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CAE-based prediction of projectile residual velocity for impact on single and multi-layered metallic armour plates

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Abstract

The present paper deals with the CAE-based study of impact of jacketed projectiles on single- and multi-layered metal armour plates using LS-DYNA. The validation of finite element modelling procedure is mainly based on the mesh convergence study using both shell and solid elements for representing single-layered mild steel target plates. It is shown that the proper choice of mesh density and the strain rate-dependent material properties are essential for an accurate prediction of projectile residual velocity. The modelling 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 approximately 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 aluminium 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 modelling approach, LS-DYNA can be used with a great degree of confidence in designing perforation-resistant single and multi-layered metallic armour plates.

Keywords

single- and multi-layered plates, jacketed projectile, residual velocity, correlation index

1 INTRODUCTION

A number of investigators have reported [3, 4, 6, 7, 10–13, 15, 16, 20] that the non-linear finite element analysis, such as employing LS-DYNA, can be the most powerful tool for predicting projectile residual velocities for impact with velocities greater than ballistic limit and performing design optimization of target plates. The main objective of the reported numerical studies was to show that analysis results can correlate against experimental data. A bulk of these simulations employs plane strain or axisymmetric elements [4, 6, 11, 13, 15, 16] 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 modelled with shell elements [12, 20]. In a limited number of studies, the target plates have also been modelled with three-dimensional elements [3, 7, 10] which are necessary for representing the behaviours of thick and multi-layered plates. Various materials for plates have been considered for simulation-based studies: Kad, Schoenfeld and Burkins [11] discussed material modelling procedure for textured Ti-6Al-4V plates; GRP (glass fibre-reinforced plastic) plates as targets were considered by Nandall, Williams and Vaziri [15]; plates of ceramic materials (alumina and silicon carbide) were the subject of work reported by Espinosa et al [6]; mild steel and aluminium plates were considered by Park, Yoo and Chung [16] for illustrating their optimisation algorithm; Borvik et al [4] used 460 E steel plates in their studies and incorporated a damage parameter in the modified Johnson-Cook constitutive model; impact on HSLA-100 steel plates using quasi-static and temperature-independent material properties were considered by Martineau, Prime and Duffey [13]. Tabei and Ivanov [20] demonstrated a computational micro-mechanical model for flexible woven fabric; Lim, Shim and Ng [12] studied the penetration of Twaron fabric; Mahfuz et al [10] simulated complex integral armour made of layers of AD-90 ceramic, EPDM rubber, S2-glass/Vinyl ester and phenolic composites.

It appears from the above references that a primary focus in numerical simulations of ballistic impact on plates has been material modelling. However, no clear guidelines exist on good modelling practices. For example, the effect of various modelling parameters (such as element size, contact algorithm etc.,) have not been elaborately investigated. No objective comparison has been made between different element configurations (such as 2D, axisymmetric, shell and solids) or constitutive modelling approaches. Even when investigators have incorporated material behaviours with thermal effects and damage, they do not appear to have verified their modelling procedure for simple tensile coupon-tests. Hence, a great deal of doubts exists on the robustness of the numerical simulation procedure reported in the literature.

In order to overcome the above listed shortcomings in the published work and to obtain a robust modelling procedure, a comprehensive mesh was carried out with respect to element size [5, 17–19]. The convergence of projectile residual velocity using Belytschko-Lin-Tsay (BLT) shell and constant stress solid elements representing mild steel plates of different thickness was studied by correlating to experimental results reported in [8]. All analyses were carried out with the explicit contact-impact analysis code LS-DYNA. The strain rate-dependent material properties were employed for the considered mild steel plates by taking into account the considerable differences in their strengths. The user-friendly contact-interface algorithm is activated by the keyword *CONTACT_ERODING_SURFACE_TO_SURFACE (CESS) in order to capture the interaction between the target plate and the projectile. The modelling 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 approximately 800-870 m/s.

In the current study, the experience gained for single-layered plates [5, 17–19] is 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 aluminium target plates with a similar level of success in test residual velocity prediction and is attempted for the first time to the author's best knowledge.

2 FINITE ELEMENT MODELLING OF TARGET PLATE AND PROJECTILE

Finite element models of a given target plate using shell and solid elements are shown in Figures 1 and 2 respectively. For analysis using LS-DYNA, BLT shell elements based on a co-rotational formulation [9] and constant stress solid elements are chosen. The plate is square in shape with dimensions of 200 mm x 200 mm and is clamped at the four corners. Plates of two different thicknesses viz. 4.7 mm and 6 mm are considered. The jacketed ogival-nosed projectile targeting the plate centre is modelled with solid elements as shown in Figure 3. 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. For shell elements, a default number of integration points (i.e. 2) have been specified in the direction normal to the plate surface.

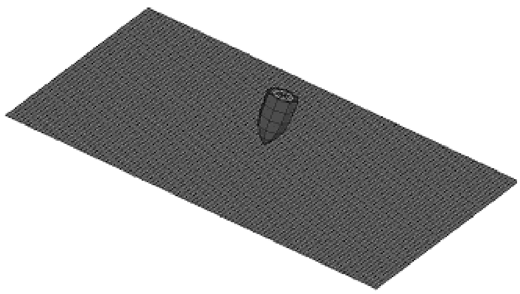


Figure 1 Plate modelled with shell elements and projectile with solid elements.

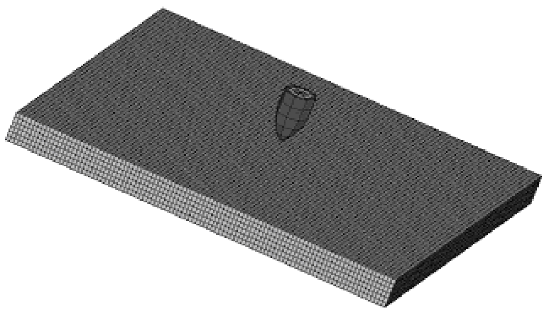


Figure 2 Plate and projectile modelled with solid elements.

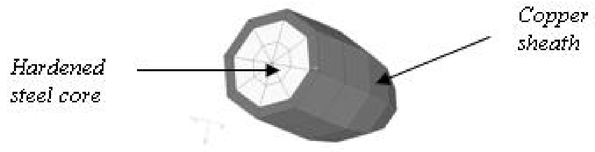


Figure 3 Close-up view of jacketed projectile modelled with solid elements in Figures 1 and 2.

2.1 Material modelling of target plates

The material model with the keyword *MAT_STRAIN_RATE_DEPENDENT_ PLASTICITY (material type 19) in LS-DYNA has been used for defining the behaviours of two variants of MS (mild steel) plates designated as MS1 and MS2 in [8]. This model contains a simple mechanism for material failure and is activated by specifying the load curves defining the yield and effective stress as a function of strain rate. It may be noted that the present material modelling approach essentially involves a rate-dependent Von Mises yield criterion combined with isotropic strain hardening [19]. The effects of adiabatic heating that can lead to a localised phase transformation in the interacting components such as projectile and target have not been considered in the current simulations. This approach is consistent with earlier observations [1] that the ordnance range impact velocities considered in the present study is unlikely to induce thermal changes in steel that will perceptibly change its material behaviour. For solid elements, once the effective stress reaches the failure stress the element is deemed to have failed and is removed from the solution. For shell elements, the entire element is deemed to have failed if all integration points through thickness have an effective stress that exceeds the failure stress. After failure, the shell element is removed from the solution [9]. In this constitutive model, yield and tensile strengths can be specified in a tabular manner with respect to effective strain rate. In [8], 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 [8] are obtained from [14] and are given in Table 1. It is pointed out that the stress-strain data obtained from [14] are assumed in the direction of tensile elongation in the coupon test.

The strain rate-dependent behaviours of yield and tensile strengths of mild steel are fully described in [5, 17, 19] and are outlined below.

Table 1 Quasi-static engineering properties of MS1 and MS2 plates.

Plate material nomenclature in [8]	Vickers hardness range in [8]	Yield strength, σ_y^{eng} obtained from [14] (MPa)	Tensile strength, σ_f^{eng} obtained from [14] (MPa)	Elongation at break, ε_f^{eng} obtained from [14] (%)
MS1	110 - 115	205	380	25
MS2	150 - 155	360	505	35

The quasi-static engineering properties are at first converted to corresponding true values.

The conversion of engineering to true stress can be carried out using the relation given below (assuming constant volume of a uniaxial test specimen):

$$\sigma^{true} = \left(\varepsilon^{eng} + 1\right) \sigma^{eng} \tag{1}$$

where, σ^{true} is the true stress, while ε^{eng} and σ^{eng} are respectively the engineering (i.e. nominal) strain and corresponding engineering (i.e. nominal) stress.

The true failure strain, $\varepsilon_f^{true} = \ln\left(\varepsilon_f^{eng} + 1\right)$ can be estimated using the value of uniaxial engineering failure strain for a given mild steel plate given in Table 1. The true yield strain, ε_y^{true}, and tangent modulus, E_T, can now be computed as follows:

$$\varepsilon_y^{true} = \frac{\sigma_y^{true}}{E} \tag{2}$$

$$E_T = \frac{\sigma_f^{true} - \sigma_y^{true}}{\varepsilon_f^{true} - \varepsilon_y^{true}} \tag{3}$$

Using Eqs. (1) through (3), the relevant quasi-static true material parameters have been computed for the variants of target plates mentioned previously (assuming a standard value of $E = 205$ GPa for all cases) and are listed in Table 2.

Table 2 True quasi-static properties of MS1, MS2 plates.

Plate material nomenclature in [8]	σ_y^{true} (MPa)	σ_f^{true} (MPa)	ε_y^{true} (%)	ε_f^{true} (%)	E_T (MPa)
MS1	205.4	475	0.10	22.0	1233
MS2	360.0	682	0.18	30.0	1079

The variations of yield and tensile strengths with respect to strain rate for three varieties of steel designated as DP800, HSLA350 and HSS590 are reproduced from [2] in Figures 4 and 5. It is observed from these figures that the rise of yield and failure stresses with respect to strain rate is more-or-less independent of the type of steel considered in [2]. Hence similar variations of yield and failure stresses with reference to strain rate are adopted for present mild steel variants (MS1 and MS2) of target plates as shown in Figures 4 and 5 respectively. In particular, the following scaling relation is applied for obtaining the dynamic yield and failure strengths of mild steel plates considered here:

$$\sigma_{\dot{\varepsilon}}^{(steel\ type)} = \sigma_{\dot{\varepsilon}_0}^{(steel\ type)} \cdot \frac{\sigma_{\dot{\varepsilon}}^{(HSS590)}}{\sigma_{\dot{\varepsilon}_0}^{(HSS590)}} \tag{4}$$

where, $\sigma_{\dot{\varepsilon}}^{(steel\ type)}$ is the strength (yield or failure) at a given strain rate, $\dot{\varepsilon}$(s-1); and, $\sigma_{\dot{\varepsilon}_0}^{(steel\ type)}$ is the corresponding quasi-static strength at a low strain rate of $\dot{\varepsilon}_0$(s-1). A regression-based curve fitting approach has been used to obtain the yield and failure strengths of a target material by extrapolation at a high strain rate (e.g. 10,000 s -1) not considered in [2]. The approach outlined above leads to a set of true stress versus true strain curves for various strain rates for each mild steel variety being studied here for projectile impact. These bilinear strain rate-dependent elasto-plastic material behaviours are given in Figures 6 and 7 respectively for MS1 and MS2.

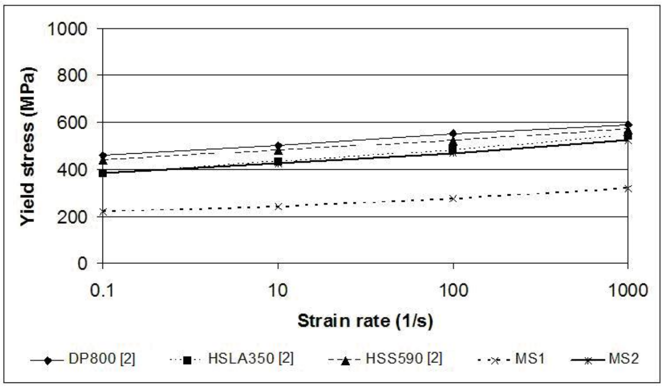


Figure 4 Yield stresses of variants of steel with respect to strain rate.

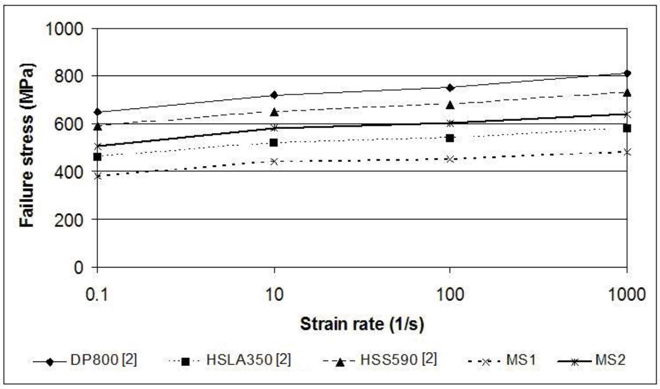


Figure 5 Ultimate stresses of variants of steel with respect to strain rate.

2.2 Material modelling of jacketed projectile

The projectile core has been assumed as rigid based on the physical observation that only sheath erosion occurred in the tests carried out in [8] against which comparisons are made here. The sheath is modelled with material type 24 in LS-DYNA designated with the key word *MAT_PIECEWISE_LINEAR_PLASTICITY using the nominal engineering properties of copper listed in Table 3. In this material model, yield stress, Young's modulus, and failure strain are defined in a tabular manner. It may be noted that strain rate sensitivity has not been considered in the material modelling of projectile sheath and also pointed out that the projectile

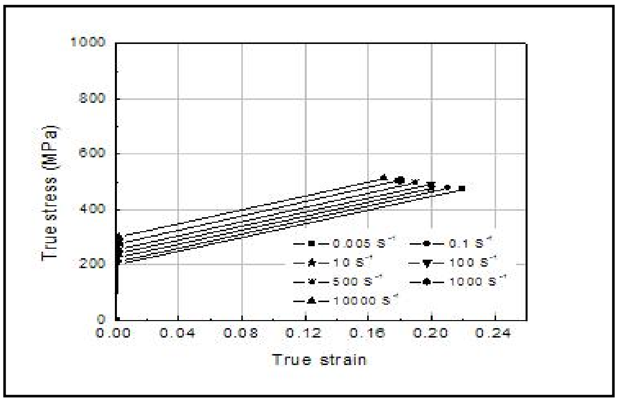


Figure 6 True stress versus true strain behaviours of MS1 plates.

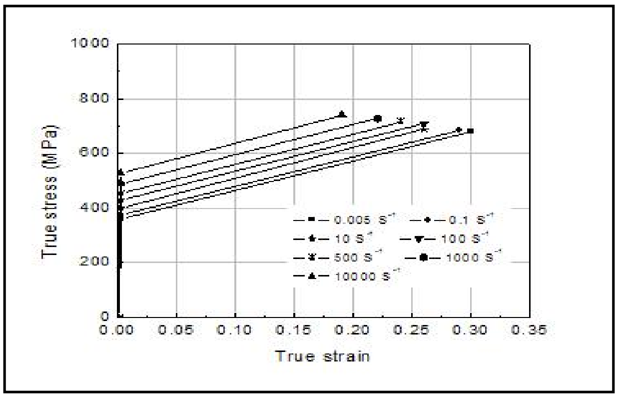


Figure 7 True stress versus true strain behaviours of MS2 plates.

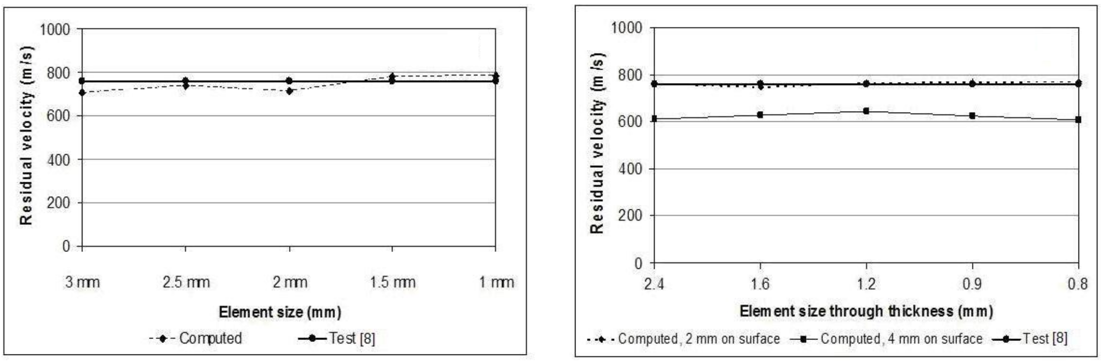
sheath erosion was defined by specifying a failure strain which is an essential parameter in the material type 24. The elements of projectile sheath will be removed from the simulation once it reaches the failure strain.

Table 3 Projectile properties used in simulation.

Projectile component	**Elastic modulus (GPa)**	**Poisson's ratio**	**Yield strength (MPa)**	**Tensile strength (MPa)**	**Elongation at break (%)**
Copper sheath	130	0.3	395	405	21
Hardened steel inner core	203.4	0.3	Rigid		

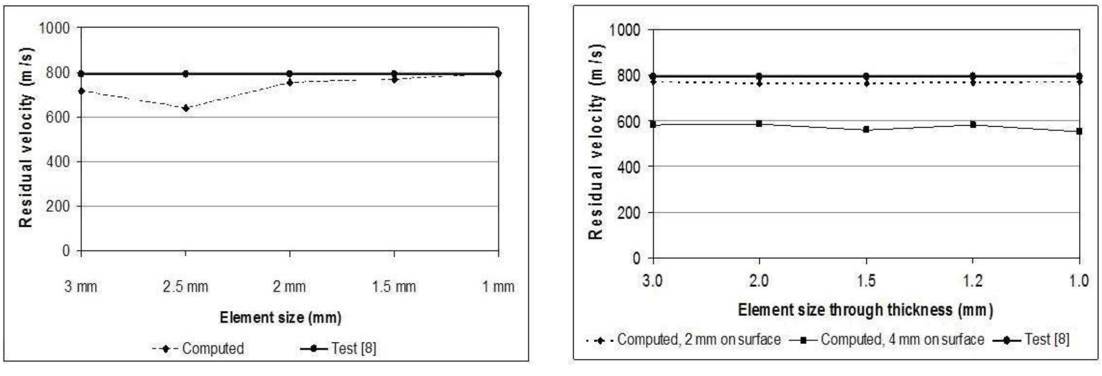
3 SINGLE-LAYERED MILD STEEL PLATES – A MESH CONVERGENCE STUDY

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 varying depths are considered and the computed residual velocities are compared (as in Figures 8 and 9) with the corresponding experimental values reported in [8]. It is found in Figures 8(a) and 9(a) 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. CESS interface in LS-DYNA is chosen for analysis. Coefficients of static and dynamic friction are respectively assigned values of 0.2 and 0.1 as is common practice. It may be concluded from this study that shell elements of size 1-1.5 mm may be used for simulating impact on mild steel target plates of aspect ratio (thickness/length) 0.02 - 0.08.



(a) (b)

Figure 8 Projectile velocities for impact on 4.7 mm thick MS1 plate modelled using (a) shell elements; (b) solid elements (impact velocity: 821 m/s).



(a) (b)

Figure 9 Projectile velocities for impact on 6.0 mm thick MS2 plate modelled using (a) shell elements; (b) solid elements (impact velocity: 866.3 m/s).

In order to assess the degree of correlation of simulation-based residual velocities with test residual velocities, the following $'Correlation\ index'$ (CI) is defined

$$CI = 1 - \left\{ \frac{\sum e_i^2}{\sum V_r^2} \right\}^{\frac{1}{2}} \tag{5}$$

where, V_r is the test residual velocity, and e_i is the discrepancy between computed and test residual velocities, and the summation is carried out over the number of cases for which a combined index of correlation is sought. It is apparent from Eq. (5) that as the degree of correlation increases, CI approaches unity.

For each modelling approach described here, a CI is calculated by considering the cases shown in Figures 8 and 9 for which residual velocity convergence study has been carried out. These CI values are listed in Table 4. It can be seen from this Table that all element types (i.e. shell and solid) considered for modelling the target plate yield extremely good correlation with the corresponding test residual velocities [8].

Table 4 Data on number of elements, computation time and the residual velocity obtained for the optimum cases.

Plate thickness (mm)	Projectile impact velocity (m/s)	Test residual velocity [8] (m/s)	Shell element-based			Solid element-based		
			No of elements (optimum element size)	Computation time (seconds)	Residual velocity (m/s)	No of elements (optimum element size)	Computation time (seconds)	Residual velocity (m/s)
4.7	821	758.6	40000 (1mm x 1 mm)	269	780.07	60000 (2mm x 2 mm x 0.8 mm)	237	769.86
6.0	866.3	792.2	17689 (1.5 mm x 1.5 mm)	185	768.82	60000 (2mm x 2 mm x 1.0 mm)	160	770.12
				CI	0.958		CI	0.952

In addition to the projectile residual velocity and the computed CI value, the number of elements used for target plate modelling and the computation time for each modelling type are given in Table 4 to compare the effectiveness of the numerical simulations.

The convergence characteristics of projectile residual velocity for plates modelled with solid elements are given in Figures 8(b) and 9(b). In these cases, the effect of solid element thickness on residual velocity is included in addition to element size on plate surface. It is seen from these figures that, a good convergence patterns are obtained for all cases considered. In general, solid elements of size 2 mm on plate surface yield residual velocities in good agreement with corresponding test values for plates considered (see Figures 8 (b) and 9(b)). The desirable thickness of solid elements is 1/6 th of plate thickness. CI value of 0.951 has been obtained from Figures 8(b) and 9(b) for solid elements.

It needs to be noted that the modelling criteria arrived at above are based on analyses for impact speeds in the range of approximately 800-870 m/s. However, the ballistic limits for the mild steel target plates analyzed are likely to be much lower than this range of the velocity. In order that the present modelling procedures can be used with confidence for plate ballistic limit prediction, the convergence of residual velocity is studied for two lower impact velocities i.e. 250 and 500 m/s. In addition, a higher impact velocity of 1000 m/s is considered. The limited convergence study of this section is carried out for MS1 plate of thickness 4.7 mm. According to the guidelines already arrived at, a solid element size of 2 mm on plate surface should be used in conjunction with CESS interface. The results are given in Figure 10 from which it can be seen that residual velocities converge to steady values for all impact velocities considered.

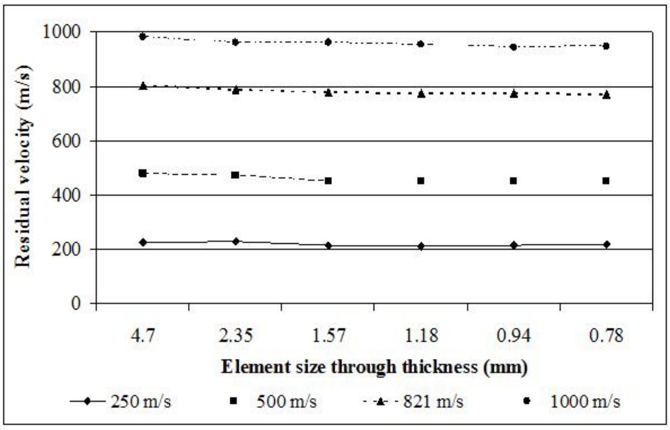


Figure 10 Effect of projectile impact velocity on convergence of computed residual velocities for a 4.7 mm thick MS1 plate modelled with solid elements.

It is also pointed that the modelling approaches such as shell and solid-based are found to yield extremely good predictions of residual velocities however the number elements and the elements sizes are different from each other.

4 MULTI-LAYERED METALLIC PLATES

Protection provided by armour plates in ballistic impact can be enhanced by providing stacks of single-layered plates in the form of multi-layered plates. Problems on perforation of single-layered steel and aluminium plates by jacketed projectiles have already been extensively studied in [5, 17, 19]. Gaining the insight gathered through simulation of single-layered plates, it is shown in the current section that similar modelling approaches can lead to good prediction of test residual velocities for multi-layered plates.

4.1 Modelling of impact on multi-layered mild steel plates

In Section 3, two different finite element modelling approaches were objectively compared: these consisted of representing single-layered target plates with shell and solid finite elements.

Although both modelling approach led to a similar degree of correlation with respect to test results, the contact between superimposed plates with no gap between them may not be properly activated when these are represented with shell elements and because of the lack of visual clarity in deformation in successive plate layers during penetration in such a representation, multi-layered plates in the current study are discretized only with constant stress (eight-node) solid elements. Validation of numerical simulations is carried out through comparison with experimental results on multi-layered mild steel and aluminium plates presented in [8]. Sectional side view of finite element models of double- and triple-layered plates are shown in Figures 11 and 12 respectively. Individual layers are kept in simple contact (i.e. not tied) as was done in experiments [8]. The CESS interface is defined between various layers of target plates and projectile according to the outcome of the mesh convergence study for single-layered mild steel plates. The material modelling of MS1 and MS2 layers is done using material type 19 in LS-DYNA with strength variations with respect to strain rate in the form of load curves as detailed in Section 2. Material type 24 is used for defining projectile material behaviour as given in Section 2.

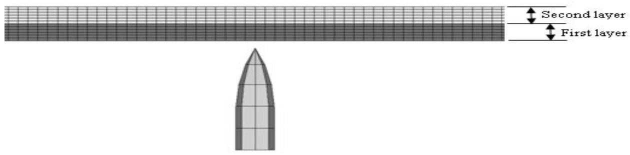


Figure 11 Sectional view of a double-layered plate with a jacketed projectile modelled with solid elements.

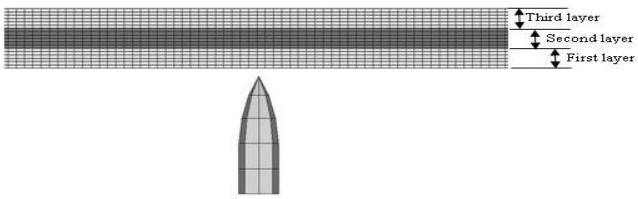


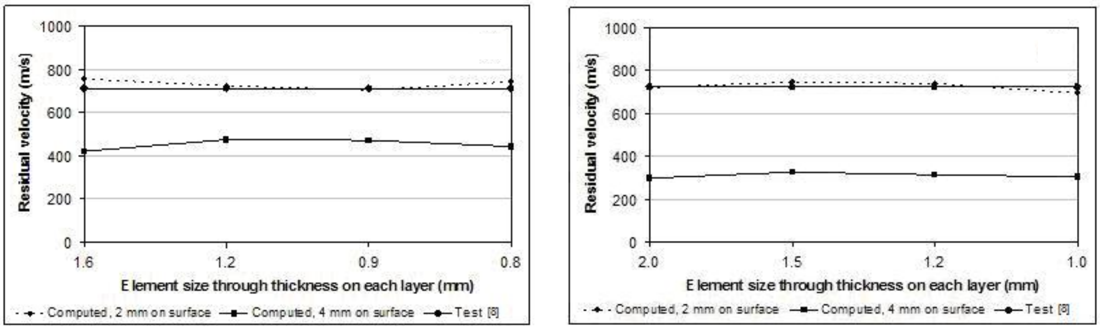
Figure 12 Sectional view of a triple-layered plate with a jacketed projectile modelled with solid elements.

In the current study, double-layered and triple-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. A mesh convergence study has been carried out for these 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 Figure 13, and a comparison of the computed residual velocities with corresponding test results is given in Table 5. Based on the data given in Table 5, the parameter CI (defined by Eq. (6)) is obtained as 0.98 which indicates a high degree of correlation.

A mesh convergence study similar to that of double-layered plates has been carried out for triple-layered plates as shown in Figure 14 and the converged results are listed in Table 6. It can be seen that element size criteria for double-layered plates (i.e. 2 mm x 2 mm on plate

Table 5 Comparison of residual velocities for double-layered mild steel plates.

Plate material [8]	Number of layers x thickness (mm) of each layer	Impact velocity (m/s)	Residual velocity (m/s)		Suggested solid element size for plate modelling
			Test [8]	Computed	
MS1	2 x 4.7	818.3	711.3	705.61	2 mm x 2 mm on plate surface and a thickness of 1/5 th of individual layer thickness
MS2	2 x 6.0	869.6	724.6	739.93	



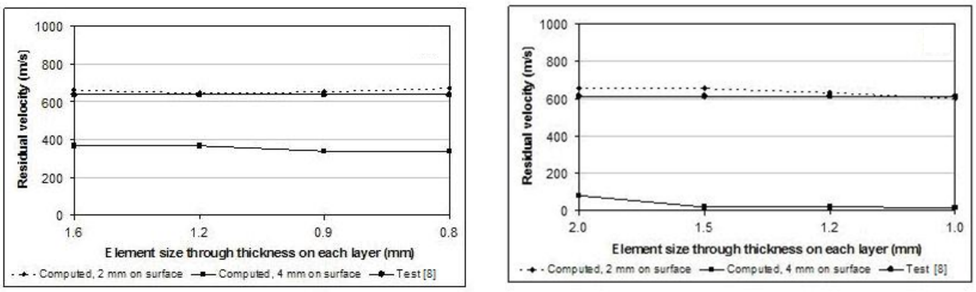
(a) (b)

Figure 13 Projectile residual velocities for impact on double-layered plates of equal thickness layers: (a) MS1 plates with 4.7 mm thick layers individual, and (b) MS2 plates with 6 mm thick layers individual.

surface and thickness of 1/5 th of individual layer thickness) also apply to triple-layered plates yielding a good CI value of 0.97 for converged residual velocities.

Table 6 Comparison of residual velocities for triple-layered mild steel plates.

Plate material [11]	Number of layers x thickness (mm) of each layer	Impact velocity (m/s)	Residual velocity (m/s)		Suggested solid element size for plate modelling
			Test [11]	Computed	
MS1	3 x 4.7	827.1	636.6	651.83	2 mm x 2 mm on plate surface and a thickness of 1/5 th of individual layer thickness
MS2	3 x 6.0	863.9	612.8	631.87	



(a) (b)

Figure 14 Projectile residual velocities for impact on triple-layered plates of equal thickness layers: (a) MS1 plates with 4.7 mm thick layers individual, and (b) MS2 plates with 6 mm thick layers individual.

4.2 Modelling of impact on single and multi-layered aluminium plates

Adopting a similar scheme for discretization of geometry as has been done in Sections 3 and 4.1 in the present paper on single and multi-layered steel plates, a study is carried out here on single and multi-layered aluminium plates investigated experimentally in [8]. The individual layers are made of an aluminium alloy (termed as AL1 in [8]) that has a hardness (90-92 VPN, [8]) that is practically same as the hardness (92 VPN, [14]) of a standard alloy (i.e. Al 6063 T83). The nominal quasi-static properties of the latter are therefore used to generate the true stress versus true strain properties for current analysis using the procedure outlined in the Section 2 for mild steel plates. Using the scaling relation given in [18], the strain rate dependent properties for AL1 alloy have been obtained. The resulting material data is shown in Figure 15. Computed residual velocities for single-, double- and triple-layered aluminium plates are compared with corresponding test results [8] in Table 7 and good correlation is observed. It is again immediately apparent in Table 2 that an acceptable degree of correlation has resulted between the computed and test residual velocities.

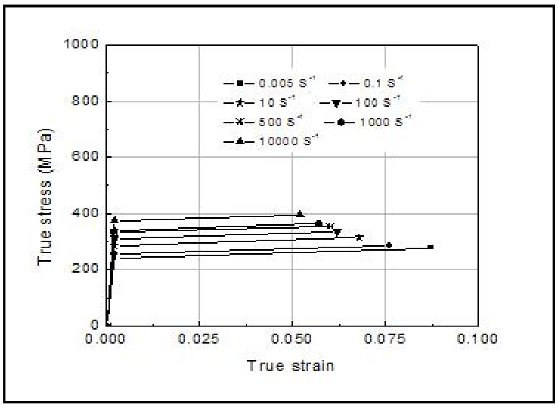
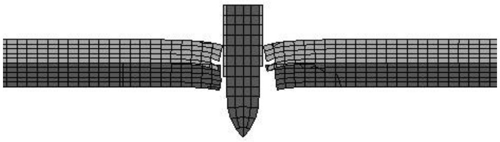


Figure 15 True stress versus true strain behaviours of Al 6063 T83 alloy.

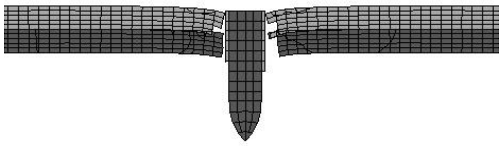
Table 7 Prediction of residual velocities for single and multi-layered aluminium targets.

Number of layers x thickness (mm) of each layer	Impact velocity (m/s) [8]	Residual velocity (m/s)		Correlation index	Suggested solid element size for plate modelling
		Test [8]	Computed		
1 x 6.1	855.4	785.4	791.7	0.991	2 mm element size on surface and 1/6th of plate depth through thickness
2 x 6.1	837.2	743.7	735.2	0.988	2 mm x 2 mm on plate surface and a thickness of 1/5 th of individual layer thickness
3 x 6.1	835.4	727.6	718.9	0.988	

4.3 Simulation-based plate failure modes

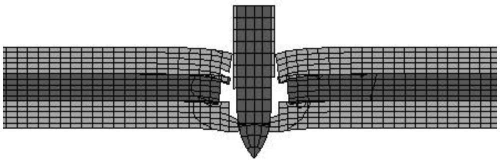


(a) At 30 μs

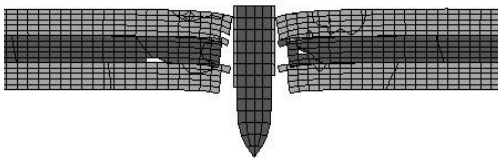


(b) At 40 μs

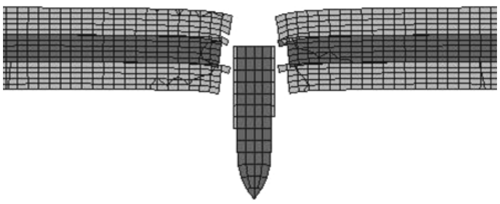
Figure 16 Truncated close-up views of penetration of double-layered MS1 plate.



(a) At 30 μs

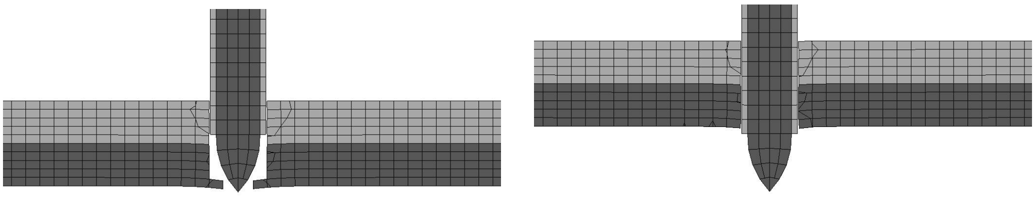


(b) At 40 μs



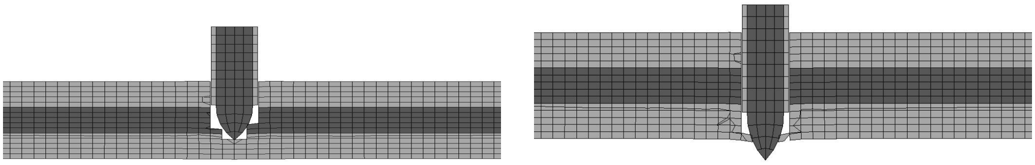
(c) At 50 μs

Figure 17 Truncated close-up views of penetration of triple-layered MS1 plate.

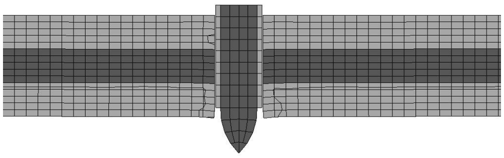


(a) At 20 μs (b) At 30 μs

Figure 18 Truncated close-up views of penetration of double-layered AL1 plate.



(a) At 20 μs (b) At 30 μs



(c) At 40 μs

Figure 19 Truncated close-up views of penetration of triple-layered AL1 plate.

Snap-shots of penetration of double- and triple-layered plates made of mild steel and aluminium at different instants of time are shown in Figures 16 through 19. As in the case of simulation of single-layered plates with solid elements in [5, 17], a localised bulging during the perforation of double- and triple-layered mild steel and aluminium plates is observed. It may be noted that the localised bulging were found to be higher in the mild steel targets compared to aluminium targets which may be due to the high ductility of mild steel. Also, the projectile sheath are severely eroded during the impact on mild steel plates where as this effect is comparatively less on the aluminium plates. It is pointed out through these studies that the projectile sheath erosion is mainly based on the strengths of the target plates in addition to the impact velocities and masses.

5 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 calibre ogival-nosed projectile. Based on results obtained in the current investigation, the following meshing criteria can be adopted for solid element-based modelling 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 1/5th of depth of each layer for double- and triple-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 (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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