www.lajss.org
Latin American Journal of Solids and Structures 5 (2008) 225–235

A simulation-driven study of oblique impact of ogival-nosed projectiles on mild steel armour plates

M. Raguraman[a,*], A. Deb[b] and N.K. Gupta[c]

[a]School of Mechanical Engineering, University of Leeds – UK
[b]Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore – India
[c]Department of Applied Mechanics, Indian Institute of Technology, New Delhi – India

Abstract

The present paper deals, for the first time, with a simulation-driven study of oblique impact of jacketed ogival-nosed projectiles on mild steel target plates. The predictability of analysis results is verified against test residual velocities reported by earlier investigators [7]. The impact velocities considered here are in the range of ˜800-850 m/s. Finite element modelling is carried out by discretizing target plate with shell elements and projectile with solid elements. The effects of strain rate on plate material behaviour are incorporated using available data on strain rate sensitivity of yield and ultimate strengths of various grades of steel. Using an explicit LS-DYNA solver, convergence of residual velocity is shown with respect to plate element size for normal as well as oblique angles of impact. In addition to predicting residual velocities, the current simulation procedure is also able to realistically represent plate failure modes such as perforation with dishing, erosion of copper sheath of hardened steel core projectile, and minimum angles of projectile ricochet for plates of different thicknesses. The study concludes with the presentation of a semi-empirical relation, based on the shear plugging mode of plate failure, which appears to predict well projectile residual velocities for both normal as well as oblique impact.

Keywords: projectile, mild steel plate, oblique impact, finite element modelling, LS-DYNA

1 Introduction

The behaviour of armour plates subject to impact by projectiles for velocities including and exceeding ballistic limits has been investigated primarily using the following tools: (1) controlled experiments, (2) closed-form solutions under idealized conditions and semi-analytical solutions, and (3) finite element-based nonlinear impact analysis. The third approach mentioned above, if properly validated, could be considered as the most efficient and powerful tool for predicting ballistic limits of armour plates and for optimal design of projectile-defeating targets. A number of investigators have reported nonlinear finite element analysis-based prediction of residual

*Corresp. author email: r.munusamy@leeds.ac.uk Received 17 Jun 2008; In revised form 29 Jul 2008

velocities of projectiles for impact with velocities greater than ballistic limit on metallic and non-metallic plates. The main objective in these studies have been to show that analysis results can correlate against experimental results including failure. A bulk of these simulation procedures employs plane strain or axisymmetric elements with the help of which primarily normal impact on flat targets can be represented. However, a limitation of this approach, with consideration given only to mechanics and less attention paid to requirements of design, lies in its inability to simulate oblique impact of projectiles, targets of arbitrary shapes, off-centred impact, etc. In the present study using the commercial explicit LS-DYNA code, plates are modelled with shell elements and projectiles with solid elements. This constitutes a general modelling approach in which three-dimensional and non-axisymmetric behaviours can be captured. It may be noted that the present elasto-plastic material modelling procedure essentially involves a rate-dependent Von Mises yield criterion combined with isotropic strain hardening; this is an extension of the commonly used approach for analyzing nonlinear material behaviour of ductile materials for quasi-static loading and can be appealing to design engineers. While material behaviour under dynamic conditions as explained above is a key consideration in analyzing the mechanics of projectile and target interaction, other parameters such as mesh density can significantly affect simulation results. In order to establish the required modelling criteria in terms of element size, a residual velocity convergence study has been carried out for impact on mild steel plates designated as MS3 in [5, 7, 9] due to jacketed ogival-nosed projectiles. The convergence of residual velocity is found to be acceptably good when compared with test results given in [7] for normal as well as oblique impact on MS3 plates. The impact velocities for the problems solved are roughly in the range of 800-850 m/s which can be considered as being in the ordnance range. The fact that good correlation of computed residual velocity and target failure mode has been obtained against test data for a number of cases indirectly confirms observations made in the past [1] that the effect of adiabatic heating may not be significant for impact velocities not exceeding the ordnance range limit. Finally, keeping in mind requirements of preliminary design of mild steel target plates, a semi-empirical relation based on shear plugging mode of failure of target plate is presented for estimating projectile residual velocity for both normal and oblique impact.

2 Finite element modelling of target plate and projectile

A finite element model of a given target plate using shell elements and a projectile represented with solid elements is shown in Fig. 1. For analysis using LS-DYNA, Belytschko-Lin-Tsay shell elements are chosen. The incremental explicit dynamic analysis is based on a co-rotational formulation for shells. To start with, these models are employed for studying the effect of plate finite element mesh size on convergence of computed projectile residual velocity with respect to test values given in [7]. The plate is square in shape with dimensions of 200 mm $\times$ 200 mm, and is clamped at its four corners. Mild steel plates of a given material type and three different thicknesses viz. 10 mm, 12 mm and 16 mm are considered. 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. The sectional view of plate and projectile during oblique impact is given in Fig. 2.

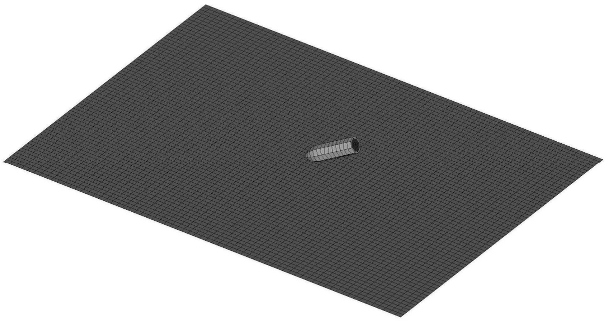

Figure 1: Plate modelled with shell elements and projectile with solid elements

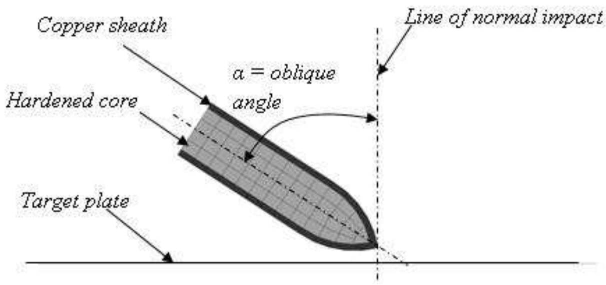

Figure 2: Sectional view of plate and projectile during oblique impact at an angle α

The material model with the keyword *MAT_STRAIN_RATE_DEPENDENT_PLASTICITY (i.e. material type 19) in LS-DYNA has been used for defining the behaviour of target plate designated as MS3 in [7]. In this constitutive model, yield and tensile strengths can be specified in a tabular manner with respect to strain rate. To start with, the quasi-static engineering properties of MS3 plates are obtained and converted to corresponding true values using a standard procedure outlined in [9]. The variations of yield and tensile strengths with respect to strain rate for three varieties of steel designated as DP800, HSLA350 and HSS590 are given graphically in [3]. It has been observed [9] that the rates of increase of yield or failure strength with respect to strain rate are nearly the same for these steel grades. Hence the dependence of yield or failure strength with reference to strain rate has been obtained for MS3 plates using the following scaling relation based on the properties of HSS590:

$$\sigma_{\dot{\varepsilon}}^{(MS3)} = \sigma_{\dot{\varepsilon}_0}^{(MS3)} \cdot \frac{\sigma_{\dot{\varepsilon}}^{(HSS590)}}{\sigma_{\dot{\varepsilon}_0}^{(HSS590)}} \tag{1}$$

where, $\sigma_{\dot{\varepsilon}}^{(Steel\,Type)}$ and $\sigma_{\dot{\varepsilon}_0}^{(Steel\,Type)}$ are dynamic yield strengths at two strain rates: $\dot{\varepsilon}(s^{-1})$ and a low reference or quasi-static strain rate of $\dot{\varepsilon}_0(s^{-1})$. An extrapolation curve fitting approach has been used to obtain the yield and failure strengths of MS3 plates by extrapolation at a high strain rate (e.g. $10,000s^{-1}$) not considered in [3]. Following the approach described, the derived true stress versus true strain behaviours of MS3 target plates at various strain rates for use in LS-DYNA material type 19 are shown in Fig. 3.

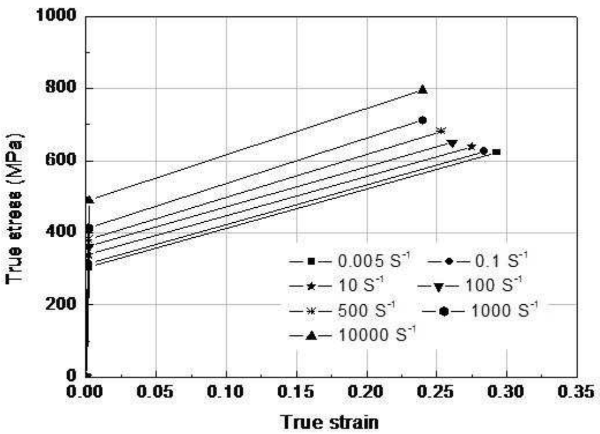

Figure 3: True stress versus true strain behaviours of MS3 plates

The projectile core and sheath have been modelled with material type 24 in LS-DYNA designated with the key word `*MAT_PIECEWISE_LINEAR_PLASTICITY` using the relevant quasi-static properties (given in [9]) of hardened steel and copper respectively. It may be noted that strain rate sensitivity has not been considered in the material modelling of projectile core as well as sheath.

3 Effect of element size on residual velocity

The objective of this study is to determine an optimal element size on plate surface which will yield reliable values of projectile residual velocity. The target plate was meshed with square elements of uniform density throughout the plate. The results for convergence of projectile residual velocity for normal and oblique impact of projectiles on 10 mm thick MS3 plates are presented in Fig. 4. It can be seen that as element size decreases the computed residual velocity converges monotonically to test residual velocity. The convergence patterns were found to be similar for 12 mm and 16 mm thick MS3 plates which have also been studied experimentally in [7].

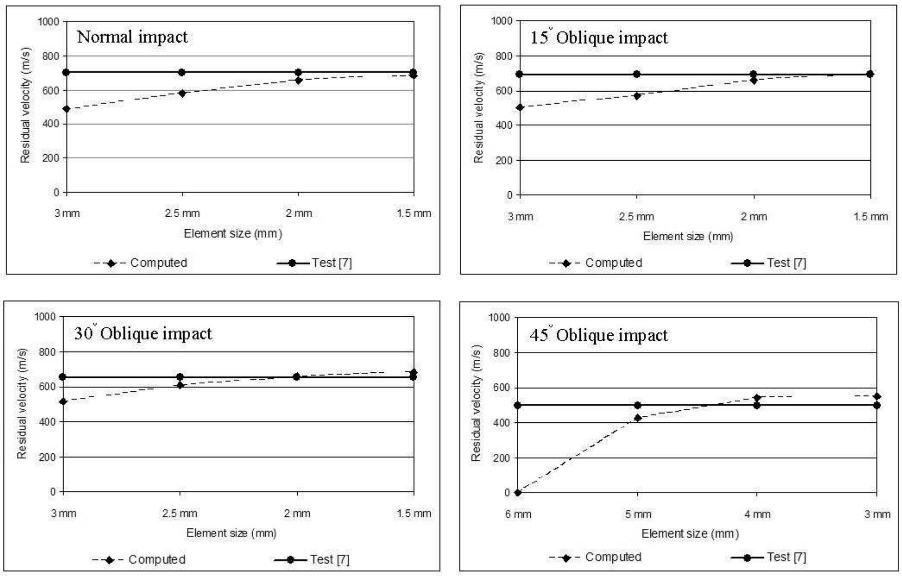

Figure 4: Mesh convergence study of 10 mm thick MS3 plates

`*CONTACT_ERODING_SURFACE_SURFACE` in LS-DYNA has been employed in the convergence study in Fig. 4. A comparison was also made with `*CONTACT_AUTOMATIC_GENERAL` algorithm; the latter option yielded good convergence of residual velocity with the projectile piercing through the target plate in each case, however, a clear perforation in the plate could not always be seen visually. Two integration points through the thickness of plate were specified in the above computations; increasing the number of integration points did not have any noticeable effect on projectile residual velocity even for the thicker target plates mentioned. It can be concluded from the current study that shell elements of size 1.5 to 3.0 mm (depending on angle of obliquity) may be used for simulating impact on mild steel target plates of current planar dimensions and thickness range. A detailed comparison of computed residual velocities with corresponding test-based velocities is listed in Table 1.

4 Simulation of failure mechanisms

Simulation-based failure patterns of target plate for different thicknesses considered in the current analysis are shown in Figs. 5 through 7. In each case analyzed, a certain amount of dishing preceded complete perforation and a similar phenomenon was observed in the tested plates. Additionally, the projectile sheath suffered partial to complete erosion in simulation as was also observed in the tests performed in [7]. Plate bulging in the impact zone appears to increase with

Table 1: Comparison of test-based and computed residual velocities

Plate material in [7]	Plate thickness (mm)	Angle of impact (deg)	Impact velocity (m/s)	Residual velocity (m/s)		% Deviation from test
				Test [7]	Computed	
MS3	10	00	827.5	702.2	685.7	-2.4
		15	815.0	690.4	696.6	+0.9
		30	825.7	654.0	657.7	+0.6
		45	790.0	500.0	549.2	+9.8
		62	821.4	ricocheted	ricocheted	
	12	00	818.0	661.5	616.4	-6.8
		15	842.7	671.6	709.7	+5.7
		30	801.8	598.0	566.4	-5.3
		45	808.0	555.3	544.0	-2.0
		59	815.3	ricocheted	ricocheted	
	16	00	819.7	562.0	519.2	-7.6
		15	817.3	544.4	523.8	-3.8
		30	817.7	496.3	456.7	-8.0
		45	806.1	ricocheted	ricocheted	
		51	819.2	ricocheted	ricocheted	

increasing angle of obliquity. Interestingly, the present simulation procedure is also capable of predicting projectile ricochet at angles close to critical angles of obliquity observed experimentally in [7]. For example, for the 10 mm thick MS3 plate, projectile ricochet that took place at an impact angle of 61.5° in test [7] has been reproduced through present numerical analysis at 62° as shown in Fig. 5(d).

5 Estimation of residual velocity using a semi-empirical procedure

In addition to detailed numerical analysis, approximate relations for estimating residual velocity can be useful tools for design. It needs to be pointed out that rather than the detailed mode of failure which is often the obsession of researchers, what matters in design is: whether perforation will take place for a given impact condition, and the estimation of ballistic limit and residual velocity within acceptable limits of engineering accuracy. To facilitate this objective of engineering design of perforation-resistant armour plates, a few semi-empirical relationships [1,2,4,6,8,10,11] have been developed in the past. These relationships are based on limit-state mechanics of varying degrees of complexity; however, they cater only to normal projectile impact on target plate and include empirical constants the values of which may be difficult to obtain.

The semi-empirical relations for residual velocity prediction for normal impact given by

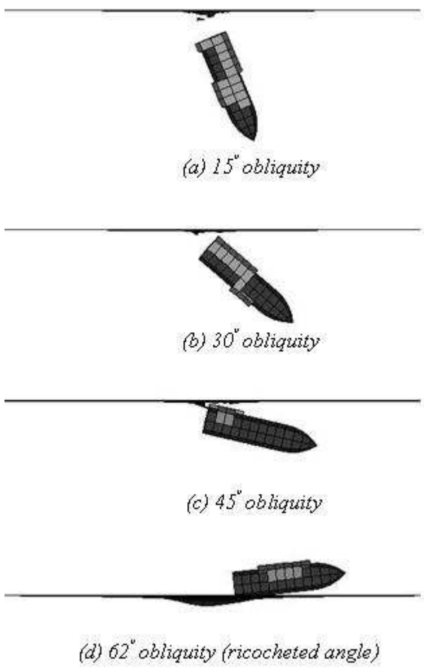

Figure 5: Sectional views of 10 mm thick MS3 plate and projectile after analysis

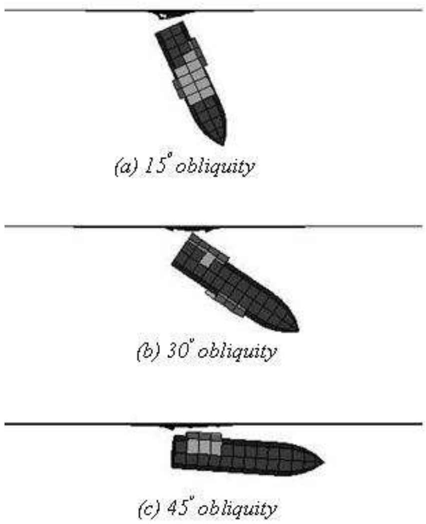

Figure 6: Sectional views of 12 mm thick MS3 plate and projectile after analysis

Gupta, Ansari and Gupta [6] are relatively simple to use, but the values of the parameters k (i.e. 7) and n (i.e. 0.89) suggested in [6] were found to yield unacceptable estimation of residual

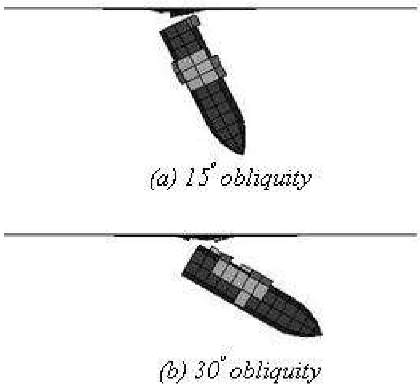

Figure 7: Sectional views of 16 mm thick MS3 plate and projectile after analysis

velocity for the present MS3 plates. To the authors' best knowledge, the only semi-empirical relation for predicting residual velocity for oblique impact on plates is given by Khan, Ansari and Gupta [8]. The relation outlined by the latter authors considers energy-absorption in both shear plugging and dishing modes of failure. However, a drawback of this relation is that it contains a parameter w_c (i.e. central plate deflection) which is not known a-priori. Hence, a simplified relation is outlined below for estimation of residual velocity, assuming a rigid projectile and removal of plate material primarily due to shear plugging, the energy balance equation for the plate-projectile system can be written as:

$$\frac{1}{2}\, m_p\, v_i^2 - \frac{1}{2}\, m_p\, v_r^2 = C\, \left(\frac{\pi\, d\, t}{\cos^2\alpha}\tau_s\right)\, t \tag{2}$$

where, m_p: mass of projectile, v_i : impact velocity of projectile, v_r: residual velocity of projectile, d : projectile diameter, t: thickness of target plate, τ_s : effective shear strength of target plate material, C : a regression factor (i.e. an empirical constant), and α : angle of impact. Analogous to the maximum shear stress theory, the average plate shear stress causing plugging failure in steel plate is assumed as

$$\tau_s \;=\; \frac{\sigma_m}{2} \tag{3}$$

In Eq. 3, the mean flow stress, σ_m, of plate material is interpreted as

$$\sigma_m \;=\; \frac{\sigma_y + \sigma_f}{2} \tag{4}$$

In Eq. 4, σ_y and σ_f are respectively the plate yield and failure strengths. Substituting Eq. 3 in Eq. 2 and rearranging, the expression for residual velocity is obtained as

$$v_r = \left[v_i^2 - \frac{2.20\ \sigma_m\ d\, t^2}{m_p\ \cos^2\alpha}\right]^{\frac{1}{2}} \tag{5}$$

For the case of present MS3 plate, σ_m can be assumed as the average of true yield strength (305 MPa in Fig. 3) and true ultimate strength (623 MPa in Fig. 3) for low strain rate.

In Eq.5, the constant 2.20 is obtained by regression analysis of test data given in the fifth column of Table 2 for both normal and oblique impact of jacketed ogival-nosed projectiles on mild steel plates. A graphical comparison is given in Fig. 8 between test-based residual velocities and those estimated by Eq. 5 for the 10 mm thick MS3 plate. It is observed from Fig. 8 as well as columns 5 and 6 of Table 2 that while the estimation of residual velocity based on Eq. 5 is fairly good at low angles of obliquity, over-estimation results with increasing angle of oblique impact. This outcome is expected as the derivation of Eq. 5 ignored energy absorbed by target plate in dishing which appears to become prominent at angles of obliquity of 25° and above.

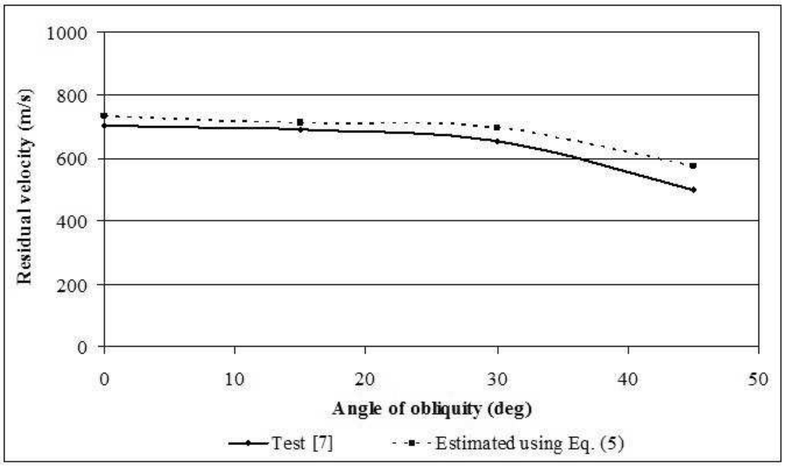

Figure 8: Comparison of residual velocities for 10 mm thick MS3 plates

6 Conclusions

In the current study, the phenomena of oblique impact of jacketed ogival-nosed projectiles on given mild steel target plates have been studied using the explicit contact-impact LS-DYNA 970 solver. A salient feature of present finite element modelling is the discretization of target plate with shell and projectile with solid elements. Strain rate-based elasto-plastic material properties are adopted for target plate and a surface-to-surface contact interface with erosion is activated for analysis. A comprehensive residual velocity convergence study relative to element size has been reported for different angles of obliquity. The final simulation-based residual velocities are the ones which are based on an appropriate mesh density indicated by the convergence study. In addition to the computed residual velocities which are all found to be within 10% of corresponding test-based residual velocities, the failure patterns involving dishing and perforation of

Table 2: Comparison of test-based and estimated residual velocities

Plate material in [7]	Plate thickness (mm)	Angle of impact (deg)	Impact velocity (m/s)	Residual velocity (m/s)		% Deviation from test
				Test [7]	From Eq. 5	
MS3	10	00	827.5	702.2	732.9	+4.4
		15	815.0	690.4	711.4	+3.0
		30	825.7	654.0	696.4	+6.5
		45	790.0	500.0	573.4	+14.7
	12	00	818.0	661.5	675.7	+2.1
		15	842.7	671.6	694.5	+3.4
		30	801.8	598.0	599.6	+0.3
	16	00	819.7	562.0	542.3	-3.5
		15	817.3	544.4	512.9	-5.8
		30	817.7	496.3	405.9	-18.2

target plate and sheath erosion of projectile obtained through simulation are similar to physical failures in tests. A simplified semi-empirical relation for residual velocity estimation based on the shear plugging failure of a target plate has been presented and shown to yield good results for zero (i.e. normal) to low angles of obliquity (not exceeding 25°).

References

[1] M.E. Backman and W. Goldsmith. The mechanics of penetration of projectile into targets. *Int J Eng Sci*, 16:1–99, 1978.

[2] Y.L. Bai and W. Johnson. Plugging: physical understanding and energy absorption. *Metals Tech*, 9:182–190, 1982.

[3] Y. Benda. Fatigue behaviour of advanced high strength steels for automotive applications. February 2003.

[4] X.W. Chen and Q.M. Li. Shear plugging and perforation of ductile circular plates struck by a blunt projectile. *Int J Impact Engng*, 28:513–536, 2003.

[5] A. Deb, M. Raguraman, and N.K. Gupta. Simulation of oblique impact of jacketed hardened-core projectiles on mild steel plates. *Proceedings of IMPLAST*, 07:631–638, 2007.

[6] N.K. Gupta, R. Ansari, and S.K. Gupta. Normal impact of ogival nosed projectiles on thin plates. *Int J Impact Engng*, 25:641–660, 2001.

[7] N.K. Gupta and V. Madhu. An experimental study of normal and oblique impact of hard-core projectile on single and layered plates. *Int J Impact Engng*, 19:395–414, 1992.

[8] W.U. Khan, R. Ansari, and N.K Gupta. Oblique impact of projectile on thin aluminium plates. *Defence Science Journal*, 53:139–146, 2003.

[9] M. Raguraman, A. Deb, and N.K. Gupta. A numerical study of projectile impact on mild steel armour plates. *Current Science*, 93(4):498–506, 2007.

[10] H-M. Wen and N. Jones. Low-velocity perforation of punch-impact-loaded metal plates. *J Pressure Vessel Tech*, 118:181–187, 1996.

[11] J.A. Zukas, T. Nicholas, H.F. Swift, L.B. Greszczuk, and D.R. Curran. *Impact dynamics.* Wiley, New York, 1982.