Accurate Prediction of Projectile Residual Velocity for Impact on Single and Multi-Layered Steel and Aluminum Plates

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Abstract

The present paper deals with the simulation of impact of jacketed projectiles on thin to moderately thick single and multi-layered metal armor plates using explicit finite element analysis as implemented in LS-DYNA. The evaluation of finite element modeling includes a comprehensive mesh convergence study not previously reported in literature, using both shell and solid elements for representing single-layered mild steel target plates. It is shown that the proper choice of contact algorithm, mesh density, and strain rate-dependent material properties is crucial as these parameters significantly affect the computed residual velocity. The modeling requirements are initially arrived at by correlating against test residual velocities for single-layered mild steel plates of different depths at impact velocities in the range of ~800-870 m/s. The efficacy of correlation is adjudged in terms of a 'correlation index', defined in the paper, for which values close to unity are desirable. The experience gained for single-layered plates is next used in simulating projectile impacts on multi-layered mild steel target plates and once again a high degree of correlation with experimental residual velocities is observed. The study is repeated for single- and multi-layered aluminum target plates with a similar level of success in test residual velocity prediction. To the authors' best knowledge, the present comprehensive study shows in particular for the first time that, with a proper modeling approach, LS-DYNA can be used with a great degree of confidence in designing perforation-resistant multi-layered steel and aluminum armor plates.

KEY WORDS: *Projectile, plate, mild steel, aluminum, residual velocity, correlation index*

1. Introduction

The behavior of armor plates subject to ballistic impact by projectiles has been studied using the following main approaches: experimentally [1-6], analytically and empirically [7,8,2], and numerically [9-19]. Amongst these approaches mentioned, a validated numerical procedure, such as employing LS-DYNA, can be the most potent tool for determining ballistic limits of projectiles and performing design optimization of target plates.

A number of investigators have reported non-linear finite element analysis-based prediction of residual velocities for impact of projectiles with velocities greater than ballistic limit on metallic and non-metallic plates. The main objective in these studies was to show that analysis results can correlate against experimental data. A bulk of these simulations employs plane strain or axisymmetric elements [9, 12, 14, 16, 18, 19] with the help of which primarily normal impact on flat targets with velocities higher than ballistic limits could be represented. For simulating impact on thin plates or membrane-type targets, the latter have been sometimes modeled with shell elements [10, 11]. In a limited number of studies, the target plates have also been modeled with three-dimensional elements [13, 15, 17] which are necessary for representing the behaviors of thick and multi-layered plates. Various materials for plates have been considered for simulation-

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based studies: Kad, Schoenfeld and Burkins [9] discussed material modelling procedure for textured Ti-6Al-4V plates; Tabei and Ivanov [10] demonstrated a computational micro-mechanical model for flexible woven fabric; Tan, Lim and Cheong [11] studied the penetration of Twaron fabric; GRP (glass fibre-reinforced plastic) plates as targets were considered by Nandall, Williams and Vaziri [12]; plates of ceramic materials (alumina and silicon carbide) were the subject of work reported by Espinosa et al [14]; Mahfuz et al [15] simulated a complex integral armour made of layers of AD-90 ceramic, EPDM rubber, S2-glass/Vinyl ester and phenolic composites; mild steel and aluminium plates were considered by Park, Yoo and Chung [16] for illustrating their optimisation algorithm; Borvik et al [18] used 460 E steel plates in their studies and incorporated a damage parameter in the modified Johnson-Cook constitutive model; and, impact on HSLA-100 steel plates using quasi-static and temperature-independent material properties were considered by Martineau, Prime and Duffey [19].

It appears from the references mentioned above that a primary focus in numerical simulations of ballistic impact on plates has been material modeling. However, in finite element analysis, a number of other factors such as element size, target thickness, impact velocity and contact algorithm can influence the computed results. Hence, unless the effects of the key factors that control the outcome of analysis are separately evaluated and convergence and accuracy of responses such as residual velocity is established, it would be difficult to say that a given finite element modeling procedure is satisfactory for application to design problems for which no experimental data is available for correlation. As an example, although sophisticated material models have been used that incorporated strain rate and temperature effects together with damage, it is claimed in [19] that good correlation with experimental results on crater formation and residual stress distributions could be obtained just by using quasi-static flow stress-strain data of steel. In the current study, with an objective of arriving at a robust modeling procedure, a comprehensive convergence study, not previously reported in the published literature, is carried out with respect to element size. Both shell and solid elements are considered and the applicability of shell elements, limited by plate thickness, in predicting experimentally determined residual velocity is ascertained. Solid elements representing target plates are shown to be reliable for both thin and moderately thick plates. The convergence of projectile residual velocity using Belytschko-Lin-Tsay shell and constant stress solid elements representing mild steel plates of different hardness is studied by correlating to experimental results reported in [1]. In the material constitutive model, the effect of strain rate on yield stress and failure strain is considered; however, thermal effects are not accounted for. For the impact velocities considered here which are well in the ordnance range, the computed results may not be much influenced by this latter assumption as also observed in [4]. All analyses are carried out with the explicit contact-impact analysis code LS-DYNA. It has been found in the current study that the contact type chosen for analysis is crucial for obtaining desired residual velocity as well as perforation of target with element erosion. The user-friendly contact algorithm activated by the keyword *CONTACT_AUTOMATIC_GENERAL (CAG) yields monotonic convergence of residual velocity starting with lower values of the same for coarser meshes for both solid and shell element-based representation of target plates. For shell elements, a similar behavior is also seen for *CONTACT_ERODING_SURFACE_TO_SURFACE (CESS) contact condition; but for solid elements, the trend for CESS is quite contrasting with respect to CAG with residual velocity converging from higher values for decreasing element size. For shells, both CAG and CESS lead to complete perforation of the considered steel plates as observed in tests for given impact velocities; however, an inconsistence of CAG for solid elements is that a through-the-thickness hole does not get created although the projectiles penetrate and emerge out of the target plates; on the other hand, CESS for solid elements leads to both numerically acceptable residual velocity and test-type plate perforation by plugging. Strain rate-dependent material properties are employed for three varieties of mild steel plates by taking into account the considerable differences in their strengths caused by different hardness. Having established confidence in the modeling procedures that will yield converged residual velocity for single-layered plates, a number of parametric studies is carried out by varying plate thickness, projectile nose shape and other geometric parameters, impact velocity, etc. The consistency of trends obtained in these parametric studies is pointed out in relation to experimental data obtained by other investigators. The modeling guidelines developed here can thus be useful in efficiently creating new design solutions which can otherwise consume considerable time and resources if attempted through physical testing.

2. Finite element modeling

A Finite element model of a given target plate using shell is shown in Fig.1. Alternatively, target plates are also represented with solid elements. For analysis using LS-DYNA, Belytschko-Lin-Tsay shell elements based on a co-rotational formulation and constant stress solid elements are chosen. To start with, these models are employed for studying the effects of mesh size on convergence of computed projectile residual velocity with respect to test values given in [1]. The plate is square in shape with dimensions of 200 mm x 200 mm and is clamped at the four corners. Plates of 2 different depths (thickness) viz. 4.7 mm and 6 mm are considered. The jacketed ogival-nosed projectile targeting the plate centre is modeled with solid elements as shown in Fig. 2. The projectile core has a diameter of 6.2 mm, is 28 mm long and weighs 5.2 grams. It is made of a hard steel alloy with an approximate hardness of 900 VPN. The core is enclosed in a copper sheath which increases the total diameter of the shot to 7.8 mm.

2.1 Material modeling

The material model with the keyword *MAT_STRAIN_RATE_DEPENDENT_PLASTICITY (material type 19) in LS-DYNA has been used for defining the behaviors of three variants of MS (mild steel) plates designated as MS1 and MS2 in [1]. In this constitutive model, yield and tensile strengths can be specified in a tabular manner with respect to effective strain rate. In [1], the hardness ranges of MS1 and MS2 are given without any details on their engineering properties. In the present study, the quasi-static properties of these steel plates for the hardness ranges quoted in [1] are obtained from [23] and are given in Table 1. The strain rate-dependent behaviors of yield and tensile strengths of mild steel are adapted from [22] and are given in Fig. 3. The projectile core and sheath are modeled with material type 24 designated with the key word *MAT_PIECEWISE_LINEAR_PLASTICITY. Nominal properties of copper and hardened steel are used in this case. For both material models as mentioned above, the visco-plastic formulation option is chosen.

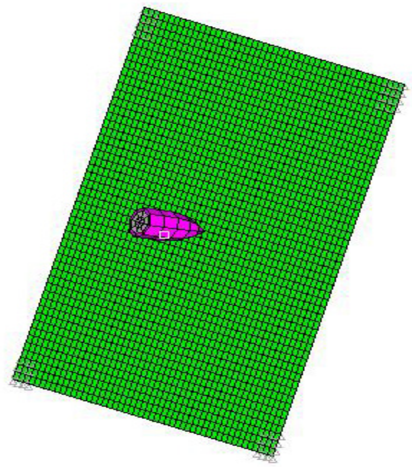


Fig.1. Plate modeled with shell elements

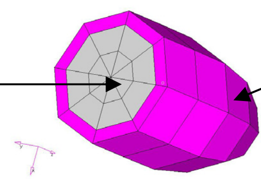


Fig.2. Modeling of jacketed projectile with solid elements

Table 1 Quasi-static properties of MS plates

Plate material nomenclature in [1]	Vickers hardness range in [1]	Trade name of material used in current study [23]	Vickers hardness of material in current study [23]	Quasi-static yield strength [23] (M Pa)	Quasi-static tensile strength [23] (M Pa)	Quasi-static elongation at break (%)
MS1	110 -115	AISI 1016 Hot rolled	115	205	380	25
MS2	150 - 155	AISI 1022 rolled	155	360	505	35

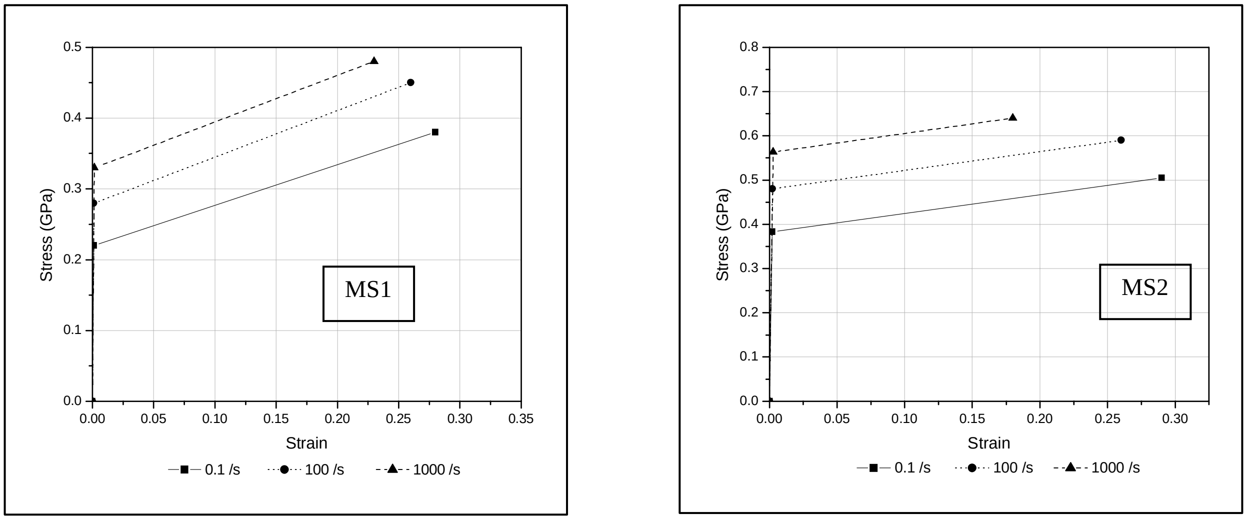


Fig. 3. True stress vs. true strain behaviors at different strain rates for MS1 and MS2 targets adapted from [22]

3. Single-layered mild steel plates – a mesh convergence study

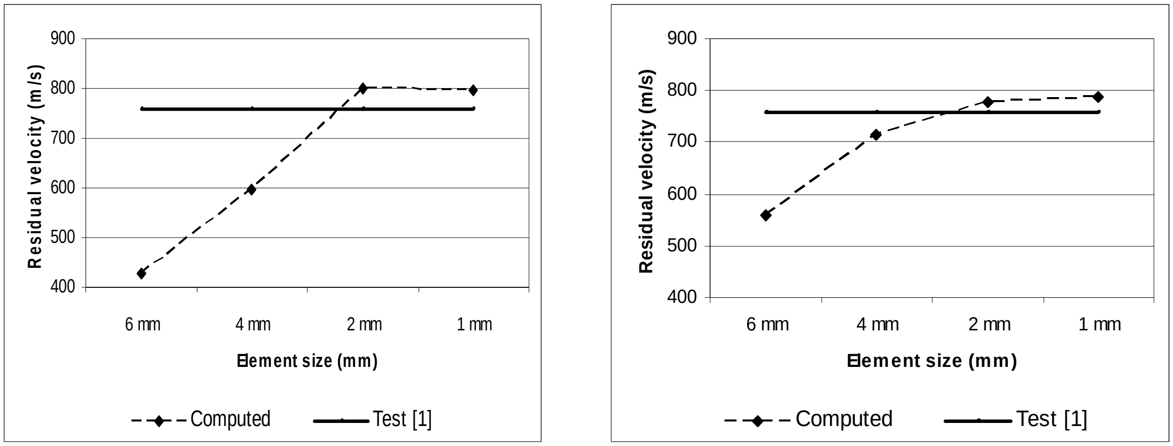
The objective of this study is to determine an optimal element size on plate surface as well as through its thickness (for solid elements) which will yield reliable values of projectile residual velocity. Plates of two different depths are considered and the computed residual velocities are compared (as in Figs. 4 and 5) with the corresponding measured values reported in [1]. It is found in Figs. 4 and 5 that residual velocity tends to converge monotonically as shell element size decreases, with stiffer meshes (with coarser elements) resulting in lower residual velocities as compared to recorded residual velocities in tests. The patterns of convergence are similar for both CAG and CESS contact algorithms; in all cases of plates modeled with shell elements, a clear perforation due to removal of elements in the impact zone is obtained. In order to assess the degree of correlation of simulation-based residual velocities with test residual velocities, the following 'Correlation Index' (CI) is defined:

$$CI = 1 - \frac{\sqrt{\left(\sum e_i^{\,2}\right)}}{\sum V_r} \tag{1}$$

where,

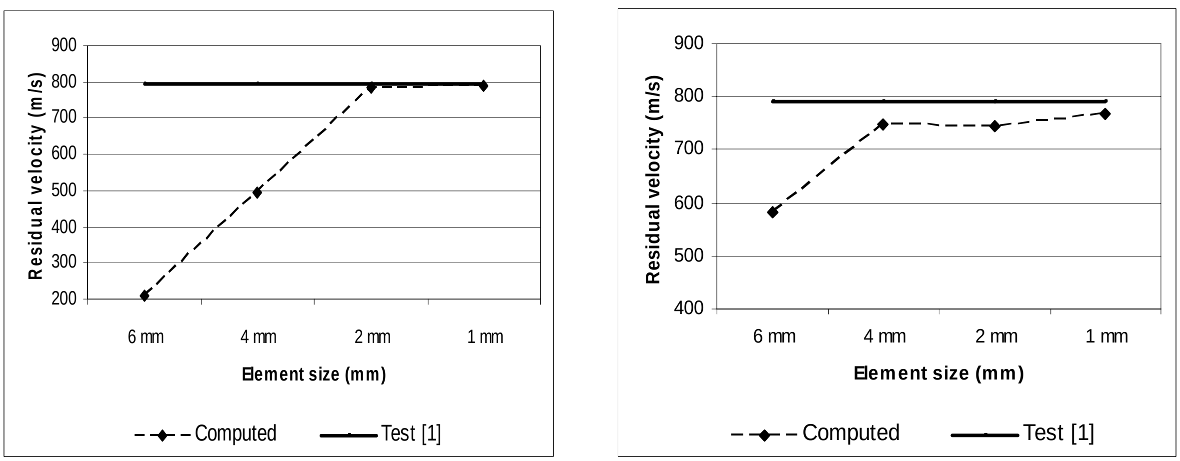
V_r is the test residual velocity, e_i is the discrepancy between computed and test residual velocities, and the summations are carried out over the number of cases for which a combined index of correlation is sought. It is apparent from (1) that as the degree of correlation increases, CI approaches unity.

CI values of 0.988 and 0.985 have been obtained from Figs. 4 and 5 for shell elements with CESS and CAG interface algorithms respectively. As the higher value of CI is obtained for shell elements with CESS interface, it may be concluded that shell element formulation (based on Reissner-Mindlin plate theory) with elements of size 2 mm can be used for analyzing thin plates with CESS interface in LS-DYNA.



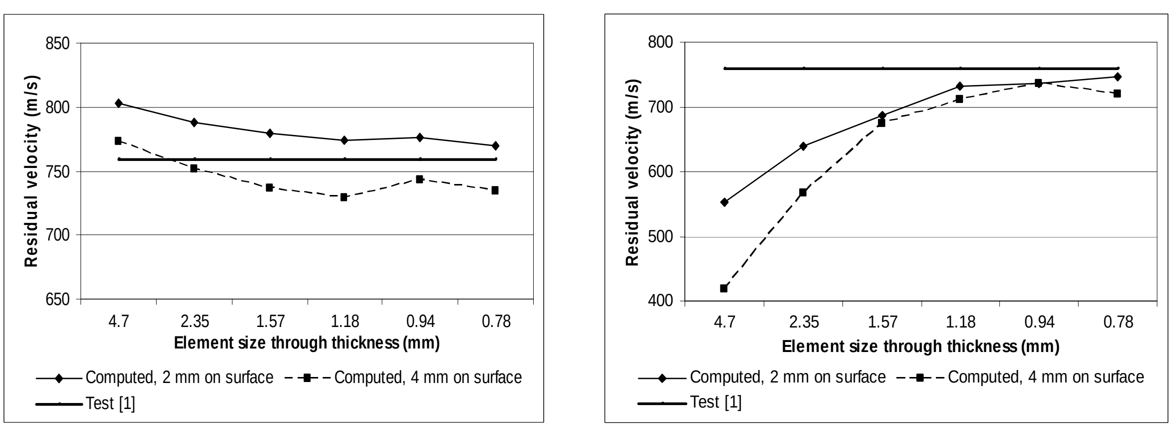
(a) (b)

Fig. 4. Projectile residual velocities for impact on MS1 plates of 4.7 mm thickness is modeled using shell elements (impact velocity: 821 m/s) with (a) CESS interface; (b) CAG interface



(a) (b)

Fig. 5. Projectile residual velocities for impact on MS2 plates of 6.0 mm thickness is modeled using shell elements (impact velocity: 866.3 m/s) with (a) CESS interface; (b) CAG interface



(a) (b)

Fig. 6. Projectile residual velocities for impact on MS1 plates of 4.7 mm thickness is modeled using solid elements (impact velocity: 821 m/s) with (a) CESS interface; (b) CAG interface

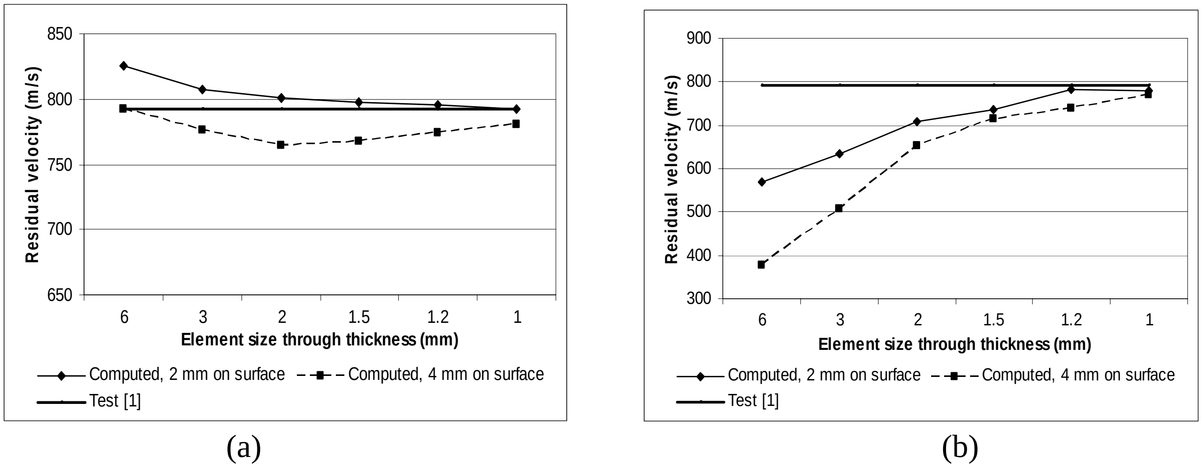


Fig. 7. Projectile residual velocities for impact on MS2 plates of 6.0 mm depths is modeled using shell elements (impact velocity: 866.3 m/s) with (a) CESS interface; (b) CAG interface

The convergence characteristics of projectile residual velocity for plates modeled with solid elements are given in Figs. 6 and 7. In these cases, the effect of solid element thickness on residual velocity is included in addition to element size on plate surface. Unlike for plates meshed with shell elements, convergence patterns for CESS and CAG algorithms are in sharp contrast to each other. It is seen from Figs. 6(a) and 7(a) that CESS yields higher residual velocities for coarser meshes; this may be because erosion of larger elements (when the mesh is coarse) leads to failure over a wider zone giving rise to higher residual velocity relative to the test-based value. From Figs. 6 and 7, good convergence characteristics are seen for solid element meshes, however, a main problem with CAG algorithm for solid elements is that a complete plate perforation is not seen although projectiles do penetrate through plates. The values of CI for solid elements with CESS and CAG interfaces are found to be 0.997 and 0.995 respectively. As the higher value of CI is obtained for solid elements with CESS interface, the latter should be the preferred contact interface for solid element-based representation of plates. As per Figs. 6(a) and 7(a), solid elements of size 2 mm on plate surface yield residual velocities in good agreement with corresponding test values, and the desirable thickness of solid elements is 1/6th of plate thickness. As the highest CI value of 0.997 (≈ 1.0) is obtained for solid elements with CESS contact interface, this representation can be treated as being likely to yield the best prediction of test residual velocities. Thus, in the studies reported in the subsequent sections of this paper, solid elements of appropriate dimensions are used for modeling target plates with CESS contact condition between plate and projectile.

It needs to be noted that the modeling criteria arrived at above are based on analyses for impact speeds in the range of ~800-870 m/s. However, the ballistic limits for the MS target plates considered are likely to be much lower. In order that the present modeling procedures can be used with confidence for plate ballistic limit prediction, the convergence of residual velocity is studied for impact velocities of a wider range i.e. 250-1000 m/s for a given plate thickness (chosen as 4.7 mm) and material (assumed as MS1). The modeling guidelines arrived at above (i.e. a solid element size of 2 mm on plate surface in conjunction with a contact type, CESS) are used in this study. The results are given in Fig. 8 and it can be readily inferred that residual velocities reach steady values for all impact velocities considered, and that a solid element thickness (viz. 0.78 mm) which is 1/6th of plate depth is generally acceptable as concluded earlier for an impact velocity of 821 m/s.

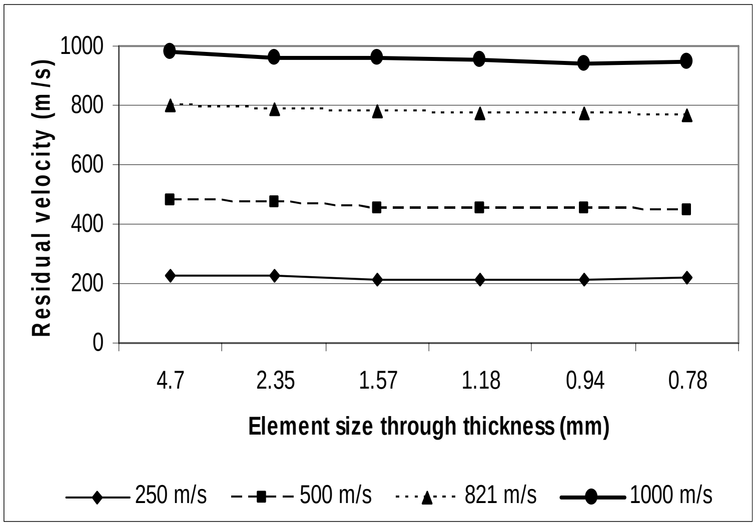
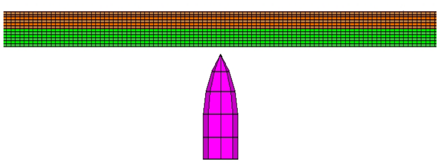


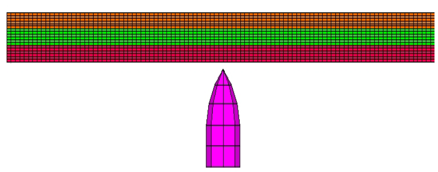
Fig. 8. Effect of projectile impact velocity on convergence of computed residual velocities for a 4.7 mm thick MS1 plate modeled with solid elements

4. Modeling of impact on multi-layered mild steel plates

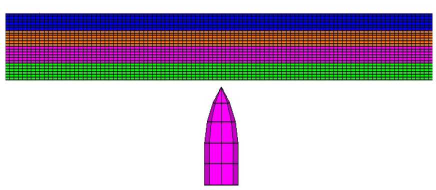
Numerical studies of the multi-layered MS plates under normal impact due to ogival-shaped jacketed projectile are next performed. The plates for a given target are modeled using solid elements, and kept in simple contact (i.e. not tied) as in experiments [1]. The CESS contact interface is defined between target plate and projectile as per the outcome of the mesh convergence study of the previous section for single-layered MS plates. Finite element models of layered plates in side view are shown in Fig. 9.



(a)



(b)



(c)

Fig. 9. Sectional views of finite element models of multi-layered MS plates and projectiles modeled with solid elements: (a) double-layered, (b) triple-layered, and (c) quadruple-layered

In the current study, double-layered, triple-layered and quadruple-layered plates are considered with two categories of material type and geometry: MS1 with 4.7 mm thick layers, and MS2 with 6 mm thick layers.

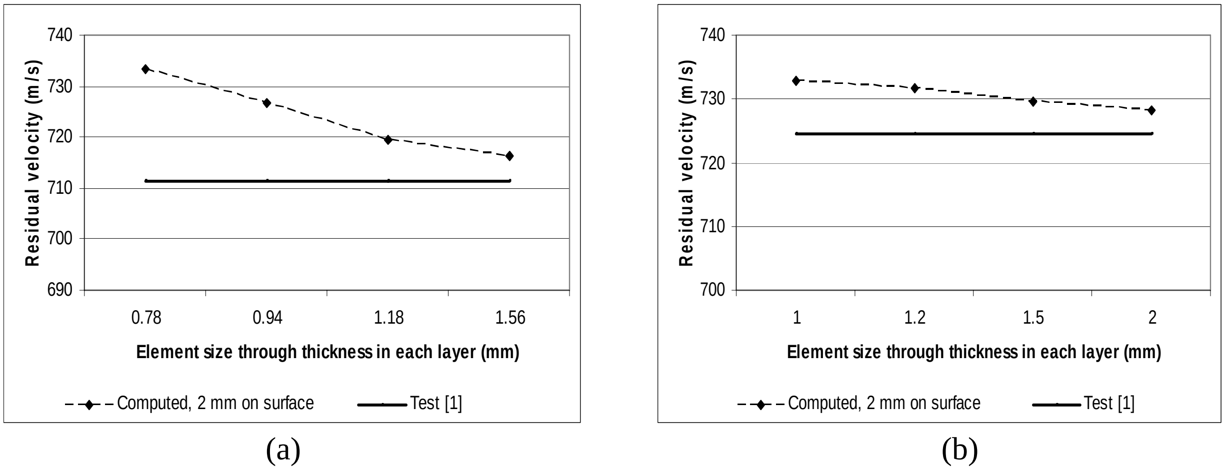


Fig.10. Projectile residual velocities for impact on double-layered plates of equal thickness: (a) MS1 plates of 4.7 mm layer depth; (b) MS2 plates of 6 mm layer depth

A mesh convergence study has been carried out for the present multi-layered plates in a manner similar to what was done in the previous section for single-layered plates. The convergence of residual velocity for double-layered MS1 and MS2 plates is shown in Fig. 10. Based on the computed residual velocities and the corresponding test values in Fig. 10, the parameter CI is obtained as 0.9732 which indicates a high degree of correlation. Since an element size of 2 mm on plate surface yielded good prediction of residual velocity for 4.7 mm and 6 mm thick single-layered plates in Figs. 6 and 7, the same has been adopted in the study in Fig. 10. The converged values of residual velocity correspond to an element thickness of 1/3rd of depth of each layer. The element size on surface as well as through thickness has been varied for the mesh size effect study for triple- and quadruple-layered MS plates in Figs. 11 and 12. As per Figs. 11 and 12, the values of the parameter CI are found to be 0.9644 for triple-layered and 0.9820 for quadruple-layered plates which again indicate a high degree of correlation. For the latter cases of triple- and quadruple-layered MS plates, an element size of 4 mm on plate surface and a thickness of 1/4th of depth of each layer have been found to yield the desired predictions of residual velocity.

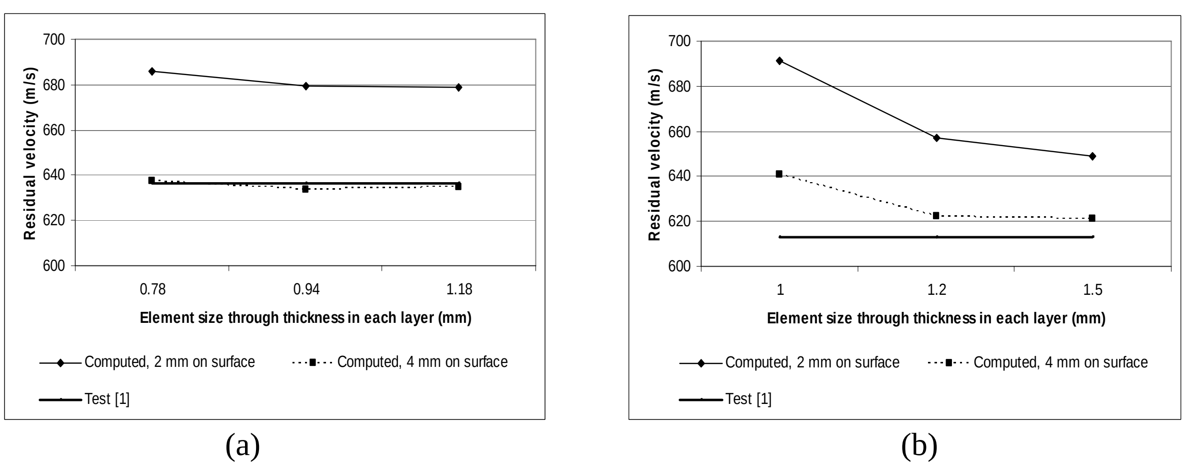


Fig.11. Projectile residual velocities for impact on triple-layered plates of equal thickness: (a) MS1 plates of 4.7 mm layer depth; (b) MS2 plates of 6 mm layer depth

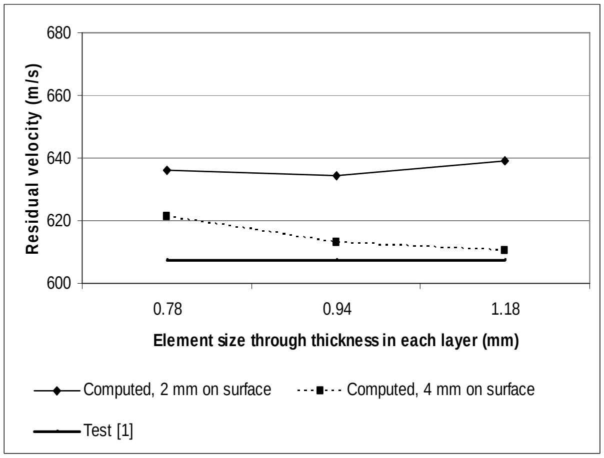


Fig.12. Projectile residual velocities for impact on quadruple-layered MS1 plates of equal thickness of 4.7 mm depth

5. Modeling of impact on single and multi-layered aluminium plates

The modeling guidelines reported in sections 2 and 3 are next adopted for simulation of projectile impact on single- and multi-layered aluminium plates which are designated as AL1 in [1]. The quasi-static properties of AL1 have been obtained from [23] using the quoted value of its hardness given in [1]. The strain-rate dependent behaviors of AL1 have been generated in the current study using the Johnson-Cook material model properties specified in [24]. The values of the parameter CI (as given in Table 2) are obtained for both single- and multi-layered AL1 plates based on the current computed residual velocities and the corresponding test values cited in [1]. It is again immediately apparent in Table 2 that a high degree of correlation has resulted between the computed and test residual velocities.

Table 2. Correlation indices obtained for different cases of AL1 target plates

Layer configuration (mm)	Impact velocity (m/s) [1]	Test residual velocity (m/s) [1]	Computed residual velocity (m/s)	Correlation index	Optimized modeling guideline
1 X 6.1	855.4	785.4	791.72	**0.9491**	2 mm element size on surface and 1/6th of plate depth through thickness
2 X 6.1	837.2	743.7	735.24	**0.913**	2 mm element size on surface and 1/3rd of layer depth through thickness for each layer
3 X 6.1	835.4	727.6	718.9	**0.910**	4 mm element size on surface and 1/4th of layer depth through thickness for each layer

6. Conclusions

The present paper is based on a numerical study of ballistic impact of single- and multi-layered mild steel and aluminium plates of different grades with a low caliber ogival-nosed projectile. The mesh convergence study reported here with shell and solid elements subjected to two commonly used contact algorithms in LS-DYNA, namely an automatic contact detection algorithm and a surface-to-surface contact condition with erosion, has provided insight into simulation of ballistic impact in the ordnance range in which thermal effects can be ignored. Based on results obtained in the current investigation, the following meshing criteria can be adopted for solid element-based modeling of thin target plates: (i) an element size of 2 mm on plate surface and a thickness of 1/6th of plate depth for single-layered plates; (ii) an element size of 2 mm on plate surface and a thickness of 1/3rd of depth of each layer for double-layered plates; and (iii) an element size of 4 mm on plate surface and a thickness of 1/4th of depth of each layer for triple- and quadruple-layered plates. Additionally, appropriate strain rate-dependent material properties should be used for the target plates; the effects of temperature and progressive damage may not be significant for the type of materials and impact velocities that have been considered. To the authors' best knowledge, the present study highlights for the first time in a systematic manner, the relative effects of mesh size, element configuration (i.e. shell or solid elements), and contact condition on the accuracy of numerically predicted residual velocity for ballistic impact on plates using LS-DYNA.

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