C"- T4+ S (12.7mm) +T2

Oblique Angle	**Impact Velocity (m/s)**	**Linear distance from Stl plate lower edge to the edge of indentation on impact side in mm**	**Linear distance from aluminum plate lower edge to the edge of hole on exit side in mm**	**Diameter on Stl Impact side in mm**	**Diameter on Al exit side in mm**	**Shape of indented geometry produced**
15 º	785	156	156	6.35	5.16	Hole
25 º	791	140	154	7.14	5.56	Hole
35 º	807	130	152	8.53	6.75	Elliptical
40 º	797	110	Not perforated	9.20	Not perforated	

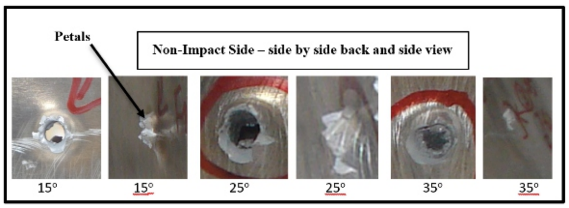


Fig. 13 Target with 12.7 mm gap non-impact side

The configuration with air gap 12.70 mm was able to defeat the projectile from perforation at 40°. On comparing it with target configuration "B", a similar ballistic performance was observed at 40° as it also stopped the projectile at the same angle which means 12.70 mm air gap is not sufficient to improve the ballistic performance and more dispersal is required to defeat the projectile.

In order to determine the deflection of the projectiles, the linear distance was measured in the similar manner. The difference in diameters were also measured. The details are presented in Table 4, Fig. 14 and Fig.15.

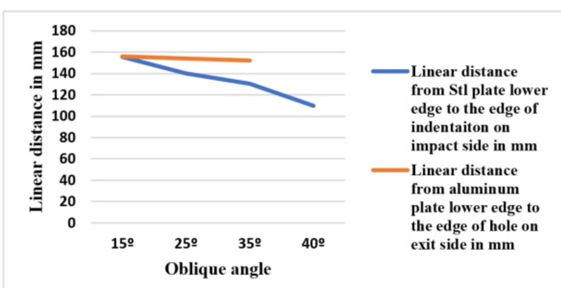


Fig. 14 Deflection of projectile with 12.7 mm air gap

As can be observed from the graph, the behavior of deflection of the projectile with air gap is different from that of the applique target configurations. No deflection was observed at 15° but after this angle the gradual increase with upward deflection was noticed. The difference in the diameters on impact and exit side is shown in Fig.15.

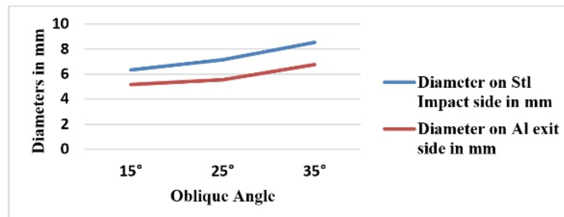


Fig.15 Difference in diameters on impact and exit side

The difference in diameters was observed consistent for the whole range of oblique angles.

The target "C" air gap was then enhanced from 12.70 mm to 25.4 mm. Two projectiles were fired at 30° and 35° oblique angles. The debris cloud had to travel more distance, almost twice the previous travelled distance. The dispersion of the cloud was also therefore increased. The projectile at 30° was found able to defeat the target however it was not able to perforate at 35°. The indentation produced at Stl impact and Al exit sides are shown in Fig.16.

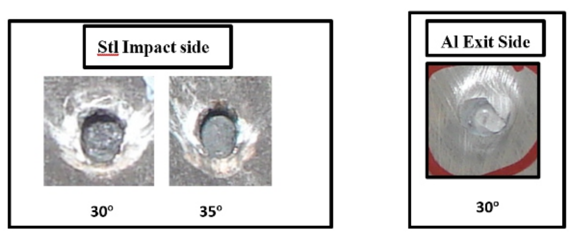


Fig. 16 Target "D" indents with 25.4 mm air gap

A similar behavior in the form of longitudinal elliptical erosion was observed on steel impact side. The rear side Al plate failed by ductile hole growth, petalling and the petals produced can be seen in Fig. 16 for 30° impact angle.

The linear distances and diameters were also measured and data is presented in Table 5.

Table. 5 Measurement of linear distance and diameters of indented geometry – Target "C" – [T_2 and T_4+ S (25.4mm) +T2]

Oblique Angle	Impact Velocity (m/s)	Linear Distance from Stl plate lower edge to the edge of indentation on impact side in mm	Linear Distance from Al plate lower edge to the edge of hole on exit side in mm	Diameter on Stl Impact side in mm	Diameter on Al exit side in mm	Shape of indented geometry produced
30°	795	86	105	7.14	5.75	Elliptical
35°	802	68	Not perforated	8.33	Not perforated	

A significant deflection of the projectile was observed at 30o. The difference in diameter is also noticeable.
This configuration was able to mitigate the energy of the projectile and did not let it perforate at 35° as 25.4 mm was sufficient to disperse the combined projectile and debris cloud thereby reducing projectile's effectiveness for perforation.

12.2.2 Target configuration "D"

Target "D" represents the same group of spaced configurations similar to that of target configuration "C". The purpose to test this configuration was to assess the possibility of gaining further advantage of deflection and dispersal of combined projectile and debris cloud with 25.4 mm air gap as was indicated previously for target "C". The difference between target "D" and "C" configuration is essentially in the thickness of rear Al plate which was reduced from 19.05 mm to 12.70 mm. Two bullets were fired at 35° and 40° and the configuration was able to stop the projectile at 40° thereby confirming the advantage achieved in the increased air gap. The indentation produced on impact and exit side are shown in Fig. 17.

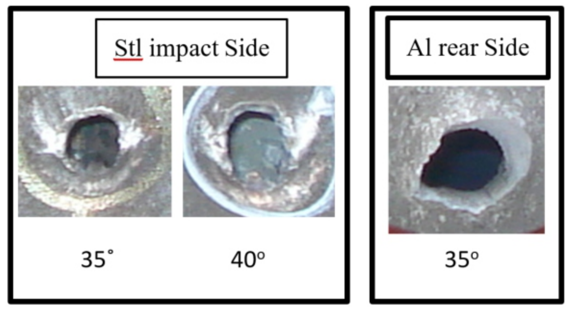


Fig. 17 Indentation of projectile with 25.4 mm air gap

The behavior of failure modes was similar to as observed for target "C".
The deflection of the projectile and difference in impact and exit diameters are shown in Table 6.

Table. 6 Measurement of linear distance and diameters of indented geometry Target- D

Oblique Angle	Impact Velocity (m/s)	Linear Distance from Stl plate lower edge to the edge of geometry on impact side in mm	Linear Distance from Al plate lower edge to the edge of geometry on exit side in mm	Diameter on Stl Impact side in mm	Diameter on Al exit side in mm	Shape of indented geometry produced
35°	795	90	107	6.60	7.11	Elliptical
40°	805	92	Not Pierced	9.65	Not Perforated	Elliptical

A similar upward deflection was observed with this configuration as well. The diameter of indentation on exit side was found greater than on impact side. Although this configuration was not able to defeat the projectile at 35° as was the case in target configuration "C" with 25.4 mm air gap but it exhibited the same ballistic performance as that of applique target configuration "B" and also of spaced target configuration "C" with 12.70 mm air gap.

12.3 Fixed angle varying oblique space group

The set of bi layered configurations in this group consisted of both high strength Stl plates arranged in a way which allowed varying space with fixed angles. Both the configurations had 4.32 mm thick Stl plate on strike end and 6.60 mm Stl plate at non-strike end but their orientation was different. Such arrangement thus allowed assessing the effect on changing the orientation of Stl plates with different thicknesses such that the impact side and rear side plates orientations were exchanged and then their ballistic performance was compared with each other.

12.3.1 Target configuration "E"

The target configuration was impacted by 01 x bullet at a point which was 49.5 mm from the top target edge where air gap was 59.2 mm as shown in Fig 2 (c). The bullet hit the 4.32 mm thick strike end plate at normal angle and pierced through it. The plate was less in thickness and was also placed normally, therefore neither it noticeably deflected the bullet nor provided any significant resistance to high energy high strength WC core projectile. The projectile produced an indent of diameter 5.6 mm which is approximately equal to the projectile core thus the jacket and aluminum cup of the diameter of the projectile was stripped off at the impact side surface of the plate. The projectile core then travelled 59.2 mm air gap and smashed the other side Stl plate of thickness 6.60 mm placed at reverse slope angle of 23°. The projectile struck the plate and due to its inclination, the tip of the projectile deflected as asymmetrical forces were acted upon by the target on the projectile.

The projectile deflection caused area contact but due to substantial residual energy of the projectile, it could not prevent it from perforation. The evidence of deflection was observed on the steel plate indentation which was 10.4 mm in diameter almost double than that it produced on the impact side. The projectile perforated in deflected position due to its high energy which produced relatively large indent. The indentation produced on both plates are shown in Fig. 18.

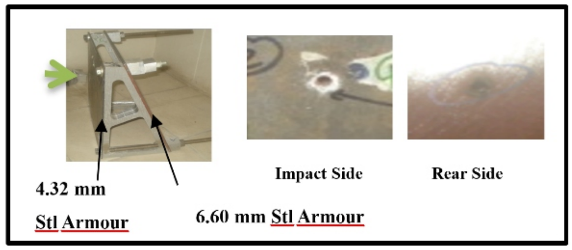


Fig. 18 Target "Q" configuration, impact side and exit side

The details of the diameters measured and linear distance recorded from the top edge of the plate are presented in Table 7. The linear distances show that the projectile deflected downwards which was due to reverse slope of the non-strike end plate.

12.3.2 Target configuration "F" (T5+S (1.5 – 6.59) +T5)

The configuration is mirror in orientation to configuration "E" in which 4.32 mm strike end Stl plate was placed at 23° inclined angle and 6.60 mm was placed at the rear as shown in Fig. 17. The projectile impacted the Stl plate at 43.2mm from the target top edge where air gap was 56.4 mm. The Stl plate at an angle caused a deflection to the projectile which then travelled 56.4 mm in the air and impacted the 6.60 mm thick Stl plate. The high strength Stl plate was able to defeat the projectile. A small bulge of 0.396 mm was produced at the back of the rear end plate. The target along with the indentations produced is shown in Fig. 19.

Table. 7 Measurement of linear distance and diameters of indented geometry Target- E

Linear Distance from front 4.32mm plate at 0° top edge to the edge of hole on impact side	Impact velocity (m/s)	Linear Distance from Stl Plate 6.60 mm at 23° plate top edge to the edge of hole on exit side	Diameter on exit side in mm	Diameter on exit side in mm	Shape of indented geometry produced
50	789	53	5.59	10.41	Hole

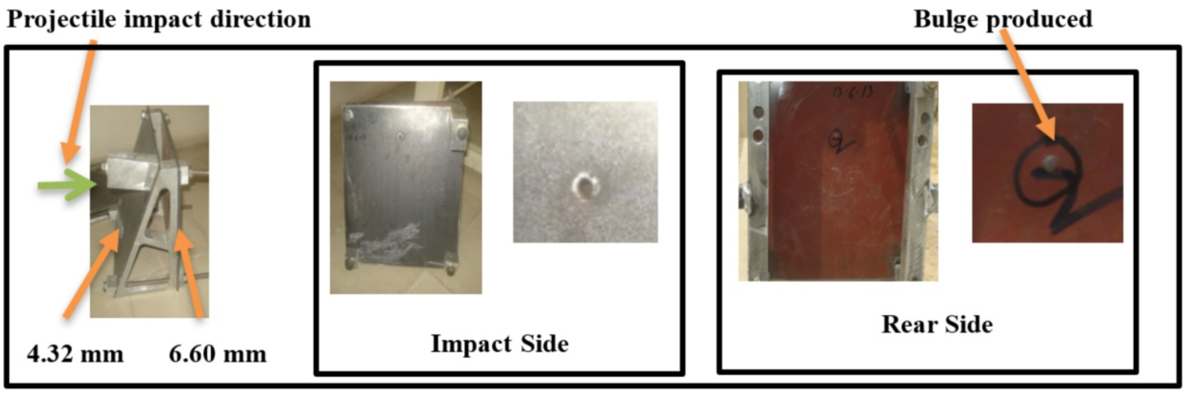


Fig. 19 Target "F" with projectile indentations

XIII. Summary of Results

13.1 Deflection of the projectile

The summary of the results obtained have been discussed in the subsequent paragraphs.

The difference in linear distance on impact and exit side indentations were worked out to depict the deflection of the projectiles for applique target configuration "B" and second group spaced configurations and are shown in Fig. 20. The defection of projectile on applique target is not significant till 25°, but is substantial at 35°. For spaced target "C", no deflection was observed at 15° and for 25°, the deflection is similar to applique target. Beyond 25°, the deflection increases but no significant variation in the slope was observed. For remaining targets shown in Fig.20, less variation beyond 25° among the spaced configurations of second group was observed. Overall a consistent upward deflection behavior was seen.

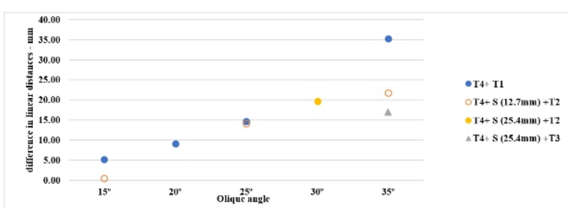


Fig. 20 Deflection of projectiles

13.2 Difference between impact and exit side diameters

The difference between diameters of indentations was calculated by subtracting the exit side diameters with the impact side and is shown in Fig. 21. The positive values shown represent that the exit side diameters are more than the impact side and reverse is true for negative values. As can be observed that for applique target, in general exit side diameters are more with one exception at 35°, where impact side diameters were more than rear side diameters. The reverse is observed for spaced targets, however for target configuration "D", the exit side diameter is more than impact side diameters. The observed variations are attributed to the unpredictable behavior of the complex ballistic impact phenomena.

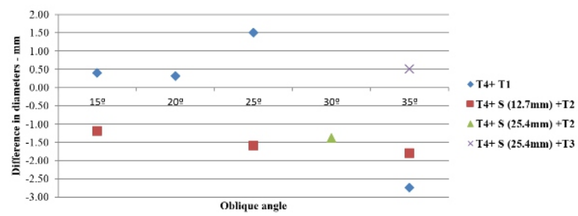


Fig. 21 Difference in diameters

13.3 Effect of Impact Velocity on exit side Diameters

The impact velocity and the effect of diameters on exit side of the target configurations T4+ T1 and T4+ S (12.7) +T2 which have more than one projectile exited through the rear end side plate have been plotted against the diameters of indents produced on exit side and are shown in Fig. 22. No specific trend in the data found.

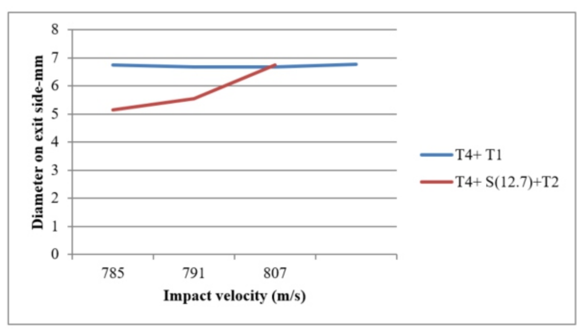


Fig. 22 Impact velocity versus diameters on exit side

13.4 Areal density/ weight comparison

Since areal density comparison represents a simple performance measure and ballistic efficiency therefore, the most significant finding of this research paper is in the comparison of areal density of various configurations with the angle of qualification which is shown in Table 8.

Table. 8 Areal density comparison

Target configuration	**Target configuration codes (space in mm)**	**Impact velocity**	**Areal density without fasteners, mounting, spacers, brackets etc. & with qualified oblique angles (kg / ft²)**	**Angle of qualification**	**% lower weight than highest weight target configuration "B"**
Applique Target "A"	T5+ T1		12.42	(0°)	14
Applique Target "B"	T4+ T1	792	14.43	(40°)	0
Spaced Target "C"	T4+ S(12.7)+T2	797	10.34	(40°)	28
	T4+ S(25.4)+T2	802	9.67	(35°)	33
Spaced Target Space "D"	T4+ S (25.4) +T3	789	8.29	(40°)	43
Spaced Target "E"	T4 0°+S (38.1 – 167.39) +T5 23°		8.49	Failed	failed
Spaced Target "F"	T5 23° +S (38.1 – 167.39) +T5 0°		8.35	(23°, 0°)	42

A substantial decrease in areal density (43%) is achieved with target configuration "D" as compared to the highest weight configuration "B". Both the configurations qualified at oblique angle 40° and were tested under similar set of conditions. The target configurations "F" in third group with both Stl plates also exhibited a very promising 42% reduction as shown in Fig. 23.

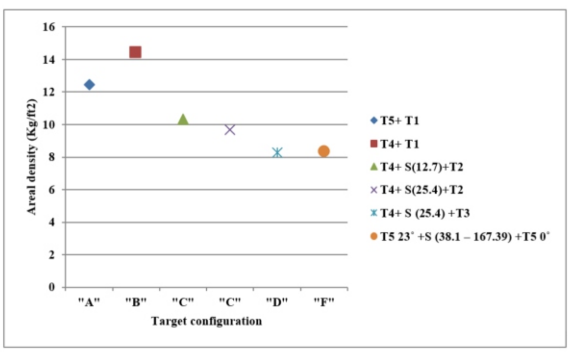


Fig. 23 Areal density comparison between target configurations

It can be inferred that the combination of space and obliquity for Stl and Al bi layered configurations can be effectively utilized to mitigate the projectile energy. It can also be inferred that higher the oblique angle, higher is the deflection of the projectile and higher the interlayer space, higher is the dispersion of debris cloud. Although the weight of spaces and mounting has not been taken into account but lighter weight mountings for example low weight square pipes etc. need to be further investigated to ascertain their performance under ballistic impact loading.

XIV. CONCLUSION

This study has used both space and obliquity by conducting experimental ballistic tests on 03 x groups of target configuration using service rifle and ogive shaped 7.62 x 51 mm WC core projectile at a distance of 10 meters in ordnance velocity range. Total 06 x armoured configurations arranged in applique, fixed spaced varying angles and fixed angle varying space layouts were experimentally investigated. Non perforation of the projectile at particular set of condition was taken as ballistic performance measure to compare the protective shields. The test results provided some interesting options to optimize the metallic ballistic configuration consisting of Al and Stl armour for low weight and cost-effective protective structure solutions thus retaining the advantages of metallic configurations with less weight. Based upon the experiments conducted, results and discussions, following conclusions can be drawn:

a) Increase in interlayer space in bi layered ballistic configurations with high hardness Stl at impact side and Al 5083 at rear non-strike side improves the ballistic performance while keeping the same variation of target inclined angles.
b) The effect of obliquity till 25° inclined target angle has marginal effect on the ballistic performance and on deflection of the bullet. Beyond 25° substantial improvement in ballistic resistance is observed.
c) The change in orientation of the research metallic plates with different thicknesses has an effect on the ballistic performance while keeping all other parameters same.
d) The bullet deflects on encountering the high

hardness Stl plate inclined at an angle and in general upward deflection of the bullet is observed for forward slope angles.

e) The higher the oblique angle hardened steel at impact side, the higher is the deflection of the projectile. The higher the interlayer air gap, higher is the dispersion of debris cloud.

f) Obliquity enhances the ballistic performance.

XV. FUTURE RECOMMENDATION

Further numerical and experimental investigations are required to understand the complex ballistic phenomena.

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