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Damage resistance investigation of Armox 500T and Aluminum 7075-T6 plates subjected to drop-weight and ballistic impact loads

Eyüp Yeter*[1],

Abstract

The main objective of this paper is to investigate damage resistance of Armox 500T and Aluminum 7075-T6 plates subjected to drop-weight and ballistic impact loads. Investigating the behavior of structures under the low or the high velocity impact loads is an important research topic. The study of materials and their combinations provides fundamental understanding of many engineering structures. In this study, firstly drop weight and ballistic impact resistance of the Armox-500T and Al7075-T6 materials was examined. Ballistic impact analyses were carried out using 7.62 API projectiles with an initial velocity of 800 m/s. During the drop-weight analyses, the drop of 5.5 kg weight from the 800 mm distance was modeled. The situations at which target plates of different thickness can be fully penetrated or not to be fully penetrated by the projectile, the final (residual) velocities in the fully penetrated plates and the amount of energy absorbed by the target plates were investigated. 6.72 API projectiles with an initial velocity of 800 m/s could not fully penetrated the 10 mm Armox-500T target and 26 mm Al7075-T6 target. When drop-weight results are concerned, the maximum impact loads of the Armox-500T target is higher than the Al7075-T6, and the deformation amount is less. In addition, 10 different hybrid models, which consist of various combination of Armox 500T and Al7075-T6 materials in different thicknesses and orientations, have been defined. These models were compared with each other and models that are more resistant to ballistic impact loads were determined. M4, M7, M9, and M10 models were found to be more resistant to the ballistic impact loads than other models.

Keywords: Damage resistance, Drop-weight, Ballistic impact, Armox 500T, Aluminum 7075-T6.

1. INTRODUCTION

Damage resistance investigation of different materials subjected to low or high-velocity impact loads are important to design structures that can withstand to these loads. The study of materials and various combinations of them contribute to the basic understandings of numerous engineering structures that are manufactured using different material choice, such as layered materials,

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sandwich panels, laminated composites, fiber metal laminates (FML) etc. Since these structures have large surface dimensions and generally used in thin forms, those structures are frequently exposed to impact loads by foreign objects. Also many times these structures are directly designed for the low or high velocity impact loads. In the initial material designs as an armor structure, the main idea or purpose was to prevent damages under the impact loads (especially for ballistic case). But, nowadays designing light-weight structures for the impact-load designs also an important design issue as the case of the other designs.

Damage mechanisms due to low and high velocity impact loads on the different materials and material combinations have been investigated extensively. In general, low velocity impact (LVI) damage is studied under the drop weight impact loadings investigating the effects of a penetrator on a target plate. On the other hand, high velocity impact (HVI) damages are mainly studied as ballistic impact loading considering totally or partial penetration of targets with different types of projectiles. In the drop weight impact event, the maximum penetration loads and deformations of structures with these loads are generally studied. In ballistic cases, the ballistic limit of targets or effects of initial velocity or final velocity of projectile after full or partial penetration of targets have been considered.

Low velocity impact behaviors of different materials have been researched by many researchers. Villavicencio and Guedes Soares [1] investigated drop weight impact characteristics of plates experimentally. From this study, it was seen that the plastic behavior of the samples is directly related to the restraint at the supports. Also, it was shown that in the majority of samples the contribution of the stiffeners to the impact response is unimportant. Liu and Guedes Soares [2] performed Quasi static punch tests and dynamic drop weight impact to investigate damage resistances of tubes. Low velocity impact characteristics of Carbon/Epoxy composites were researched numerically and experimentally by Moura and Marques [3]. Boonkong et al. [4] studied on the low velocity impact characteristics of aluminum sandwich plates using Finite element methods (FEM) to obtain the dynamical responses of these plates. Liu and Liaw [5] performed low velocity impact tests on cast acrylic plates reinforced with aluminum plates using drop-weight impact machine. Impact load characteristics, impact energy and delamination were modeled using experimentally obtained results. Shi et al. [6] researched the impact characteristics of fiber reinforced composite plates by numerically and experimentally. Obtained results from numerical study has close agreement with experimental results. Sevkat et al. [7] studied the progressive damage characteristics of hybrid fiber reinforced laminates (S2 Glass-IM7 graphite /Epoxy) impacting with drop weight loads with various impact velocities. Also, a nonlinear numeric model developed to predict failure behavior. Menna et al. [8] used FEM to predict low velocity impact effects on Glass/Epoxy composites considering orthotropic failure criteria and stress based contact failure between plies. Santiago et al. [9] researched the influences of local impact loads on the fiber-metal laminates which produced with the combinations of aluminum alloys and polypropylene. Soliman et al. [10] studied LVI behaviors of laminated composite plates using 3 different fabric types (2D plain woven, 3D orthogonal and 3D angle interlock having Kevlar 29). The results indicated that the impact characteristics was directly related with the in-plane stiffness of the composites. Feng and Aymerich [11] illustrated the usage of FEM to simulate failure characteristics of sandwich composite plates subjected to LVI loads. The developed model could be used to simulate impact damage size. Rawat et al. [12] studied failure characteristics of laminated composite plates using impactors having various shapes (hemispherical, spherical, oval shape, flat) under the impact loadings. Mass of the used impactors was 5.23 kg and impact velocity was 3 m/sec. Numerical analyses were performed using the LS-DYNA analysis program. Impacting with 23.5 J energy, oval shape impactor caused fiber breakage, but flat impactor caused no fiber damage. Sarasini et al. [13] researched the LVI responses of hybrid E-Glass-Basalt/Epoxy composites. Loads at Various impact energies (5j-12.5j-25J) were applied to the samples which have different orientation angles. High impact energy capacities obtained using hybrid composites than the composites have glass fibers. Zhang et al. [14] performed a study on the investigation of the mechanic characteristics of honeycomb sandwich panels under LVI.

Ballistic impact behaviors of different materials have also been investigated by many researchers. Deluca et al. [15] tested various dimensions of laminated plates by applying ballistic impact loads at different velocities. The relationship between damage load and the extension of the failure in terms of the average damage fraction was obtained. Meyer and Kleponis [16] studied on the characterization of the titanium alloy by comparing Johnson-Cook and Zerilli-Armstrong numerical models of ballistic experiments. Silva and Chiorean [17] reported results of experiments and numeric study carried out on the Kevlar-29 laminated composites. Close results between numerical and experimental study have been obtained. Ballistic impact characteristics of laminated composites have been investigated using 2D woven fabrics by Naik et al. [18]. Analytic formulation was used to obtain ballistic limit, contact duration at ballistic limit, and the size of the damaged part. Demir et al. [19] investigated impact characteristics of the 7075 and 5083 aluminum, and AISI 4140 steel using 7.62 mm projectile considering the different heat treatments of materials. It was obtained that 7075-T651 have higher impact strength. López-Puente, Jorge Zaera, and Ramón Navarro [20] developed a finite element (FE) numeric model to obtain final velocity and failure characteristics of Carbon/Epoxy composites under the high impact velocities. Experiments were also performed to obtain data to validation of numerical study using a gas gun. The effects of the impact velocity and oblique angle (0° and 45°) were considered. Talib et al. [21] studied the impact behavior of a hybrid Kevlar-Al2O3 powder/Epoxy laminates under the high velocity impact loads. A relationship between the ballistic limit velocity and the thickness of laminates have been given. The parametrical numeric study was done to obtain ballistic performance of sheet steels using Abaqus FE program by Jankowiak, Rusinek, and Wood [22]. A numeric research was performed to obtain ballistic behavior of Kevlar-29/Epoxy under the various types of projectiles using LS – DYNA FE program. Residual velocity and ballistic limit of target plate have been identified. Zhu et al. [23] investigated ballistic performance of the dry-fabrics numerically using LS-DYNA FE program. Absorbed energy, deformation, and extension of damaged zone have been considered. Bandaru et al. [24] performed a detailed study on the hybrid composite armors produced using various combinations of Glass-Carbon-Kevlar fibers. It was obtained that using Kevlar fibers at the rear part, Glass fibers in the exterior and Carbon fibers on the front part gives better ballistic impact response. E-Glass/phenolic composite armors were investigated for their ballistic characteristics by Reddy et al. [25]. The relation between plate thickness and energy absorption capacity of target plates have been given. Experimental and numerical study was performed to investigate ballistic performance of AA6070 aluminum plates by Holmen et al. [26]. Bandaru et al. [27] researched the ballistic characteristics of hybrid composite armors reinforced with Kevlar and basalt fabrics of 2D by experimentally and numerically. It was shown that overall stacking sequence have important effects on the ballistic response of composite armors. Senthil et al. [28] investigated ballistic performance of 2024 aluminum under the ballistic impact loads with 12.7 mm steel projectiles using ABAQUS FE software and JC material model. Sharma et al. [29] investigated impact performance of AA2014-T652 plates by experimentally and numerically using velocities between 800 m/s and 1300 m/s. Johnson-Cook damage model parameters were calibrated using information obtained from stress-strain data. Yeter [30] investigated ballistic impact characteristics of different aluminum alloys hybridized with Kevlar/Epoxy composite. It was concluded that 7075-T6 aluminum alloy has the best ballistic performance among the compared aluminum alloys and hybridization of this alloy with a composite material like Kevlar have some advantages.

In this study, damage resistance of Armox 500T and Aluminum 7075-T6 plates subjected to drop-weight and ballistic impact loads were investigated. The behavior of plates under the low or high-velocity impact loads are an important concern to the researchers. The study of materials and their combinations provides fundamental understanding of many engineering structures. In this study, firstly drop weight and ballistic impact resistance of the Armox 500T and Al7075-T6 plates were researched for the conditions that they are in single form in the plates. Ballistic impact analyses were carried out using 7.62 API projectiles with an initial velocity of 800 m/s. During the drop-weight analyses, the drop of 5.5 kg weight from the 800 mm distance was modeled. The situations at which target plates of different thickness can be fully penetrated or not to be fully penetrated by the projectile, the final (residual) velocities in the fully penetrated plates and the amount of energy absorbed by the target plates were investigated. Energy absorption of targets in each time interval of ballistic impact and residual velocity of projectiles were determined. Combining different materials in a structure is an important issue to use superior properties of them. Hence, 10 different hybrid models, which consist of various combination of Armox 500T and Al7075-T6 materials in different thicknesses and orientations, have been defined. These models were compared with each other and models that are more resistant to ballistic impact loads were determined.

2. MATERIALS AND METHOD

In the first section of materials and methods, material properties of Armox 500T steel and 7075-T6 aluminum alloys are given. Second, numerical modeling and validation of ballistic impact event used in the study is given. Then, numerical modeling for drop weight impact event is given.

2.1. Material Properties of Plates

In the study, Armox 500T and Aluminum 7075-T6 materials were used as the target plates and their resistance under the low velocity (drop weight) and high velocity (ballistic impact) loads are investigated. The material properties of Armox 500T are taken from a reference study which was carried by Iqbal et al. [31]. The material properties of Armox-500T obtained in this detail study is listed in Table 1.

Aluminum 7075-T6 is the mostly used material in the light weight impact applications and it's material properties are taken from material library of ANSYS [32] and the material parameters are given in Table 2.

Table 1. Material parameters of Armox-500T

Parameter		Value
Young's Modulus (GPa)		201
Poisson's Ratio		0.33
Density(kg/m^3)		7850
Specific Heat (J kg^-1 K^-1)		455
Initial Yield Stress (MPa)		1372.488
Hardening Constant (MPa)		835.022
Hardening Exponent		0.2467
Strain Rate Constant		0.0617
Thermal Softening Exponent		0.84
Melting Temperature (K)		1800
Damage Constants	D1	0.04289
	D2	2.1521
	D3	-2.7575
	D4	-0.0066
	D5	0.86
Reference Strain Rate (/sec)		1

Table 2. Material parameters of Al7075-T6

Parameter	value
Density (kg m^-3)	2804
Specific Heat (J kg^-1 C^-1)	848
Initial Yield Stress Y (MPa)	420
Maximum Yield Stress Ymax (MPa)	810
Hardening Constant B	965
Hardening Exponent n	0.1
Derivative dG/dP G'P	1.741
Derivative dG/dT G'T (Pa C^-1)	-16450000
Derivative dY/dP Y'P	0.02738
Melting Temperature Tmelt (C)	946.85
Gruneisen Coefficient	2.2
Parameter C1 (m s^-1)	5200
Parameter S1	1.36

2.2. Numerical Modeling and Validation of Ballistic Impact

Numerical simulations were performed using ANSYS Finite elements analysis program. The Explicit Dynamics system is used to model the ballistic impact phenomenon which is designed for simulating of nonlinear structural mechanic applications involving high velocity impact loads, complex material behavior including material damage and failure characteristics, and large deformations and geometric nonlinearities. Explicit Dynamic is the most appropriate for events occurring in a very short time (milliseconds or less). The Johnson-Cook failure model could be used in all element types under the various loads including impact loads. JK model can be used to demonstrate the strength behavior of materials with large strains and high temperatures. With this model, the yield stress depends on the strain, strain rate, and temperature. In the ANSYS, using this model, yield stress can be defined as [31];

$$Y = \left[A + B\varepsilon_p{}^n\right]\left[1 + C\ln\varepsilon_p{}^*\right]\left[1 - T_H{}^m\right] \quad (1)$$

$$T_H = \left(T - T_{room}\right) / \left(T_{melt} - T_{room}\right) \quad (2)$$

In Eq. 1, εp is the effective plastic strain, εp^* is the normalized effective plastic strain rate, A (Initial Yield Stress), B (Hardening Constant), n(Hardening Exponent), C and m are the material constants. The expression in the first parenthesis group gives the stress as a function of strain when εp^* equals to 1.0 s-1 and TH equals to zero. The expressions in the second parenthesis group give the influences of the stress rate on the yield strength of the material. The reference stress rate at which material data is measured is used to normalize the plastic strain rate increase. In Eq. 2, $Tmelt$ and $Troom$ are the melting and room temperatures, respectively.

The target plate used during the ballistic study was taken as 200x200 mm square plate with various thickness. 7.62 Armour-Piercing Incendiary (API) projectile was used during the numerical study. Figure 1 shows the dimensions of the projectile used in this study. Material parameters of the used projectile is given in Table 3. In the FE model of ballistic impact, element erosion was activated. A friction coefficient that equals to 0.2 was considered between the projectile and targets.

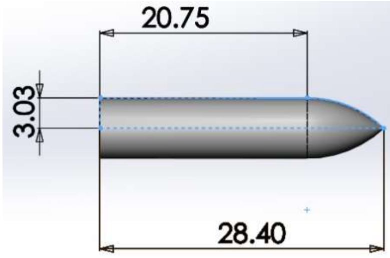

Figure 1. Dimensions of the projectile (in mm)

Table 3. Material parameters of API projectile

Parameter		value
Young's Modulus (GPa)		200
Poisson's Ratio		0.3
Density(kg/m3)		7850
Bulk Modulus (Pa)		1.97059E+11
Shear Modulus (Pa)		75563909774
Specific Heat (J kg^-1 K^-1)		455
Initial Yield Stress (MPa)		1657.71
Hardening Constant (MPa)		20855.6
Hardening Exponent		0.651
Strain Rate Constant		0.0076
Thermal Softening Exponent		0.35
Melting Temperature (K)		1800
Damage Constants	D1	0.0301
	D2	0.0142
	D3	-2.192
	D4	0
	D5	0.35
Reference Strain Rate (/sec)		1

The validation of ballistic numerical model is done comparing the result obtained in the reference study which was performed by Iqbal et al. [30]. Impact velocities of 823.62 m/s and 823.02 are applied against to 8 mm Armox 500T steel target with 7.62 API projectile in the reference study. In Table 4, the comparison of experimental and numerical results taken from reference study, and numerical results of current study are given. Also, projectile velocity reductions during ballistic impact for two different initial projectile velocities of the current study is given in Figure 2. It is seen from Table 4 and Figure 2 that the residual velocity values of current study is close to the experimental and numerical results of reference study and thus, the numerical model can be accepted to investigate the targets under ballistic impact.

Table 4. Ballistic resistance of Armox 500T 8 mm target plate with 7.62 API projectile

Initial velocity (m/s)	Final velocity (m/s)		
	Experimental (ref[31])	Numerical (ref [31])	Numerical (current study)
823.62	334.28	349.6	325.07
823.02	343.74	358.1	341.49

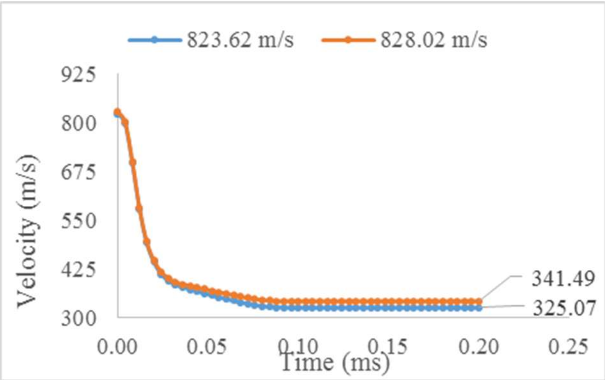

Figure 2. Residual velocities in current simulation

2.3. Numerical Modeling for Drop Weight Impact Event

In this study, the damage resistance of materials to a drop weight impact event is also researched numerically. The numerical models were developed using the transient finite element module of ANSYS. Simulation of the impact event is performed by the collision of two parts, namely, the impactor and the target plate. A hemispherical impactor which has totally 5.5 kg mass and 8mm tip radius are used and as shown in figure 5, the distance between the impactor and target plate is 800 mm. In other words, the impactor is released from 800 mm distance. The target plate dimensions are 150 mm length and 100 mm width. During the analyses, the target plate (as shown in figure 3) fixed from all edges.

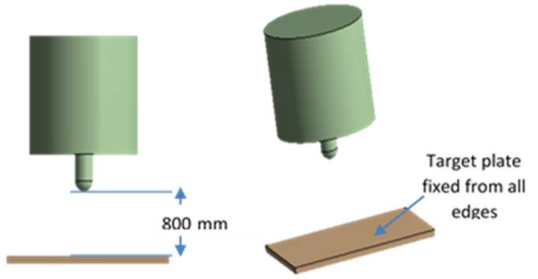

Figure 3. Impactor and target plate properties

3. RESULTS AND DISCUSSION

Results are given in the three section. In the first section, results and discussion of the ballistic impact responses of the Armox 500T and aluminum 7075-T6 are given.

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3.1. Ballistic Impact Responses of Armox 500T and Al 7075-T6

During the ballistic impact researches, generally, two conditions are searched. The first condition is the full penetration of target plates, and in this case, the target plates were totally penetrated by the projectile and the projectile has a velocity reduction after total penetration of plates. The second condition is a partial penetration or non-penetration of the target plates. In this case, the projectile has zero final velocity which means that this projectile cannot fully deform these plates. The used initial velocity at which the plates cannot be fully perforated can be called the ballistic limit velocity of this thickness of the plate. Initial and final velocities of projectiles and absorbed energy values of different plates are compared by researchers generally. In this study, the projectile is considered as rigid and an initial velocity of 800 m/s is applied. The target plate is fixed from all edges.

Projectile velocity reduction during ballistic impact for Armox 500T for 1, 3, 6, 9, and 10 mm plate thicknesses are given in Figure 4. As expected, residual velocity decreases with the increase of thickness due to the increased energy absorption capacity in thicker targets. As seen in Figure 4, when the thickness is increased to 10 mm, the final velocity of projectile reduces to the zero. Which means that the plate cannot be perforated when the thickness is 10 mm and the higher. And it is seen that the projectile velocity reduces to zero after 0.05 ms.

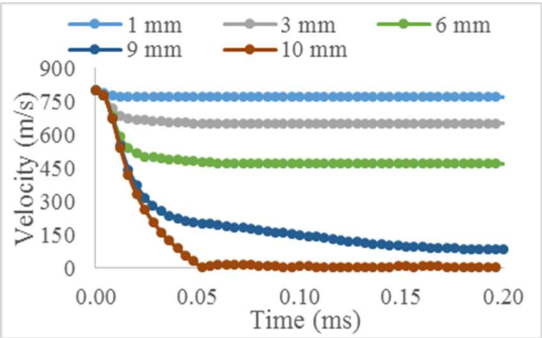
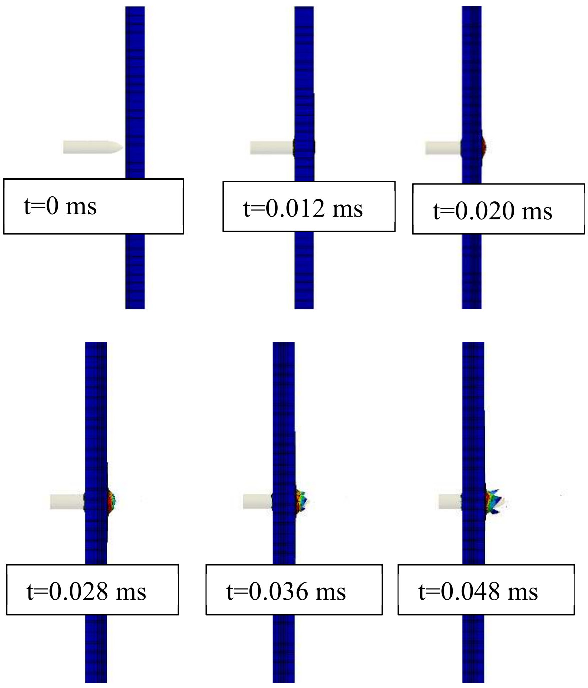


Figure 4. Projectile velocity reduction during ballistic impact for Armox 500T plates for different thicknesses



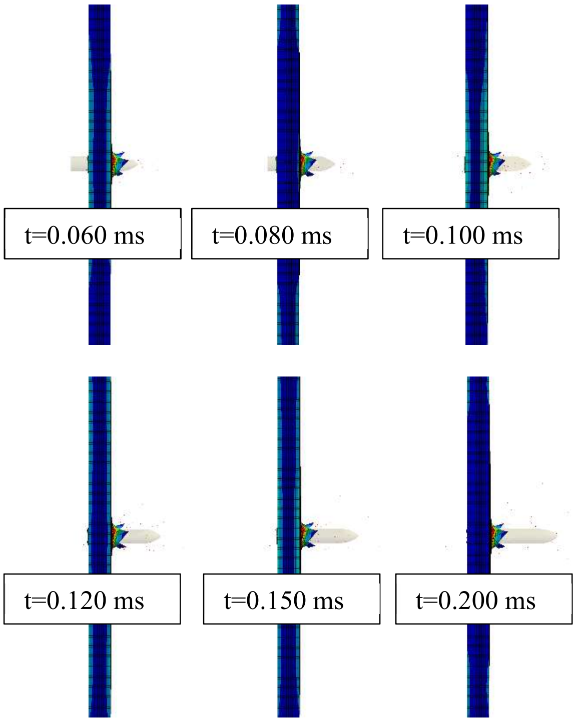


Figure 5. Damage propagation on the 9 mm target (Armox 500T) under the ballistic impact loading

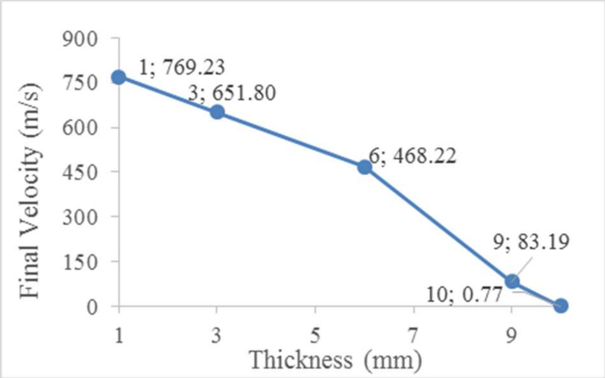
Absorbed energy after ballistic impact event can be calculated by using initial, final velocities of projectile, and mass of the projectile. This equation is given as:

$$E = \frac{1}{2} m (V_i^2 - V_f^{\,2}) \tag{3}$$

Where;

E= Absorbed Energy by the target (J); m= Projectile mass (kg); Vi= Projectile initial velocity (m/s); Vf= Projectile final velocity (m/s)

Final velocity of Armox 500T target plate and absorbed energy by the Armox 500T target plate during the ballistic impact event is given in Figure 6 and Table 5 for different thicknesses of target plate. The figure and the Table show that with the increase of the thickness to 10 mm from 1mm, the final velocity is decreased 0 m/s from 769.23 m/s. And amount of absorbed energy is increased to 1811.93 J from 136.70 J.



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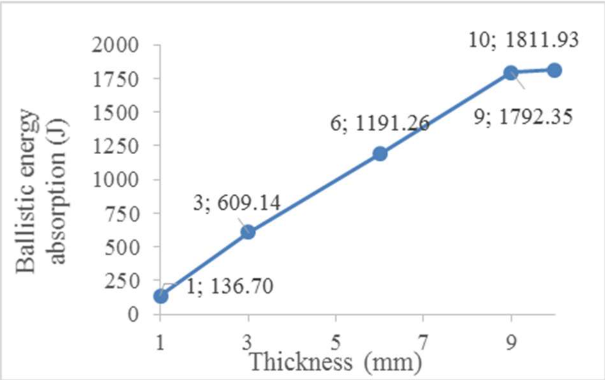


(b)

Figure 6. Variation of Final velocities (a) and Energy absorptions (b) of Armox 500T for different thicknesses

Table 5 Final velocities and Energy absorptions of Armox 500T for different thicknesses

Thickness (mm)	Final velocity (m/s)	Ballistic energy absorption (J)
1	769.23	136.70
3	651.80	609.14
6	468.22	1191.26
9	83.19	1792.35
10	0.77	1811.93

*$V_{initial}$=800 m/s

Projectile velocity reduction during ballistic impact for Aluminum 7075 T6 for 3, 6, 9, 18, and 26 mm thicknesses are given in Figure 7. As seen in figure 7, when the thickness is increased to 26 mm, the final velocity of projectile reduces to the zero. Which means that the plate cannot be fully perforated when the thickness is 26 mm and the higher. And it is seen that the projectile velocity reduces to zero after 0.1 ms. So it is seen that the thickness for Aluminum 7075-T6 at which the target plate cannot be fully perforated 2.6 times higher than the thickness of the Armox 500T. When “velocity first reduction to zero time” of Armox 500T and Aluminum 7075-T6 are compared, it is seen that “velocity first reduction to the zero time” for Aluminum 7075-T6 is 2 times higher than the “velocity first reduction to the zero time” for Armox 500T.

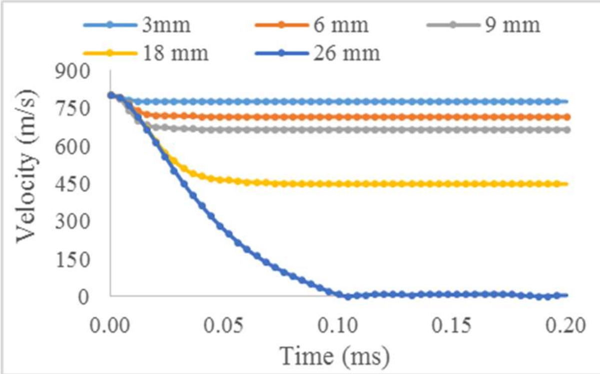
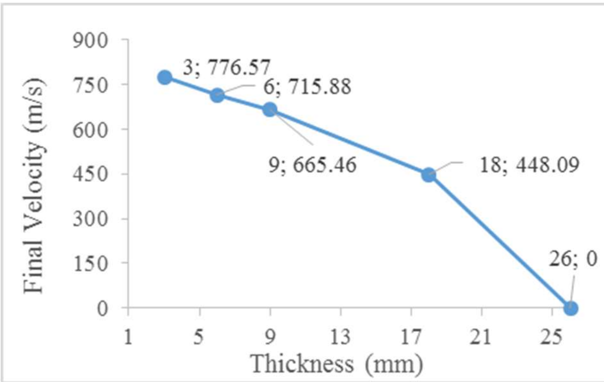


Figure 7. Projectile velocity reduction during ballistic impact for the different thicknesses of AL7075 T6

Final velocity of Al 7075 T6 target plate and absorbed energy by the Al 7075 T6 target plate during the ballistic impact event is given in Figure 8 and Table 6 for different thicknesses of target plate. The figure and the Table show that with the increase of the thickness to 26 mm from 3mm, the final velocity is decreased 0 m/s from 776.57 m/s. And amount of absorbed energy is increased to 1811.93 J from 104.58 J.



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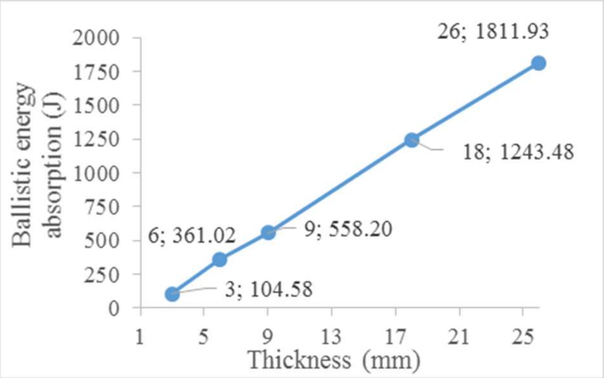


(b)

Figure 8. Variation of final velocities (a) and energy absorptions (b) of Al 7075 T6 for different thicknesses

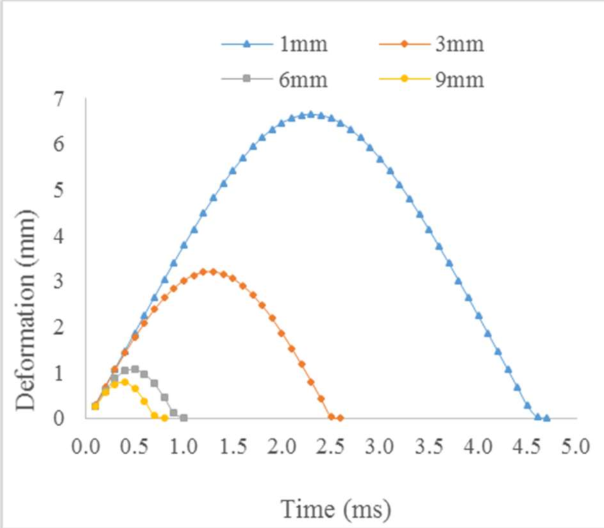
Table 6. Final velocities and energy absorptions of Al 7075-T6 for different thicknesses

Thickness (mm)	Final velocity (m/s)	Ballistic energy absorption (J)
3	776.57	104.58
6	715.88	361.02
9	665.46	558.20
18	448.09	1243.48
26	0.71	1811.93

*$V_{initial}$=800 m/s

3.2. Drop Weight Impact Results of Armox 500T and Al7075 T6

The damage resistance of materials to a low-velocity loading considering drop weight impact event is given in this section. In this part of the study, both understanding characteristics of Armox 500T and AL7075-t6 plates under the drop-weight loading and comparing the results obtained with this loading and ballistic impact loading is aimed. Deformation comparison of Armox 500T and AL7075-T6 plates are given in Figure 9 for 1-9 mm plate thicknesses. As seen in figure 9 and table 7, maximum deformation of Armox 500T nearly 25% less than maximum deformation of Al7075 T6 for 1mm plate thickness. For 1 mm plate thickness, the impactor and Armox 500T target plate are in contact nearly 4.5 ms and this contact duration is 6 ms for Al 7075-T6.



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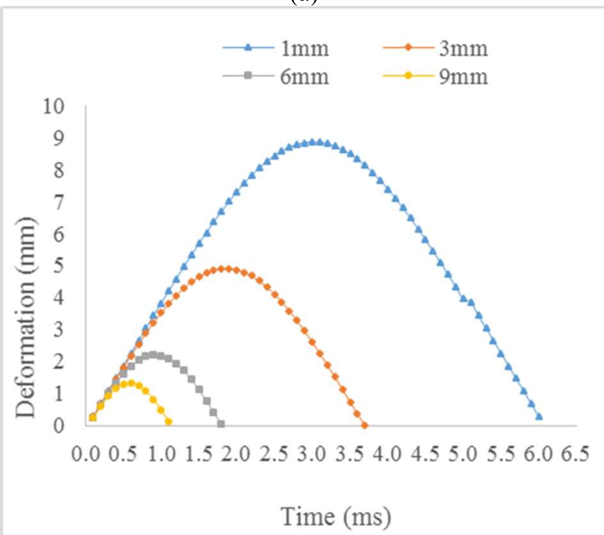


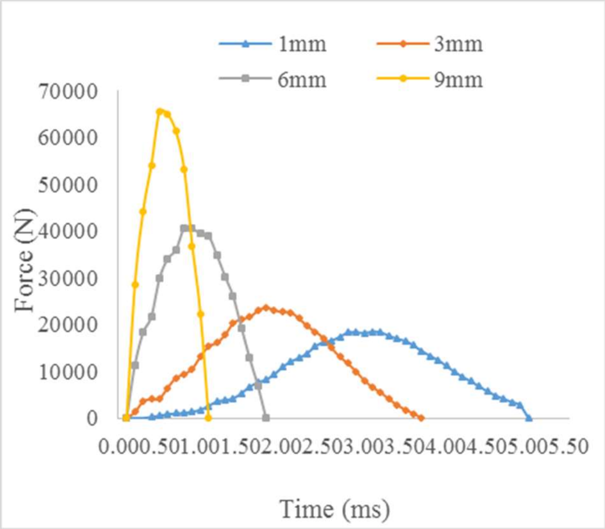
(b)

Figure 9. Deformation graph for different thicknesses of a) Armox 500T b) Al 7075-T6

Table 7. Maximum deformations for Al 7075-T6 and Armox 500T

Thickness (mm)	Al 7075-T6	Armox 500T
1	8.8638	6.6506
3	4.9062	3.2011
6	2.2018	1.0631
9	1.3317	0.77717

Impact force comparison of Armox 500T and AL7075 T6 plates are given in Figure 8 for 1-9 mm plate thicknesses. As seen in figure 10 and table 8 , impact force of Armox 500T nearly 28% less than impact force of Al7075 T6 for 9mm plate thickness.



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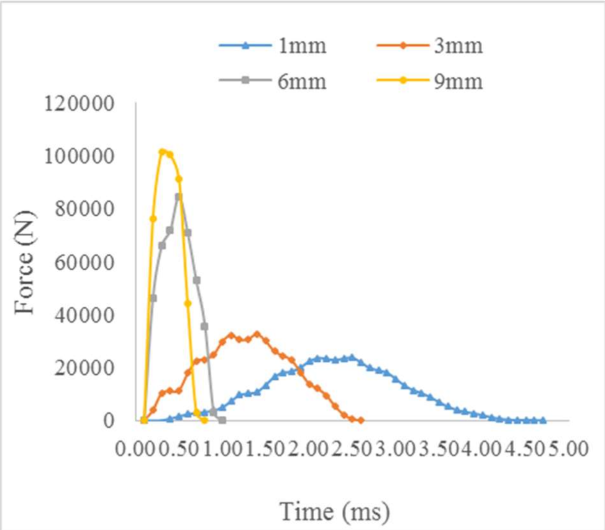


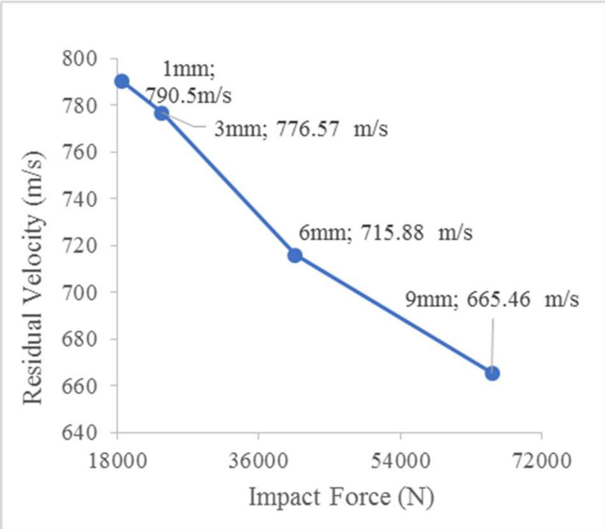
(b)

Figure 10. Impact Force graph for various thickness of a) Al 7075-T6 b) Armox 500T

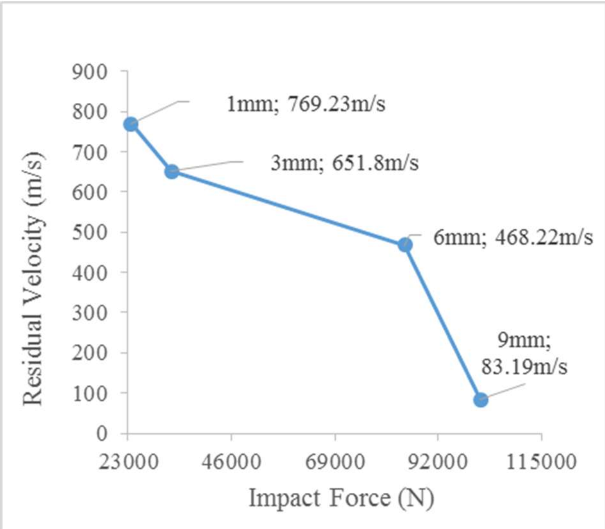
Table 8. Impact forces for Al 7075-T6 and Armox 500T

Thickness (mm)	Al 7075-T6	Armox 500T
1	18475	23600
3	23640	32583
6	40601	84520
9	65685	101470

"Residual velocity after ballistic impact" versus "impact force after drop-weight" comparison is given in Figure 11 for Al7075 T6 and Armox 500T plates. For aluminum plate, when thickness increased to 3 mm from 1 mm, the residual velocity decreased 776.57 m/s from 790.5 m/s, and impact force increased to 23640 N from 18475 N. So, when the thickness is 3 times increased, residual velocity is 1.018 times decreased and impact force is 1.28 times increased. For steel plate, when thickness increased to 3 mm from 1mm, the residual velocity decreased 651.8 m/s from 769.23 m/s, and impact force increased to 32583 N from 23600 N. So, when the thickness is 3 times increased, residual velocity is 1.18 times decreased and impact force is 1.38 times increased.



(a)



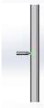
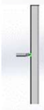
(b)

Figure 11. Residual velocity versus impact force graph for various thickness of a) Al 7075-T6 b) Armox 500T

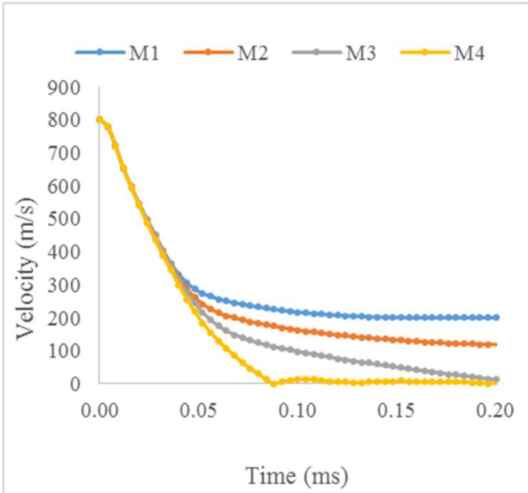
3.3. Ballistic Impact Responses of Hybrid Models

In the third part of the study, 10 different hybrid models with different combinations of Armox 500T (Ar) and Al 7075 T6 (Al) were proposed. These combinations are 2AR + 13AL+2AR, 2AR + 14AL+2AR, 2AR + 15AL+2AR, 2AR + 16AL+2AR, 3AR + 9AL+3AR, 3AR + 10AL+3AR, 3AR + 11AL+3AR, 4AR + 4AL+4AR, 4AR + 5AL+4AR, and 4AR + 6AL+4AR. These combinations are named as M1, M2, M3, M4, M5, M6, M7, M8, M9, and M10 as shown in Table 9.

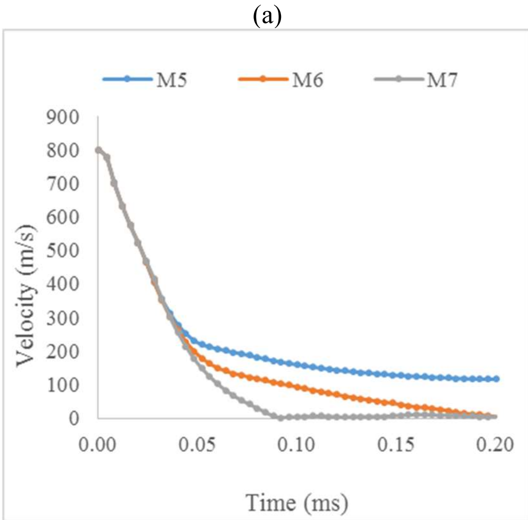
Table 9. Schematic representation of different hybrid models

Model	Geometry	Thickness of the individual plate (mm)	Total Thickness (mm)
M1 (2AR + 13AL+2AR)		2+13+2	17
M2 (2AR + 14AL+2AR)		2+14+2	18
M3 (2AR + 15AL+2AR)		2+15+2	19
M4 (2AR + 16AL+2AR)		2+16+2	20
M5 (3AR + 9AL+3AR)		3+9+3	15
M6 (3AR + 10AL+3AR)		3+10+3	16
M7 (3AR + 11AL+3AR)		3+11+3	17
M8 (4AR + 4AL+4AR)		4+4+4	12
M9 (4AR + 5AL+4AR)		4+5+4	13
M10 (4AR + 6AL+4AR)		4+6+4	14

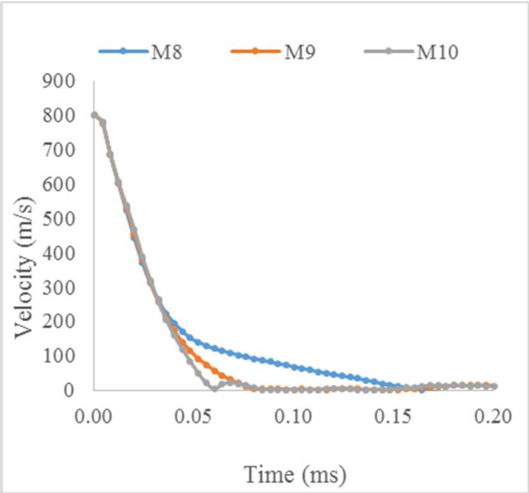
Projectile velocity reductions during ballistic impact event of these proposed models are given in figure 11. M1, M2, M3, and M4, which have 2mm Armox 500T at the left side and right side of the hybrid models, are compared in figure 12(a). Among M1, M2, M3, and M4, residual velocity of M4 decreased to zero. M5, M6, and M7, which have 3mm Armox 500T at the left side and right side of the hybrid models, are compared in figure 12(b). Among M5, M6, and M7, residual velocity of M7 decreased to zero. M8, M9, and M10, which have 4mm Armox 500T at the left side and right side of the hybrid models, are compared in figure 12(c). Residual velocity of M8, M9, and M10 decreased to zero.



(a)



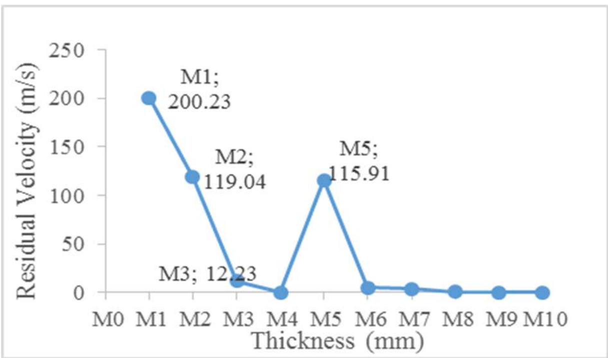
(b)



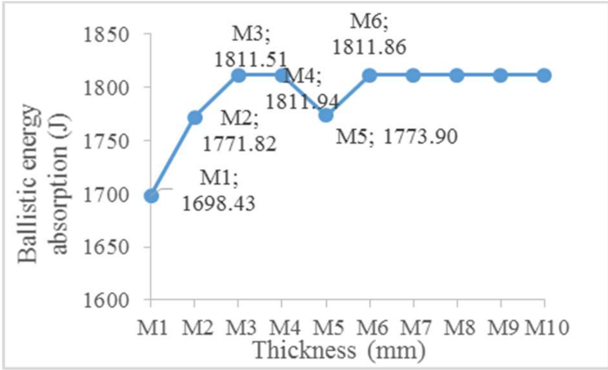
(c)
Figure 12. Projectile velocity reduction during ballistic impact for the hybrid targets

Demir et al. [19] and Yeter [32] has shown that Al7075 has the best ballistic performance among the compared aluminum alloys. So in the current study Al7075 is used for hybridization purpose. Like the reference studies [9, 13, 24, 30], it is seen in the current study that position of materials in different layers directly effects the ballistic performance. And it is also shown that with the correct position of different materials, same ballistic performance can be obtained with less thickness.

Comparisons of residual velocities and absorbed energies of all hybrid models are given in Figure 13 and Table 10. As seen in this figure and table, residual velocities of M4, M6, M7, M8, M9, and M10 are zero or very close to zero. Also absorbed energies of these models are nearly same to each others. Considering these models, targets exhibited approximately identical responses in terms of residual velocity of the projectile.



(a)



(b)
Figure 13. Variation of residual velocities (a) and energy absorptions (b) of hybrid models for different thicknesses

Table 10. Residual velocities and Energy absorptions for different material models

Material Models	Residual (Final) velocity (m/s)	Ballistic energy absorption (J)
M1	200.23	1698.43
M2	119.04	1771.82
M3	12.23	1811.51
M4	0.51648	1811.94
M5	115.91	1773.90
M6	5.0448	1811.86
M7	4.0018	1811.89
M8	1.0413	1811.93
M9	0.27063	1811.94
M10	0.058176	1811.94

Weight comparisons of hybrid models and non-hybrid (monolithic) materials are given in Figure 14. As seen in this figure, weight of M4 is 2.87 %, M7 is 0.54 %, and M9 is 2.23 % less than Armox 500T (10mm). Also, weight of M4 is 4.26% higher than Al 7075 T6.

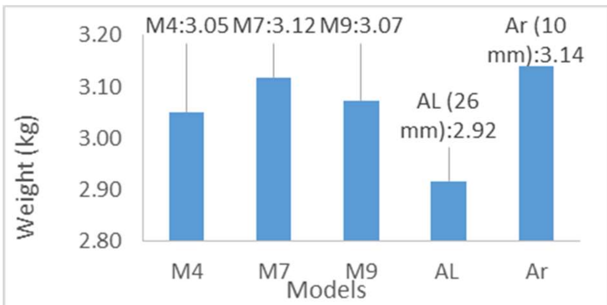
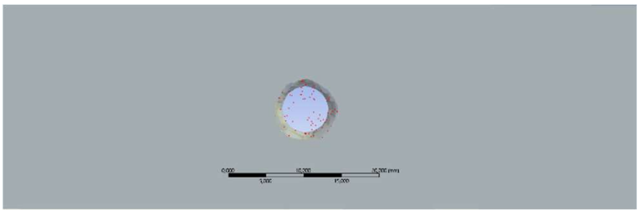
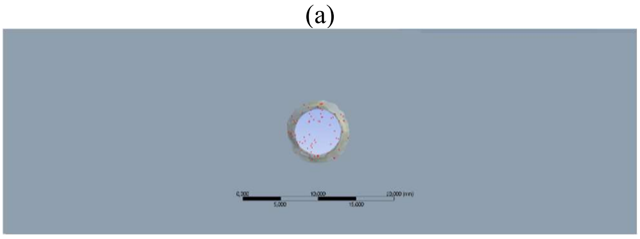


Figure 14. Comparison of Hybrid models and non-hybrid material weight

The front, back and side view of models M1 and M10 are given in Figure 15 to see the damages on the upper and lower surfaces of the layers. As seen in the figure, in model M1 the outlet part of the projectile (back side of the plates) has higher deformation than inlet part of the projectile. In model M10, outlet part of the projectile has less deformation than inlet part of the projectile since in this model there is partial penetration.



(a)



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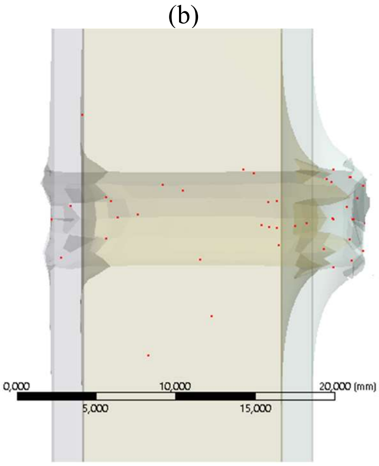

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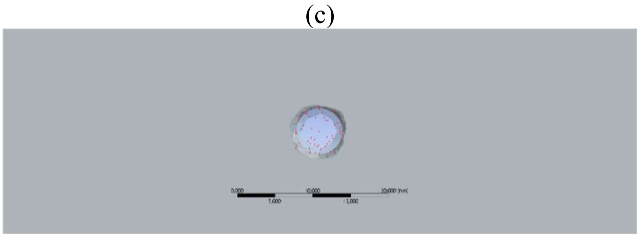
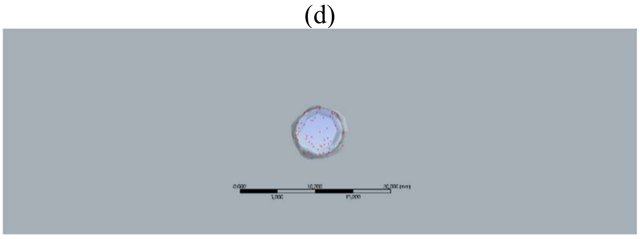
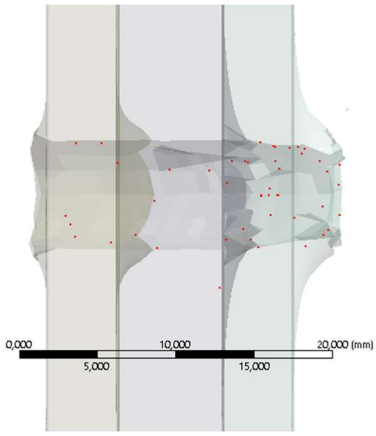


(d)



(e)



(f)

Figure 15. Deformation on the models (a) M1 front view, (b) M1 back view, (c) M1 side view, d) M10 front view, (e) M10 back view, (f) M10 side view.

4. CONCLUSIONS

In this study, damage resistance of Armox 500T and Aluminum 7075-T6 plates subjected to drop-weight and ballistic impact loads were investigated. The behavior of plates under the low-or high-velocity impact loads are an important concern to the researchers. In this study, firstly drop weight and ballistic impact resistance of the Armox 500T and Al7075-T6 plates are investigated for the conditions that they are in single form in the plates. Combining different materials in a structure is an important issue to use superior properties in a single structure. Then, 10 different models are proposed with different orientations of these materials in a plate. The main specific results are;

- The thickness at which residual velocities of the target plates reduce to the zero is less for Armox 500T than Al 7075 T6. Residual velocity decreases with the increase of thickness due to the increased energy absorption capacity in thicker targets. When the thickness of Armox 500T is increased to 10 mm, the final velocity of projectile reduces to the zero and amount of absorbed energy is increased to 1811.93 J from 136.70 J.
- For Al 7075 T6, when the thickness is increased to 26 mm, the final velocity of projectile reduces to the zero. The

thickness for Aluminum 7075-T6 at which the target plate cannot be fully perforated 2.6 times higher than the thickness of the Armox 500T.

- Under the drop-weight impact loads, maximum deformation of Armox 500T nearly 25% less than maximum deformation of Al7075 T6 for 1mm plate thickness. Contact between the impactor and the target plate, is completed in nearly 4.5 ms for Armox 500T and 6 ms for Al 7075-T6 for 1 mm plate thickness. Impact force of Armox 500T nearly 28% less than Impact force of Al7075 T6 for 9mm plate thickness.
- For aluminum plate, when thickness increased to 3 mm from 1mm, the residual velocity decreased 776.57 m/s from 790.5 m/s, and impact force increased to 23640 N from 18475 N. So, when the thickness is 3 times increased, residual velocity is 1.018 times decreased and impact force is 1.28 times increased. For steel plate, when thickness increased to 3 mm from 1mm, the residual velocity decreased 651.8 m/s from 769.23 m/s, and impact force increased to 32583 N from 23600 N. So, when the thickness is 3 times increased, residual velocity is 1.18 times decreased, and Impact force is 1.38 times increased.
- Residual velocities of M4, M6, M7, M8, M9, and M10 are zero or very close to zero. Also absorbed energies of these models are nearly same to each other's. Considering these models, targets exhibited approximately identical responses in terms of residual velocity of the projectile.

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