Computational Approaches for Ballistic Impact Response of Stainless Steel 304

A. Mostafa

Abstract—This paper presents a numerical study on determination of ballistic limit velocity (V_{50}) of stainless steel 304 (SS 304) used in manufacturing security screens. The simulated ballistic impact tests were conducted on clamped sheets with different thicknesses using ABAQUS/Explicit nonlinear finite element (FE) package. The ballistic limit velocity was determined using three approaches, namely: numerical tests based on material properties, FE calculated residual velocities and FE calculated residual energies. Johnson-Cook plasticity and failure criterion were utilized to simulate the dynamic behaviour of the SS 304 under various strain rates, while the well-known Lambert-Jonas equation was used for the data regression for the residual velocity and energy model. Good agreement between the investigated numerical methods was achieved. Additionally, the dependence of the ballistic limit velocity on the sheet thickness was observed. The proposed approaches present viable and cost-effective assessment methods of the ballistic performance of SS 304, which will support the development of robust security screen systems.

Keywords—Ballistic velocity, stainless steel, numerical approaches, security screen.

I. Introduction

DURING their service life, security screens are exposed to harsh environment and aggressive loading conditions. Their accurate responses to such conditions are still being developed. For this reason, security screen made of carbon steel fails and needs to be replaced frequently. Consequently, the use of stainless steel in the production of security screens has been established as an important alternative to promote the specific corrosion loss decreasing [1]. Experimental investigations of dynamic behaviour of stainless steel can be very expensive, time consuming, and mostly require multiple standardized test equipment. Physics-based computational approaches allow to accurately model the ballistic impact behaviour based on a thorough study of the material microstructure, mechanical properties and failure mechanisms [2]. The ballistic limit velocity (V_{50}) for a material is defined as the velocity for which the probability of penetration of the chosen projectile is 50%. It is usually estimated using experimental data on the basis whether projectile penetrates the material completely or partially. V_{50} can be determined by first measuring the impact and residual velocities (Vi and Vr) of the projectile and then performing the classic ballistic limit analysis. There are various semi-empirical models and theoretical models to predict V_{50} [3]. Ben-Dor et al. [4] compared the relation between the ballistic impact and residual velocities based on the Recht-Ipson formula [5], which is valid for a rigid striker penetrating into a thin metallic plate perpendicularly, and the Lambert-Jonas correlation [6], which takes into account the effects of plate thickness and impact angle. Both Recht-Ipson and Lambert-Jonas equations were derived based on the conservation of energy and momentum. They concluded that the accuracies of both models are almost the same. In the present investigation, ABAQUS/Explicit was used to numerically simulate the dynamic loading of SS 304 upon impact by ballistic projectile. Three approaches were used to estimate V_{50} of SS 304 sheets with 0.8, 1.0, 1.2 and 1.5 mm thicknesses. These numerical approaches include: numerical damage model based on the mechanical properties of SS 304, numerical calculated residual velocity after impact and numerical calculated residual energy after penetration. The results obtained from each approach were then compared and employed to determine the relationship between V_{50} and the sample thickness over broad range of impact velocities.

A Mostafa is with the Southern Cross University, Australia (e-mail: ah_mostaffa@yahoo.com).

II. FE Simulation

A. Material Models

Johnson-Cook plasticity formulation, which defines the flow stress as a function of equivalent plastic strain, strain rate and temperature, was employed in all simulations to model the mechanical response of SS 304. The dynamic flow stress is expressed by [7]:

$$\bar{\sigma}_d = \left[A + B(\bar{\varepsilon}_{pl})^n\right]\left[1 + C\ln\left(\frac{\left(d\bar{\varepsilon}/dt\right)_{pl}}{\left(d\varepsilon/dt\right)_0}\right)\right]\left(1-\theta^m\right) \quad (1)$$

where $\bar{\sigma}_d$ is the dynamic flow stress, $\bar{\varepsilon}_{pl}$ is the equivalent plastic strain, $\left(d\bar{\varepsilon}/dt\right)_{pl}$ is the equivalent plastic strain rate, $\left(d\varepsilon/dt\right)_0$ is a reference strain rate, A, B, n, m and C are material parameters and θ is the non-dimensional temperature given by:

$$\hat{\theta} = \begin{cases} 0 & T < T_{transition} \\ \left(T - T_{transition}\right)/\left(T_{melt} - T_{transition}\right) & T_{transition} \le T \le T_{melt} \\ 1 & T > T_{melt} \end{cases} \quad (2)$$

where T is the current temperature, T_{melt} the melting temperature and $T_{transition}$ is the transition temperature defined as the one at or below which there is no temperature dependence on the expression of the yield stress. The constant *A* is the yield stress under quasi-static conditions, *B* and *n* are strain hardening parameters, *m* controls the temperature dependence and *C* the strain rate dependence. The values of the Johnson-Cook parameters used in the present work, which were obtained from Jerusalem et al. [8], are listed in Table I.

TABLE I
JOHNSON-COOK BEHAVIOUR LAW PARAMETERS OF SS 304

Parameter	Value
Young modulus, E	207.8 MPa
Poisson's ratio, v	0.3
Density, ρ	8000 N/m^3
Melting temperature, T_{melt}	1673 K
Transition temp, $T_{transion}$	1000 K
Initial yield strength, A	280 MPa
Hardening modulus, B	802.5 MPa
Strain hardening exponent, n	0.622
Thermal softening exponent, m	1.0
Strain rate constant, C	0.0799
Reference strain rate, $(d\varepsilon / dt)_0$	1.0 s^{-1}

B. Numerical Procedure

ABAQUS/Explicit [9] was used for the simulations of the dynamic impact of SS 304 sheet. The numerical model consists of two parts created separately: sheet and a projectile (Fig. 1). Due to symmetry, only quarter model was considered. The sheet was modelled as deformable solid with 8-node linear brick elements (C3D8R) which offer reduced integration and hourglass control (800 mm x 800 mm in size corresponding to the screen standard size). The 4 kg blunted tip projectile was created as a discrete rigid to reduce the contact interaction difficulties and to save the computation time. The sheet was fixed along all four edges using the encastre boundary condition, while the projectile was confined to travel in the impact direction normal to the sheet. Surface-to-surface contact with penalty friction (0.15) was utilized at all interfaces.

III. ESTIMATION OF BALLISTIC LIMIT VELOCITY, V_{50}

A. Numerical Damage Criterion

FE models were employed to simulate the ballistic response of SS 304 under impact velocities ranges between 108 to 350 m/s. V_{50} was determined by taking the average of the highest partial penetration velocity and the lowest full penetration velocity. Fig. 2 shows the predicted V_{50} of the SS 304 sheet with various thicknesses.

B. FE Calculated Residual Velocities

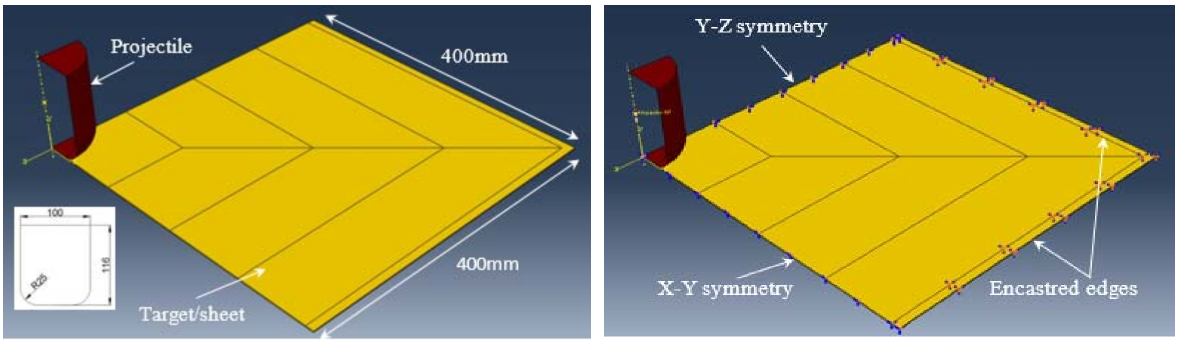
The V_{50} can be estimated once V_i and V_r are determined from the experimental impact test. In some cases the ballistic impact test set-up might not be capable of capturing residual velocities and consequently V_r became unobtainable. Thus, it is inevitable to obtain V_r using validated FE model. The energy transferred to the target sheet, E_t, can be written as:

$$E_t = \frac{1}{2} m \left(V_i^2 - V_r^2 \right) \tag{5}$$

where m is the mass of the projectile. When V_r becomes zero in this equation, V_i would be equal to V_{50}. Fig. 3 shows the predicted V_r obtained from the FE simulation in which the data can be fitted by least square regression to the classical Lambert-Jonas equation [6]:

$$V_r^p = A V_i^p - B \tag{6}$$

where A and B are two dimensionless regression coefficients and the power P = 2 for the Recht-Ipson equation [5]. The ballistic limit V_{50} is the velocity when V_r becomes zero.



(a) (b)

Fig. 1 FE model of SS 304 sheet (a) model geometry, and (b) boundary conditions

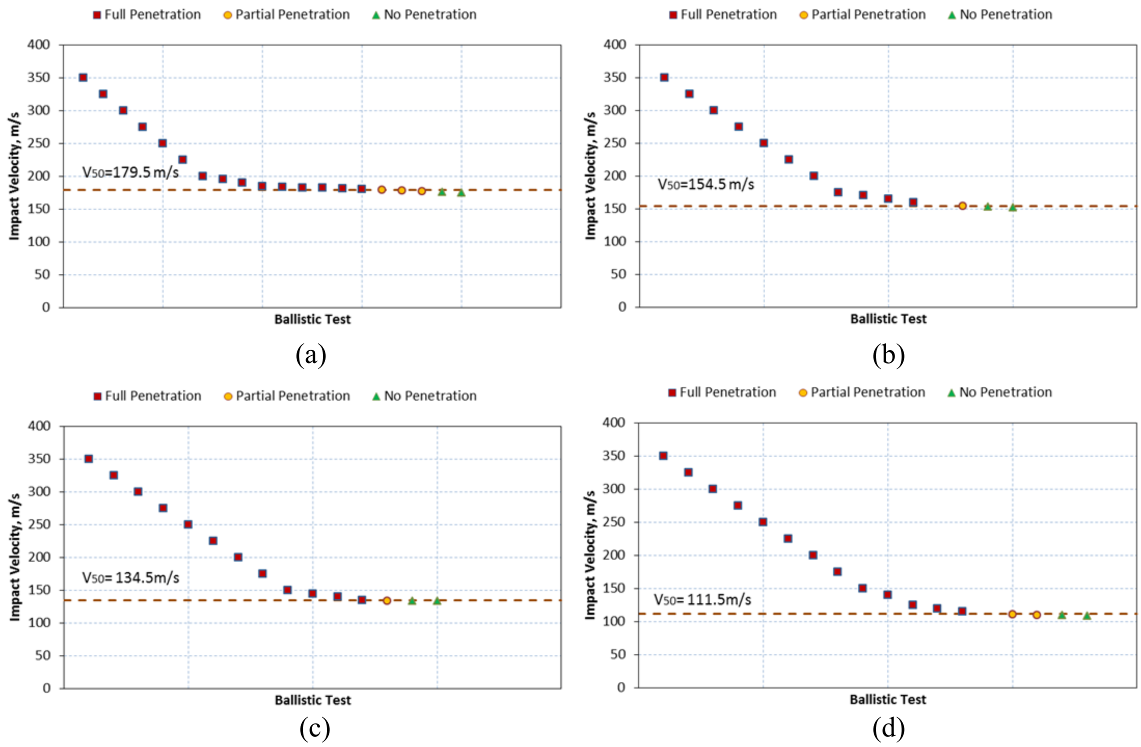


Fig. 2 Predicted V_{50} for (a) t = 1.5 mm, (b) t = 1.2 mm, (c) t = 1.0 mm and (d) t = 0.8 mm

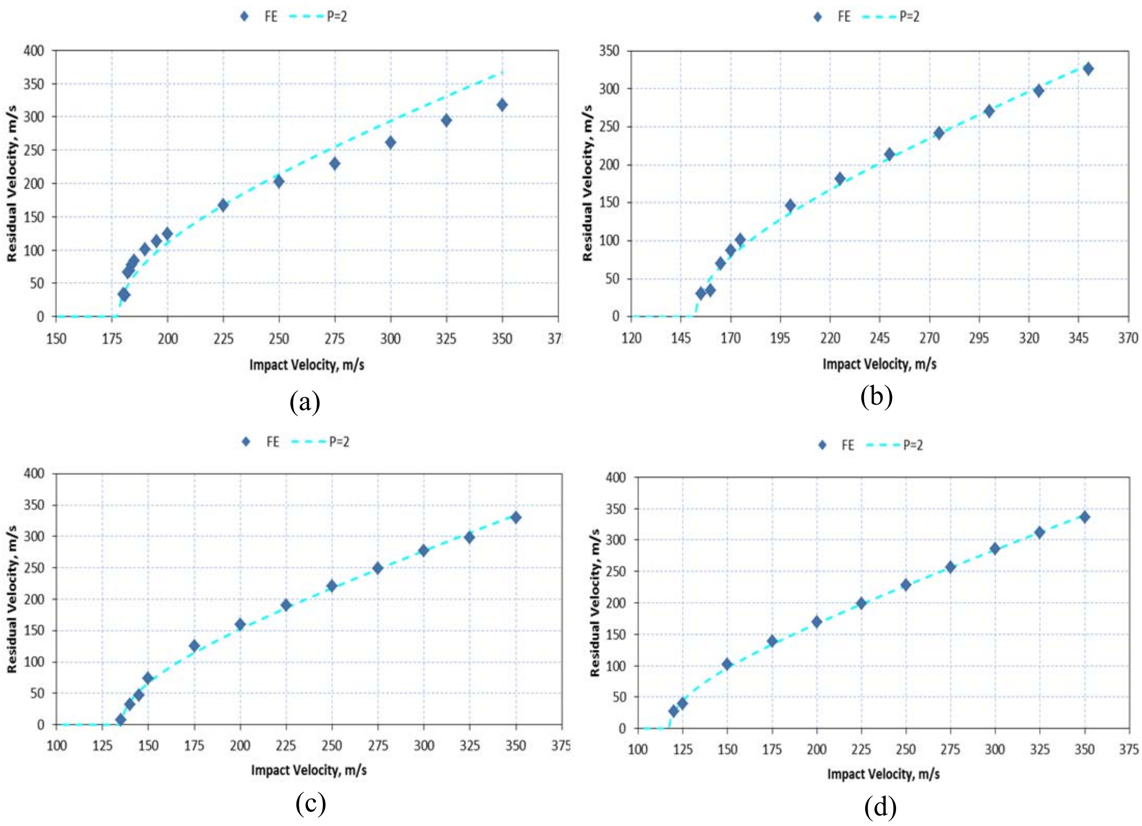


Fig. 3 Predicted V_r/V_i for (a) t = 1.5 mm, (b) t = 1.2 mm, (c) t = 1.0 mm and (d) t = 0.8 mm

C. FE Calculated Residual Energies

Energy-time histories of the projectile during the simulated impact tests can be used to predict V_{50}. The initial part of the energy histories represents the projectile kinetic energy, called the impact energy (E_i). After the projectile impacted the sheet, some of its energy will be transfer to the sheet, called transferred energy (E_t), and continue to travel with the residual energy (E_r). If all the kinetic energy of the projectile is transferred to the sheet, there is a great chance of partial penetration. On the other hand all impact velocities up to V_{50} show partial penetration. The transferred energy (E_t) can be written as:

$$E_t = E_i - E_r \tag{7}$$

If there is no full penetration, the residual energy E_r in this equation becomes zero and the equation can be written as:

$$E_t = E_i \tag{8}$$

The velocity that satisfies the above equation determines V_{50}. Fig. 4 shows the simulated impact, residual and transferred energies of SS 304 sheet with various thicknesses.

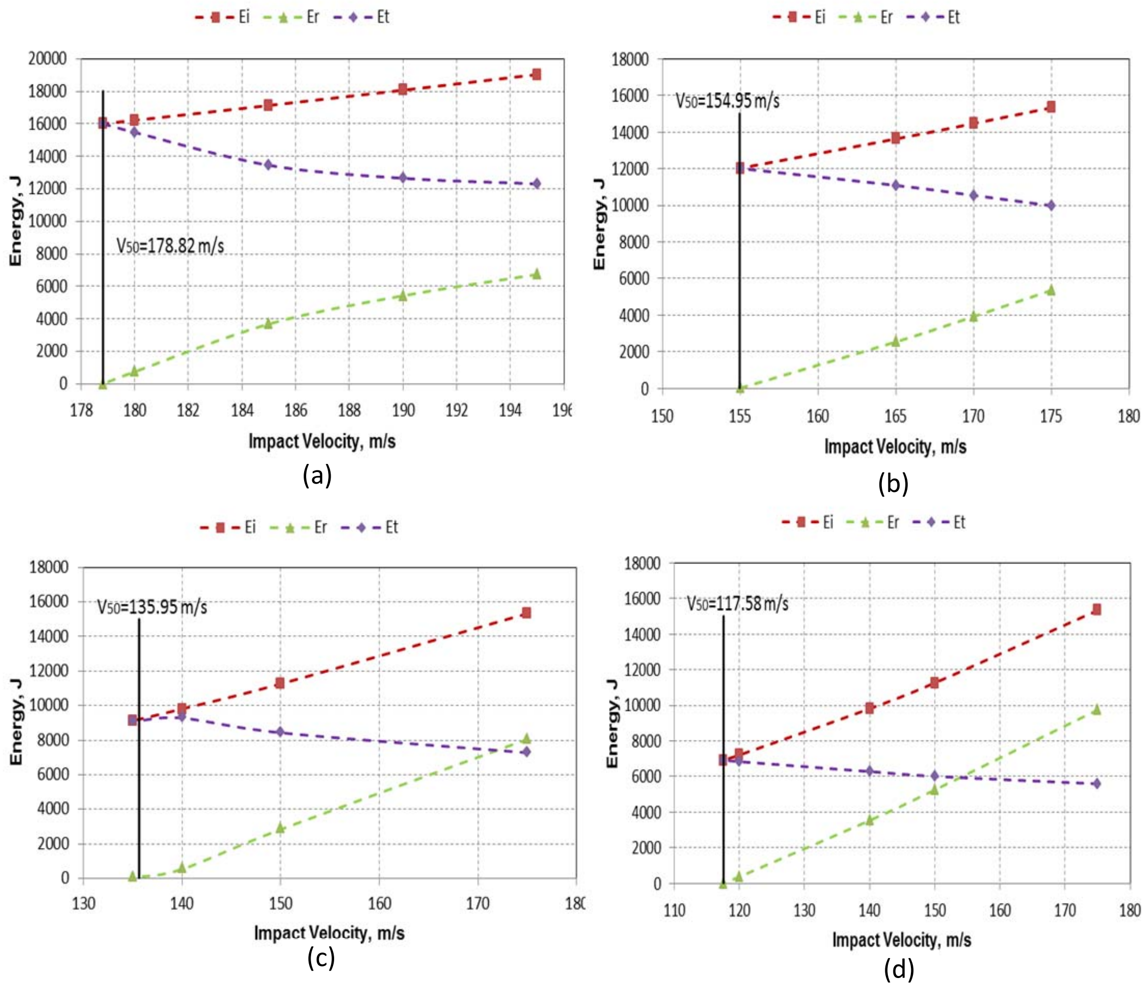


Fig. 4 Predicted projectile impact, residual and transferred energies for (a) t = 1.5 mm, (b) t = 1.2 mm, (c) t = 1.0 mm and (d) t = 0.8 mm

Good agreement has been observed between the predicted V_{50} using the three investigated methods (Fig. 5). It has been observed that V_{50} increases quite linearly with the increase in the sheet thickness. This result could be used to predict V_{50} for other sheet thicknesses without performing expensive experimental tests. This will provide the security screen manufacturers with a cost-effective and reliable design tool to predict V_{50} of the SS 304 sheets.

IV. Conclusions

Three numerical approaches were studied for assessing the ballistic limit velocity V_{50} of SS 304 sheet used in security screen industry upon impact by a 4 kg blunted projectile. Four frequently used sheet thickness in security screen production were used in the current study, namely 0.8, 1.0, 1.2 and 1.5 mm. Johnson-Cook plasticity algorithm was employed which was coupled with the strain rate-dependent and critical plastic strain fracture criterion. The three approaches used to define

V_{50} are: damage criteria based on the mechanical properties of SS 304, the residual velocity after impact and the residual energy after penetration. The predicted V_{50} were in a good match between all models. Moreover, it has been observed that V_{50} increases almost linearly with the increase in the sheet thickness. The investigated approaches have a great potential for the design evaluation of the structural components of the security screen.

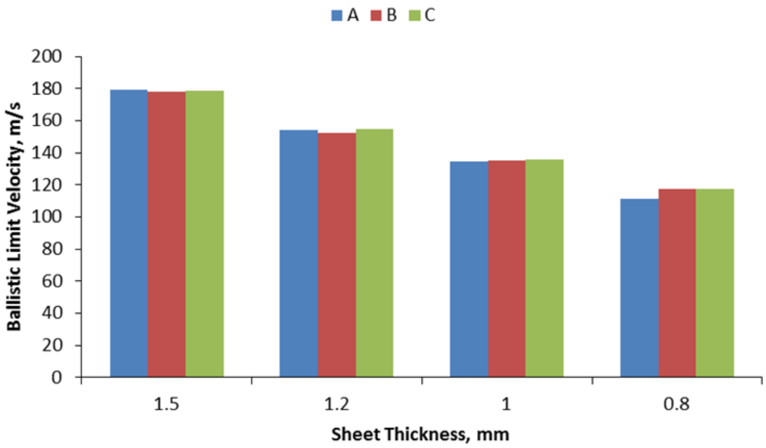


Fig. 5 Predicted V_{50} of SS 304 sheet using method A (numerical damage prediction), method B (numerical residual velocity) and method C (numerical residual energy)

REFERENCES

[1] Silva,C. et al., *Austenitic and ferritic stainless steel dissimilar weld metal evaluation for the applications as-coating in the petroleum processing equipment.* Materials & Design,2013.47:p.1-8.

[2] Grujicic, M., et al., *Optimization of Gas Metal Arc Welding (GMAW) Process for Maximum Ballistic Limit in MIL A46100 Steel Welded All-Metal Armor.* Journal of Materials Engineering and Performance, 2015. 24(1): p. 229-244.

[3] Leigh Phoenix, *A new membrane model for the ballistic impact response and V50 performance of multi-ply fibrous systems.* International Journal of Solids and Structures,2003.40(24):p. 6723-6765.

[4] G. Ben-Dor, A. Dubinsky, and T. Elperin, *On the Lambert–Jonas approximation for ballistic impact.* Mechanics Research Communications, 2002. 29: p. 137-139.

[5] Recht, R.F, *Ballistic Perforation Dynamics.* Journal of Applied Mechanics, 1963. 30(3): p. 384-390.

[6] Lambert JP and J. GH., *Towards standardization of in-terminal ballistic testing velocity representation*, in *Report No. BRL-R-1852. Aberdeen,* , M.B.R. Laboratory, Editor. 1976.

[7] Johnson, G.R. and W.H. Cook, *Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures.* Engineering Fracture Mechanics, 1985. 21(1): p. 31-48.

[8] Frontán, J., et al., *Ballistic performance of nanocrystalline and nanotwinned ultrafine crystal steel.* Acta Materialia, 2012. 60(3): p. 1353-1367.

[9] Systèmes, D., *ABAQUS*. 2016.